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BOOK OF ABSTRACTS

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411: 20 Year Old Real-Time Sensor and Management Systems

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Incheon International Airport in South Korea was built on an artificial island. This artificial island primarily consisted of clayey and silty hydraulic filled materials overlain by marine soft clayey soils. Due to the inherent low strength and high settlement expected from these weak soils, massive ground improvement techniques were designed. Additionally, a pilot test fill was built with several different ground improvement techniques with 965 sensors for performance monitoring, and performance was supposed to be reported on daily basis. To meet the reporting frequency requirement, an automatic data logging (called "tele-measuring" at that time) system and real time data analysis/reporting system was adapted. With this system, daily performance reporting could be made without any difficulties – it even could predict the future settlement, possible completion time of consolidation, and amount of extra fill materials needed. In addition the system could predict the impending failure of a 21 ft. high slope on a rainy day – the contractor was immediately alerted for the retrofitting work and failure was prevented. This presentation contains most components that modern Cyber Infrastructure Management System contains in an old fashioned way. But it clearly shows some insight on the capability of modern Cyber Infrastructure Management System.

149: 2D Meso-Scale Modeling of Masonry Elements Using Cohesive Elements

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Many stone masonry structures that were constructed in the past centuries are now counted towards the cultural heritage. The low strength and brittle behavior make these heterogeneous structures very vulnerable to various natural or man-made disasters such as earthquakes. In order to ensure their structural safety and to implement appropriate interventions, engineers need to understand the failure mechanism and to estimate the force and deformation capacity. Since it is difficult to obtain detailed material properties and simulate strong discontinuities, advanced simulation techniques have only been applied recently to masonry structures. In this paper, we simulate stones and mortar separately on a meso level and use cohesive zone modeling for simulating dynamic crack propagation. With this approach, cracks are modelled explicitly and the properties of the crack interface can be easily reflected. We apply the extrinsic cohesive zone model developed by Snozzi and Molinari, 2013. In the extrinsic method, the cohesive element will not be inserted until the stress on the corresponding element edge meets a certain criterion. The finite element analysis is developed using the open source software Akantu, newly developed by LSMS, EPFL. The available cohesive element is enhanced to consider the transfer of friction across interfaces and the added code is parallelized to make use of the high performance computing capacities of Akantu. We conduct parametric studies to investigate the influence of several variables on the force-deformation characteristics of stone masonry (e.g., strength ratio between mortar and interface, the friction coefficient). The influence of the randomness of the material properties on the masonry mechanical behavior is also examined and the effect of different assumptions with regard to the correlation of variables explored.

249: 3D Experimental Investigation of Fabric Evolution During Triaxial Compression of Granular Materials

Andrew Druckrey, University of Tennessee
Khalid Alshibli, University of Tennessee

Fabric of granular materials is used to describe particle-to-particle association within a mass of a granular material. It is well known that fabric has a significant influence on the behavior of granular materials. Microstructural directional data in granular materials such as branch vectors or contact normal vectors can be quantified by fabric tensors to describe fabric anisotropy. Such 3D experimental measurements have been elusive until recently. Synchrotron micro-computed tomography (SMT) imaging technique was used to acquire multiple in-situ images during triaxial compression experiments on rounded spherical glass beads and angular silica sand. Contact normal vector and branch vector fabric elements are quantified for both materials. Fabric element orientation is analyzed and fabric tensors are calculated at incremental strain levels. Internal fabric anisotropy within the two materials, defined by the normalized second invariant of the second order deviatoric fabric tensor, correlates well with the global loading of the material. The presentation will discuss the effects of particle-scale morphology on the initial fabric and fabric evolution within sheared specimens of granular materials.

242: 3D Experimental Investigation of Local Shearing in Triaxial Testing of Sand

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Khalid Alshibli, University of Tennessee

Strain localization into zones of intensive shearing known as shear bands has been extensively investigated in the literature. The failure mode of specimens tested under axisymmetric triaxial compression is commonly manifested through shear bands or diffuse bifurcation (bulging). However, particles may not shear along a single band during the hardening regime before the development of the specimen global failure. To investigate particle shearing during pre-peak loading stage, a thorough grain scale approach is required to determine the behavior of the granular material. 3D synchrotron micro-computed tomography (SMT) scans of sand and glass beads were acquired at multiple strains during in-situ triaxial testing. Individual particles were identified and tracked through incremental strains and particle translation was calculated. Each particle's neighboring particles were determined, and translation fields for each of the neighboring particles were calculated. The Euclidian length differences between the particle translation vector and neighboring particles translation vectors were averaged, resulting in a translation gradient relative to the particle's neighboring translation vectors. The translation gradient can be utilized to determine localized shearing within granular materials. Progression of local shearing into a final well defined single or multiple shear bands provides a micro-mechanics insight into mechanisms that cause failure within sheared granular materials.

41: 3D Modeling of Grain Boundaries Using a Fully-Nonlocal and High-Performance Realization of the Quasicontinuum Method

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Dennis Kochmann, California Institute of Technology

Grain boundary-dislocation interactions have been a subject of great interest for studying and predicting deformation mechanisms in polycrystalline materials. Grain boundaries are generally responsible for size effects in the effective properties of polycrystals, e.g., affecting their strength through the Hall-Petch relation or alternative plastic mechanisms of grain boundary sliding and rotation in nano-crystalline systems. For small-scale

structures where the geometric feature size is on the same order as the characteristic microstructural size, such interactions have been shown to produce more complex size effects that may change material properties significantly. Modeling grain boundaries and studying their interactions with dislocations gives us insight into the underlying mechanisms that give rise to the aforementioned size effects. Here, we investigate the interaction of dislocations with grain boundaries in aluminum and study the energy and strength of the grain boundary. Dislocations are created by nanoindentation and travel towards the grain boundary. To overcome size limitations in atomistic models, we use a fully-nonlocal quasicontinuum (QC) method which enables us to coarsen the model away from the grain boundary and to dramatically decrease the degrees of freedom in the system. Therefore, QC allows for the modeling of simulation sizes beyond the scope of traditional molecular dynamics, which are comparable to nano-crystalline structures that are studied experimentally. We use fully non-local energy-based QC with an optimal summation that minimizes force artifacts and energy errors usually associated with other existing QC frameworks. This results in an adaptive framework which reduces full atomistic resolution to those regions where it is indeed required (e.g., around the moving dislocation or near the grain boundary). We will summarize the methodology and discuss representative results for grain boundary-dislocation interactions in aluminum.

704: A 2D Fluid-Structure Interaction Method for Modeling the Performance of Resetting Semi-Passive Stiffness Dampers (RSPSD)

Antonio Velazquez, Ohio University
Ken Walsh, Ohio University

Natural and man-made hazards, such as earthquakes, hurricanes or implosive loads, have the potential to cause large-scale forfeiture on civil infrastructure in general, often compromising significant economic losses and, in some utmost cases, even human life. Structural vibration control offers an alternative solution for mitigating damage during these extreme load solicitations by absorbing the exceeded energy imposed on the structure. Semi-passive control mechanisms, especially the ones that do not depend on multi-component feedback control constituents subjected to reliability issues, have emerged as an alternative solution to alleviate the structural overload that generates risk of failure and loss. In this line of thinking, energy diffusion micro-mechanics, diverted patterns of heat transfer and fuzzy temperature pathways within the gas chamber, as well as the identification of thermodynamic demeanours of critical components such as valve mechanisms and pressure release tubes, have not been fully addressed in the literature. The objective of this investigation is to present a numerical model that properly characterizes the performance of the so-called resetting semi-passive stiffness damper (RSPSD), based on the principles of the dynamics equation (mass and momentum) and the unsteady 2D incompressible heat-transfer Navier-Stokes equations combined. A computational structural dynamics (CSD) model of the internal chamber configuration of the RSPSD device, along with a computational fluid dynamics (CFD) model of the contained inviscid fluid (gas) are coupled to perform the fluid-structure interaction (FSI) phenomenon. The numerical solution considers a dedicated solver for each of the two stiffness-dependent physical systems involved. Examination of the interaction between the gas contained in a 2D enclosed innertube and a moving piston shaft attached to an external fixed spring is performed for indistinct passive resetting conditions that depend on reaching minimum strike lengths of the piston shaft. The physical FSI model is conceived as a duplex interaction mechanism: (1) the piston structural dynamics where the input is defined as the pressure exerted on the shaft section by the contented fluid, while the outputs become the shaft instant position and velocity and, (2) a secluded fluid flow model where the inputs are both the piston's position and velocity and the output becomes the instant fluid pressure. In the last stage of the investigation, a numerical optimization scheme, based the principles of parallel computing, is performed to account for low frequency responses of the piston that could lead to a quasi-steady-state evolution of the fluid.

542: A Bayesian Framework for Interactive Design of Staged Excavation Based on MSD

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Giovanna Biscontin, University of Cambridge

In the past few decades, the construction of underground spaces has become a necessity in urban areas where the population is very dense. At the same time, the impact of the construction of underground structures on other infrastructure raises a lot of concerns because the deep excavations might cause movements that can damage adjacent structures. Therefore conventionally engineers tend to choose unfavourable conditions for the analysis and design of excavation supporting systems. Although sophisticated finite element models may be able to give accurate predictions of the displacements, it is difficult to consider all sources of information during construction, objective and subjective, and identify all sources of underlying uncertainties. Thus, the characteristic parameters used for design are inevitably conservative, which also means uneconomical. Interactive design provides a way to modify design as the construction progresses, by incorporating knowledge learnt during the process. It can achieve a leaner design based on most probable rather than most unfavourable possibilities, resulting in savings of both money and time. During construction, back analysis is conducted matching predicted and measured deformations to find a set of soil parameters that also give more accurate predictions for later stages. Then the decision to carry out a modified design can be made using these new values of relevant soil properties. This procedure needs to be rapid and simple. A probabilistic methodology using Bayesian updating is developed to estimate soil properties and model uncertainty for back analysis. The posterior statistics of the unknown soil properties and the model parameters are computed using the DRAM algorithm (Laine 2008), which is an adaptive Markov Chain Monte Carlo (MCMC) simulation method. Rather than embedding time-consuming finite element methods in this process, a simplified method, Mobilisable Strength Design (MSD), is incorporated. The MSD is a general unified simple design methodology, which can satisfy both safety and serviceability in a single step of calculation (Osman and Bolton 2004). Therefore, time for iteration between soil modelling and MCMC can significantly reduce. This numerical procedure is applied to reassess the soil behaviour of a 30 m deep excavation for the Western Ticket Hall (WTH) in Crossrail London Tottenham Court Road station. The field observations were obtained from inclinometer data that measured lateral movements of the soil behind the diaphragm walls throughout construction. At each construction stage, the new added measurements are fed into the probabilistic method and a set of updated parameters can be achieved. Based on the 'most probable' parameters from earlier stages, better predictions of deflection with confidence interval can facilitate the interactive design during construction.

405: A Comparison between Measured and Predicted Least Principal Stresses Using a Viscoplastic Model

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Mark Zoback, Stanford University
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In this study, we examine the variation of viscoplastic properties of shale samples with depth from an area of "stacked pay" in the Permian Basin of West Texas. In this area, multiple horizontal wells are drilled and hydraulically-fractured at different depths to exploit the hydrocarbons in different reservoirs. By better understanding variations of the least principal stress with depth, we hope to help optimize the drilling and hydraulic fracturing process. Following Sone and Zoback, (Jour. Petrol. Sci. and Eng., 2014) we are studying the degree to which viscoplastic creep in some formations leads to a more isotropic stress field. In other words, the least principal stress is expected to increase in more viscoplastic rocks, creating frac barriers. We report here a

series of creep experiments on samples from different depths to test this concept. Also following Sone and Zoback (2014), a power-law creep model is used to obtain the creep constitutive parameters. To calculate stress magnitude at depth, we need to constrain the overburden stress, minimum principal stress and Young's modulus, as well as a parameter that describes the tendency for viscous deformation of the rock. Finally, the computed least principal stress is compared with the minimum principal stress measurements provided from Diagnostic Fracture Injection Tests (DFITs).

503: A Comparison Between the Finite Element Method and Material Point Method in Mesoscale Crystal Plasticity Simulations

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Ashley Spear, University of Utah
Rebecca Brannon, University of Utah
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The Finite Element Method (FEM) is one of the most widely used computational methods in structural and solid mechanics problems. The domination of FEM is substantiated by its versatility and computational performance, but is not a comprehensive method of analysis for all problems. Due to the popularity of FEM, many engineers follow the paradigm of exclusively utilizing FEM. However, there are various solution methods other than FEM that are advantageous in particular problems such as the Material Point Method (MPM). This work aims to perturb this paradigm by comparing the computational performance, accuracy, and convergence between FEM and MPM to establish casual guidelines for various applications in solid and structural mechanics. MPM is known to be more computationally expensive in general, but has been said to be more favorable for simulations involving large deformation or discontinuities as re-meshing is unnecessary. However, these characteristics have not been directly substantiated thoroughly in the literature. Here, the favorability or lack thereof of modern MPM will be quantitatively characterized through the use of simple case studies using a crystal plasticity constitutive model. Specifically, for simulations of small deformation and a continuous material, the convergence rate and error of FEM and MPM will be compared. Furthermore, the convergence of FEM for large deformation simulations will be compared to MPM. For materials such as metallic foams, compression can cause element/particle contact. As contact algorithms are necessary to avoid element interpenetration in FEM, the overall performance and results will be compared with an MPM implementation (where implementing an explicit contact algorithm is unnecessary). With these results, a general guideline for which method to implement can be developed to optimize simulation convergence and accuracy.

770: A Comparison of Two Damage-Plasticity Formulations for Concrete Like Materials

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The pre- and post-peak performance features of two widely used damage-plasticity constitutive formulations are assessed for modeling the multiaxial response behavior of cementitious-frictional materials such as concrete. Two critical benchmark problems were studied within the commercial software system ABAQUS using the Lee-Fenves damage-plasticity two-invariant concrete formulation, and the Duvaut-Lion three invariant formulation of Concrete Material 195 which has been implemented in LS-DYNA. Consistent parameter identification was performed to calibrate both formulations and the response characteristics of the two constitutive formulations were studied under uniaxial tension, compression and pure shear for the purpose of verification. Using

displacement and mixed control, the nonlinear response features and damage states were observed in conventional triaxial compression, CTC, and extension, CTE, with focus on the difference between the two formulations to capture the transition of volumetric compaction into volumetric dilation (Reynolds effect). The study demonstrates that both constitutive implementations are capable to capture the anticipated reversal of volumetric behavior close to failure, though they show deficiencies in the case of high levels of lateral confinement. Focusing on the reversal from compaction to expansion under biaxial and triaxial confinement, the performance of the two damage-plasticity formulations was compared in terms of uniqueness and stability limiters with regard to the damage evolution and dilative behavior under the triaxial load histories. Based on these failure diagnostics, the main shortcomings of each formulation are discussed and possible enhancements and remedies are proposed for the pre- and post-peak features.

523: A Computational Approach to Model Dtrain-Induced Crystallization in Rubber

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Christian Linder, Stanford University

Strain-induced crystallization (SIC) is a process in which small crystalline regions appear inside the amorphous rubber material when it is subjected to large amounts of stretch. Formation of these polymer crystals around the crack tip is often linked to rubber's superior fatigue and fracture properties [1]. A computational framework is proposed, based on the micro-mechanical properties of polymer chains, to model SIC computationally using finite elements method. Statistical mechanics description of crosslinked polymer chains provides explanation for the elastic response of rubber material as well as the SIC phenomenon [2,3]. The proposed multi-scale model uses non-Gaussian formulation of semi-crystalline polymer chain. The macroscopic deformation of rubber is linked to the microscopic stretch and rotation of polymer chains using MAPC [4] homogenization method. Experimental results show that almost all of the polymer crystals are orientated in the stretch direction [5]. These oriented crystals are assumed to create induced anisotropy in the stretched polymer. In this model, a macroscopic crystallinity parameter is defined which describes the magnitude and orientation of the polymer crystal. The degree of crystallinity of any polymer chain depends on this macro-scale crystallinity parameter as well as the chain's orientation with respect to the direction of the crystal. Numerical simulation results are presented including uniaxial tension tests and complex 3D simulation of SIC around a cracked region. The simulation data shows agreement with experimental results [1,5] even in complex stress situations around a crack. The effect of induced anisotropy is studied in these simulations. [1] Rublon, P., Huneau, B., Verron, E., Saintier, et al. (2014). Multiaxial deformation and strain-induced crystallization around a fatigue crack in natural rubber. Engineering Fracture Mechanics, 123, 59-69 [2] Kroon, M. (2010). A constitutive model for strain-crystallising Rubber-like materials. \Mechanics of Materials, 42(9), 873-885. [3] Mistry, S. J., Govindjee, S. (2014). A micro-mechanically based continuum model for strain-induced crystallization in natural rubber. International Journal of Solids and Structures, 51(2), 530-539. [4] Tkachuk, Linder. (2012). The maximal advance path constraint for the homogenization of materials with random network microstructure. Philosophical Magazine, 92(22), 2779-2808. [5] Toki, S., Sics, I., Ran, S., Liu, L., Hsiao, B. S. (2003). Molecular orientation and structural development in vulcanized polyisoprene rubbers during uniaxial deformation by in situ synchrotron X-ray diffraction. Polymer, 44(19), 6003-6011.

698: A Computational Framework to Transfer 3D Imaging Data into a Multifield Flow Profile of the Liver

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Stein Stoter, University of Minnesota

A major challenge for liver flow simulations is to represent the multiscale geometry of the vessel network that gradually subdivides from larger arteries and veins into microscopic capillaries, including a change of flow properties. We begin by reviewing the notion of diffuse geometry, illustrate its integration into finite element analysis, and discuss implications with respect to accuracy and convergence. We then combine image processing techniques, diffuse geometry concepts, and adaptive finite element methods to automatically transfer imaging data of the liver vessel network into multifield flow profiles. Our technology first employs unsupervised image segmentation to separate vessel and hepatic space. It then generates a smooth phase-field representation of the vessel domain by solving the transient Allen-Cahn equation. Assuming Navier-Stokes flow in the vessels and Darcy flow in the hepatic space, we leverage information provided by diffuse interfaces to re-express all surface coupling terms of the variational formulation into volume terms. We compare diffuse geometry based flow results with standard simulations based on sharp interfaces and discuss the future potential of our approach for patient-specific automatic liver simulations.

97: A Computational-Experimental Framework To Estimate Transport Properties Of Multi-Phase Composites

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This study presents a straightforward framework to determine the effective transport properties (e.g., diffusivity or conductivity) of multi-phase composite materials based on diffusivities of their constituents. The proposed framework addresses various controversial factors affecting the diffusivity of particulate composites, such as consideration of accurate microstructures, high contrast in properties of constituents, and high volume fraction of particles. In this framework, either random particle generation algorithms or available X-ray images are used to re-construct microstructure of particulate composites. Then, finite element (FE) diffusion simulations of the re-constructed a particulate composite is conducted based on the diffusivity of its constituents. The effective diffusivity of particulate composite is then estimated by analyzing and comparing the results of FE simulations with relevant analytical relationships. The proposed computational framework is then validated against available analytical solutions; experimental data regarding oxygen diffusivity of fine aggregate matrix (FAM) of asphalt concrete; and experimental data regarding thermal conductivity of a copper-solder composite. These comparisons show that the proposed framework is capable of predicting the effective transport properties of multi-phase materials. Finally, the proposed technique is used to simulate 2D and 3D oxygen diffusion problem in a dense-graded asphalt concrete mixture. Results confirm the wide applicability of the proposed method.

142: A Constitutive Model for Matching Modulus Reduction and Damping Behavior

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Soil is known to exhibit nonlinear behavior at very small strains, which is often represented using modulus reduction and damping curves. Constitutive models commonly used in soil dynamics problems typically do not match both modulus reduction and damping, forcing users to accept a misfit between the desired soil behavior and that achieved by the constitutive model. Modulus reduction and damping curves are known to depend on

confining pressure, which complicates their adoption in constitutive models for cases where effective stress changes during loading (e.g. when excess pore pressure develops under undrained loading). In this presentation we present a constitutive model that uses modulus reduction and damping curves that are formulated with respect to stress ratio instead of shear strain. Formulating in this manner has two benefits: (1) the curves are independent of confining pressure, and (2) the plastic modulus can be directly computed based on position in stress-space. The formulation allows users to perfectly match dynamic properties (i.e. modulus reduction and damping curves). The input parameters are all well-known engineering properties easily measured in laboratory tests. We present the performance and the calibration of the model through simulations of cyclic triaxial and simple shear tests. Finally, we present the performance of the model in 2D site response simulations. With this presentation the audience will learn: - How we derived our constitutive model - How to calibrate our constitutive model - How to use our constitutive model in dynamic simulations

761: A Continuum Micromechanics Approach to the Elasticity of Planar Fiber Networks: Applications to Paper Materials

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Viktoria Vass, Vienna University of Technology
Josef Eberhardsteiner, Vienna University of Technology
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Production of materials consisting of planar fiber networks, of which paper materials (hereafter: paper) represent a subset, has been a major driver of science and engineering. With respect to the stiffness of these materials, we bring a proposition that goes beyond traditional statistical correlations with porosity or empirical structure-property relationships, as to decipher the microstructural interactions governing their overall macroscopic mechanical behavior. This behavior is predicted from the material microstructure, elastic properties and composition through an homogenization method with foundations in the theory of continuum (micro)mechanics. Thereby, we envision planar fiber networks as planar transversely isotropic porous polycrystals consisting of needle-like fibers with non-vanishing stiffness and disk-like pores with vanishing stiffness; before we ultimately reach a groundbreaking self-consistent micromechanical model describing the elastic behavior of such networks. Experimental validation of our model is done for the specific case of paper and relies on two independent experimental sets. A first set consists of elasticity constants relating to macroscopic paper stiffness micromechanically predicted for the full range of possible porosities. These predictions, computed on the basis of typical, paper-making, high and low bounds of microscopic pulp fiber stiffness, generate a region in ℝ2, to which, a second set, consisting of the corresponding elasticity constants relating to macroscopic paper stiffness, experimentally determined for some specific porosities, should belong to. Our model predictions beautifully frame the corresponding experiments, thus highlighting the potential of micromechanical modelling in improving design of materials consisting of planar fiber networks, and more specifically of paper, both from environmental and economic-social standpoints, through optimization of key parameters such as porosity or mechanical and geometrical properties of fibers and pores, in order to achieve the desired macroscopic elastic properties.

12: A Continuum Model for Additively Manufactured Lattice Meta-Materials

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Mathew Barham, Lawrence Livermore National Laboratory
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Nathan Barton, Lawrence Livermore National Laboratory

Additively manufactured lattice materials are exceptionally light relative to their stiffness and strength and lattice structures provide designers an excellent framework for tailoring a material to a particular application. However, discrete models of such structures, which resolve each individual microscale feature, rapidly become computationally unaffordable, even on the largest supercomputers. This presentation describes the development of an equivalent continuum model designed to vastly reduce the computational expense of modeling complicated structures made of lattice meta-materials. A key component of the model is a method for capturing the microinertia of the lattice structures, which turns out to be critical in accurately representing the dynamic characteristics of the equivalent continuum. The presentation further describes the validation of the model against experimental tests on small specimens of lattice material and discusses potential applications of lattice meta-materials to structures designed to mitigate shock loadings.

389: A Coupled DPD/DEM Model Towards Functionally Graded Material Fabrication by a Combined Vibration and Sedimentation Method

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Zhenyu Shou, Columbia University
Fangliang Chen, Columbia University
Huiming Yin, Columbia University

A novel vibration and sedimentation combined approach has been recently developed to fabricate an aluminum/High-Density Polyethylene (HDPE) functionally graded material (FGM) for a multifunctional building envelope for high performance of energy efficiency. The FGM is fabricated by mixing solid particles in HDPE suspension with a high solid load (~70 vol%). Our laboratory test showed that distinct mixtures were obtained by using different size and concentration of the solid particles. To optimize the manufacturing process, a better understanding of the physics lying behind this phenomenon is highly demanded. For this purpose, a coupled dissipative particles (DPD)/ discrete element method (DEM) model is developed to simulate the fabrication process. The solid-liquid and liquid-liquid particle interactions are described by extending the reduced rough sphere model in DPD, whereas the solid-solid particle interaction was governed by DEM. The size ratio between solid and liquid particles are studied, and the empirical equation is provide to predict the size ratio of solid to liquid particle at a given particle concentration. Heterogeneous computing based on GPU is carried out to accelerate the simulation, which makes it possible to simulate the mixing system with particles up to 4 million particles.

748: A Damage Analysis for Brittle Materials Using Stochastic Micro-Structural Information

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Shih-Po Lin, Ford Motor Company

In this work, a micro-crack informed stochastic damage analysis is performed to consider the failure process of material with stochastic microstructure. The derivation of the damage evolution law is based on the Helmholtz free energy equivalence between cracked microstructure and homogenized continuum. The characteristics of stochastic representative volume element (SRVE) used in the construction of the stochastic damage model is investigated based on the principle of the minimum potential energy. The mesh dependency issue is addressed by

introducing a scaling law into the derivation of damage evolution equation. The proposed methods are validated with a triaxial test of an ultra-high strength concrete.

386: A Discontinuous Unscented Kalman Filter for Non-Smooth Problems

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Eleni Chatzi, ETH Zürich

A wide range of engineering problems involve strongly non-linear behavior. In such cases the numerical identification of the corresponding numerical models poses challenges for algorithms based on linearization, such as the Extended Kalman Filter, as already documented in existing literature. On the other hand, the Unscented Kalman Filter, suggested by Julier and Uhlmann, has been shown to be substantially more robust in dealing with this type of problems. Nonetheless, the previous methods were developed under the assumption that all of the dynamic states of the problem are observable and all parameters are identifiable for a given set of measurements. While this is a property that can be satisfied for smooth systems by careful selection of the measurement set, it cannot be consistently satisfied for non-smooth problems, i.e., problems whose state-space derivatives are not infinitely differentiable. The latter case often appears in engineering problems involving plasticity, friction or impacts amongst many other cases. For such cases, one or more of the parameters may switch from being identifiable to unidentifiable between successive time instances depending on the realization of the states. This behavior inevitably affects existing Kalman Filter based algorithms and their behavior and calls for a special treatment that the authors call the 'Discontinuous modification'. In this presentation, the Discontinuous alternative will be combined with the robust Unscented Kalman Filter resulting in the Discontinuous Unscented Kalman Filter (DUKF). The advantages and robustness of DUKF over the standard UKF will be illustrated using selected engineering examples involving non-smooth behavior.

635: A Discrete Filter Scheme for Topology Design with Material Nonlinear Behaviors Using the Ground Structure Method

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Adeildo Ramos Jr., Federal University of Alagoas
Glaucio Paulino, Georgia Institute of Technology

Topology optimization of trusses using the ground structure method is a practical tool that allows for improved design with minimal design iterations. However, the final topology consists of a large number of undesirable thin bars that may add artificial stiffness and degenerate the condition of the structural equations, leading to an invalid final structure. Moreover, most work in this field has been restricted to linear material behavior, yet real materials generally have nonlinear behavior. To address these issues, we propose an efficient reduced-order filter scheme that can be applied to large-scale two- and three-dimensional topology optimization of trusses with nonlinear constitutive behavior. The proposed scheme is capable of accounting for the influence of nonlinear constitutive relations and load levels on optimizing a structure, yielding the true displacement field without artificial stiffness by simply using the bars that exist in the structure, and improving convergence performance within nonlinear structural problems. The use of the reduced-order information significantly results in significantly smaller structural and optimization systems within a few iterations, leading to drastically improved computational performance. Through several examples and practical designs in two- and three-dimensions, we demonstrate that the proposed scheme with material nonlinearity is a practical design tool that takes into account real-life demands in material, design, and manufacturing aspects. Its application to a large-scale nonlinear optimization problem shows that the proposed filter algorithm, while offering the same optimized structure, is 45 times as fast as the

standard GSM.

454: A Discrete Hydro-Thermal-Chemo-Mechanical Model for Deterioration of Concrete Structures

Giovanni Di Luzio, Politecnico di Milano (University)
Gianluca Cusatis, Northwestern University
Xinwei Zhou, Engineering and Software System Solutions, Inc.(ES3)
Daniele Pelessone, Engineering and Software System Solutions, Inc.(ES3)

Recently a advanced multi-physic computational frameworks (Di Luzio and Cusatis, 2013; Alnaggar et al 2013; Abdellatef et al 2015) has been proposed and successfully used to model: (1) the mechanical behavior of concrete, including visco-elasticity (creep/relaxation), cracking and damage, hygro–thermal deformations; (2) heat transfer due to environmental temperature variations and internal heat generation by exothermic chemical reactions; (3) moisture variation and moisture diffusion associated with environmental exposure and internal water consumption; (4) the evolution of chemical reactions occurring at early-age in concrete and, more generally, in cementitious composites; and (5) aging, that is the evolution of the mechanical and hygro–thermal material properties from the time of casting to the completion of early-age chemical reactions. However, in those frameworks there isn't a full coupling between the mechanical model and the hygro-thermo-chemical model since they have been run as a staggered problem, with the heat, moisture transport and chemical analyses preceding the mechanical analysis. This approach is working well as long as cracking of the concrete is limited. With increasing damage such cracking is known to increase the effective permeability of concrete and the hygro-thermo-chemical model should take into account this effect. The present work describes recent developments of a discrete model for coupled fracture-flow analyses of cementitious materials. The discrete lattice discrete particle model (LDPM) mesostructure is used to construct the edges (the elements of the flow lattice) which are along the triangular facets of the LDPM mesostructure, where the polyhedral cells are in contact. This creates a dual-lattice model, fracture analyses are performed on the structural lattice, whereas flow analyses are performed on the flow lattice. In order to couple the fracture and flow analyses, the amount of crack opening of each structural element which exhibiting fracture, is used to evaluate the permeability increase of the surrounding flow lattice elements, in accordance with theory or experimental observations. The capabilities of this model are demonstrated by simulating experimental data relevant to water absorption in cracked reinforced concrete.

691: A Distributed Electro-Conductive Finite Element Method Devoted for Energy-Harvesting and Self-Monitoring Applications on Plate-Like Reinforced Structures

Antonio Velazquez, Ohio University
Munir D. Nazzal, Ohio University
Hajir A. Ali, Ohio University

Vibration-based energy harvesting technologies have been heavily inquired over the last decade, whereas advanced structures and materials with integrated self-monitoring capabilities are becoming vital in the rapid development of "smart" mechanical systems applied to civil infrastructure. In this line of thinking, models in this field had incorporated concepts from different background including three-dimensional linear elastic and dielectric theories aiming at powering up small electronic components by converting the waste vibration energy available in the environment into electrical drive source. Many civil structures, such as geosynthetic reinforcement on flexible pavement, are regarded as distributed and flexible in nature. In those cases, distributed dynamic measurements and active vibrations are both the two main features for achieving structural stress-strain

monitoring and micro-electrical power harvesting. An electromechanically-conductive finite-element (ECFE) model is presented under the basis of piezoelectric transduction principles devoted for modeling both electropotential-strain mapping and vibration-to-electricity conversion. A computational program, grounded in the mechanical energy of the structure and the electrical energy of the piezoelectric material, is implemented for analyzing the static and dynamic behavior of piezoelectric-layer based composites. A plate-type formulation with internal degrees of freedom is performed to account for aspect ratios of piezoelectric energy harvesters that could withstand symmetric and non-symmetric excitations. Generalized Hamilton's principle applied to electro-conductive elastic bodies is reviewed, whereas Kirchhoff plate theory is applied to model piezoelectric energy on thin - plate like - structural configurations. Electrical field is coupled with the stress–strain equations by means of the Maxwell stress tensor, and relevant parameters in the model are systematically varied to track their influence down on the resulting piezoelectricity estimation. Predictions of the ECFE model are verified against analytical solutions (i.e. unimorph and bimorph cantilevers with tip mass) and evaluated under cyclic as well as static loads. Finally, an optimization problem is solved to account for the embedding conditions of the piezoceramics in order to maximize electrical power within the vibration constraints stipulated by the structural monitoring behest.

352: A Domain Decomposition Based Pre-conditioner for the Solution of Shear Bands

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Haim Waisman, Columbia University

Shear bands are one of the most fascinating instabilities in metals that form under high strain rates. They describe narrow regions, on the order of microns, where plastic deformations and significant heating is severely localized that eventually lead to fracture nucleation and failure of the component. In this work shear bands are described by a set of four strongly coupled thermo-mechanical equations discretized by a mixed finite element formulation. A thermo-viscoplastic flow rule is used to model the inelastic constitutive law and finite thermal conductivity is prescribed which gives rise to an inherent physical length scale, governed by competition of shear heating and thermal diffusion. The residual equations are solved monolithically by a Newton type method at every time step and has been shown to yield mesh insensitive result. The Jacobian of the system is sparse and has a nonsymmetric block structure that varies with the different stages of shear bands formation. The goal of our current work is to develop a preconditioner that first takes advantage of the particular discretization used in the irreducible shear band NURBS quadrilateral element. To do so a Schur complement is used to eliminate two of the four discretized fields. Subsequently a domain decomposition approach is used to decompose the domain into a shear band subdomain and a zone further away that doesn't suffer intense plastic deformation, so called healthy subdomain. The key idea is then to form the preconditioner by reusing the information in the healthy subdomain while the shear band subdomain is fully resolved in each linear solve. This results show that such domain decomposition preconditioner is robust and results in optimal cpu times when applied to standard bilinear shape functions and high order NURBS shape functions.

134: A Feasibility Study of a Shape Analysis Based Nondestructive and Noninvasive Material Property Characterization Strategy for the Human Right Ventricle Wall

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Marc Simon, University of Pittsburgh Medical Center
Timothy Wong, University of Pittsburgh Medical Center
Wilkins Aquino, Duke University
John Brigham, University of Pittsburgh

Pulmonary hypertension is a severe cardio-pulmonary disease, which may lead to dysfunction or even failure in the right ventricle (RV). There is limited capability to judge both the early stages of this deadly disease, as well as the likelihood of progression to heart failure directly, but the size, shape, and material properties of the RV are promising indicators of how severe the disease is in terms of cardiac function. Previous work by the authors has found clear relationships between the size and shape of the RV and the state of pulmonary hypertension. The current study intends to extend this research to investigate the relationship between the material properties (e.g., elasticity) of the RV wall and the state of pulmonary hypertension in humans. However, it is first necessary to establish a sufficient technique to nondestructively and noninvasively characterize the material properties of the RV wall. As such, an inverse problem solution technique is being developed, and will be presented herein, to characterize the right ventricle wall properties from clinically attainable cardiac medical images (e.g., CMRI) and measurable hemodynamics. A core component of this approach is the novel use of shape analysis of the imaging data to construct the objective functional for the inverse solution procedure. By using harmonic topological mapping, a quantitative shape-based objective functional comparing simulated right ventricle deformation to the medical imaging data can be constructed and utilized within an optimization strategy to estimate the unknown material properties. Following the details of the solution framework, a set of numerical test cases will be presented to show the potential capabilities of the inverse characterization procedure. Lastly, conclusions and future directions will be discussed.

767: A Framework for Hurricane Hazard Mitigation in Traffic Lighting Support Structures

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Milad Rezaee, Louisiana State University
Aly Mousaad Aly, Louisiana State University

Traffic signals play a major role in transportation security all over the world, by controlling conflicting traffic flows, particularly at road intersections and crosswalks. Traffic signs and signals are extensively used as vital elements in highways and urban roads for making communications with drivers in order to convey the rules, guidance, warnings, and other highway agency information. On this basis, it is crucial to have reliable and well maintained traffic signs and signals in order to make certain that the desired massages are properly conveyed to the drivers on the streets in various environmental conditions; so, a safe drive can be achieved. A typical support structure for traffic signals is a cantilever consisting of a vertical pole and a horizontal mast arm. These structures are slender and lightly damped, and because of their long span they are very flexible and susceptible to windstorms. In addition, fatigue life of these structures is an issue that highlights the importance of vibration mitigation in traffic light support structures. This paper investigates the aerodynamic characteristics of a mast arm cantilever traffic signal support structure by using a time dependent approach, i.e., Large Eddy Simulation (LES) within a CFD model. Following the CFD simulations, for wind load estimation, the study is conducted to explore different vibration suppression schemes. It focuses on identifying potential damping solutions in terms of selecting and implementing strategies to mitigate damages and minimize the consequences of failure. It is envisaged that using this damping enhancement framework, and incorporating real-time data, a decision making tool for resilient and sustainable traffic light support structures can be developed. This will lead the US to sustainable solutions that can improve the performance of the transportation infrastructure under wind loads, reduce structure life cycle costs and increase efficiency in design.

76: A Functionally Layered Sensing Skin for Structural Health Monitoring

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Milad Hallaji, WSP Group USA
Aku Seppänen, University of Eastern Finland

Recently, there has been a growing interest in the development and use of large area sensors for rapid damage and crack detection in structural elements. In previous works, the feasibility of Electrical Impedance Tomography (EIT) -based sensing skin for damage monitoring has been demonstrated. In this presentation, we show the feasibility of a multi-layer multi-functional EIT-based sensing skin. This sensing skin consists of a chloride ion sensing layer and a damage sensing layer. The multi-layer sensing skin, therefore, enables detection and differentiation of chloride ions and cracking. We apply this sensing skin to polymeric and concrete substrates. We show the results of qualitative reconstruction using classical difference imaging scheme with smoothness prior as well as quantitative reconstructions using a novel absolute imaging scheme with Total Variation (TV) prior and modeling error approximation. The results indicate that absolute EIT reconstructions are more successful in capturing the cracking pattern than difference reconstructions, especially when the crack patterns are complex. The results indicate that this functionally layered sensing skin can be potentially used for monitoring critical infrastructure systems where cracking and leakage of certain ions might be of concern.

419: A General Formulation for Modeling Impacts of Deterioration on Reliability of Infrastructure Systems

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Paolo Gardoni, University of Illinois

Infrastructure systems deteriorate during their lifetime due to due to either regular operation, or extreme loading conditions, or environmental conditions. Deterioration may considerably reduce the service life and reliability of infrastructures. Therefore, it is critical to consider and incorporate the impacts of deterioration in the analysis and design of infrastructures, especially regarding reliability, maintenance, life-cycle analysis, remaining service life etc. This paper investigates a general formulation to model the impacts of deterioration on capacity, demand, and reliability of the infrastructure system. Since infrastructure systems are usually subject to multiple deterioration mechanisms, the general formulation needs to incorporate this aspect. While existing research usually assumes independence between different deterioration mechanisms for modeling convenience in reality they are dependent and their interaction may have important implications and needs to be considered for better characterization of actual deterioration. The key idea of the general formulation is to model the impacts of deterioration on the state of the system. At the state level, impacts of different deterioration mechanisms and more importantly their interactions can be conveniently captured. Also, through introducing a general age and state dependent deterioration rate function for the system state, this formulation allows a consistent representation of the two general deterioration mechanisms, i.e. shock deterioration and gradual deterioration. Once the system state considering impacts of deterioration can be estimated, probabilistic capacity and demand models that take system state as input can be used to model the impacts on the capacity, demand, and reliability of the infrastructure system. In the end, the proposed approach is illustrated through modeling the impacts of deterioration due to earthquakes and corrosion on the shear and deformation fragility of a reinforced concrete (RC) bridge.

681: A Gradient Based Adaptive Sparse Grid Collocation Method for Uncertainty Quantification

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Lori Graham-Brady, Johns Hopkins University

Non-intrusive approaches[1] have gained a lot of popularity in the last decade because of its flexibility of being used in many different fields of problems. Sparse grid collocation methods[2] are one of such approaches. Discrete projection collocation method has the notable feature of having fast convergence rates when approximating smooth functions but lacks the feature of tracking stochastic discontinuities. Another variant is the piecewise linear collocation interpolation approach which tracks discontinuities efficiently but converges slowly in smooth regions. The proposed methodology, based on an existing work on adaptive hierarchical sparse grid collocation algorithm[3], enjoys both the aforementioned advantages and aims at avoiding unnecessary number of function evaluations in smoother regions of the stochastic space by a gradient evaluation technique in all the dimensions. With increasing complexity of the deterministic problem in consideration, the extra reduction in the number of function evaluations proves to be more and more valuable. This also helps in achieving faster convergence in the smoother regions than what is achieved in the existing collocation interpolation approaches. This method is well suited for high-dimensional stochastic problems, and elliptic problems with stochasticity of dimensionality as high as 75 have been dealt with effectively.

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381: A Gradient Based Polynomial Chaos Approach for Topology Optimization under Uncertainty

Vahid Keshavarzzadeh, University of Illinois
Daniel Tortorelli, University of Illinois

We present a gradient based approach for robust and reliability based topology optimization employing stochastic expansion methods. An accurate and e_fficient uncertainty propagation scheme based on a non-intrusive polynomial chaos expansion is used to evaluate the statistical moments and probabilities of the cost and constraint functions [1-3]. The statistical moments and their gradients with respect to design variables can be readily obtained via polynomial chaos approach. However, the evaluation of the probabilities of the cost and constraint functions and their gradients, requires the integration over the range that corresponds to the failure region. Introducing an indicator function in the integral that characterizes the probability of failure, the integration can be carried over the entire range of random variables. In order to alleviate the non-differentiable property of the indicator function, a smooth approximate of the indicator function is utilized. To demonstrate the signi ficance of the design optimization under uncertainty, results of the deterministic topology optimization are obtained and compared with the topology optimization under uncertainty results.

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521: A Heuristic Seismic Optimization Approach Based on Topology Optimization

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Reinforced concrete moment resisting frames (RCMRF) buildings are widely used to withstand earthquake forces in different countries across the world. Presently, the dimensions of beams and columns for most of these buildings are determined following a trial and error procedure that in the majority of times leads to suboptimal designs. This situation occurs because existing seismic optimization approaches have failed to capture the attention of practitioners due to their computational costs, and their limited integration with the structural design workflow. Based on the results of topology optimized RCMRF, we developed a heuristic seismic optimization approach that integrates within the workflow of structural design offices and improves the seismic performance of buildings. This research describes the development of a procedure which designers can use together with structural analysis software. A detailed example of the application is presented for a 3D irregular building, with the summary of results for another 14 buildings. To benchmark the proposed optimization approach, OpenSees was used to create three dimensional models of the optimized and traditional buildings, which were subjected to pushover analysis. The results demonstrate that the proposed optimization approach improves the seismic performance of buildings, with the optimized building having greater overstrength and ductility. These improvements occur regardless of building irregularity and site seismicity, showing that the proposed approach is useful for general RCMRF buildings.

51: A Hierarchical Finite Strip Method for Buckling Analysis of Composite Shells

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Kan Feng, Beijing Aeronautical Science & Technology Research Institute

A Hierarchical Finite Strip Method (HFSM) is developed by hybridizing hierarchical and finite strip method. The Legendre orthogonal polynomial series are chosen as the hierachical shape functions for the composite shell strips. The buckling of composite cylinder shells with various radii subjected to axial loads are performed by the proposed HFSM. The numerical results illustrate that the HFSM combines the merits of both hierarchical theory and finite strip method, and can be used for analyzing the buckling problems of composite shells quickly with ease and fidelity.

262: A Hybrid Algorithm to Solve the Time-Dependent Interdependent Network Design Problem

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Leonardo Dueñas-Osorio, Rice University
Andrés L. Medaglia, Universidad de los Andes
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Accurately modeling and optimizing the resilience of a system of infrastructure networks is an important yet complex task. It requires considering the limited capacities in the system, existing demands, the availability of resources, and the physical and geographical interdependencies between different infrastructure networks. To optimize the resilience of such a complex system, we define the time-dependent Interdependent Network Design Problem (tdINDP), which focuses on finding the optimal spatio-temporal recovery strategy of a system of interdependent networks. To solve the tdINDP, we formulate a Mixed Integer Programming (MIP) model, which determines the recovery strategy that maximizes the overall resilience of the system. Even though this model guarantees the optimality of the results, unfortunately, its complexity increases exponentially with the size of the studied system of infrastructures and the length of the time horizons. To overcome such challenges, we propose a hybrid algorithm that decomposes the tdINDP into two iterative phases, one focused on determining feasible

recovery strategies for the system, and the other focused on evaluating the performance of any given recovery strategy. The first phase is composed of tailored heuristics such as path relinking, genetic, and memetic algorithms to provide favorable recovery strategies, while the second phase uses exact analytical optimization models to determine the best possible system performance associated to each recovery strategy. Once the second phase has evaluated the performance of the provided recovery strategies, the first phase collects such information to provide improved recovery strategies, and the iterative process restarts until a performance threshold is met. The proposed strategy has shown to be robust, being able to solve instances that could not be solved by the tdINDP MIP model. The proposed hybrid algorithm is particularly well suited to study large systems, since the optimization models used in this approach run in polynomial time, in comparison to the NP-hardness of the naïve tdINDP MIP model approach. We show a full comparison between the tdINDP MIP model with the proposed hybrid algorithm for a set of idealized systems of different sizes and topologies, showing the high efficiency of the proposed algorithm across a wide space of inputs. Finally, we analyze the water, power, and gas networks in Shelby County, TN. under an earthquake hazard, as a practical application, showing that the proposed hybrid algorithm provides a practical tool to analyze and optimize the resilience of realistic scenarios.

173: A Hybrid Multi-Scale Computational Framework for Transport Problems in Porous Media

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Simulation of some of the most important chemical and physical phenomena in porous media depends on reliable solvers for transport equations. Due to variety of chemical and biochemical reactions and fluid-solid interaction dynamics, disparate length and time-scales remain a challenge in numerical simulation of porous media problems. Since simulation of features occurring at fine length and time-scales is computationally demanding, it is not a viable approach for most practical applications. Furthermore, it is well known that numerical simulation based on macroscopic models are not able to provide reliable estimates to pore-scale details. A major trend in development of computational methods for porous media is to combine numerical methods based on continuum models with the ones that perform better at pore-scale. Hence, one can achieve relative computational efficiency without sacrificing accuracy. Finite Element Method (FEM) is one of the most popular numerical methods for solving continuum models. However, implementing this method for complex pore network geometries and chemical reactions occurring at such length scales is difficult. Recently, Lattice Boltzmann Method (LBM) has gained the attention of researchers as a valid numerical method for fluid dynamics simulations. It can handle complicated geometries easily and is highly parallelizable. It can also account for various chemical reaction models either inside the pores of at the solid-fluid interface. Kinetic relations can be included in a LBM simulation with relative ease. A computational framework that allows both of these methods (FEM and LBM) to be used along one another is highly desirable.In this presentation we will introduce a new computational framework that is capable of bridging the gap between the disparate scales mentioned earlier. This framework is based on domain decomposition scheme and allows different time-steps and grid sizes in different subdomains. To account for pore-scale details, we will use LBM and macroscopic features are solved for using FEM. Details of the proposed method and several numerical examples showcasing capabilities of this framework will be provided.

89: A Lower-Bound Formulation Including Spatial Orientation for Topology Optimization of Modular Truss Structures

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Ashley Thrall, University of Notre Dame
Benoît Descamps, Université libre de Bruxelles

Rajan Filomeno Coelho, Université libre de Bruxelles

Modularity is a growing area of interest in civil engineering since it may lead to substantial economical and environmental improvements for large-scale applications. Modular structures are divided into simpler subsystems that can be mass-produced, leading to better quality control and reduced fabrication cost. While there has been prior research investigating the optimization of modular structures, the notion of modularity remains a challenge. Most studies focus on the repeatability of the topology through translations and rotations, leading to final designs where material parts remain inefficiently used. An extension to module orientation optimization was therefore investigated by the authors [1], but the strategy is limited due to the hybrid nature of the design variables: continuous cross sections were used to efficiently perform the topology optimization while discrete rotations ensured a correct assembly of the modules. In this contribution, a fully continuous formulation is proposed for optimizing the spatial orientation and the topology of modular structures. A preprocessing based on group theory has been developed to isolate the final module orientations that ensure a correct assembly of the whole structure. These rotations are modeled by permutation matrices and give an explicit formulation of the module properties in terms of the spatial orientation and the topology. This representation is integrated in a lower-bound plastic design formulation for truss topology optimization, treated by a simultaneous analysis and design. In addition, a relaxation technique using complementary constraints allows the circumvention of the discrete character of the spatial orientations, leading to a final formulation written explicitly in terms of all of the design variables. Consequently, the present formulation is well-suited for mathematical programming techniques, taking advantages of the inherent sparsity of the problem as well as the capability of providing analytically the Jacobian matrices. The efficiency of the proposed strategy is illustrated through a benchmark study of a two dimensional cantilever truss structure. More economical designs are obtained by using the proposed formulation, compared to standard optimization approaches for modular structures with a fixed orientation. Additionally, the correlation between the final design and the material properties in tension and compression is demonstrated.

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540: A Maximum Filter for the Ground-Structure Method

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Adeildo Ramos Jr., Federal University of Alagoas
Glaucio Paulino, Georgia Institute of Technology

A maximum filter for the ground structure method: An optimization tool to harness multiple structural designs Emily R. Daniels, Adeildo S. Ramos Jr., and Glaucio H. Paulino A maximum filter is presented to translate the ground structure method for maximum stiffness design from a truss-sizing problem to a topology optimization problem in which members are removed during the mathematical programming. A bisection algorithm is used to determine the maximum allowable filter in a given optimization iteration, which is applied to reduce the design space while preserving global equilibrium and limiting the increase in the objective from the previous iteration. Minimization of potential energy with Tikhonov regularization allows for solution of the singular system of equilibrium equations resulting from the filtered designs, and a reduced order model on both the state problem and the optimization problem allows for increased computational efficiency. The present approach leads to unambiguous truss designs (i.e., undesirable thin and hanging members are eliminated) that are guaranteed to satisfy global equilibrium. Additionally, by controlling the change in the objective due to the filter and the number of iterations between applications of the maximum filter, a suite of discrete designs is obtained. Although these local minima are not as stiff as the globally optimal solution to the sizing problem, the control provided by the maximum filter allows for multiple physically realizable structures, providing flexibility and promoting increased presence of the ground structure method in the structural engineering design industry. Numerical examples are presented to demonstrate the capabilities of the maximum filter, including its use as an end filter in the traditional plastic and nested elastic approaches to the ground structure method.

40: A Mesoscale Model of Grain Boundary Faceting: The Role of Facet Junctions

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The physical properties of materials systems are greatly influenced by several features at the microstructural level. Of particular interest are interfaces and the various processes that occur due to anisotropic interfaces and their interactions with other microstructural defects. Thermodynamically, the study of such interfaces dates back to over a century ago. The classic Wulff construction provides a treatment for the dependence of the crystal equilibrium shape on interface anisotropy. For strong anisotropy, it may be thermodynamically favorable for an interface to evolve and exclude a range of orientations leading to the formation of facets, corners and edges.□□In a polycrystalline metal and for a given orientation of two adjoining grains, cusps or depressions in the grain boundary (GB) energy may exist as a function of GB inclination, defined by the plane normal, indicating the presence of low energy planes. Therefore, an initially flat GB may facet resulting in a "hill-and-valley" structure. In general, dislocation-like defects exist at GB facet junctions due to differences in the translation states at these intersecting facets. Herein, we present a mesoscale modeling framework for GB faceting that is capable of capturing anisotropic GB energies and mobilities, and accounting for the excess energy due to facet junctions and their non-local interactions. As a demonstration, we consider the case of a □=5 <001> tilt boundary in BCC iron, where we investigated facets along {210} and {310} planes both experimentally via high resolution scanning TEM and with the aid of atomistic calculations for the inclination-dependent GB energy, which was used as an input in our model. Linear stability analysis and simulation results highlight the role of junction energy and associated non-local interactions on the resulting facet length scales. Broadly speaking, our modeling approach provides a general framework to examine the spatio-temporal evolution of anisotropic GBs in polycrystalline systems.□□Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

192: A Minimalist Model for Rapid Simulation of Multiple Hydraulic Fracture Growth

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Andrew Bunger, University of Pittsburgh
Anthony Peirce, University of British Columbia

Hydraulic fracturing is a critical technology for production of oil and gas, especially from low permeability reservoirs. There has been an increasing drive to optimize hydraulic fracturing treatments in the sense of maximizing the effectiveness of the stimulation over the space of the controllable parameters (spacing between fractures, fluid viscosity and pumping rate, etc.), measured for example in terms of the generated fracture area or uniformity of stimulation along a horizontal well. However, a prerequisite to optimization is a forward model that both captures the relevant physical behaviors and that executes rapidly enough to be called upon hundreds or thousands of times by an optimization scheme. For hydraulic fracturing this is a problem because fully coupled models for multiple hydraulic fracture growth in 3D can take days or even weeks for a single simulation. Motivated, then, by the need for rapidly computing models, we present a minimalist approach for modeling simultaneous growth of multiple hydraulic fractures. Our approach is built firstly upon asymptotic solutions for single hydraulic fractures growing in simplified geometries. We introduce interaction through an asymptotic expansion of the induced stresses around the hydraulic fractures, coupling the fractures together by enforcing global energy balance. The resulting simulator's accuracy is verified by comparison with a fully coupled, 3D simulator for multiple, parallel, planar hydraulic fractures. Besides providing sufficiently accurate predictions of the length, width, and fluid influx to each hydraulic fracture to be useful, the new simulator computes in 1-2 seconds, which is less than 1/100,000th of the time required to run the fully coupled planar 3D simulations.

775: A Mixed-Mode Rate-Dependent Cohesive Zone Model Using Fractional Viscoelasticity

Oliver Giraldo-Londoño, University of Illinois
Glaucio Paulino, Georgia Institute of Technology
William Buttlar, University of Illinois

We present a new mixed-mode rate-dependent cohesive zone model (CZM) that combines the features of the Park-Paulino-Roesler (PPR) cohesive model and a fractional standard linear solid (SLS). The formulation is derived in the context of damage mechanics, where the undamaged viscoelastic stresses are obtained from a fractional SLS. To account for damage, the PPR cohesive model is redefined in the form of an anisotropic Helmholtz free energy function. This leads to two damage-type parameters that allow simulating the breakage of atomic bonds in front of the crack tip under mixed-mode conditions. The proposed model is able to predict the rate-dependent fracture behavior of different materials for a wide range of loading rates.

596: A Multi-scale Multi-physics Approach to Modeling Coastal Bridge Collapse

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Xuebin Chen, Sun Yat-sen University
Agnimitro Chakrabarti, Louisiana State University
Jiemin Zhan, Sun Yat-sen University

A large number of coastal bridges were destroyed by recent hurricanes and tsunamis. Considerable research effort, including field, laboratory and numerical investigations, has been devoted to the understanding of the bridge failures and the determination of the hydrodynamic loading for the design and retrofit of bridge superstructures. To effectively predict and mitigate such a hurricane-induced hazard in a coastal built environment, a multi-scale, multi-physics, interdisciplinary approach is needed. Firstly, the spatial scale for a hurricane and its associated storm surge, ocean waves and hydrodynamic forces on a coastal bridge spans from thousands of kilometers (106 m) to a few center meters (10-2 m). Secondly, the temporal scale of a hurricane event and its impact varies from weeks as it forms and develops in the ocean to seconds when hurricane-generated waves slam on a bridge deck and cause damage or failure. The physics of coastal bridge collapse during a hurricane are not limited to solid mechanics or structure engineering. Integrated knowledge and models in atmospheric science, oceanography, coastal engineering and structure engineering are required. Using Hurricane Ivan (2004) and the collapse of the Interstate Highway 10 (I-10) bridge over Escambia Bay, Florida as a case study, the paper demonstrates a multi-scale, multi-physics approach to the modeling of hurricane-induced coastal bridge collapse. Firstly, a coupled hurricane wind-wave-surge modeling system covering the entire Gulf of Mexico and part of the Atlantic Ocean is utilized to provide the boundary conditions for the local-scale model of Escambia Bay where the collapsed bridge is located. Secondly, the nested basin-scale and local-scale models produce the storm surge hydrograph as well as the time series of wave height and wave period at the bridge site, which is used as the boundary conditions for a multi-phase (air, water and solid) computational fluid dynamics (CFD) model to simulate wave-structure interactions. The CFD model considers the air phase as the air trapped between the girders and bridge deck increases the wave-induced uplift force, the wave motion impacting the structure, and the sway and heave motions of the bridge deck. Results from the integrated multi-scale, multiple-physics models are presented to provide inside into the coastal bridge collapse processes, which are not captured by an isolated field, laboratory or numerical study. The effectiveness of this integrated modeling approach and computational requirements will be discussed. Funding for the study has been provided in part by the National Science Foundation.

740: A Multiscale GFEM for Fiber Reinforced Composites

Phillipe Alves, University of Illinois
C. Armando Duarte, University of Illinois

Fibers reinforcements are used in a variety of materials such as Ceramic Matrix Composites (CMCs) and Polymers (FRPs). They increase the strength, stiffness, ductility and resistance to fatigue of the unreinforced material. Applications of CMCs are found in power generation systems, rockets and hypersonic missiles. Currently, the design of these structures relies on physical testing to establish the various parameters affecting their performance. Computational simulations can significantly reduce the overall cost of these components and improve the understanding of their failure mechanisms. However, modeling of damage evolution and the multiscale interactions in composite materials using available Finite Element Methods face significant barriers. Realistic simulations of 3D microscale features, like fibers and inclusions, are in general not practical. This work reports on recent advances of the Generalized Finite Element Method (GFEM) for multiscale three-dimensional modeling and simulation of fiber reinforced composites. Fibers are discretely modeled using a modified version of Embedded Reinforcement with bond Slip (ERS), which is here generalized in order to handle enrichment functions for matrix and fiber meshes. Cracks are described using discontinuous functions as in GFEM for homogeneous materials. This procedure is able to address some of the limitations of existing FEMs by describing both cracks and fibers independently of the underlying finite element mesh. Scale bridging between fiber and structural scales is performed with the GFEMgl—the GFEM with global-local enrichment functions. This strategy allows modeling damage mechanisms while accounting for interactions between structural and material scales while using meshes that are significantly coarser than those required by available FEMs. Examples illustrating the capabilities and the robustness of the method are presented.

607: A Multiscale Micromechanical Model for Soft Collageneous Tissues

Claire Morin, Mines Saint-Etienne
Stéphane Avril, Mines Saint-Etienne
Christian Hellmich, Vienna University of Technology

Soft collageneous tissues, such as tendons or arterial walls, are hierarchical materials, made of a hydrogel-like matrix embedding an arrangement of collagen and elastic fibers; the latter are made of an arrangement of microfibrils embedded in a soft matrix. In the unloaded state, both fibers and microfibrils are crimped and differently oriented, while the application of a mechanical loading leads to their stretching and realignment along the load direction [1]. It is now well accepted that these geometrical rearrangements are one of the microscopic mechanisms explaining the non-linear mechanical behavior exhibited by these soft collageneous tissue. We here propose a multiscale approach to investigate to which extent the complex and highly non-linear behavior of soft tissue may be explained through combined rotation of fibers and fibrils being embedded at two separated scales in a matrix. Accordingly, we consider one representative volume element (RVE) of a hundred-micrometer size made of soft tissue material, which hosts different relatively stiff, linear elastic, variously oriented, fiber-like inclusions, as well as a soft, linear elastic hydrogel-like matrix in between. The fibers are in turn represented by a lower scale RVE, with a characteristic length of some micrometers, made of stiff, linear elastic, variously oriented fibrils together with a soft matrix in between. The larger scaler RVE is subjected at its boundary to a prescribed homogeneous strain rate history. The mechanical response of this hierarchical tissue representation, together with the reorientations of the different fibers and microfibrils families, are computed within the framework of continuum micromechanics under finite strains, based on an extension of the Eshelby problem [2]. The resulting multiscale model for collageneous tissue allows to qualitatively reproducing the macroscopic response of different soft tissues, as well as the evolution of the fibrillar inclination during loading, opening a new framework for the development of 3D multiscale constitutive laws for soft tissues, able to quantify the specific contribution of each constituent on the overall response of the tissue.

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731: A New Methodology to Model Interdependency of Critical Infrastructure Systems during Hurricane Sandy's Event

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Anil Agrawal, The City College of New York
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The paper proposes a methodology to evaluate the resilience of the critical infrastructures networks hit by Hurricane Sandy in October 2012. The region analyzed in the case study is New York metropolitan area which includes New York City and the nearby state of New Jersey. This region was the most affected by the storm and it is one of the most densely populated regions of the United States due to its high concentration of businesses and several critical infrastructures. The identified critical infrastructure systems are highly interconnected, forming a heterogeneous network that is very vulnerable to catastrophic events, such as hurricanes. Due to several existing interdependencies, the systems are subjected to disruptive cascading effects. The disruption of one or more of these systems directly affects people, businesses, the government and leads to additional indirect damages. After a critical comparison of the different methodologies to analyze infrastructure interdependency, the input-output method is selected in order to indentify and rank the different types of dependencies in the network as well as to prioritize the different actions during the restoration process. Previous analyses have shown that power, transportation, and fuel were the most damaged networks in the region generating severe cascading effects due to the interdependencies between them. A series of recommendations to improve the global resilience in the region are provided which will be able to prevent cascading effects and prioritize the recovery effort in the future.

334: A New Sample-Based Method to Estimate Global Sensitivity Indices

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The variance-based Sobol indices computation is a prominent methodology in global sensitivity analysis. Most current sample-based methods for this computation have a computational cost proportional to the dimension of model inputs thus encounters the curse of dimensionality. The motivation of this paper is to reduce the

computational cost in computing the Sobol index. This paper also aims to solve the following challenge: if Monte Carlo simulations of a physics/ computational model have already been conducted, how to extract the Sobol indices from the recorded input/output samples without more model evaluations? Current sample-based methods cannot solve this challenge since they require the availability of the physics/computational model to generate input/output samples for each different model input. This paper proposes a new efficient sample-based method to solve the challenges above. First this paper shows that calculating the mean or variance of a model output corresponding to a range of values of a model input is equivalent to calculating the conditional mean or variance of the model output for some unknown value of the input within that range, based on the extreme value theorem and intermediate value theorem. This concept leads to the proposed method that uses the same Monte Carlo sample sets to compute the first-order Sobol indices for different model inputs. As a result, the computational cost of the proposed method is not proportional to the dimension of the model inputs, thus overcoming the curse of dimensionality. The proposed method also separates model input sampling, model evaluation, and Sobol index calculation into stand-alone processes; thus the first-order index can still be computed if only legacy Monte Carlo simulation data or field data are available but the underlying model is not available. Another important advantage of the proposed method is the ability to compute the first-order indices of correlated model inputs. Most current sample-based methods or analytical methods assume independent model inputs. Considering that the first-order index is a desired metric to rank model inputs even when the model inputs are correlated, the proposed method contributes to filling this gap. All the above advantages of the proposed method are revealed by comparing it with current sample-based methods in three numerical examples.

53: A Nitsche Method for Wave Propagation Problems and its in Time Domain

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Weak boundary conditions often times can simplify the computational data structure of a finite element method, as it is not necessary to directly prescribe the values of the numerical solution's degrees of freedom on the boundary. This aspect makes the weak enforcement of boundary conditions preferable, especially when considering simulations in complex geometries. We propose a new Nitsche-type approach for Dirichlet and Neumann boundary conditions in the context of time-domain wave propagation problems in mixed form. A peculiar feature of the proposed method is that, due to the hyperbolic structure of the problem considered, two penalty parameters are introduced, corresponding to Dirichlet and Neumann conditions, respectively. A stability and convergence estimate is also provided, in the case of a discontinuous-in-time Galerkin space-time integrator. The spatial discretization used is based on a stabilized method with equal order interpolation for all solution components. In principle, however, the proposed methodology is not confined to stabilized methods. The robustness and accuracy of the proposed approach are investigated by an extensive set of tests. We further extend the proposed approach to embedded boundary problems for the wave equation. Our results are promising, and unaffected by the small-cell instability problem.

353: A Non-Local Gradient-Enhanced Damage Model for Viscoelastic Materials

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Predicting the direction, growth rate and damage zone is crucial in order to model correctly the degradation of viscoelastic materials under creep, relaxation and strain rate loadings. While local damage models have been popular in the literature, they are all similar in that they lack a length scale that will regularize the solution and lead to mesh independent results. In this work, we propose a new regularization approach based on an equivalent stress measure concept and apply it to a generalized viscoelastic Maxwell model with a Murakami type damage-rate law. Viscoelastic behavior is achieved by a semi-analytical integration of the constitutive law assuming time dependent behavior of the deviatoric component and purely elastic response of the volumetric part. The scheme leads to a coupled set of nonlinear equations which are solved simultaneously using a monolithic Newton framework to obtain displacement and damage fields as function of time. The Jacobian matrix of the Newton scheme is formulated analytically. Mesh-insensitive behavior is demonstrated for one and two dimensional problems showing promising results for creep, relaxation and strain-rate loading conditions.

245: A Numerical Approach to Describe Failure of Wood - From the Wood Cell Level up to Wood-Based Products

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In order to increase the competitiveness of wood-based products over other building materials, the full mechanical potential of the material wood must be exploited. To achieve this, a more accurate prediction of the mechanical behavior of wood, especially when it comes to failure, is urgently needed. Due to the complex microstructure of wood, traditional methods for the estimation of its bearing strength are usually not able to characterize the failure mechanisms correctly close to or after the point of failure. But, for example, with the introduction of reinforcements in dowel-type timber connections or the use of layered wooden boards in cross-laminated timber, where the formation of cracks may be allowed up to a certain limit, exactly these regions of the mechanical behavior become more and more important. Traditional failure criteria for orthotropic materials, which are based on the evaluation of maximum stress or strain values, vastly underestimate the load-carrying capacity of timber elements, as very local peak values usually do not lead to structural failure, because of stress redistribution effects, such as localized cell wall failure. By applying new approaches, based on detailed material models on lower length scales, such effects can be considered within numerical simulations. Thus, a multiscale damage approach, using the unit cell method in combination with XFEM, was taken, where, within a first step, failure mechanisms at the single wood cell level were identified to obtain crack directions for several loading conditions. The resulting failure criteria for different cell types (i.e. late- and earlywood) were then used in simulations of a new unit cell at the annual year ring level. This finally led to the development of a single multisurface failure criterion for clear wood, where XFEM is used to describe brittle failure mechanisms under tensile and shear loading, and plastic behavior to describe plastification-like failure mechanisms under compression. By utilizing previous developments of a numerical simulation tool for wooden boards, which enables the mathematical description of fiber deviations in the vicinity of virtually reconstructed knots, realistic simulations of complex failure mechanisms of not only single wooden boards but also more complex wood-based products, like Glulam and CLT elements, were rendered possible. Furthermore, the simulation tool is used in the development of new wood composites, by making the material wood more predictable and, thus, more interesting for engineering applications.

124: A Numerical Study on Modeling Heterogeneous Coastal Sediment Transport Using Multiphase Eulerian and Euler-Lagrangian Approaches

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Regional scale coastal evolution models do not explicitly resolve wave-driven sediment transport and must rely on bedload/suspended modules that utilize empirical assumptions. Under extreme wave events or in regions of high sediment heterogeneity, these empirical bedload/suspended load modules may need to be reexamined with detailed observation and more sophisticated small-scale models. Significant research efforts have been devoted to modeling sediment transport using multiphase Eulerian or Euler-Lagrangian approaches in the past decades. Recently, an open-source multi-dimensional Reynolds-averaged two-phase sediment transport model, SedFOAM was developed by the authors and it had been adopted by many researchers to study momentary bed failure, granular rheology in sheet flow and scour around structures. In this abstract, we report our recent progress made in extending the model with 3D turbulence-resolving capability and to model the sediment phase with the Discrete Element method (DEM). Adopting the large-eddy simulation methodology, we validated the 3D Eulerian model with measured fine sand transport in oscillatory sheet flow and demonstrated that the model was able to resolve sediment burst events during flow reversals. To better resolve the inter-granular interactions and to model heterogeneous properties of sediment (e.g., mixed grain sizes and grain shape), we used an Euler-Lagrangian solver called CFDEM, which couples OpenFOAM for the fluid phase and LIGGGHTS for the particle phase. We improved the model by revised the fluid solver following SedFOAM, which better enforced the mass conservation. Meanwhile, a random-walk model was implemented to account for the effect of unresolved fluid velocity fluctuation on the particle motion. The modified CFDEM solver was used to study the effect grain-size distribution and grain shapes on resulting sediment transport. Preliminary results showed that the armoring effect was captured and under Stokes 2nd-order wave forcing, the armoring effect is more significant during the energetic positive peak, and hence the net onshore transport is reduced. More detailed investigation on the effect of grain shape will be presented in the conference. This research is supported by Office of Naval Research and National Science Foundation.

474: A Numerical-Experimental Approach to Characterize Fracture Properties of Fine Aggregate Asphalt Mixtures at Different Temperatures and Loading Rates

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This paper employs an integrated numerical-experimental approach to evaluate the temperature- and rate-dependent fracture characteristics of a fine aggregate asphalt matrix (FAM). Two bending tests (semi-circular bending, SCB, and single-edge notched beam, SE(B)) and one tension test (disk-shaped compact tension, DC(T)) are performed in the laboratory at three temperatures (-10oC, 10 oC, and 25 oC) and three loading rates (0.5 mm/min., 1.0 mm/min., and 2.0 mm/min.). The fracture tests are further simulated using a computational model based on the finite element method that is incorporated with material viscoelasticity and cohesive zone fracture. Two cohesive zone fracture parameters, i.e., cohesive strength and fracture energy, are determined via a calibration process until a good match between experimental and numerical results are observed. To illustrate the efficiency of the integrated numerical-experimental approach, fracture properties are also determined by a traditional methodology that uses globally averaged material displacements far from the actual fracture process zone. The results obtained indicate that temperature- and rate-dependent fracture properties of asphalt mixtures

can potentially be evaluated based on simulations of different testing configurations and sample geometric characteristics. The accurate determination of such properties is a key step towards the implementation of successful computational microstructure predictive models, which can provide meaningful insights into the effects of constituents on the overall mixture performance, with significant savings in experimental costs and time.

239: A Parallel MCMC Method

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We present the development of a parallel Monte Carlo Markov Chain method called Saches, Scalable Adaptive Chain-Ensemble Sampling. Saches combines the loosely coupled multiple chains of DREAM (Differential Evolution Adaptive Metroplis) for global exploration with a parallel version of DRAM (Delayed Rejection Adaptive Metropolis) to refine the posterior probability estimates. We demonstrate Saches on the Community Land Model (CLM) for Bayesian calibration of model parameters. Bayesian calibration of expensive simulations is often done with emulators because of the computational cost of MCMC sampling. In this case, the parallel chain scheme allows us to directly run CLM and not emulators for inference of the model parameter distributions.

609: A Peridynamic Model for Hydraulic Fracture

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Mukul Sharma, The University of Texas at Austin

We present a coupled nonlocal model based on peridynamic theory for the poromechanical deformation and failure of rocks targeting applications of hydraulic fracture. The model is capable of reproducing known analytic solutions to simple fracture geometries as the characteristic nonlocal length-scale vanishes; however, the nonlocal nature of the formulation is particularly useful in regularizing (i.e., removing mesh dependence) cases of complex fracture propagation and coalescence of propagating hydraulic fractures with natural fractures. This presentation will shows the model equations along with validation results for a series of test problems. Additionally, we show regularized large-scale simulations that exhibit sufficient complexity to demonstrate the utility of the model. This complexity includes the effects of heterogeneities in elastic, fracture, and fluid transport properties, as well as the effects of complex natural fracture networks on hydraulic fracture propagation.

637: A Phantom Node Approach for Modeling Intersecting Fractures

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The phantom node approach was originally introduced by Hansbo and Hansbo [1] to model strong and weak

discontinuities in solid mechanics. The equivalence of the phantom node formulation and the eXtended Finite Element Method (XFEM) was shown in [2]. Since its inception, the approach has arguably become the most popular form of XFEM and has begun to appear in commercial software packages. The popularity of the approach stems from its flexibility in being incorporated in an existing finite element package with minimal intrusion in the finite element data structures. While the approach has been extended to many diverse application areas including dynamic crack and shear band propagation, fluid-structure interaction and micro-structural materials, relatively few studies have focused on the important problem of intersecting interfaces ([3, 4]). The challenge with this method in the presence of intersecting interfaces lies in the consistent generation of phantom nodes such that connectivity between neighboring cracked elements is honored. We present a method that extends the phantom-node approach to the case of complex fracture networks including multiple intersecting fractures and fracture tips. We discuss a hierarchical framework for altering the background mesh-topology in the presence of many intersecting fractures. Finally, we assess the numerical performance of the method through several benchmark numerical examples in 2D and some preliminary studies in 3D.

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269: A Phase Field Model for Diffusion Induced Fracture in Lithium-Ion Batteries

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Lithium-ion batteries (LIBs) are important energy storage devices, widely used in portable electronics. Industries, especially the emerging electric vehicle industry or renewable energy industry, persistently require LIBs with higher energy storage density and longer cycling life. Silicon (Si) is one of the most promising new anode materials for LIBs with a high theoretical specific energy of 4200mAh/g, compared with 372mAh/g for graphite used in current commercial LIBs. However, large volume change (~300%) of Si during (de)lithiation process causes plastic deformation and fracture of electrodes, which leads to chemical degradation, capacity loss and shortened cycling life of LIBs. To design of high performance LIBs, a thorough understanding between mechanical deformation and battery cycling performance is required. In this work, a plastic-damage model is proposed to bridge the mechanical deformation with the electrical properties of LIBs. In the proposed model, we account for accumulated (de)lithiation induced plastic deformation and fracture of electrodes. Those mechanisms are modeled through a chemo-mechanical coupled computational framework [1,2]. A newly proposed new plastic-damage model allows us to investigate identify factors that limit the cycling performance of LIBs.Our numerical simulation results are compared with existing experimental data. Based on our simulation results, we summarize several criteria that are important for designing high performance LIBs.

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106: A Preliminary Computational Investigation of the Efficacy of a Concept for Smart Material, Adaptive, and Reconfigurable (SMART) Building Surface Tiles

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Building technology is continually evolving to improve habitability and energy efficiency within new and existing building stock. One technological category that is of high conceptual interest is adaptive exterior building components (e.g., any portion of a building envelope that comes in contact with the environment). Adaptive building components change their configuration in response to environmental stimulus. Potential applications range from methods to selectively improve building ventilation to methods to control heat and natural light. The authors herein have initiated investigation of one such adaptive technology entitled Smart Material, Adaptive, and Reconfigurable (SMART) Tiles. The objective of the SMART Tile concept is to develop a building façade that is comprised of a smart material (e.g., shape memory polymer), which can vary its surface topography (i.e., morph) on demand in response to solar insolation. More specifically, a SMART Tile will track incoming solar radiation and transition to a self-shading configuration during periods of extreme solar insolation. The present effort is focused on an initial computational proof of the SMART Tile concept that involves development and utilization of a computational inverse problem solution framework to maximize desirable solar interaction, thereby raising total building energy efficiency. Details of this computational inverse problem framework will be presented, including the forward method to simulate the smart material tile morphing process given activation and actuation parameters, as well as the optimization objective and solution technique for the tile design. A particular focus of the optimization component is the method used to quantify the solar radiation given various tile shape, latitude, orientation and environmental conditions. Case studies will be presented to demonstrate the potential benefits of the SMART Tile concept and a discussion of future research directions will be presented.

554: A Preliminary Study of the Rocking Response of Artifacts Subjected to Sound Induced Vibrations

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The interest of the engineering community towards the response of non-structural elements has increased over the last decades. Amongst these are museum artifacts which are both irreplaceable and, being parts of our cultural heritage, invaluable. These artifacts are often connected to their support media with tensionless connections which allows them to experience large rigid body displacements and rotations. This is due to improving their functionality, especially portability, but also as a design philosophy aiming at alleviating the associated stresses. The latter is quite important as the corresponding construction materials are often brittle and sensitive to large values or cycles of stress or strain. As a result, the mode of failure of these artifacts is instead associated to excessive sliding and rocking which may result to the object colliding with a boundary or another object. Moreover, due to their dimensions these objects are sensitive to sources of vibration that are usually not affecting the response of structural elements. Such sources include sound induced excitations on the supporting medium of the artifacts, such as pedestals and shelves. Given the frequency content, amplitude and duration these vibrations may cause the artifacts to rock and slide even to undesirable levels. It is therefore important to model the response of artifacts when subjected to such types of excitations. This study will investigate the stability of rocking bodies subjected to sound induced vibrations. Different sources generating the sound content will be

taken into account. Conclusions will then be drawn on the connection between the musical content and the response of artifacts.

654: A Probabilistic Life-Cycle Assessment for Quantifying the Effect of Design Life and Analysis Period on the Environmental Sustainability of Pavements

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The process of pavement design requires prediction of the pavement performance for a prescribed design life period over which the pavement remains functional until a maintenance and rehabilitation (M&R) activity is required. The set of M&R schedules are determined by pavement designers over an analysis period that defines the entire temporal boundary of the system. This research addresses a quantitative method for assessing the implications of effect of analysis period and design life on the life-cycle sustainability of pavements. In order to improve the reliability and robustness of assessment the environmental life-cycle analysis is performed under uncertainty in measurements and major input parameters. A probabilistic life-cycle assessment model that takes into account the major sources of uncertainty is employed to compare the global warming potential of two alternative pavements. In particular we account for the uncertainty due to the prediction of roughness over pavement lifetime and propagate the consequence into the overall footprint. The uncertainty propagation is conducted using a Monte Carlo simulation. Making use of a comparison indicator, the difference in the environmental impacts of two alternative designs is statistically characterized taking into account the correlation in the input parameters. The probabilistic life-cycle assessment is performed under different scenarios associated with prescribing different sets of standard values for the design life and analysis period. We intend to examine the degree by which the conclusion regarding the environmental implications of the pavement types is influenced by these parameters under uncertainty.

225: A Proposal for a Cell-Based Bone's "Mechanostat" Theory: The Need to Account for the Desensitisation and Replacement of the Mechanosensing Cells

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Bone's "mechanostat" theory proposed by H. M. Frost describes the adaptation of bone tissues to their mechanical environment. Regions of bone experiencing high mechanical loads become consolidated, while regions of bone experiencing low mechanical loads are removed. This leads to the structural optimisation of bone's porous microarchitecture and overall shape. Many experiments have investigated and observed such structural adaptation. However, there is still much uncertainty about the existence of a well-defined and perdurable reference mechanical state at which bone structure is adapted and stable. Such a reference state is difficult to define and to relate to the cellular biology of bone's mechanosensitivity. Near the neutral axis of a long-bone cross-section, bone tissue always experiences mechanical strains below the reference mechanical state proposed by Frost. However, these regions are not resorbed. A simple mechanical feedback loop is also unable to account for the several time scales involved in the mechanical adaptation of bone tissues. Indeed, clinical situations and experiments have exhibited bone adaptations ranging from short term bone gain following daily exercises, to long term bone loss following spinal cord injury. In this contribution, we develop a mechanostat theory that takes into account the cellular origin of bone's mechanosensitivity. This theory includes (i) a cell-specific reference state that enables mechanosensing cells to gauge a mechanical stimulus and to respond to it; (ii) a rapid, but partial desensitisation of the mechanosensing cells to the mechanical stimulus; and (iii) the replacement of the mechanosensing cells during bone remodelling, with the possibility to reset the cell-specific reference state depending on the current mechanical stimulus. Our proposed cell-based mechanostat theory is based on experimental evidence, and gives a cellular interpretation of the different phenomena occurring during the mechanical adaptation of bone tissues. This definition enables to resolve several limitations of the standard mechanostat theory. Our proposed mechanostat theory is tested by simulating several deregulating circumstances with a mathematical model: long-term disuse (modelling spinal cord injury), long-term biochemical deregulation (modelling osteoporosis), and short-term loadings (modelling daily exercises). All simulations lead to porosity-dependent and loading-history-dependent bone changes that agree with experimental observations.

694: A Reliability-Based Approach to Probabilistic Remaining Useful Life Prediction in Mechanical Systems

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The key goal in prognostics is to predict the remaining useful life (RUL) of engineering systems in order to guide different types of decision-making activities such as path planning, fault mitigation, etc. The remaining useful life of an engineering component/system is defined as the first future time-instant in which a set of safety threshold conditions are violated. The violation of these conditions may render the system inoperable or even lead to catastrophic failure. This paper develops a computational methodology to analyze the aforementioned set of safety threshold conditions, calculate the probability of failure, and in turn, proposes a new hypothesis to mathematically connect such probability to the remaining useful life prediction. A significant advantage of the proposed methodology is that it is possible to learn important properties of the remaining useful life, without simulating the system until the occurrence of failure; this feature renders the proposed approach unique in comparison with existing direct-RUL-prediction approaches. The methodology also provides a systematic way of treating the different sources of uncertainty that may arise from imprecisely known future operating conditions, inaccurate state-of-health state estimates, use of imperfect models, etc. The proposed approach is developed using a model-based framework prognostics using principles of probability, and illustrated using a numerical example.

118: A Semi-Analytical Methodology for the Reliability-Based Design of Linear Dampers Used for Seismic Hazard Mitigation of Buildings

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This paper presents an efficient semi-analytical reliability-based methodology for the seismic design of visco-elastic dampers used for seismic hazard mitigation of independent and coupled buildings. The proposed methodology is consistent with modern performance-based earthquake engineering frameworks and explicitly considers the uncertainties affecting the nonstationary seismic input and the model parameters, as well as the correlation between multiple limit states. The problem of the dampers' design for a target performance objective is cast in the form of a reliability-based optimization problem with a probabilistic constraint on the system failure probability during the buildings' design life. The general approach proposed in this study is specialized to stochastic seismic excitations and performance levels for which the structural behavior can be assumed linear elastic. Under these conditions, the optimization problem can be solved efficiently by taking advantage of recently developed analytical techniques for estimating the system reliability of linear elastic systems subjected to non-stationary stochastic excitations. This analytical design solution is an approximation of the optimal design and can be used as a hot-start point for simulation-based techniques such as the SIM and HYB algorithms, which were previously developed by the authors for the design of the separation distance between adjacent buildings subject

to seismic pounding hazard. These simulation-based techniques can be employed to find the optimal design solution of the visco-elastic dampers within a prescribed accuracy. An efficient semi-analytical correction formula is proposed to obtain an improved design solution that is generally sufficiently close for engineering purposes to the optimal design solution obtained from significantly more computationally expensive simulation-based techniques. The proposed design methodology is illustrated and validated by considering the retrofit of two steel buildings, modeled as shear-type multi-degree-of-freedom linear elastic systems, by using viscous dampers. The dampers' viscous constants are assumed as design variables. The application examples considered include individual and coupled buildings, deterministic and uncertain structural models, and viscous dampers characterized by uniform and variable properties at the various buildings' stories.

587: A Simple, Unified and Accurate Scheme for the Evaluation of Singular and Quasi-Singular Integrals in the 2D Boundary Element Method

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The implementation proposed herein had its basic features already addressed in two previous papers (Dumont, N. A.: On the efficient numerical evaluation of integrals with complex singularity poles, Engineering Analysis with Boundary Elements, Vol 13, pp 155-168, 1994; Dumont, N. A., and Noronha, M.: A simple, accurate scheme for the numerical evaluation of integrals with complex singularity poles, Computational Mechanics Vol 22, Nr. 1, pp 42-49, 1998) and starts by acknowledging that dealing with quasi singularities implies dealing with complex numbers. This is to the authors' best knowledge the only feasible, mathematically consistent technique for the evaluation of general quasi singularities that occur in the boundary integral equation formulations. As shown in the present paper, this implementation results in a robust code and implies no additional computational effort. On the contrary, just a few numerical integration points turn out to be required for highly accurate results along curved boundaries. Moreover, the closer a source point is to an integration interval, the more accurate the numerical results become. It is shown that the evaluation of results at internal points – even if one is using the (singular) Kelvin's fundamental solution – requires dealing with high-order quasi singularities, which is a crucial issue in a numerically consistent boundary element implementation. In fact, if a numerical integration is carried out properly, as proposed, there is no need of regularizing a boundary element formulation – a procedure that in general leads to just a rough numerical approximation of the actual mathematical problem and sometimes creates more numerical troubles – as well as there is no need of trying to arrive at time-consuming analytical evaluations for any particular configuration. The present developments cannot be outmatched in terms of simplicity and accuracy, as shown by means of several numerical examples.

109: A Simplified Analytical Wind-Field Model for Hurricane Boundary Layer

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The wind field model is one of the most important components for the hurricane hazard assessment, thus careful consideration should be given to it for a better representation of the hurricane event. Unfortunately solving the full non-linear equation analytically is demonstrated quiet challenging. Although neglecting non-linear terms by linearizing the problem may result in errors in the solutions as pointed out by previous studies, the linear model shows great promising to give simple solution with good approximation to the wind field and can be readily adopted for engineering applications. This study aims to investigate a more elaborate linear analytical model of the boundary layer for a moving hurricane. The wind velocity is expressed as the summation of two components:

the gradient wind in the free atmosphere and the frictional component on the ground surface. The gradient wind was first derived, then the frictional component was obtained based on the scale analysis of the full non-linear Navier-Stokes equations. Unlike previous studies, the variation of the wind field with respect to the angular coordinate was considered since its contribution cannot be ignored in the first-order approximation. Vertical profiles of the wind speed in the hurricane boundary layer are also examined. The new model was compared with the one proposed by Meng et al. (1995; 1997) and the major differences between the two models were highlighted. The last part of this study was devoted to the validation of the new proposed wind filed model. The results obtained indicate that the current model gives more accurate representation of the wind speed and profile.

378: A Stochastic Formulation to Model Resilience of Engineering Systems

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Armin Tabandeh, University of Illinois

Resilience of engineering systems is related to their ability of absorbing both gradual and abrupt changes under exposure conditions and rapidly recover from disruptions. Modeling the recovery process and quantification of resilience is a key element in assessing the performance of engineering systems and guiding the decision support to optimally allocate limited resources. In this work, we develop a general stochastic formulation to model the recovery process and quantify system's resilience. In particular, we develop models for time-dependent capacity of a system and the imposed demand, under joint effects of recovery and shock deterioration processes. The developed models can closely replicate the reality of progress made in repair/reconstruction project. Using the developed models, a recovery curve is formulated in terms of system's reliability. Furthermore, we propose a novel approach for resilience quantification, using the analogy between a recovery curve and a sequence of probability distribution functions (CDFs). Each segment of a recovery curve, between two successive shocks, that is a nondecreasing function, is treated as a CDF. Partial descriptors of the CDFs (e.g., their means) are aggregated to quantify the resilience of the system. In contrast to current approaches, the proposed approach makes distinction in resilience of systems with different recovery patterns but the same bounded-area between the recovery curve and the time axis, over a given time period. Semi-analytical solutions are derived for the probability distributions of various quantities including, number of recovery steps, number of shocks to recover, time-to-recover, and resilience. Numerical examples are provided to illustrate how the developed formulation can be used in practice.

754: A Stochastic Model for the Human Heading for Uncertainty Quantification of TBI Prediction

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The slow degradation of brain function due to Traumatic brain injury (TBI) makes it extremely difficult to identify events and corresponding mechanical and physiological responses that trigger TBI. Detailed finite element (FE) modeling of the scalp, skull, and brain subjected to loading scenarios provide a means to quantify mechanical response within the brain and brain stem. Although the relation between mechanical response and injury is highly unknown, the exceedance of threshold pressure within the brain is a commonly used criterion for injury due to blast loading. Preliminary parametric studies varying head morphologies of FE models have shown significant variation of pressure based metrics.The aim of this work is to develop a stochastic model describing the

morphology of human scalp, skull, and brain. Data is obtained from the International Consortium for Brain Mapping (ICBM) database, which is a collection of serial section grayscale images (e.g. magnetic resonance images (MRIs)) of human heads from varying sources. The head components are segmented using image segmentation algorithms found in the Brainsuite and Simpleware softwares. A mean head is established using image registration procedures, and affine maps from the mean to each subject are obtained through optimization using the AIR (automated imaging registration) software. The affine mapped heads contain significant errors with respect to the target subjects, therefore, statistical shape analysis (SSA) methods are also tested. These methods do not assume a model form, such as an affine or polynomial transformations. Instead, landmarks are defined for each subject head and mappings from mean to each subject is done through optimization by minimizing the distance between landmarks while satisfying smoothness constraints on the mapping. Due to the extreme computational cost of the FE models, the fewest number of parameters describing head morphology are sought. In order to accomplish this, linear and nonlinear dimensionality reduction methods are applied to the mappings; specifically, the compressibility of the data using principal component analysis (PCE) and local linear embedding (LLE) techniques are evaluated.

311: A Stochastic Simulation Method of Ground Motions for Specified Earthquake Scenarios

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A novel stochastic method for simulation of earthquake ground motions is developed, using a user-specified earthquake scenario description as input and resulting in fully non-stationary acceleration time-histories at a site of interest. A bimodal parametric evolutionary Kanai-Tajimi (K-T) model lies in the core of the predictive stochastic model. The K-T model parameters are linked to common seismic ground motion predictors through advanced regression models. An extensive Californian subset of the NGA-West2 database is used to calibrate the regression models. Model parameter realizations are obtained through fitting the K-T model to the selected Californian database records, and their resulting marginal distributions are effectively described by simple probability models. The sample parameters are subsequently translated to the standard normal space for computational and simulation efficiency. Linear random-effect regression models are constructed to associate the normal model parameters with the moment magnitude Mw, closest distance Rrup and shear-wave velocity VS30 at the site of interest. The random effects in the considered mixed linear models take effectively into account the correlation of ground motions pertaining to the same earthquake event, and the fact that each site is expected to have its own effect on the resulting motion. The covariance structure of the normal model parameters is estimated and together with the developed regression models form a multi-variate normal probability model, that can be easily simulated for a given earthquake scenario. The sample model parameters are translated back to their physical space through their fitted marginal distribution models. The simulation of sample acceleration time-histories associated with the resulting evolutionary K-T model is facilitated by the Spectral Representation Method (SRM). Finally, median plus/minus one standard deviation elastic response spectra of simulated acceleration time-histories for various earthquake scenarios are compared and found in close agreement with the associated NGA-West2 GMPEs response spectra.

726: A Survey of Methods for Integration of Uncertainty and Model Form Error in Prediction

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An open question of active research is determining how validation results can provide information about model form error and subsequently be used to adjust and improve predictions. Instead of simply making a binary validation assessment (i.e. accept or reject the model outright) and using the model to predict as is, some methods under current research aim to use the quantitative validation evidence (both bias and uncertainty) to improve upon the prediction. The methods for achieving an improved prediction must consider a number of factors including (1) the magnitude of the observed error, (2) the uncertainties in the model output and experimental observation, (3) the proximity of the validation tests to the application regime, and (4) the degree of coverage of relevant physics in the experiments. The present work investigates how different assumptions about these factors affect the prediction of interest. Several existing methods for incorporating calibration and validation information into a prediction of interest are explored. Calibration and validation tests are typically performed in simplified scenarios with respect to both configurations and inputs. These tests may be composed together to form a validation hierarchy in which information at different levels has varying degrees of complexity and relevance to the application and is therefore used in different ways. The goal of each prediction methodology is to integrate all available information and make a prediction for a target application that includes the errors and uncertainties that have been quantified at lower levels of the hierarchy. This integration of information has been referred to as "roll-up" of error and uncertainty to prediction. In this work, the assumptions that underlie each approach are described, and then the methods are compared on the basis of their individual strengths and weaknesses.

783: A Texture-Based Video Processing Framework for Autonomous Crack Detection on Metallic Surfaces

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Regular inspection of nuclear power plant components is an important task to improve their resiliency; however, the current practice is time-consuming where an operator manually locates the cracks on metallic surfaces in a video. On the other hand, the existing automatic crack detection algorithms fail to detect cracks on metallic surfaces since these cracks are typically very tiny with low contrast. In addition, the existence of scratches, welds, and grind marks lead to a large number of false positives if state-f-the-art vision-based crack detection algorithms are used. In this study, we propose a novel approach based on local binary pattern (LBP) to accurately detect cracks in video frames. We use Bayesian decision theory to remove falsely-detected cracks by tracking the cracks in different video frames. The performance of the proposed approach is evaluated by using several inspection videos where the results show that the proposed framework is more robust than the existing automated vision-based approaches.

403: A Two-Scale Nonlinear Generalized FEM for the Simulation of Spot Welds in Large Structures

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Spot welds are commonly used to join thin gauge metallic structural components of automotive and aerospace vehicles. The failure of spot welds may lead to the catastrophic loss of the structure. Hence, modeling spot welds and resolving local stress fields with high fidelity is rather important. Several approaches are currently available for modeling spot welds. The representation of welds in the Finite Element Method (FEM) involves the introduction of a refined mesh to represent the welded area. This approach provides some basic information about the local stress distribution. However, it requires rather extensive time building and solving the FEM model if an accurate stress field is desired. The disparate scales involved in a large structure with dozens to hundreds of welds prevent one from having all the welds represented within a single model. It is not just because of the extensive computational cost involved, but also by the difficulty of generating such a mesh. Another common approach is to use Rigid Elements or Multi-Point Constraints which are introduced as point-to-point representations of the actual connectors. This rather simplistic solution serves the purpose of connecting thin structures, but it provides no useful information about the stresses around the welds. We propose a Generalized Finite Element Method with global-local enrichment (GFEMgl) to resolve the spot weld problem. This GFEMgl is a multiscale framework which uses the solution of a local problem defined for each weld as enrichment functions for the structural-scale model. This methodology offers great flexibility. It allows the discretization of each spot weld independently of each other using fine meshes, while keeping the global mesh fairly coarse. It also allows the adoption of different element types in global (hex) and local (tet) models. This framework can be further improved by introducing a cohesive interface defining the geometry of each spot weld. This results in no need to create local meshes fitting the welds. Instead, uniform meshes can be used, which significantly ease the process of generating local models. Additionally, contact between welded structural components can be naturally simulated by proper selection of cohesive law at the interface between the components. Numerical experiments show that the accuracy of the proposed GFEMgl is comparable with that provided by a direct finite element simulation with the fine-scale features discretized in the global mesh. This user-friendly and accurate GFEMgl also provides very good computational efficiency by exploring the natural parallelization of local problem computations.

519: A Two-Way Linked Multiscale Model to Analyse and Predict Pavement Damage Performance

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This study presents a multiscale computational model and its application for predicting damage-associated structural performance of bituminous pavements that are composed of heterogeneous mixtures. In the model framework, two length scales (i.e., local scale mixtures and global scale pavements) are two-way coupled based on a thermo-mechanical finite element formulation. The local scale is regarded as a bituminous mixture by heterogeneous representative volume elements (RVEs), while the global scale is represented by a homogeneous pavement layer. Since individual component properties in the local scale mixture, microstructural heterogeneity, elastic-viscoelastic deformation, and fracture damage in mixture microstructures are considered in the model for predicting damage-induced pavement performance through the two-way coupled multiscaling, typical distresses in bituminous pavements such as rutting and cracking can be examined more accurately as a function of core design factors such as properties of mixture components, mixture microstructures (e.g., aggregate gradation, volume fraction, additives, and air voids), traffic loading conditions, and pavement layer configurations. Additionally, experimental costs and time for pavement structural design are expected to be significantly reduced by this model that requires only mixture component-level properties, rather than test results of entire mixture specimens. Model simulation results clearly demonstrate the sensitivity of the model to the core design inputs and show that the multiscale model presented herein has a great potential to be a promising tool for a mechanistic pavement design/analysis and materials selection.

292: A Variable Density Model for Water Air Structure Interaction Problems

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Modeling of wave-induced fluid forces on structures such as buildings, bridges, or offshore platforms can be a complex water-air-structure interaction problem. To accurately capture the physics and compute these forces, it is often necessary to model the interface between water and air, which presents numerous challenges. The interface separating liquid and gas is extremely thin, resulting in a discontinuity. The large density difference between the two fluids must be accounted for, and a wide range of time and length scales must be resolved. In this work, a simple variable density model is applied with a discontinuity in the density. Both air and water are modeled using the incompressible Navier-Stokes equations with variable density, which are solved using the software Dolfin-hpc and Licorne, both of which are components of the open-source project FEniCS, which applies a finite element method (FEM) solver. Because most structural analysis is performed using FEM, this approach can eliminate the need for coupling of different numerical models to predict fluid-structure interaction responses. To solve the model equations with FEM, a residual base artificial viscosity stabilization was developed to take care of the instabilities of the convection dominant problem, as well as instabilities along the interface due to the large jump in density. In addition level set method techniques are used to maintain the interface. The turbulent nature of the flow is taken into account by the implicit large eddy simulation (LES), where the unresolved scales are represented by the dissipation of the numerical scheme. The computational framework can utilize massively parallel architectures to achieve the required model resolutions. Validation studies are presented for two cases. First, the evolution of the Rayleigh-Taylor instability (RTI) in a rectangular domain is presented, where two fluids have a small density difference and the heavier fluid is located above the lighter fluid and the system is driven by the gravitational force. Second, water waves are modeled based on experimental flume tests of flow around both a cylindrical column and a square column in a three-dimensional domain. This work is very relevant for researchers studying water-air-structure interactions around complex geometries. As computational power increases, many researchers are exploring new avenues to model these phenomena, and this work presents a novel contribution to the field.

732: A Wearable Wireless Sensor Network for Emergency Cases in Buildings Using a Customized Structural Health Monitoring System

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The paper presents a novel system based on a wearable WSN and a customized SHM system for managing emergencies in buildings. In this system, the wearable devices are nodes of the WSN, while the customized SHM system collects data from the nodes and sends them to the server. The proposed SHM system is not only a normal SHM system which can be used for structural monitoring applications by measuring vibration, displacement, temperature, and etc., but is also designed to be used as the sink in the wearable wireless sensor network. This SHM system is able to communicate with the nodes using radio frequency which also provides the possibility of indoor localization of the nodes (people) with a reasonable precision. In addition to the different sensors which have been used to measure vital signs (body temperature, heart rate, and etc.), this system is equipped with RF and GSM modules in order to communicate with servers through RF and mobile networks respectively. When the telecommunication infrastructures are damaged due to the disaster, the RF module will be used to send data to the servers through a customized SHM system. This system is useful during an in emergency (earthquake, fire, flood, and etc.) in order to define the location and the overall status of the victims (dead/alive and conscious/unconscious) who are trapped inside the damaged buildings. Using the data collected by the system, it

is possible to develop maps which include approximate location of people and their status. These data will help emergency teams to improve efficiency and speed of searching and rescuing, and consequently, save more lives and decrease recovery time.

362: Active Elastic-Wave Imaging of Heterogeneous Fractures: From Geometric Reconstruction to Interfacial Characterization

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Major strides have been made toward the simultaneous geometric reconstruction and interfacial characterization of fractures via seismic waveform tomography. So far the proposed methods, often reliant upon a rudimentary parameterization of the fracture geometry (e.g. planar fractures) and nonlinear minimization, entail a number of impediments including: i) high computational cost; ii) sensitivity to the assumed parametrization resulting in multiple sets of "optimal" solutions and thus the ambiguity of such obtained information; iii) computational instabilities requiring multiple stages of regularization, and iv) major restrictions in terms of the seismic sensing configuration, namely the location of sources and receivers relative to the (planar) fracture surface. To help meet the challenge, the goal of this study is to establish a comprehensive platform for the 3D reconstruction and mechanical characterization of arbitrarily-shaped, distinct fractures in quasi-brittle materials. In particular, the focus will be on i) developing a robust framework for geometric reconstruction of fractures from the scattered field data using a carefully designed indicator functional that features low sensitivity to measurement noise and imposes no major restrictions on the illumination frequency or the sensing configuration, and ii) recovering the fracture's heterogeneous boundary condition. Over the past decade, research in applied mathematics and engineering has produced a suite of non-iterative approaches to inverse scattering, such as the linear sampling method (LSM), that are capable of accurately recovering the 3D geometry of subsurface anomalies. In the present work, this goal is accomplished via an extension of the so-called generalized linear sampling method (GLSM) to enable geometric reconstruction of fractures regardless of their interfacial condition. With such result at hand, the proposed inverse solution will entail a 3-step hybrid approach where: 1) the fracture surface is reconstructed without the knowledge of interface; 2) given the geometry, the fracture opening displacement (FOD) profile is recovered from an integral transform relating FOD to the observed seismic waveforms; and 3) given FOD, the spatial distribution of specific stiffnesses is resolved from the boundary integral equation for fracture, incorporating its (inhomogeneous) elastic contact condition. This scheme is integrated into a recently developed BEM code. The proposed developments will then be verified in a laboratory setting, making use of the recently acquired Scanning Laser Doppler Vibrometer (SLDV) that is capable of monitoring triaxial waveforms on the specimen's surface.

346: Adaptive Discretizations for Bone-Implant Systems Using the Finite Cell Method

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In recent years, the finite element method has been increasingly used to study the biomechanics of bone-implant

systems. Patient-specific models need to consider the individual geometry for every case. Typically, geometric models of the bone are reconstructed from medical images - most commonly CT scans [1]. Following segmentation, a finite element mesh has to be generated. This can be a simple voxel-based mesh, where a predefined number of voxels constitute one finite element in a grid that matches the voxel model. Alternatively, geometry-conforming meshing procedures can be used to generate an unstructured mesh. To this end, the surface points are extracted from the voxel model and converted to a solid model, which is then meshed into an unstructured grid. Similarly, the geometry of the implant is usually reconstructed from medical images, or provided by Computer-Aided-Design (CAD) models, and then incorporated in the finite element mesh. The adequate treatment of the bone-implant interface demands the spatial refinement of the finite element mesh at the interface for an accurate solution. For voxel-based finite elements, a very fine resolution is already necessary to resolve the implant's geometry. This leads to an extremely high number of degrees of freedom, as the whole grid has to be refined. On the other hand, geometry-conforming finite elements need more pre-processing (converting the bone's voxel model to a solid model), and complex meshing procedures to resolve geometries of the bone and the implant with graded refinement of the mesh towards the interface. In this contribution, we will use the finite cell method (FCM) [2] in conjunction with a hierarchical hp-refinement scheme [3] to model a vertebral fixation system. The FCM discretization completely circumvents the mesh generation procedure, as the geometry is resolved on the integration level. Here, the flexibility of FCM in dealing with different types of geometric representations is demonstrated: the bone's geometry is represented by the voxel model from a CT-scan, whereas the implant's geometry is directly described by a CAD solid model. Both representations are directly used in the FCM framework, thereby substantially reducing the pre-processing effort. Furthermore, the hierarchical refinement scheme yields a higher accuracy at the bone-implant interface by adaptively refining the FCM grid.

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8: Adaptive Kriging Metamodeling for Simultaneous Uncertainty-Propagation and Design-Optimization

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This investigation focuses on design-under-uncertainty problems that employ a probabilistic performance as objective function, and consider its estimation through stochastic (Monte Carlo) simulation. This approach offers great flexibility since it has no constraints on the computational and probability models adopted to characterize the system performance. Its drawback is, though, the high computational cost required to estimate the objective function, especially for design problems involving complex, high-fidelity models. To alleviate this burden a framework relying on surrogate modeling to approximate the system performance is developed. Kriging is utilized as surrogate model since it has been proven highly efficient for approximating complex response functions while simultaneously providing gradient information. The metamodel is developed to simultaneously support the design optimization as well as the uncertainty propagation adopting a trust-region approach for the numerical optimization. A sub region of the design space is defined and a kriging metamodel is built to approximate the system response (metamodel output) with respect to both the design variables and the uncertain model parameters (metamodel input). High-fidelity model evaluations are obtained at properly selected support points (“experiments”), and the kriging model is then developed employing this information. This metamodel is then used within a stochastic simulation setting to approximate the system performance when estimating the objective function and its gradient for specific values of the design variables, where the stochastic simulation is ultimately established with respect to the random model parameters. This information (i.e. estimate of objective function and gradient) is then used to search for a local optimum within the previously established design sub domain. Only when the optimization algorithm drives the search outside this sub domain, a new metamodel is generated, and the process is iterated until convergence is obtained. Emphasis is placed on both the design of experiments (DoE) as well as the selection of the exact number of experiments. An iterative approach is suggested for the latter. An initial number of support points is first used to develop the metamodel and then accuracy criteria are developed related to the approximated gradient through the metamodel. If criteria are not sufficient, then additional support points are generated. For the DoE an adaptive sampling approach is established, populating more densely those regions in the random variable space that have higher contribution to the integrand quantifying the probabilistic performance while also incorporating (within the aforementioned iterative approach) the anticipated accuracy of the surrogate model.

180: Adaptive Selection and Validation of Coarse-Grained Models of Atomistic Systems in the Presence of Uncertainties

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Advances in material science, biology, nanomanufacturing, drug design, and in many other fields, have dramatically expanded interest in the use of atomistic models to study a wide variety of physical phenomena and to analyze the behavior of many engineering and medical systems. The enormous size and complexity of systems of interest far exceed the capabilities of today's largest super computers or even those envisioned decades into the future. Coarse-grained (CG) models of atomistic systems, in which groups of atoms are aggregated into larger units to reduce the number of degrees of freedom, have been used for decades in significant technological and scientific applications. The development of a reliable reduced-order model, however, raises long-standing issues in computer modeling and simulation, including model selection, calibration, validation, and error estimation, all in the presence of uncertainties in the data, prior information, and the model itself. The development of a rigorous mathematical, physical, and statistical foundation for the process of coarse graining is, hence, a goal of great importance in computational science. A general Bayesian setting is developed to address these challenges, which, when augmented with tools such as sensitivity analysis, information theory, and model selection methods, provides a unified framework for model selection, validation, and prediction under uncertainty. The Occam-Plausibility ALgorithm (OPAL), so-named for its adherence to Occam's Razor and the use of Bayesian model plausibilities, chooses, among a large set of models, the simplest valid model that may be used to predict chosen quantities of interest. While each step in the coarse-graining process can introduce significant uncertainties in the target predictions, OPAL provides a unified framework for assessing the predictability of CG models. An illustrative example application to the construction of coarse-grained models of atomistic polyethylene is given.

168: Adaptive Surrogate Model-Based Stochastic Search Algorithms for Locating Implicitly Defined Limit Surfaces for Structural Reliability Analysis

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The reliability of structural system is defined as the probability of satisfactory performance of the system under

uncertain external excitations and (or) system parameters. Depending upon the type of external excitation, reliability can be broadly classified into being time-invariant or time-variant. While the former corresponds to static uncertain loads, the later corresponds to dynamic random loads. The complexity of both the categories however remains nearly the same due to the correlated non-Gaussian nature of the uncertainties, and highly non-linear nature of the limit state function. With the limitations of analytical approximations – First and Second order reliability methods, asymptotic methods, etc. – the research over the past two decades moved towards (i) development of efficient simulation based methods, i.e. simulation methods with reduced variance, and (ii) construction of alternate mathematical models as a substitute to the limit surface, which is, more often than not, highly non-linear, implicitly defined, and computationally expensive to evaluate. The methods developed in this work, at the present stage, deals with development of surrogate models for moderate dimensional time-invariant reliability problems. The paper proposes two search algorithms with in-built adaptive features to locate and trace an implicitly defined function. Both the methods consist of two steps. The first step involves propagating a series of pseudo-Markov chains to locate various disjoint failure regions. The word "pseudo" is used to represent the fact that a surrogate model based approach is used as an acceptance criterion for the future states of the Markov chain, instead of the conventional approach of using an accept/reject criterion built on the proposal and target density functions. The second step, which is, tracing the function, demarcates the two methods. The first method uses the global features of the limit surface function to add samples in the vicinity of the limit surface, and the second makes use of the local features of the limit surface. For both the methods, the underlying surrogate model evolves continuously as and when a new sample is added. The methods presented are independent of the type of surrogate model used, although, machine learning algorithms such as Artificial Neural Networks and Support Vector Machines are preferred, due to their robustness. Performance of the method is illustrated through problems with highly nonlinear limit state functions and high dimensional non-Gaussian random variables.

221: Advanced System Identification for Super High-Rise Building Using Shear-Bending Model

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A new system identification method (SI method) for a high-rise building structure is proposed based on the recording data of micro-tremor. The ARX model and a shear-bending model are used in this method. Compared with conventional SI methods to identify the modal parameters (e.g. natural periods and damping factors), the proposed SI method aims to directly identify physical parameters, such as story stiffnesses and damping coefficients. A shear building model may be the simplest physical model for this purpose, but the SI method using a shear model is not necessarily suitable for high-rise buildings. This is because the influence of the bending deformation needs to be taken into account especially for high-rise buildings. A shear-bending model is therefore used in the proposed SI method where the shear and bending stiffnesses are unknown. In the proposed SI method, identification functions (IDF) are efficiently utilized which can be derived by using the transfer functions between horizontal displacements at upper and lower floors of a target story. It has been proved theoretically that the limit value of the IDF at the zero frequency indicates the shear stiffness of the shear building model. However, the evaluation of the limit value of the IDF includes a technical difficulty in the case of dealing with actual recorded data because of the low S/N ratio in the low frequency range. In this paper, the estimation of the limit value of the IDF is improved by using the ARX model and updating itself by an optimization approach to the corresponding shear model. Since the limit value of the IDF can also be used in the identification of the building structure as the shear-bending model, the improvement of the accuracy of the limit value of the IDF can provide the reliable identification results in the shear-bending model. The concept of updating the evaluation of the limit value of the IDF in the previously proposed SI method using the shear model plays an innovative role in the

proposed SI method for the shear-bending model. It can be expected that the identification accuracy of the shear and bending stiffnesses is improved, which can provide useful information on the damage detection in the structural health monitoring system. The validity of the proposed SI method is examined through numerical simulations including actual recorded micro-tremor data.

198: Advances in Dynamical Simulation and Analysis of Granular Flows

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Anthony Rosato, New Jersey Institute of Technology

Several advances in the investigation of granular flow affected by a combination of discrete element simulation and dynamical systems modelling and analysis are described. This includes a simplified infinite-dimensional dynamical system model that, informed and confirmed via simulation, is capable of predicting both the motion and density wave behavior of a wide range of granular flows. In addition, it is shown how simulations inspired and verify the efficacy of approximate reduced models, in the form of low-dimensional discrete dynamical systems, able to predict with surprising accuracy such features as bifurcations, transitions to chaos, strange attractors and perturbation wave properties. Examples for tapping and periodic shaking of granular configurations are presented to illustrate the effectiveness of the combined simulation – dynamical systems approach. Finally, open problems and plans for future research are presented.

155: Advances in Fluid-Structure Interaction Simulations of Wind Turbines, Aerospace and Offshore Structures.

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Advances in Fluid-Structure Interaction (FSI) simulations of wind turbines, aerospace and offshore structures are presented. The challenges associated with large problem size, complex nonlinear geometrical model and material distribution, highly turbulent flow and complicated multi-physics coupling are accounted in presented simulation tools and computational techniques to overcome these challenges are discussed. Recent developments in isogeometric analysis (IGA) and multilayer composite material modeling are also shown together with the finite-element-based stabilized and variational multi-scale methods for fluid mechanics and FSI problems. Advanced numerical examples of wind turbines, aerospace and offshore structures are presented together with experimental validation.

112: AE Based Damage Detection of Steel Bridge Superstructures

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One third of the approximately 600.000 bridges listed in the United States National Bridge Inventory (US-NBI) are either structurally deficient, or functionally obsolete or both. Therefore, most of these bridges need real-time health monitoring. This paper is concerned with investigating the effectiveness and applicability of the acoustic emission based health monitoring systems on steel bridge superstructures, by undertaking both experimental and

numerical investigations. Model steel bridge girders were designed, tested under cyclic loading and monitored in the laboratory with the help of an acoustic emission based monitoring system. After testing, the recorded data was post-processed with the help of some powerful methods from the arsenal of mathematical data processing tools, including wavelet transformation, Fourier transformation and artificial neural networks for noise elimination, event source location and signal characterization. Accurate numerical (finite element) modeling of the test specimens and piezoelectric acoustic emission sensors were undertaken for further verification/validation of the acoustic emission based health monitoring scheme.

135: Algorithms for Bayesian Network Modeling of Multi-State Infrastructure Flow Systems

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Iris Tien, Georgia Institute of Technology

Infrastructure systems are critical to our everyday lives and to the health, safety, and functioning of society. These systems are complex, comprised of many interconnected components. The Bayesian network (BN) is a useful tool to model and analyze these systems. The BN captures the probabilistic dependencies between component and system performance, with inference in the BN informing decision making in the management of these systems. However, one of the major challenges in the analysis is the exponentially increasing computational complexity as the number of components in the system increases. Previously, compression and inference algorithms have been developed for BN modeling of binary systems. Compared with binary systems, multi-state system modeling provides a more detailed description of system reliability and enables the analysis of flow instead of connectivity networks. The dimensionality of the problem, however, also increases. This paper aims to address the computational challenges associated with Bayesian network modeling of multi-state infrastructure systems. We present new compression and inference algorithms for multi-state components and apply them to a test application. Their ability to conduct inference across the system is demonstrated and performance measured compared to existing algorithms in terms of both memory storage and computational time.

272: Alloying Effects on Grain Boundary Motion and Microstructure Evolution

Stephen Foiles, Sandia National Laboratories
Fadi Abdeljawad, Sandia National Laboratories
Christopher O'Brien, Sandia National Laboratories

The evolution of the grain microstructure is a central issue in materials science. There is substantial current interest in the stabilization of nanocrystalline grain structures to maintain the enhanced properties of nanocrystalline metals. It is known that alloying can have a profound influence on microstructure evolution. However, there is ambiguity about the relative roles of various mechanisms including thermodynamic stabilization due to alloy segregation, impurity drag and precipitate-boundary interactions. In this talk, we will use a combination of atomistic simulations and phase field modeling to elucidate the relative importance of these various mechanisms. Atomistic simulations will be used to investigate the heats of segregation of alloying elements to grain boundaries, the influence of segregated species on grain boundary mobility and the variability of these factors with boundary type. Phase Field simulations will be used to study the influence of these factors, both individually and in concert, on the overall microstructure evolution. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.

237: An Adaptive Method for Solving Stochastic Equations Using Local Taylor Approximations and a Posteriori Error Estimates

Wayne Isaac Uy, Cornell University
Mircea Grigoriu, Cornell University

A non-intrusive adaptive method is proposed for solving stochastic equations, in particular, differential equations parameterized by random coefficients. We pursue a sequential approach in which an initial coarse partition of the range of the random entries is refined until a specified accuracy is met. The method is based on a surrogate model of the solution constructed through a Voronoi tessellation of the samples of the random coefficients with centers chosen to be statistically representative of these samples. Surrogate models are first order Taylor expansions in the probability space that match solutions and their gradients at the centers of the Voronoi cells. Unlike Monte Carlo solutions, which requires numerous calls of deterministic solvers, relatively small numbers of deterministic calculations are needed to implement surrogate models. These models can be used to generate large sets of solution samples with a minimum computational effort. In this work, we propose a framework for an adaptive procedure of refining the Voronoi cells which incorporates the mapping between the random coefficients and the solution. The framework relies on error bounds for the surrogate model and various error metrics, such as adjoint-based a posteriori error. Numerical examples are furnished to illustrate the implementation of the proposed framework and demonstrate the accuracy gained from this adaptive approach.

613: An Application of a Modified Colliding Bodies Optimization Algorithm in Health Monitoring of Structures Using Flexibility Changes

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In this study an effective method for structural damage identification is presented. Using changes in the flexibility matrix between damaged and healthy states, a new damage-sensitive cost function is proposed and then, the Modified Colliding Bodies Optimization Algorithm (MCBO) is employed for finding the locations and severities of the damages. The applicability of the presented method is demonstrated by studying several damage patterns on two numerical examples of frames when the input data are contaminated with different levels of noises. In addition, some comparative studies are carried out to evaluate the applicability of the MCBO algorithm in comparison with other evolutionary optimization approaches, especially in the presence of patterns with multiple damage locations which can be considered as an optimization problem with complex solution domain. The obtained results show the good performance of the presented method in estimation of structural damages and introduce the MCBO as a robust optimization strategy in solving ill-posed inverse problems.

22: An Approach to Quantify Ground Motion Uncertainty for Incremental Dynamic Analysis

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Ground motion (GM) uncertainty, as an essential part of Performance Based Earthquake Engineering (PBEE), has been widely regarded as the dominant contributor to PBEE uncertainty. In simplified analysis or codified procedures, GM uncertainty is usually assumed to have a constant impact to engineering demand parameters regardless of seismic hazard levels. For more advanced analysis utilizing nonlinear time history simulation, the GM uncertainty is represented empirically through use of pre-selected GM suite. In this paper, a semi-closed-form propagation equation for the contribution of GM uncertainty to nonlinear SDOF system acceleration demand was proposed. This was accomplished through parameterizing the shape of the incremental dynamic analysis (IDA) curves using intensity-independent GM parameters. To validate the accuracy of the proposed formula, eight ground motions were randomly selected from the PEER database. The results show a good agreement with the simulated results through nonlinear time history IDA analysis. Additionally, the validation was done through constructing an "equivalent" GM suite for a pre-selected GM suite, which results in the same the structural responses uncertainty across all intensity levels.

264: An Approach to Track Crack Connectivity for Hydraulic Fracturing Using Graph and Disjoint-Set Data Structures

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Hydraulic fracturing is widely employed to stimulate oil and gas reservoirs to increase their productivity. Various numerical techniques exist to examine hydraulic fracture propagation. However, in most these methods, there are a few non-interacting cracks that propagate or the interaction between the hydraulically loaded crack and the other cracks is not incorporated. Motivated by this observation, we present an approach that implements complex data structures within a finite element method scheme to dynamically track crack connectivity and hydraulic load propagation. Fracture solutions are determined by a spacetime discontinuous Galerkin finite element analysis scheme which offers greater accuracy, efficiency than conventional (continuous) finite elements methods and enables direct tracking of arbitrary crack propagation patterns. As cracks propagate, their patterns can be modeled analogous to a simplicial complex and geometrical information can be managed with a graph theory approach. In conjunction with graph theory algorithms, a disjoint-set data structure is used to monitor load propagation and transfers between independent sets of fracture inclusions. This not only results in correct modeling of interaction between different cracks, but also allows imposing independent loading conditions for arbitrary sets of fracture sets. Numerical results from various crack configurations and loading conditions will be presented. The simplest case that will be considered is the interaction of a hydraulically loaded and horizontally oriented crack with an arbitrarily oriented unloaded natural fracture. This has applications in the stability analysis of natural faults close to hydraulic fracturing wells. Using the graph and disjoint-set data structures, the loaded crack will propagate subsequently intersecting the natural fracture allowing the load information to transfer. We will also present more complex examples where the hydraulic load is transferred to already existing natural fissures in rocks and results in the extension of these fissures due to the transferred load.

120: An Atomistic-to-Continuum Approach to Modeling Size Effects in Polymer-Carbon Nanotube Composites

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We propose a computational procedure to assess size effects in polymer-carbon nanotube (CNT) composites. The characteristic dimension of CNTs, in the order of nanometers in the radial direction, calls for a detailed analysis of the atomic structure of the polymer in the region surrounding the CNT. This region, known as the interphase layer, plays a central role in the overall response of polymer-CNT composites [1] and can be related to the occurrence of size effects. In this contribution, the interphase layer and the CNT-induced size effects are characterized by means of Molecular Dynamics (MD) simulations on a polymer-CNT representative unit. An optimization procedure is then employed to define a mechanically equivalent continuum model which describes the CNT, the polymer-CNT interface, and the interphase as a three-dimensional equivalent fiber [2]. Having established the mechanical equivalence between the atomistic and the continuum model, we investigate size effects in the mechanical properties of a CNT-polymer composite with realistic CNT volume fractions. In particular, we use the Generalized Finite Element Method [3] to efficiently handle the inclusion of the equivalent fibers in a polymer matrix.

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368: An Elasto-Plastic Constitutive Model for Monotonic and Cyclic Behaviour of Gravel-Structure Interface

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A new elasto-plastic model is proposed for modelling the constitutive behaviour of the interface between gravelly soil and construction material. This model is based on bounding surface plasticity framework and it is compatible with the concept of critical state soil mechanics. The model requires 8 calibration parameters and is capable to predict the monotonic and cyclic behaviour of gravel-structure interfaces with only a single set of model parameters. All parameters have physical meaning and can be easily evaluated by the standard shear tests. The model simulates cyclic densification and shear degradation of the interfaces and considers the effects of normal pressure and stress path on the interface behaviour. The performance of the proposed constitutive models is validated by monotonic and cyclic test data under different normal stress and various boundary conditions.

634: An Enhanced Stochastic Averaging Method for Optimal Control of Structures with Nonlinear Soil-Structure Interactions

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Conventional control designs require simplified models of nonlinear dynamic systems. These models are derived based on linear elastic or equivalent linear properties; therefore, nonlinearities of the system are neglected in the design process. Stochastic control based on the concept of stochastic averaging has the potential to address this challenge. This method uses Ito’s differential representation of system dynamics which explicitly incorporates the nonlinearity of the system and stochasticity of excitations to derive the Fokker-Planck-Kolmogorov (FPK) equation governing the probability distribution of system responses. A Hamilton-Jacobian-Bellman (HJB) equation is then derived for the optimization problem based on a prescribed cost function and force constraints. However, this approach assumes that the system is lightly damped, has a restrictive form of damping matrix, and is subjected to independent stochastic excitations. These constraints may limit the application of stochastic averaging for control of nonlinear civil engineering structures that often do not satisfy those conditions. To address these shortcomings, a procedure is developed to generate an equivalent nonlinear model for general nonlinear non-integrable structural systems subjected to stochastic excitations. Before implementing the stochastic averaging method, the derived nonlinear model of the system is modified in order to account for off-diagonal damping terms which are neglected in conventional stochastic averaging methods. This goal is achieved by equating the stationary FPK equation of the actual system to that of the modified system and applying the method of weighted residuals to the difference of FPK equations. The modified diagonal damping matrix of the new system is computed using the second-order-moments of velocities and displacements. Additionally, the conventional method is enhanced to apply a single stochastic excitation rather than independent excitations to a non-integrable system to represent the case of a structure that is subjected to a hazard excitation. The application of the proposed method is demonstrated for the stochastic control of a one-story building on a raft foundation in loose sand. The nonlinear soil-structure interaction is characterized using a Bouc-Wen model. The stochastic averaging of this MDOF system considers hysteretic models for component behaviors in deriving the Hamiltonian energy of the system. The proposed method is applied to derive the HJB equation for the optimal control of the building; this equation is solved using dynamic programming techniques. Numerical results show that the proposed strategy properly accounts for the nonlinearity of the dynamic system facing stochastic excitations. In addition, larger response reductions are achieved compared to traditional control algorithms.

122: An Experimental Study of Rod-Like Debris Flight with Particular Application to Fire Spotting

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As a consequence of a warming climate, the risk of fire spotting to people, property, and infrastructure is increasing significantly, in particular in the wild-land urban interface (WUI). Spot fires occur when firebrands are lofted into the atmosphere by the fire plume, transported downwind by the atmospheric boundary layer, and land where they may ignite another fire. In order to understand and mitigate the associated risks, it is crucial to understand the dynamics of firebrand flight. However, due to the complex stochastic nature of the problem and its large scale, there are virtually no experimental data sets that can be used to validate existing flight models. This study quantifies and evaluates performance of current firebrand transport models by quantifying the aerodynamic behavior of firebrands through a series of free-fall experiments. In each set, non-combusting cylindrical firebrand models with different aspect ratios are dropped approximately 1000 times each from various heights under a zero-wind condition. Each release is conducted with zero initial velocity and with randomly varied initial release angles. For each drop, the radial travel distance of the firebrand is captured through audio and image processing analysis. A deterministic six degrees of freedom debris flight model with steady aerodynamic force and moment coefficients is used to simulate these free falls. The flight model is run with initial release angles that are randomly generated from a uniform distribution ranging from 0 to 90. Statistical analysis and comparison between PDFs and CDFs of radial distances from experimental results and the corresponding Monte-Carlo simulations, suggest that the flight model is capable of predicting the statistical signature of the firebrand flight. Moreover, the results support the theory that unsteady aerodynamic force and moment coefficients are only important during the early stages of flight where the acceleration is high. Further, we present results of large scale wind tunnel experiments where lofting and transport of firebrand models are tested to provide data for validating current fire spotting models. The results have application beyond firebrand transport as they represent the most comprehensive experimental analysis of rod-like debris flight in a turbulent boundary layer yet conducted. As such, the results will be of value to modeling risk from windborne debris impact during severe storms.

296: An Experimental Study on Finite Element Model Updating for a Pedestrian Bridge Considering Temperature Effects

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In modal-based damage detection, changes in dynamic properties of a structure are usually interpreted as an indicator of damage occurrence. By comparing changes in dynamic properties of the finite element (FE) model prior to and after damage, one can estimate both the location and extent of the damage. However, temperature induced changes in dynamic properties are often comparable to those caused by low to medium level of structural damage. Environmental changes, especially temperature fluctuation, have been shown by many researchers to significantly impact on dynamic properties (notably natural frequencies and mode shapes) of a structure. The long term monitoring effort for the Z24 Bridge in Switzerland has shown that the variation of its first few natural frequencies is closely related to the ambient temperature. Recent study on the Tamar Bridge in England also demonstrates a strong correlation between its dynamic properties and the ambient temperature. Therefore, the accuracy and effectiveness of structure damage identification might be compromised due to the uncertainties brought by significant environment impact, such as temperature variation. □□To address the above issue, this paper presents an experimental study on a bridge FE model updating considering temperature effects. A novel FE model updating method that incorporates temperature information into the FE formulation is developed. In the updating process, Bayesian analysis is applied to evaluate the uncertainties embedded in the FE model. A series of accelerometers, strain gages and thermal couples are installed on the pedestrian bridge located at the University of Alabama campus. With the sensors installed, both the bridge vibrational data and its ambient temperature data are collected to update the FE model. The modal properties predicted by the updated model are compared with measured values to demonstrate the effectiveness of the proposed FE updating method.

636: An Explicit Numerical Integration Algorithm for Force-Based Hybrid Simulation

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Hybrid simulation is a technique combining experimental testing and numerical simulation by dividing a structural system into experimental and numerical substructures. While hybrid simulation provides an efficient mean for evaluation of the performance of structural systems under seismic loading, it has some limitations for other types of loading such as strong winds, hurricane and tsunami. One of the reasons is that force equilibrium is not always satisfied because the formulation in the conventional hybrid simulation is based on the displacement. This study proposes an explicit force-based numerical integration algorithm that ensures force equilibrium in the equation of motion at every time step. In the proposed algorithm, an □-shifted time discrete equation of motion is used as the governing equation. The proposed formulation allows explicit solution procedure based on the restoring force without need of stiffness matrix. Theoretical and numerical studies of the algorithm are performed

to investigate its stability, accuracy as well as feasibility in hybrid simulation. In the theoretical study the influence of parameters on the poles and zeros of transfer function in Z-domain are assessed. Accuracy of the algorithm is evaluated in comparison with the conventional form of the discrete equation of motion. Results in these theoretical and numerical investigations are discussed in this paper.

486: An Improved Displacement Control Algorithm for Real-Time Hybrid Simulation

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It is important to use a reliable real-time controller for servo-hydraulic actuator systems to ensure the stability and accuracy of real-time hybrid simulation. Numerous real-time hybrid simulations have been conducted based on the displacement control of actuators, where the equations of motion are numerically solved with the measured restoring force from the experimental substructure. A number of displacement-based control algorithms have been developed to impose the target displacement onto the test specimen with minimal time delay. Among them, the adaptive time series (ATS) controller has been successfully used for implementing recent large-scale real-time hybrid simulations. The ATS compensator adaptively changes the system parameters to the response of servo-hydraulic actuator systems; it shows a satisfactory global performance for the tracking of target displacement even though the servo-hydraulic actuator system has a nonlinear behavior. However, the local performance of the ATS compensator still needs to be improved when the system nonlinearity cannot be accounted for by using an averaged polynomial-based time series function. In this study, a newly developed displacement control algorithm for servo-hydraulic actuator systems is introduced, which can improve the local performance of the ATS compensator. An auxiliary block is added to the existing ATS compensator to compensate for the tracking error between the target and measured displacements. The auxiliary block utilizes a polynomial-based time series function with an input from the tracking error. Basically, the primary compensated displacement from the original ATS compensator and the second compensated displacement from the auxiliary unit are added together and fed into the actuator as an input displacement to improve the actuator tracking performance. The experimental test results by using this new compensator are provided and its performance is discussed.

336: An Interfacial Model for Mode-I and Mode-II Dynamic Crack Propagation in Rocks with Stick–Slip Contact Transitions

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Transitions between separation, contact–stick, and contact–slip modes generate sharp discontinuities in stress and velocity fields. For example, consider a potential contact interface, initially in separation mode, where the two sides approach each other with the same speed. At this stage, there is a nonzero velocity jump while the traction fields on both sides vanish. Upon contact, the response switches abruptly to a compressive stress state that defines the wave strengths and elastodynamic characteristic values, while the velocity jump suddenly vanishes. Discontinuities may also arise in numerical simulations at stick¬–slip transitions, depending on the details of the friction response and the algorithmic details of a particular computational model. Capturing these discontinuities and sharp transitions presents a significant challenge to the numerical analyst. The problem becomes more challenging when fracture is incorporated, as in dynamic scenarios where a given point on a fracture surface may

experience mode-I, mode-II, or mixed-mode crack propagation followed by contact-stick or slip modes associated with crack closure. We present an interfacial damage model in which the effective stress that drives damage evolution is consistent with a Coulomb friction model. The effective stress, in turn, depends on the normal and shear components of the traction, a friction-type coefficient and a shear strength parameter. This model is particularly relevant in rock contact and fracture applications. We present numerical results that demonstrate the effectiveness of this model in fracture applications where mode-I or mode-II response dominates. In the first example, we study fracture in a rock sample where there is a mismatch between horizontal and vertical compressive loads. A vertical compressive shock load induces maximum shear stresses at +/-45 degrees. We demonstrate that the proposed fracture model predicts cracks forming at a steeper angle closer to the vertical axis, and the fracture mode subsequently transitions to slip mode along the generated fracture lines. We will also present examples involving hydraulic and shock fracturing techniques, such as electrohydraulic discharge methods in rocks.

406: An Interval Approach for Analysis of Structures Subject to Uncertain Displacements

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This paper describes a new method for static analysis of structures subject to interval displacements. This approach combines the steps of traditional static analysis (1. determine the displacements, and 2. determine internal forces) into a single step, along with using interval displacements, leading to direct calculation of interval internal forces/moments and stresses. Using this method, the interval functional dependencies (a major source of overestimation) are removed to obtain sharp results. Examples that illustrate the performance of the developed method and comparison to Monte-Carlo simulation results are presented.

100: An Inverse Source Problem for Maximizing Wave Motion in Subsurface Poroelastic Formations: A Computational Framework for Field Implementation of a Wave-Based Enhanced Oil Recovery Method

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Loukas Kallivokas, The University of Texas at Austin

Post-earthquake observations at depleted oil fields, as well as field and laboratory experiments suggest that vibrational energy focusing to a reservoir may lead to recovery of the oil otherwise deemed irrecoverable by conventional methods. The effectiveness of such a method hinges, among other factors, on the magnitude and spatial reach of the vibrations generated in the reservoir. In this work, we develop an optimization algorithm for prescribing the time signals and locations of surface sources that maximize the wave motion in the reservoir. We report the results of our numerical experiments attesting to the ability of the optimizer to yield the optimal spatio-temporal source characteristics. We simulate the underlying wave physics for a two-dimensional, semi-infinite solid. We use hybrid perfectly-matched-layers (PMLs) at the truncation boundaries of the computational domain to mimic the semi-infiniteness of the physical domain of interest. We model the oil reservoir as a poroelastic solid (using Biot's equations of poroelastodynamics), and the surrounding formations as elastic solids. We assume that a) the properties and overall geometry of the reservoir and its surroundings are known, and b) the wave motion is initiated by surface sources (Vibroseis trucks). We cast the search for optimal source characteristics as an inverse-source problem using a partial-differential-equation (PDE)-constrained optimization technique, where minimization of a suitably defined objective functional is tantamount to the maximization of the wave motion in the reservoir, and the governing PDEs are side-imposed as constraints. We resolve the inverse-source problem using a reduced-space approach. We conduct numerical experiments using a prototype geo-formation to exercise the inversion algorithm. Our numerical experiments show that: a) the algorithm successfully recovers the optimal spatio-temporal load characteristics, b) optimal placement of loads plays a crucial role in focusing the wave energy to the target reservoir, c) horizontally polarized loads are better at delivering the wave energy to deeply situated formations than vertically polarized loads, and d) the fluid acceleration generated in the reservoir is capable of discharging crude oil particles trapped in the pore space. Thus, we develop a computational framework for prescribing the spatio-temporal characteristics of surface wave sources that focus the wave energy into a poroelastic target. This allows a priori determination of the economic feasibility and efficiency of wave-based enhanced oil recovery methods.

47: An Investigation of Numerical Approaches for Analyzing Structural Response under Blast Loads

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Blast-effect analysis is critical for the design of armor materials and protective structures. The effect of a blast load on a structure is dependent on several factors, including the mass and composition of the explosive and standoff distance, as well as the material, geometry, and support conditions of the target structure. Blast waves cause large pressure loads over a short time period, causing shockwaves to propagate through the structure. The ConWep empirical model has been used extensively to analyze the effects of a blast wave on a structure at large lead-off distances, where the pressure distribution across the target structure is relatively uniform. At short distances, it is necessary to more rigorously consider the fluid-structure interaction effects between the explosive and the structure. One technique for modelling near field blasts is a coupled Eulerian-Lagrangian (CEL) approach, in which the target material is modeled as a solid in a Lagrangian framework, and an Eulerian mesh is used to track the flow of splinter material through space following detonation. In this study, ConWep and CEL methods are used to model a structure subject to a charge of TNT placed at various standoff distances. Response metrics such as maximum deflection of the target panel, shockwave speed, and stress distributions observed in the target are compared for the two approaches.

464: Analysis of the Rocking Response of Unrestrained Equipment on Rolling Isolation Systems

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This paper examines the rocking response of unrestrained seismically isolated equipment. Pendulum-type isolation systems, such as rolling isolation systems (RISs), have been used extensively to protect individual pieces of essential electronic equipment, as well as valuable artifacts, from earthquake-induced floor motions. The protected object is mechanically decoupled from horizontal components of base motions via a rolling interface. Horizontal deflections across the interface result in vertical motion, increasing the gravitational potential energy and generating mass-proportional recentering forces. The equations of motion (in the absence of damping/friction) are independent of the isolated object's mass, which eliminates the need to tune stiffness parameters – a desirable feature in seismic isolation technologies. However, in the process of reducing horizontal accelerations, the isolation system transmits vertical accelerations that otherwise would not have been present. These vertical accelerations have been shown to exceed tolerable limits in some cases. Vertical motion in isolation systems has not previously been considered when examining the rocking response of isolated object. By permitting the equipment to rock, the dynamics of the RIS-equipment system are altered. In this paper, we will

model the dynamics of the RIS-equipment system including vertical motion in the RIS. Vassiliou and Makris (2012) showed that slender objects exhibit superior stability when they are not isolated. This paper reports on a parametric study in which the stability of slender unrestrained equipment is assessed when vertical isolator motion is excluded and included in the RIS-equipment model. The equipment-to-isolator mass ratio and equipment slenderness provide the parametric variations. The primary set of RIS-equipment geometries considered was representative of existing installations of protected computer servers.

433: Analysis of Three-Dimensional Curved Beams Using Isogeometric Approach

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Curved, as opposed to straight, structural members are frequently used by architects in the design of modern space structures. To handle the increased geometric complexity of 3-D space structures, new structural analysis methods are needed that can accurately and efficiently analyze these structures. Isogeometric analysis (IGA), introduced by Hughes et al [1], is capable of exactly representing geometries generated from computer aided design (CAD), as opposed to traditional finite element analysis (FEA) in which the geometries are approximated. In this study, an isogeometric finite element formulation for spatially curved 3-D beams is presented that can exactly preserve the geometry in the FEA. These elements employ the same non-uniform rational B-spline interpolations as used in the CAD to interpolate both the geometry and unknown fields in the finite element analysis, leading to a seamless transition between complex CAD models utilized by architects and the analysis models used by engineers. The effectiveness of the proposed method is demonstrated on a variety of curved structural geometries of varying complexity.

412: Analytical Evaluation on the Effect of Damage Location on Collapse Performance of Reinforced Concrete Perimeter Frames

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Sergio Breña, University of Massachusetts Amherst
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Requirements for structural integrity of reinforced concrete buildings were first introduced in the 1989 version of the American Concrete Institute Building Code (ACI 318-89). The intent of these requirements is to provide redundant load paths so that progressive collapse is avoided in the event of the unintended loss of an interior support. ACI 318-11 section 7.13.2.4 requires that splices of structural integrity reinforcement in perimeter beams have to be designed as Class B splices near mid-span for top reinforcement and near the support for bottom reinforcement. However, ACI 318-11 does not provide a clear definition for the support region where bottom reinforcement splices should be located. In addition, bottom reinforcing bar splices at the face of the support or inside the beam-column joint have the potential for generating congestion and introducing difficulties during construction. This study is part of a research project intended to evaluate the effect of lap splice location on collapse behavior of perimeter reinforced concrete frames after loss of an interior support. This paper will focus on results from analytical simulations that include damage location and three-dimensional effects as parameters that may affect collapse performance of perimeter frames detailed in accordance with ACI 318. The structures analyzed will include details of frames built in non-seismic regions. The results of analytical simulations will complement experimental testing of representative specimens of perimeter frames and that are planned to be tested in a future phase of the project.

152: Analytical Studies of a Test Model for Soil-Abutment Interaction under Seismic Loads

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Seismic response of bridges could be considerably affected by soil-abutment-structure interaction (SASI). Skew angle may significantly influence the mobilized passive resistance of the backfill soil and the behavior of soil-abutment-bridge system due to the induced in-plane rotation and translation of the superstructure. Current design criteria do not consider the effect of skew angle on the passive capacity of soil-abutment systems. Previous soil-abutment experiments have shown that there is a significant reduction of abutment passive resistance due to presence of the skew angle. However, those tests on the skewed abutments were done under static loading scenario and could not capture the dynamic loading effect and damping influence. Large-scale shake-table experiments are being performed at University of Nevada, Reno (UNR) to study the effect of skew angle on the seismic interaction of soil-abutment systems. A 90-kips (400 kN) block resting on 6 lead rubber bearings (LRBs) that respectively simulate the superstructure mass and the substructure flexibility is placed on the shake-table that simulates the earthquake motions. Three concrete walls with the height of 5.5 ft (1.68 m) and projected width of 10 ft (3.05 m) with skew angles of 0º, 30º and 45º represent the abutment backwalls in three different tests. A 25 ft long by 19 ft wide engineered backfill of clean sand represents the soil embankment. The shake-table tests provide data on the effect of skew angle on the contact soil pressure distribution and the corresponding mobilized passive resistance of backfill behind the abutment backwall as a result of impact between the superstructure model and the abutment backwall. Analytical studies using PLAXIS2D and FLAC3D were conducted to simulate some of the previous static soil-abutment tests and evaluate the adequacy of detailed analytical models. In addition analytical studies of the shake table test models have been conducted using OpenSEES. The presentation will highlight the analytical and shake-table studies.

460: Analytical Study of Structural Damage Detection Using Stochastic Subspace Identification and Finite Element Model Updating

Li Yang, University of Louisville
Young Hoon Kim, University of Louisville

This paper proposed an analytical procedure to identify dynamic characteristics and system matrices considering uncertainties of modal and ambient excitations. The uncertainty of ambient excitation during operation of structural system remains big challenges in the application of system identification techniques. Two methods are integrated in this procedure: Stochastic Subspace Identification (SSI) algorithm and Finite Element Model Updating (FEMU) method. Using only output measured responses under ambient vibration, a SSI algorithm is used to identify the mode shapes, natural frequencies and damping coefficient. Using dynamic characteristics a FEMU method is used to determine the mass, stiffness, and damping matrices. The proposed method is evaluated using various types of ambient and environmental excitation. This study aims to quantify the accuracy of the proposed procedure to detect the damage under different types of ambient and environmental excitation. In addition, the proposed procedure is examined to detect the different damage levels and locations. This numerical simulation procedure can improve the reliability of in-operation structural health monitoring.

463: Anomalous Stochastic Resonance Modeled by Fractional Fokker-Planck Equation

Yan Wang, Georgia Institute of Technology

Stochastic resonance is a phenomenon that a stochastic system exhibits oscillation between stable states. It has been observed in various physical and biological systems. The phenomenon is typically modeled by the Fokker-Planck equation (FPE) with time-dependent alternating driving forces under Gaussian noise. In this work, FPE is extended to space-time fractional FPE (fFPE) to consider anomalous diffusion that occurs with heavy-tailed distributions, where long-range spatial correlations and memory effect are modeled. The study shows that the anomalous resonance is sensitively dependent on the fractional orders and can oscillate at multiple states simultaneously.

528: Application of Functional Quantization to Probabilistic Service-Life Models for Corrosion of Reinforced Concrete

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Corrosion of reinforcing steel is one of the most important degradation mechanisms affecting concrete structures worldwide, especially structures located in chloride-rich environments. In new structures, the concrete serves as a physical barrier that protects the reinforcement from environmental stressors. Moreover, the high alkalinity of concrete leads to the formation of a passive film on the surface of the reinforcement that protects it from corrosion. However, this condition is not permanent. There are physical-chemical processes which, over time, will result in the breakdown of the passive film, initiate corrosion and cause degradation. One of the most important of these processes is the transport of chloride ions from the exterior environment into the bulk of the concrete; in this case, corrosion will initiate once a critical chloride concentration is reached at the location of the reinforcement. Several models have been proposed to estimate the service life of concrete structures in chloride-rich environments, defined in this context as the time to corrosion initiation. Such models must be fully probabilistic to account for the large uncertainties associated with the chloride transport process. The probabilistic model proposed in FIB Bulletin 34 [1] is perhaps the most widely used in practice, but its implementation requires extensive use of Monte Carlo simulations (MCS). In this paper, as an alternative to traditional MCS, we use a technique based on the Functional Quantization concept [2,3] to compute probabilistic service life using the FIB Bulletin 34 model. We select a set of non-Gaussian and non-stationary random samples that optimally represent the sample space of the relevant time-dependent limit state function. In addition, we provide coefficients to "weight" the contribution of each sample (as opposed to traditional MCS where all samples are equally weighted). Preliminary results show that the accuracy of the representation is significantly enhanced; also, substantially fewer samples are required to reach the same level of accuracy.
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624: Application of OpenFOAM in solving Coastal Engineering problems by massively parallel Navier Stokes solvers using Large Eddy Simulation turbulence closures

Agnimitro Chakrabarti, Louisiana State University
Qin Jim Chen, Louisiana State University

The phenomenal growth of High Performance Computing (HPC) over the past decade has opened up new capabilities to model complex near-shore free-surface fluid structure interaction problems in the field of coastal engineering. In this work, we will present results from two important flow cases, one at a typical laboratory scale and another a field scale application: 1) Wave flow through an array of emergent vegetation placed in a typical laboratory tank and 2) Wave-structure interaction, over-topping and resulting flow field behind a submerged breakwater placed close to a marsh edge at the field scale. The flow solvers have been validated against well-established laboratory experiments involving flow around cylinders and wave breaking on a near-field scale beach. The range of applications will encompass resolving O(10-3) to O(100) m range of eddy sizes and seek to address the current capabilities that can be realistically attained with reasonable accuracy and optimized use of computational resources. The Navier Stokes equation with a Volume of Fluid (VOF) method for surface tracking is used here. Large Eddy Simulation (LES) based turbulence closure schemes have been tested and found superior to Reynolds Averaged Navier Stokes (RANS) methods for first and second order velocity quantities for similar flow problems. LES is the only realizable method to simulate such high Reynolds number problems at the moment. We will present sensitivity analyses and optimum LES model choices for the above two problems. Massively parallel simulation runs optimized by known scaling curves will be used to solve the flow equations using the well known open-source finite-volume solver OpenFOAM. For the first problem, detailed velocity structures within the canopy, free-structure effects around the stems and force signatures on the stems will be analyzed using both high-resolution and low-resolution studies depending upon the parameters of interest. Three-dimensional (3D) vortex structures under different wave phases will be visualized and are expected to provide valuable insight into the complex flow phenomena of wave-vegetation interaction, such as stem sheltering effects. For the second problem, the analyses will focus on the wave height evolution with and without a structure, mean and root mean square velocity profiles in the vertical direction as well visualization of the mean flow field between the marsh edge and the structure resulting from wave over-topping. Force estimates obtained from the pressure distribution and shear stresses on the marsh edge face will be shown to understand the critical flow and submergence conditions under which slamming and scour induced failure may occur at the marsh edge.

553: Application of the Trajectory Cluster Analysis for Road Surface Monitoring

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Andrew Smyth, Columbia University

In the past decade, massive trajectory data of public and private vehicles have become more accessible due to the development of satellite systems and tracking facilities. The advances in sensor technology and its price reduction permit one to collect various types of data such as accelerations in addition to trajectory data. There is the practical need for processing big trajectory data and those additional data to extract a useful information which can be used to enhance intelligent transportation systems. Trajectory clustering possesses a robust capability in mining of big trajectory data by grouping trajectories not only based on the proximity of their locations, but also based on their moving direction. This powerful data analytics method enables one to combine and process additional data based on the corresponding locations and moving directions. The trajectory cluster analysis is applied to real data measured from the mobile data collection kits mounted on vehicles to obtain practically important up-to-date information that can bring about safer and more reliable road networks. In the developed road surface monitoring system, each vehicle collects tri-axial acceleration and GPS positioning data, which are used as a mean of detecting street defects on public road networks such as potholes. At a backend server, the trajectory cluster analysis is applied to data that are transmitted from multiple vehicle clients to identify road conditions. The accuracy of the road surface monitoring system is improved by merging a great deal of collected data from multiple vehicles.

374: Applications of Mixed Mode Fracture Criteria for Cement Mortar and Asphalt Binder

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Philip Park, Texas A&M University

Six fracture criteria are compared to predict the fracture resistance and kinking angle of cement mortar and asphalt binder subjected to mixed mode loads. Cement concrete and asphalt mixture are two representative particle reinforced composites that are widely used for civil infrastructures. Cement mortar and asphalt binder are their matrices of those composite materials governing the strength and fracture resistance. The six fracture criteria employed in this study include three traditional criteria based on energy release rate (G), maximum tangential stress (MTS), and maximum tangential strain (MTSN) and the expanded versions of those considering the first nonsingular stress/strain term usually called T-term. The stress and strain field parameters around crack tip are obtained from finite element simulations, and the effects of each parameter on stress and strain distribution are studied. For asphalt binder, a set of fracture tests are conducted at low temperature, and the crack kinking angles and fracture resistances under pure mode I, pure mode II, and mixed mode I/II conditions are measured. In case of cement mortar, previously published experimental data are used for validating the accuracy of the fracture criteria. The comparisons of the six criteria to the experimental data show that the three traditional criteria only considering the singular stress/strain terms have limitation in predicting mixed mode fracture. On the other hand, modified stress based criterion (GMTS) and extended strain based criterion (EMTSN) provide significantly improved predictions by taking into account the first nonsingular stress/strain term. However, strain energy density criterion (SED), which is an energy based criterion considering the effect of the nonsingular term, does not provide sufficient improvement in the fracture predictions. Comparison of GMTS and EMTSN reveals that the extended strain based criterion provides better predictions than the modified stress based criterion in mode II dominant conditions. The similar results are obtained in case of cement mortar: the GMTS and EMTSN predict the mixed mode fracture resistance and crack propagation angle with high accuracy while the other traditional criteria are not. The results for both materials indicate that the first nonsingular term, T-stress/strain, plays an important role in the crack propagation of the binders of concrete and asphalt mixture. Since the mixed mode and pure mode II brittle fracture of the construction materials are rarely investigated so far, the results of this study will help researchers to understand the mechanism of crack propagation in civil infrastructures.

103: Approach to Blast Resistant Design of Urban Steel Structures with Little or No Stand-Off Distance

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Michael McBrien, Manhattan College

Most practical engineering and design approaches available for blast resistant design and analysis of structures are based on military facilities. A certain stand-off distance between a threat (potential detonation location) and a target (a facility) can be maintained at most military facilities. However, such a stand-off distance is not nearly possible in urban environment: Due to the congested nature of urban environment, essential structural members of such infrastructures are often exposed to the public without much protection. For this reason, the analysis to design urban structures against blast loading should be performed with a detonation in an extremely close-in distance; with little or no stand-off distance. The most prevalent building code does not cover any provision for the blast resistant design. Rather, blast resistant designs for urban structures have been developed individually

only by limited number of structural engineers without being shared or reviewed by qualified third parties in an effort not to disclose security sensitive information. However, for the quality control perspective of structural engineering and designs, a systematic and consistent development of a design code is required in blast resistant designs of urban structures. With the advancement of computers and software, blast analysis has become more available to public. The purpose of this study is to perform a series of numerical parametric study analysis and to suggest simplified approaches or charts for use by general structural engineers to design blast resistant steel structures in urban environment with little or no stand-off distances. The analysis is detailed nonlinear explicit dynamic analyses for investigation of high-intensity and short-duration blast effects on structures using a fully coupled interaction technique between computational fluid and structural dynamics, using Ansys/Autodyn software. A total of 160 computer models were built to cover all AISC standard W14 columns subject to various blast conditions. To account for strain rate and temperature changes for steel structures during detonation, Johnson and Cook material model was used. Five parameters of the material model are suggested for the structural steel. The results of the study are summarized, and presented by means of a performance based design. Five damage criteria are suggested for the performance based design. A practical design example is accompanied to demonstrate how the study results can be used.

780: Are the Cohesive Zone Models Necessary for Delamination Analysis?

Zifeng Yuan, Columbia University
Jacob Fish, Columbia University

We develop a dual-purpose damage model (DPDM) that can simultaneously model intralayer damage (ply failure) and interlayer damage (delamination) as an alternative to conventional practices that models ply failure by continuum damage mechanics (CDM) and delamination by cohesive elements. From purely computational point of view, if successful, the proposed approach will significantly reduce computational cost by eliminating the need for having double nodes at ply interfaces. At the core, DPDM is based on the regularized continuum damage mechanics approach with vectorial representation of damage and ellipsoidal damage surface. Shear correction factors are introduced to match the mixed mode fracture toughness of an analytical cohesive zone model. A predictor-corrector local-nonlocal regularization scheme, which treats intralayer portion of damage as nonlocal and interlayer damage as local, is developed and verified. Two variants of the DPDM are studied: a single- and two- scale DPDM. For the two-scale DPDM, reduced-order-homogenization (ROH) framework is employed with matrix phase modeled by the DPDP while the inclusion phase modeled by the CDM. The proposed DPDM is verified on several multi-layer laminates with various ply orientations including double-cantilever beam (DCB), end-notch-flexure (ENF), mixed-mode-bending (MMB), and three-point-bending (TPB).

575: Assembly of Micro/Nanomaterials into Complex, Three-Dimensional Architectures by Compressive Buckling

Vonggang Huang, Northwestern University

Complex, three dimensional (3D) structures in biology (e.g. cytoskeletal webs, neural circuits, vasculature networks) form naturally to provide essential functions in even the most basic forms of life. Compelling opportunities exist for analogous 3D architectures in man-made devices, but design options are constrained by existing capabilities in materials growth and assembly. Here we report routes to previously inaccessible classes of 3D constructs in advanced materials, including device-grade silicon. The schemes involve geometric transformation of two dimensional (2D) micro/nanostructures into extended 3D layouts by compressive buckling. Demonstrations include experimental and theoretical studies of more than forty representative geometries, from

single and multiple helices, toroids and conical spirals to structures that resemble spherical baskets, cuboid cages, starbursts, flowers, scaffolds, fences and frameworks, each with single and/or multiple level configurations.

763: Assessing the Structural Health of CFRP I-Beams under Bending: Electrical Resistance Methods and Ultrasonic Sensor Methods

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Valeria La Saponara, University of California, Davis

Carbon fiber-reinforced polymer (CFRP) composite materials are currently utilized for aerospace, civil, wind energy, naval and automotive applications. This study reports methods and results of two structural health monitoring (SHM) techniques that have successfully estimated strain and damage of CFRP I-beams under static and/or fatigue bending. The I-beams were designed to serve as spars in small-scale wind turbine blades, which were reverse-engineered from the blades of a 1 kW Bergey XL.1 turbine. They were built in-house using hand-lay up, molds, and cured under vacuum pressure. Field testing shows the ability of these reverse-engineered spars to withstand 70 rpm with no apparent damage, and hence proves the structural soundness of the I-beams. In the first SHM method, changes to the electrical resistance of the conductive carbon fibers are monitored, first for rectangular and I-beam coupons. The coupons are tested under static and fatigue conditions, in four-point bending. The methods are then scaled up to 1.2 m I-beams, tested on a custom-made cantilever loading device powered through a stepper motor controlled by an Arduino Uno board, and data acquisition accomplished through LabVIEW. In the second SHM method, waveforms are launched by surface-mounted off-the-shelf piezoelectric transducers, at low ultrasonic frequencies. The waveforms are processed using Gabor wavelet transforms and their contours, quantified through contour perimeters. Contours change because of the waveforms interacting with damage features in the material, i.e. micro-scale cracks in the transverse plies that eventually coalesce into intra-ply cracks. The method is scaled up to 1.2 m I-beams using the same testing set-up detailed above. The applicability and limitations of both methods are discussed.

223: Assessment of Collapse Status of 220kV Guyed Portal Transmission Tower Subjected to Extreme Wind Loads

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The guyed portal towers are widely used to 220kV transmission structures in China. Compared to traditional lattice steel towers, the guyed portal towers are vulnerable to extreme wind loads to collapse under extreme weather conditions, such as downburst, hurricanes etc.. In 2012, a few transmission towers were blown down in a thunderstorm weather, including some typical guyed portal towers. In the present paper, collapse status of a typical guyed portal tower is assessed under extreme wind loads using the experimental parameters and FEM analysis. To understand the interactions of wind and the lattice sections of the transmission tower, wind tunnel tests are carried out under a normal wind field and a partial simulated downburst wind field. A 3-D guyed portal tower aero-elastic model with lattice sections is fabricated based on a prototype guyed portal tower. The static force coefficients, the gust load factors and the wind induced responses are obtained. To evaluate the collapse status of the tower, the wind loads are calculated in FEM model under extreme conditions and in different wind directions considering the corresponding true projected area. The typical downburst wind profile is generated and the time-varying wind loads are obtained. Then the failure modes at different scenario-based conditions are compared with the real tower collapse mode. The collapse status of the guyed portal tower, therefore, can be analyzed through the obtained data. This will help the designer to make effective measures or strategies to avoid hazards to turn into catastrophic failures.

766: Atmospheric Boundary Layer Simulation and Aerodynamics Investigations of Low-Rise Buildings in an Open-Jet Facility

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Open-jet facilities have newly been introduced as an effective tool in order to conduct experiments for the simulation of wind effects on structures, especially in the case of small scaled model tests of low-rise buildings and ground-mounted solar panels which was always a challenge in wind tunnels to properly simulate aerodynamic characteristics of those scaled models due to the lack of capability in turbulence modelling at a reasonably large scale. In addition, testing a low-rise building in a wind tunnel would cause an issue with the Reynolds number that can be far different from the one in nature. Advanced open-jet facilities for destructive wind testing would provide wind engineers with valuable information on the complex effects of storm winds and hurricanes at a very high wind speed which means that the issue with Reynolds number would be greatly improved. In the same path, recently, a new open-jet facility has been constructed within the Windstorm Impact & Structural Engineering (WISE) research group at Louisiana State University (LSU). In this paper, the challenges involved in the appropriate simulation of wind characteristics through the open-jet facility are investigated based on conducting experimental tests on small scaled models of a low-rise building, and comparing the results with those from the wind tunnel testing available at the National Institute of Standards and Technology (NIST)/University of Western Ontario (UWO) aerodynamics database. The first target of this study was defined to determine the optimal size of a test building and its location from the exit of the open-jet facility, and the other motivation was to investigate the scale effect on the flow characteristics around the building by conducting experimental tests on two small scaled models, i.e. 1:15 and 1:22, with the same aspect ratio. A model with the scale of 1:100 from the NIST/UWO database was selected as a benchmark, and the pressure coefficients' time series were extracted accordingly. Based on the results, it was shown that the LSU WISE open-jet facility is capable of producing mean wind profile and turbulence intensities representing an open terrain condition. Also, for the models that are placed at a horizontal distance of 2.5H (H is the total height of the open-jet wind profile) from the exit of the open-jet, the contours of mean and peak pressure coefficients are consistent with the results obtained from NIST/UWO. Furthermore, it has been proved that testing models as large as 16 % blockage ratio is feasible within the open-jet facility which was already a challenge in BLWTs. This reveals that open-jet facilities are promising robust tools to alleviate the scale issues involved in the physical investigations of flow patterns around civil engineering structures. Finally, the results and findings of this study can be extended and used for proposing guidelines on conducting test scenarios in open-jet facilities, eventually helping the development of improved standard provisions on wind effects on low-rise buildings.

338: Atomistic Modeling of Toughening Graphene Through Bio-Inspired Topological Design

Huajian Gao, Brown University

It has been claimed that graphene, with the elastic modulus of 1TPa and theoretical strength as high as 130 GPa, is the strongest material. However, from an engineering point of view, it is the fracture toughness that determines the actual strength of materials, as crack-like flaws (i.e., cracks, holes, notches, corners, etc.) are inevitable in the

design, fabrication, and operation of practical devices and systems. Recently, it has been demonstrated that graphene has very low fracture toughness, in fact close to that of ideally brittle solids. These findings have raised sharp questions and are calling for efforts to explore effective methods to toughen graphene. Recently, we have been exploring the potential use of topological defects to enhance the fracture toughness of graphene (1-3). For example, it has been shown that a sinusoidal graphene containing periodically distributed disclination quadrupoles can achieve a mode I fracture toughness nearly twice that of pristine graphene. Inspired by the vein-membrane structure of insect wings (4), here we investigate a bio-inspired approach to toughening graphene through topological designs. A phase field crystal method (2) is adopted to generate the atomic coordinates of graphene with various topological patterns, including wavy-flat, blister-pack and staggered patterns that mimick insect wings and other biological structures. We then perform molecular dynamics simulations of crack propagation in the designed graphene sample, and observe a variety of toughening mechanisms, including crack tip blunting, crack trapping, ligament bridging, crack deflection and daughter crack initiation and coalescence. The bio-inspired designs result in up to six-fold enhancement in fracture toughness of graphene. It is speculated that similar concepts may be generally applicable to the toughening of 2D materials. 1. T. Zhang, X. Li, H. Gao. Defects controlled wrinkling and topological design in graphene. J. Mech. Phys. Solids 67, 2–13 (2014). 2. T. Zhang, X. Li, H. Gao. Designing graphene structures with controlled distributions of topological defects: a case study of toughness enhancement in graphene ruga. Extreme Mech. Lett., 1(1), 3–8 (2014). 3. T. Zhang, H. Gao. Toughening graphene with topological defects: a perspective. J. Appl. Mech. 82, 051001 (2015) 4. J.-H. Dirks, D. Taylor, Veins improve fracture toughness of insect wings. PloS One 7, e43411 (2012).

743: Atomistic to continuum homogenization method

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The method of granular micromechanics involves discrete-to-continuum homogenization and has been used to incorporate the effects of micro-scale inter-particle interactions on the macro-scale deformation and failure of the material. These effects include inter-particle contact, grain interlock, fiber buckling, liquid bridge, fluid pressure, swelling, and viscoelasticity. Several of these are associated with interactions at atomic scale; thus potentials developed for use at this scale are highly beneficial for modeling. We present an extension of the granular micromechanics approach for homogenization from atomic to continuum scale, which enables direct incorporation of atomic-scale interactions in the granular micromechanics framework. We first divide the energetic contributions to the stress with respect to the moments of atomic vibration about the mean position. In doing so, we separate the energetic conjugates for the first and higher spatial orders of strain, which only capture change in average position with deformation, from those for vibrational moments. Consequently, the vibrational moment fields used at continuum scale are directly obtained from the atomic trajectories, retaining a localized description at continuum scale. This is in contrast to the traditionally used phonon gas approach for finite temperature homogenization methods, where the local mapping is lost due to the nonlocal nature of phonon. In addition, our approach also obviates the necessity for the canonical transformation generator function, which is used to derive the traditional form of the virial stress. The entropic contributions to the stress are calculated separately. Further, the quasi-harmonic approximation is not necessary in this case since the moments of deformation can be extended up to any order using Taylor series. Such features make the method especially attractive for investigating high temperature deformation of anharmonic materials. We demonstrate our method using room temperature uniaxial deformation of fcc Aluminum. The molecular dynamics simulation of the deformation is performed using an NVT canonical ensemble in LAMMPS, using a Nose-Hoover thermostat. Observations from the analysis include: a) determination of maximum order of vibrational moments necessary to model the deformation, b) separation of energetic contribution to stress into parts from strain and vibration, c)

variation in anisotropy of the vibrational moments with deformation, particularly at failure strain, d) variation in symmetry of vibrational moments with deformation, and e) comparison of stress calculation to those from the canonical transformation approach.

247: Bayesian Calibration of Spatially Varying Model Parameters with High-Dimensional Response

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Bayesian calibration is the process of estimating the values of model parameters based on experimental data or observations. In some problems, for a given set of inputs, the output is not a single-valued response but a vector of responses at a single spatial location over many time instants or an array of responses at multiple spatial locations and at multiple time instants. The high-dimensional response brings challenges to the Bayesian calibration. Especially for spatially varying calibration parameters, the calibration result at different location is affected by not only the observation at the corresponding location, but also observations at other locations due the correlation over the space. The first challenge is how to build a surrogate model for the high-dimensional response since the surrogate model is often used to substitute the computationally expensive simulation models in Bayesian calibration. The second challenge is how to properly model the model discrepancy of the physics simulation model. The third challenge is how to efficiently perform Bayesian calibration for the spatially varying parameters. In this paper, a new framework is developed for the Bayesian calibration of spatially varying parameters using observations collected from high-dimensional response. The high-dimensional response is first reduced to low-dimensional representation through singular value decomposition (SVD). Based on that, the SVD-Kriging surrogate model is constructed for the high-dimensional response. Since the model discrepancy of the simulation model with high-dimensional response is also high-dimensional, the well-known Kennedy and O'Hagan (KOH) framework is extended to problems with high-dimensional response based on the SVD-Kriging model. Necessary equations are derived to achieve this extension by following the principle of the original KOH framework. Based on the constructed SVD-Kriging surrogate model and the developed model discrepancy model, the spatially varying parameter is calibrated based on the Karhunen–Loeve expansion and particle filter technique. The proposed surrogate modeling method, model discrepancy quantification approach, and Bayesian calibration method are demonstrated using a heat transfer problem, in which the spatially varying conduction and convection coefficients of a concrete structure are calibrated using experimental data collected from a high-resolution thermal imaging infra-red camera.

267: Bayesian Methods for Nonlinear Finite Element Model Updating and Damage Identification of Civil Structures

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This paper presents a framework for the identification of mechanics-based nonlinear finite element (FE) models of civil structures using Bayesian methods. Batch and recursive Bayesian estimation methods, namely the Extended Kalman filter (EKF) and Unscented Kalman filter (UKF), are used to update a mechanics-based nonlinear FE model of the structure (such as a building, bridge, or dam) using the input-output or output-only dynamic data recorded during an earthquake event. Capable of capturing the damage mechanisms and failure

modes of the structural system, the updated nonlinear FE model can be further used to identify the damage in the structure after a damage-inducing event. This can be simply achieved by running the updated FE model subjected to the recorded or identified seismic input. Unknown parameters of the nonlinear FE model characterizing material constitutive models, inertia, geometric, and constraint properties of the structure can be estimated using limited response data recorded by accelerometer or heterogeneous sensor arrays. For those estimation methods that require the computation of structural FE response sensitivities (total partial derivatives) with respect to the unknown modeling parameters and the loading time-histories, the accurate and computationally efficient direct differentiation method (DDM) is used. The proposed framework has the potential to tackle real-world applications by linking advanced mechanics-based nonlinear FE models and Bayesian methods. Numerically simulated response data of a three-dimensional 5-story 2-by-1 bay reinforced concrete frame building with unknown material model parameters subjected to bi-directional seismic excitation are used to illustrate the performance of the proposed framework in terms of convergence, accuracy, robustness, and computational efficiency.

220: Bayesian reliability analysis using OpenBUGS

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Bayesian networks (BNs) have become increasingly popular in the field of engineering risk analysis. They enable the efficient modeling of dependent random variables and, in particular, facilitate learning of the probabilistic model when data and other information becomes available. In engineering risk analysis, it is often required to make models for the prediction of rare events, e.g. failure of engineering structures or extreme natural hazard events. The BN models are often hybrid, i.e. they consist of both continuous and discrete random variables. To perform inference, the continuous random variables can be discretized, to enable exact inference algorithm. However, such discretization is non-trivial and has certain restrictions. Alternatively, the hybrid BN can be evaluated by approximate sampling-based methods such as Markov chain Monte Carlo (MCMC). However, when estimating probabilities of rare events, a (possibly prohibitively) large number of samples is required to achieve sufficient accuracy. Additionally, in function of the model structure and the obtained observations generating a sample may be computationally demanding. In this contribution, we apply subset simulation (Au and Beck, 2001) to perform inference for rare events in hybrid BNs to limit the computational demand. In subset simulation, the probability of a rare event is expressed as the product of the probabilities of more frequent conditional events. We develop a coupling of the subset simulation approach with OpenBUGS (Lunn et al., 2009), an open-source software for performing Bayesian analysis in continuous BNs through MCMC with Gibbs sampler. This coupling enables the efficient computation of rare event probabilities with just a fraction of the samples required otherwise, while making available all features of OpenBUGS for modeling and Bayesian analysis. The performance of the approach is evaluated using a number of verification examples. AU, S.-K. & BECK, J. L. 2001. Estimation of small failure probabilities in high dimensions by subset simulation. Probabilistic Engineering Mechanics, 16, 263-277. LUNN, D., SPIEGELHALTER, D., THOMAS, A. & BEST, N. 2009. The BUGS project: Evolution, critique and future directions. Statistics in medicine, 28, 3049.

397: Benefits of Load Redistribution to the Capacity of a Simple Cold-Formed Steel Floor System

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Typical cold-formed steel floor systems involve many repetitive joist members laid in parallel, yet the design codes are based upon the reliability of individual members alone. Through the use of Monte Carlo simulations, this paper investigates the benefits that load redistribution and residual capacity may have upon the system reliability of a simple cold-formed steel (CFS) floor. A MATLAB program was developed which is capable of rapid iterative load redistribution upon an arbitrary sheathing-covered CFS floor system. Capacities are calculated based upon the 2012 American Iron and Steel Institute S100 design specification, while demands are devised by simulating a load path through sheathing to the joists. A simple rectangular floor system was devised based upon the CFS-NEES project building, consisting of CFS joists spaced at 24 inches on-center and sheathed with 24/16 oriented strand board. The MATLAB program was validated to an accuracy of approximately 5% against detailed ABAQUS finite element analyses of this floor. Monte Carlo simulations were then performed using randomized live loads and joist capacities with the goal of quantifying the failure rate of floor systems both with and without load redistribution. Load redistribution is found to provide a benefit of between 12 and 15% to the capacity of the floor system. Such a benefit could in future be reflected in a repetitive member factor for CFS, similar to that currently used in the National Design Specification wood codes.

512: Bio-Inspired Design of Cement Polymer Composites

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The structure of abalone nacre was adopted to develop a new paradigm in the design of structural composites with the goal of high tensile strength, ductility, and toughness. A bio-inspired multilayered structural composite was created using a cement mortar and a variety of polymeric fiber blends, cast into the cells of a 3D printed matrix. The impact of this microstructure on the strength and fracture toughness of multilayered composites was studied as a function of the cell's geometry and scale in a parametric study, using various methods of integrating the nacre cell structure into a system composite with concrete. Flexural strength and fracture toughness of the composite beam specimens were found to be greater than the control specimens. Compressive strength and splitting tensile strength of the cement mortar and polypropylene-fiber blend was also tested, respectively. The control beams reinforced with 1% PP fibers displayed a more gradual break and increased strain versus the beams without fibers. The composite beams proved to be outperforming the control specimen, due to the overall distribution of cracks throughout the beam that results in a higher strain at the beam failure. The composite beams showed more layer shear sliding during the break, whereas the control beams showed more diagonal shearing failure. After an initial first break early on, the composite beams gradually deformed plastically due to interlocking elements, and overall achieved a higher stress before failure.

643: Bioinspired Infrastructure Materials: The Interaction Between Peptides and Calcium-Silicate-Hydrate

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Nature has demonstrated biological materials with intricate microstructure and superior mechanical and functional properties. Biomolecules including amino acids, peptides, nucleic acids etc. have been recognized as the primary species facilitating such processes as biomineralization and soft organic-hard inorganic interactions.

Peptides are composed of amino acids linked together through covalent bonds. Each amino acid in peptides imparts a specific functionality thereby permitting a large variety of interactions between peptides and inorganic materials. In this presentation, the effect of peptides on calcium-silicate-hydrate (CSH) formation, which constitutes a biomineralization process, as well as the binding interactions between peptides and CSH are presented. Due to large diversity in the structure and charge characteristics of peptides, a myriad of peptides can be synthesized using the combinatorial biology methods, such as phage display and yeast display, and studied for their affinity with a target material surface. The effect of peptides on the structure of CSH was evaluated using X-ray diffraction. The interactions between peptides and CSH were studied using adsorption measurement as well as analytical techniques. Atomic force microscopy (AFM) was utilized to investigate the binding between peptides and CSH. The results from this study aid in increasing our understanding of the influence of biological species on CSH and provide us with an innovative pathway to impart desired properties and functionalities to cement-based materials.

75: Blast Resistance of Concrete Protective Cladding with/without Cutouts

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In response to present concern regarding the safety of critical buildings against terrorist attacks, the use of appropriately strengthened exterior claddings in considered to be a possible solution as the first line of defense. This work in concerned with the effectiveness of such building armors against IED blast and small arms fire. Both experimental and computer based simulations are being undertaken for this purpose on reinforced and prestressed concrete panels without and with protected openings. The effect of incorporating protective mesh in such panels is also being considered. Preliminary studies indicate reasonable correlation between experiment and simulation. Details of different modeling strategies and the outcomes will be presented.

544: Bonded Anchors in Concrete Structures suffering from ASR Damage

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Lauren Stenroos, Renssellaer Polytechnic Institute
Mohammed Alnaggar, Renssellaer Polytechnic Institute
Roman Wendner, University of Natural Resources and Life Sciences Vienna

Fastening elements play a crucial role in the construction industry. They allow the connection of load bearing structural members with each other, and with appliances during initial construction. In course of the structural life-time post-installed anchors are key elements in all types of rehabilitation and restoration efforts. In recent years the deterioration of concrete structures due to alkali silica reaction (ASR) has become a concern in many fields of structural engineering ranging from bridges to nuclear containment. In this contribution we present a systematic investigation of how the long-term load carrying capacity of bonded anchors under tension is affected by (a) pre-existing ASR induced damage, or (b) by ongoing ASR after installation of the anchor. In particular, we will present a full experimental characterization of a standard concrete in reference conditions as well as after different durations of accelerated testing in alkaline rich solution. For each scenario pull-out tests according to the RILEM recommendation are performed on two typical post-installed chemical anchor systems as well as the reference case of a standard cast-in rebar. Additionally, for all scenarios pull-out tests with wide support are performed prompting concrete cone failure. The results of the experimental investigation will be presented and serve for the calibration as well as validation of multi-phase multi-scale numerical simulations. The latter are performed to study in detail the relevant mechanisms and extrapolate the observed behavior to life-times far beyond those of laboratory tests and alternative geometrical configurations. A model parameter sensitivity analysis completes the study.

653: Breach Behavior of Soil-Filled Barriers Due to Blast

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Barriers used as contingency base camp perimeters can be subjected to blast loads. Due to the inherent risk that would be caused by a breach in a perimeter of a base camp, a need exists to rapidly assess the effects of blast on barriers. The objective of this research was to characterize the mechanics involved when breaching soil-filled barriers due to blast, specifically HESCO® Concertainer barriers. A multifaceted approach was used to examine breach behavior of barriers including full-scale experimentation, scaled centrifuge testing, high-fidelity computational modeling, and fast-running, physics-based modeling. Full-scale experimental testing was completed with various barrier and explosive charge configurations. Blast pressure, barrier displacement, barrier acceleration, and breach size were measured. Blast pressure versus time was measured in the free field, behind the barrier, and on the barrier using pressure transducers. Barrier displacement and acceleration relative to time was recorded using rack and pinion gages and accelerometers, respectively. Additionally, barrier response was captured using high-speed videography. Scaled experimentation was executed in the U.S. Army centrifuge at ca. 1/50 scale and ca. 1/100 scale. Lidar was used to collect locational data along the barriers in both the full-scale and scaled centrifuge experiments. The lidar data allowed the breach sizes and cross-sections in the experiments to be directly compared to other experiments and model results. High-fidelity computational models using finite element method and a fast-running engineering models using rigid body motion were validated using the experimental data and were used to further examine the breach behavior of the barriers including additional barrier configurations and explosive weights.

773: Bridging Topology Optimization and Additive Manufacturing

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Topology optimization is a technique that allows for increasingly efficient designs with minimal a priori decisions. Because of the complexity and intricacy of the solutions obtained, these techniques were often bounded to research and theoretical studies. Additive manufacturing, a rapidly evolving field, fills the gap between topology optimization and application. Additive manufacturing has minimal limitations on the shape and complexity of the design, and is currently evolving towards new materials, higher precision and larger build sizes. Two topology optimization methods are addressed: the ground structure method and density-based topology optimization. The results obtained from these topology optimization methods require some degree of post-processing before they can be manufactured. A simple procedure is described by which output suitable for additive manufacturing can be generated. In this process, some inherent issues of the optimization technique may be magnified resulting in an unfeasible or bad product. In addition, this presentation aims to address some of these issues and propose methodologies by which they may be alleviated. The proposed framework has applications in a number of fields, with specific examples given from the fields of health, architecture and engineering. In addition, the generated output allows for simple communication, editing, and combination of the results into more complex designs. For

the specific case of three-dimensional density-based topology optimization, a tool suitable for result inspection and generation of additive manufacturing output is also provided.

372: Buckling and Post-Buckling Analysis of Stiffened Composite Panels under Different Load Conditions

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The buckling and post-buckling analysis of stiffened composite panels has been investigated in this paper using finite element method. Three different configurations and loading conditions were considered, including the flat plate under axis/shear loading, the cylinder shell under axis/internal air pressure loading, and the cylinder shell under shell loading. All the panels were stiffened by composite frames and omega stringers. The commercial program ABAQUS was employed for numerical analysis. The linear buckling loads and modes of the panels were computed first. The results showed that local buckling of composite skin appeared before global buckling, which indicates that stiffeners improve the buckling restriction of the panels effectively. Then the post-buckling behaviors were investigated with the arc-length method introduced to search for post-buckling paths, and the ultimate maximum load after the global buckling was obtained. The present analysis is capable of simulating the buckling and post-buckling behavior of stiffened composite panels under different loading conditions.

556: Buckling and Postbuckling Analysis of Hat-Stringer-Stiffened Composite Panels

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Abstract:Stiffened composite panel is the typical structure used in airplanes ,such as fuselage, wing and so on. Because of the laminate mechanical properties, Stiffened composite panel has high nonlinear behavior. Its buckling and postbuckling behaviors, failure modes and load carrying capacity are closely related to the skin curvature, the stringer form and the stringer pitch. It is very important to study the stability of stiffened composite panel under different load conditions. The results can be used to the aircraft design using this kind of structure.In this paper, the buckling and postbuckling behaviours of the stiffened composite panels under axial compression and under shear load were studied by experiments and numerical analyses. There are five group stiffened composite panels under axial compression and one under shear load. The effects of the curvature and thickness of the skin, the stringer pitches on the structural stability under axial compression were studied in details.First, the composite panels under compression were studied. The experiment results of stiffened composite panels under compression were obtained and analyzed. Some formulae to calculate the buckling load of stiffened composite panels with curvatures were modified to achieve high fidelity. The FEM (finite element method) were used to simulate the experiments. The perfect models and imperfect models were used in FEM. The relationship between local buckling load, ultimate load and curved plate parameter was obtained. The existing buckling load formulation was modified and the local buckling load of stiffened panels was calculated. An improved engineering approach was proposed to determine the ultimate load. The results were in agreement with the experiments. The proposed engineering approach is feasible and of high value for structural application.Then, the Grid-stiffened composite curved panels under shear were tested and studied. A new shear test method was

proposed. Numerical simulate was also done. The influence of transverse frames was also studied in this paper. Good agreement between experimental and numerical results was obtain. Finally, stacking sequence optimization of composite laminates was proposed and results show the great vccuracy and faster convergence rate.

236: Budgeting Model Calibration Experiments with Expected Information Gain

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In the case of multi-physics phenomena, as observed in aircraft structures subjected to combined extreme environments during hypersonic flight, it is difficult to replicate all loads (e.g., aero-thermo-acoustic) in a single experiment. Often, combinations of experiments that impose subsets of loads are performed, and the resulting data is fused through various uncertainty quantification activities, such as model calibration and model validation. Due to the nature of experiments, the cost associated with different types of tests and measurement techniques can greatly vary. For example, the cost of an experiment that excites a panel with an acoustic load is likely much cheaper than one that simultaneously places acoustic, thermal, and aerodynamic loads on the same panel. Additionally, the quality and resolution of the experimental technique, such as full-field strain measurements vs. strain gages, significantly affects the cost. Researchers have examined methods to efficiently calibrate computational models, attempting to minimize the number of experiments due to cost. Expected information gain is one popular criterion that determines which experimental design is optimal in obtaining the most informative data for model calibration. However, it is often confined to comparisons of experimental design geometry (e.g., panel design) or test conditions (e.g., Mach number), rather than which type of experiment to perform (e.g., acoustic vs. thermo-acoustic loading). This research combines the expected information gain (EIG) criterion and cost information to optimally determine both specimen geometry and experiment type to collect data for model calibration at minimal cost. This is achieved by placing a weight that increases as the quality and resolution of the experiment increases, as well as the number of loads present. Additionally, data collection methods can balance global and local accuracy around an event of interest (EoI), such as failure. In previous work, the authors have developed the Targeted Information Gain for Error Reduction (TIGER) method that uses the EIG for this purpose. This work extends the TIGER method to consider the relative cost of data collection. The weight that is placed on an experiment is based on complexity of the experiment and goal of the experiment. For example, this could allow design trade-offs of high cost experiments but near the EoI against low cost experiments away from the EoI. The methods are demonstrated on the modified Camelback function that is adapted to represent two types of tests at different costs and complexity due to the loading in the experiment (i.e., thermal only and thermo-acoustic).

562: Building Portfolio Fragility Functions to Support Scalable Community Resilience Assessment and Effective Risk Communication

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Resilience is often regarded as an attribute of communities rather than a property of individual civil infrastructure facilities. Therefore, community resilience planning, risk mitigation and recovery optimization need to take on a system perspective at the overall community built environment, including its building inventory. While engineers can quantify the performance of individual buildings and facilities, these information has to be aggregated to reflect the vulnerability of the building inventory as an integrated system in order to support the resilience-based decisions at community level. Furthermore, these decisions ideally should involve collective efforts from

engineers, social scientists and economists among other community decision makers. Aggregated measurements of building portfolios are more effective in risk communication with social scientists and economists than those quantified at the individual building level. The objective of this study is to present a methodology for relating performance of individual buildings exposed to natural hazards to the social-economic resilience metrics that can directly inform resilience-driven decisions at the community level. This paper proposes a concept of building portfolio fragility function (PFF) to characterize the vulnerability of a building portfolio as an integrated system. The PFF is defined as the probability of a building portfolio failing to achieve a certain level of system performance objective conditioned on hazard intensity parameters. The building portfolio can range from a building block, a zone, a critical facility (e.g. hospitals and schools) to the entire building inventory at various scales and resolutions. The system performance objectives corresponds to particular community resilience metrics, such as direct monetary losses, population dislocation and recovery characteristics with respect to the studied building portfolio. In this work, we quantify these portfolio metrics by aggregating individual building performances using Monte Carlo Simulation (MCS) coupled with Gaussian copula, incorporating uncertainties in the hazard demand and in structures' damage susceptibility to the hazard event. Additionally, spatial correlations in demand intensity over a large geographic area and the correlations in structures' performances due to common building practices and code enforcement are also taken into account in the MCS-based aggregation algorithms. Consequently, the impact of these uncertainties and the positive spatial correlations on system performance of the portfolio are automatically captured in the resulted PFFs. The paper concludes with an illustration of developing and implementing PFFs to support risk-informed decisions regarding effective risk mitigation policies and rapid post-disaster recovery within a hypothetical community.

342: Calibration of Input Dependent Parameters in Multi-Fidelity Problems

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The aim of this research is to investigate the use of structural dynamics computational models with multiple levels of fidelity for the calibration of input dependent parameters. Non-linear materials often lead to system model parameters that are input dependent (function of time, temperature, loading, etc.). Different types of models may also be available for the estimation of unmeasured system properties, with different levels of physics fidelity, mesh resolution and boundary condition assumptions. In order to infer these system properties, Bayesian calibration uses information from multiple sources (including experimental data and prior knowledge), and comprehensively quantifies the uncertainty in the calibration parameters. Estimating the posteriors is done using Markov Chain Monte Carlo sampling, which requires a large number of computations, thus making the use of a high-fidelity model for calibration prohibitively expensive. On the other hand, use of a low-fidelity model could lead to significant error in calibration and prediction. Therefore, this paper develops an approach for input dependent model parameter calibration with a low-fidelity model corrected using higher fidelity simulation data. The methodology is illustrated for a curved panel located near a hypersonic aircraft engine, subjected to increasing acoustic loading decibel levels. The damping properties of the panel are assumed to be dependent on the acoustic decibel levels. Two models (a frequency response analysis and a full time history analysis) are combined to calibrate the damping characteristics of the panel. An additional challenge is the description and incorporation of model discrepancy in Bayesian calibration. The calibration of damping properties of the panel is based on sensor readings at multiple locations, and the model discrepancy is different at different locations. The proposed methodology includes a rigorous random field approach for modeling the spatial variability of model discrepancy, and for including the model discrepancy within the Bayesian calibration.

501: Carbon Nanotube-reinforced Structural Composites Enabled by the PopTube Approach

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Jialai Wang, The University of Alabama

An ideal candidate to accomplish the reinforcement of the matrix and interphase zone of FRPs is carbon nanotubes (CNTs), because of their superior mechanical properties and excellent thermal and electrical properties. Direct dispersion of CNTs into the matrix of composites has been shown to be very difficult. A more effective way to reinforce FRPs using CNTs is to grow CNTs directly on the reinforcing fibers/fabrics. A novel method, referred to as the PopTube Approach, has recently been developed at The University of Alabama and Auburn University. This method uses microwave irradiation to grow CNTs in 15-30 seconds at room temperature in air, without the need for inert gas protection or additional feed stock gases. Compared to other existing manufacturing methods of CNTs, the PopTube Approach enjoys many advantages: little damage/chemical alteration is induced in the fibers; high-yield, large-scale manufacturing requires only simple equipment; and energy efficiency and cost effectiveness is greatly enhanced. This novel method paves the way for the next generation of structural spacecraft materials by providing a practical means of producing large-scale CNT-reinforced structural composites.

628: Cardiac Isogeometric Simulations using Cubic Hermite Meshes with Extraordinary Nodes

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Edward Pszczolkowski,
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Cubic Hermite hexahedral finite element meshes have some well-known advantages over linear finite element meshes in anatomic modeling and biomechanics simulations using isogeometric analysis. Cubic Hermite meshes require fewer degrees of freedom to represent smooth geometries and stress solutions. However, it is not possible to create closed complex objects with only regular nodes; these objects require the presence of extraordinary nodes (nodes with 3 or >5 adjacent elements in 2D) in the mesh. The presence of extraordinary nodes requires new constraints on the derivatives of adjacent elements to maintain continuity, which can be achieved through special global-to-ensemble derivative maps. We have developed a new method that uses a local to global derivative map to maintain continuity across edges containing extraordinary nodes. We have successfully used this mapping to create topologically complex cubic Hermite meshes of the left and right atria. Here, we take advantage of this mapping to create cubic Hermite models of the four-chamber heart and derive the finite element methods required to solve biomechanics problems on these meshes. Using our method, we can simulate a full cardiac cycle using a cubic-Hermite mesh of the human heart with extraordinary nodes. Since these meshes are capable of representing complex geometries with fewer elements, the computational time is significantly reduced. Computing the element stiffness matrix for each element is the most computationally intensive operation in higher-order finite element analysis. Using our method, a complete four-chamber heart could be represented with a mesh consisting of only 474 cubic Hermite elements. Using anatomically accurate heart models for biomechanics simulations will enable modeling of complex interactions that were not previously possible with ventricular models that do not include the valve plane. One example is modeling mitral valve regurgitation by linking it to changes in the mitral valve annuli during the heart cycle. Finally, using the four-chamber mesh can help us accurately model the effect of atrial geometry on the heart function as well as apply anatomically accurate boundary conditions.

195: Cell Response to Static and Cyclic Compression in a Three-Dimensional Matrix

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Cells adapt forms and functions in response to external loads through their machinery, actin stress fibers. Despite recent progress in the biomechanics of stress fibers, how this machine works under compression in a three-dimensional (3D) matrix remains an open question. Here, we report our efforts to determine the reorientation of human prostatic normal tissue fibroblasts (NAFs) and cancer associated fibroblasts (CAFs) and force reaction generated by stress fibers under static and cyclic compression in a type I collagen gel. We first analyzed cell reorientation in response to static compression using confocal microscopy and a Fast Fourier Transform (FFT) method. Our results show that NAFs are directed to specific angles under compression while CAFs maintain a random orientation. To explain the observation, we developed a mathematical model based on the minimum energy principle, which discloses the important role of stress fibers and inherent cell contractility in cell reorientation. Further, we employed a computer-controlled setup to examine the cell force response to cyclic compression. Interestingly, we observed that cell stress fibers generated higher force to "fight back" the cyclic compression initially and then settle down to a plateau, illustrating the time course of generated force. These studies provide new insights into the working mechanisms of stress fiber machine under static and cyclic compression in a 3D collagen matrix.

652: Challenges with Uncertainty Quantification for Hypersonic Aircraft Structures

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The current lack of confidence in structural response and life predictions of a vehicle exposed to combined, extreme environments for extended durations prevents the USAF from fielding affordable, reliable, and reusable hypersonic platforms. The goal of the current study focuses on developing validated, risk-informed methods for design, simulation, and life prediction of aero-structures subjected to the intense, combined loads characteristic of high-speed flight. Significant strides have been made in modeling the complex interactions of the multi-physics, fluid-thermal-structural coupling applicable to hypersonic flow conditions. However, prohibitive computational cost of high-fidelity, coupled, aerothermoelastic simulation and the inability to fully replicate in-flight aero-thermo-acoustic loads through ground tests poses a significant challenge for model validation and assuring the needed confidence in model predictions. This presentation identifies fundamental challenges related to: (a) enabling the quantification of uncertainty in these coupled multi-fidelity, multi-physics models; (b) assessing the prediction confidence for a hypersonic aircraft structure; and (c) determining how to best increase the prediction confidence when it is inadequate.

480: Characterization of Chemical Composition and Microstructure of Synthesized Alkali-Silica Gel with Small-Angle Neutron and X-Ray Scattering

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Xiao Sun, Michigan Tech
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The expansive Alkali-Silica Reacted gel in concrete imposes severe threat to the durability of concrete structures. This study aims to characterize the microstructure and chemical composition of synthesized ASR gels by using small-angle neutron and X-ray scattering, providing direct insights of the ASR damage development in concrete and high-alkali activated geopolymerization. The synthesized ASR gels were prepared with silica source (the glass powder and silica gel) and the alkaline solutions ($NaOH$ and KOH solutions). The small-angle neutron scattering tests were conducted to analyze the chemical composition based on the scattering contrasts of the three different synthesized ASR gels prepared with 100% H_2O, 100% D_2O and 50% H_2O with 50% D_2O. The chemical formulation of the amorphous gel, written as $(Na_2O)_x(SiO_2)(H_2O)_y$, the ratios between the chemical groups can be determined with the Porod scattering intensity model. The small-angle X-ray scattering measurements were also conducted to compare with the small-angle neutron scattering analysis results. To obtain different X-ray scattering contrast, three different alkaline solution (100% $NaOH$, 100 KOH and 50% $NaOH$ with 50% KOH) were prepared. Both results gave close prediction to the ASR gel chemical composition. The microscale gel size distribution and surface area of the gel particles were also determined by using both scattering techniques with the Guinier-Porod model. The fitting results were compared with image techniques such as SEM and micro CT. The study demonstrates that the small angle neutron and X-ray scattering can be used to study microstructure and chemical composition of the synthesized alkali-silica gel. Future work will be extended to study both microstructure and chemical characteristic changes of expanded gels with different percentages of absorbed water.

377: Characterization of Mechanical and Electrical Properties of SMA-PVA Fiber-Reinforced Cementitious Composites

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Fiber reinforced concrete contains fibers of different types and forms while having nearly the same cementitious matrix composites as a plain concrete. Many researchers have studied the use of discontinuous fibers such as steel, glass and synthetic fibers to enhance tensile strength, ductility, and toughness of concrete. Self-sensing concrete is a relatively new development in concrete research. Self-sensing ability can be obtained by adding functional fillers such as carbon fibers, carbon nanotube and nickel powder into conventional concrete. The fillers form an extensive conductive network inside the concrete and as the concrete is deformed/stressed the electrical properties of the composite are changed. Therefore, strain, stress, crack, and damage under various conditions can be detected through measuring the electrical properties. This paper investigates the use of shape memory alloys (SMAs), which combine robust superelasticity with strain-dependent electrical properties, as fibers in cementitious composites together with synthetic fibers. The research aims at simultaneously achieving strain hardening, self-centering, crack width control and self-sensing abilities in a single composite material. The self-sensing and self-centering capabilities are introduced by integrating the SMAs into the mixture of the conventional engineered cementitious composite, which exhibits strain hardening. Different volume fractions of SMA and polyvinyl alcohol (PVA) fibers are used to identify the optimal mixture composition. Prismatic specimens are prepared and tested under four-point bending in a displacement-controlled manner. The specimens are loaded in increasing displacement increments and unloaded to evaluate the mechanical and piezoresistive response of the developed composite. Digital Image Correlation (DIC) is used to capture the full field strains and deformations, with the crack development monitoring capability. Test results are analyzed in terms of mid-span deflection, residual deformation, crack width, energy dissipation and change in resistivity of the specimens.

472: Chemo-Poro Elastic Fracture Mechanics of Wellbore Cement Liners: The Role of Eigenstress and Pore Pressure on the Risk of Fracture

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Franz-Josef Ulm, Massachusetts Institute of Technology

Between 2001 and 2010, United States natural gas wells have been drilled at a mean annual rate of 24,500. Moreover, an investigation in the Marcellus region revealed a 3.4% incidence rate of well-barrier leakages that were caused primarily by casing and cementing problems. Considering the detrimental consequences even a single failed well can have on the health of vast expanses of ecosystems, the quality of groundwater aquifers, and the production efficiency of fossil resources, ensuring the integrity of cement liners is of utmost importance. While much attention has been devoted to the mechanical analysis of the cement sheath during temperature and casing pressure cycles in the hardened state, modeling efforts of the early-age shrinkage and pore- pressure developments have thus far proved inadequate. This motivates us to study the cement sheath as a poro-elastic media under growth and stiffening of its solid structure, and connect bulk stress and pressure development to worst-case fracture scenarios. Specifically, a bottom-up approach is herein developed to incorporate the microscale behavior of the hydrating cement phases into a predictive risk-of-fracture model. We incorporate recent findings of the driving mechanism of eigenstress de- velopment in CSH-gel and connect it, via Levine's theorem, to pore-pressure changes in the sheath. Coupled to the boundary conditions of an inner steel casing and an outer rock formation, the bulk stress in the sheath is calculated incrementally with reference to the growing solid skeleton. The added risk due to the off-center place- ment of the casing is quantified in a novel Laurent series solution to the stress state. Finally, energy release rates are derived for (i) the micro-annulus formation along the steel-cement and rock-cement interfaces, and (ii) the occurrence of a single radial fracture emanating from the steel-cement interface.

644: Chemomechanics of Soft Hydrogels as a Water Reservoir in a Cementitious Matrix

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Hydrogels consist of a polymeric network dissolved in a solvent and their chemical and mechanical responses are sensitive to external stimuli such as temperature, pH, concentration of salt solution, electric field etc. These characteristics of hydrogels can be employed in a wide array of applications in biomedical and mechanical engineering. The use of hydrogels with a large absorption capacity in the infrastructure applications is an emerging line of research aimed at improving the durability of cement-based materials. Applications include mitigating autogenous shrinkage cracking in cement-based materials with low water to cement ratios. Hydrogel can also be used as an encapsulation medium for a large variety of nanoparticles and biological species, which can then be released into the cement-based matrix to achieve desired tasks. Cement-based materials consist of a complex microstructure and exhibit variations in their physicochemical characteristics. Therefore, understanding the behavior of hydrogels in such an environment is critical in the optimum design of cement-based materials containing hydrogels. In this presentation, we report an experimental investigation into the mechanical and chemical interactions of hydrogels in an alkaline environment. The swelling/deswelling and deformation behavior of the hydrogels and their dependence on alkali ions and their concentration in the solution were studied. The effect of mechanical stress on the behavior of hydrogels was elucidated and discussed. The uniaxial tensile test was used to evaluate the mechanical properties of hydrogels. The effect of pore structure of a cement-based matrix on the deswelling of the hydrogel was examined. It was observed that the hydrogel response was strongly influenced by the concentration and type of the alkali counterions as well as mechanical stress. Alkali counterions were shown to affect the mechanical properties of hydrogels. The results from this study provide valuable insight into the underlying mechanisms governing the behavior of hydrogels in a cement-based matrix.

140: City-scale Structural Health Monitoring by Wide-range Video Camera Sensing and Novel Computer Vision

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Rapid urbanization is undergoing associated with significant demand on constructions and maintenance of safe, economic, and sustainable infrastructure, which presents new challenge of advancing the structural health monitoring technology to the city-scale. While the wireless sensor network (WSN)-based paradigm of infrastructure health monitoring has shown evident promise for individual structures, it is point-wise with low spatial sensing resolution, and has many challenges including supplying energy to sensor nodes, communication bandwidth, and the high costs associated with installation, which could hinder its wide deployments in the city-scale. Furthermore, it is uncertain that these issues will be solved (e.g., by new battery technology or energy harvesting) on the timescale associated with rapid urbanization. In this context, it is most motivated to develop new solutions that facilitate monitoring and construction verification in an agile, affordable manner that goes beyond the individual structure scale to the city-scale. This work explores the feasibility of using the ubiquitous video cameras that are low-cost, non-intrusive, and with very high spatial sensing resolution, coupled with novel computer vision techniques for wide-range, city-scale sensing and monitoring of urban infrastructure. The proposed framework is validated by lab experiments and real-world study cases. The goal of this work is developing a novel cost-effective, deployable, high-resolution, and wide-range structural health monitoring solution that could help address the sustainable development of urban infrastructure associated with rapid urbanization.

282: Cohesive Crack Analysis of Size Effect for Samples with Blunt and Sharp Notches

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Giovanni Di Luzio, Politecnico di Milano

This paper deals with the analysis of size effect in concrete. An extensive campaign of accurate numerical simulations, based on the cohesive crack model, is performed to compute the size effect curves (CSEC) for typical test configurations featuring both sharp and blunt notches. The results are analyzed with reference to the classical Bazant's size effect law (SEL) to investigate the relationship between CSEC and SEL. This analysis shows that as specimen size tends to infinity, the SEL represents the asymptote of the CSEC in the case of sharp notches, and that the SEL parameter known as the effective fracture process zone length is a material property which can be expressed as a function of the cohesive crack law (CCL) parameters. For blunt notches, however, the nominal strength of infinite size samples tend to a horizontal asymptote corresponding to the elastic limit. It shown that the two results are not in contradiction because the elastic limit tends to zero as the radius of curvature tend to zero due to the stress singularity at the notch tip.

29: Combined Effects of Catenary and Tensile Membrane Actions in Reinforced Concrete Beam-Slab Systems to Resist Progressive Collapse Under Different Loading Methods

Anh Tuan Pham, Nanyang Technological University
Kang Hai Tan, Nanyang Technological University

Although catenary action in beams and tensile membrane action in slabs are generally believed as higher levels of protection to mitigate progressive collapse in a reinforced concrete (RC) building, most previous studies just separately investigated each of the two mechanisms instead of studying their combined effect. Besides, recent tests on RC frames under single column removal scenario were conducted by applying a concentrated load at the middle joint after the supporting column had been notionally removed, whereas actual buildings are normally designed for uniformly distributed loads. To study the combined effects of beams and slabs under progressive collapse, finite element models are developed based on solid elements and are validated by quasi-static tests of RC structures under a middle-column removal scenario applied with point-load condition. Further numerical investigations are carried out for beam and beam-slab structures under concentrated load (CL) and uniformly distributed load (UDL) conditions. A 4-point loading method is proposed to represent UDL on beams, whereas a 16-point loading method is applied for slabs. For beam-only structures, results show that the response of applied load from the UDL condition is exactly twice the related value from the CL condition while both cases provide identical horizontal reaction. However, the ultimate displacement from UDL case is only half compared to the CL case. The two loading cases also have different failure-mode sequences. Besides, catenary action, which is fully developed under CL case, cannot be effectively mobilised under UDL case. The study on beam-slab system shows that, while slabs under UDL condition can effectively mobilise tensile membrane action with final failure modes including full-depth cracks and rebar fracturing, premature failure due to punching shear occurs in slabs under CL condition and limits the contribution of membrane behaviour. The contribution of interior beams is constrained within flexural mechanism with limited enhancement from catenary action due to small value of maximum deformation. Effect of boundary restraint stiffness is also investigated for the beam-slab system. It is concluded that tensile membrane action is not influenced by horizontal restraint for both of the loading cases, but is affected by rotational restraint under the UDL condition.

175: Community-Scale Multi-Fidelity Modeling of Tsunami Forces on Coastal Structures

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Michael Motley, University of Washington
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Frank Gonzalez, University of Washington

The U.S. Pacific coast is highly susceptible to a tsunami event similar to recent Pacific and Indian Ocean tsunamis that have caused hundreds of thousands of deaths and billions of dollars in damage to coastal communities. Increased computing power has prompted the development of novel numerical approaches tailored to capture specific physical phenomena related to tsunami impact, including complex multiphysics models to simulate complex system interactions. For the last several years, researchers have been developing probabilistic inundation models and corresponding hazard curves for water level, velocity, and momentum flux at community-scale or larger. But in current practice, inundation maps are often developed that do not account for coastal structures; instead, bare earth topography with bottom friction terms are used to account for the interaction of flow with any surface features. Even a moderately densely populated region can have a significant local effect on flow and resulting fluid forcing. The complex nature of such flow around structures creates additional difficulty in predicting local fluid forces using inundation models, as these models generally do not calculate fluid pressures and rely on other ways to estimate local hydrodynamic forces. High-fidelity computational fluid dynamics (CFD) models can be used to predict fluid pressure and viscous forces on individual structures, but at great computational expense. Here, the results of a series of wave basin experiments of flow through a scale model of Seaside,

Oregon are used to validate flow predictions of two models: the GeoClaw tsunami model, an inundation model which solves the two-dimensional shallow water wave (SWW) equations, and a three-dimensional CFD model that uses the open-source OpenFOAM software that allows for computation of fluid forces on the faces of structures. Comparisons of water level, velocity, and momentum flux are presented for both models with and without the presence of structures to highlight the variability in momentum flux predictions, and force predictions from the CFD analyses are presented for selected structures within the physical model. The goal of this work is to assess the effectiveness and limitations of the more efficient 2D SWW models such as GeoClaw to predict tsunami forces and to determine under what circumstances it is necessary, to use the more costly, 3D CFD analysis to obtain reliable estimates. These developments are essential to bridge the gap between computationally practical techniques and high-fidelity numerical models and will provide specific tools for improving the safety and resilience of coastal communities.

280: Computational 3D fluid-structure interaction involving large deformations

Ye Chen, Vanderbilt University
Siyuan Chang, Vanderbilt University
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Fluid-structure interaction between flow and elastic materials plays an important role in human bodies and in biomedical applications. Some of examples that involve large deformations of tissues include the vocal fold and heart valves. With great advancement in computing power and computational algorithms, it is now possible to perform coupled high fidelity numerical simulations with both three-dimensional flow and three-dimensional nonlinear tissue mechanics. In our work, a versatile in-house code has been developed to specifically simulate those biological FSI problems with high fidelity. For the flow solver, a direct-forcing immersed-boundary method is applied to solve the viscous incompressible Navier-Stokes equation on Cartesian grids; for the solid mechanics solver, a finite-element method is implemented for soft bodies undergo large deformations. Hyperelastic constitutive models have been implemented in the program to model tissue materials. The computational fluid dynamics (CFD) solver and the computational structural dynamics (CSD) solver are coupled together in a partitioned but strong-coupling manner, so that the FSI program can handle both high mass ratio (inertia of solid v.s. inertia of fluid) and low mass ratio cases. Both CFD and CSD programs are parallelized efficiently and can take advantage of most recent high performance computing technology. We will demonstrate application of this numerical method in both voice production and cardiovascular flows. In particular, we simulate the flow-induced vibration of the vocal fold and FSI of the aortic valve whose flexible leaflets interact with blood flow. In the vocal fold case, we have done simulations using both idealized vocal fold models and subject-specific model that is based on imaging data, and we have studied the effects of the materials and tissue structures. In the heart valve case, we have been studying the relationship among the vortex formation, the leaflet deformation, and the pressure field during transient opening/closing phases of the valve. Characteristics of the flow and solid bodies in both problems will be presented, and future directions will be discussed.

679: Computational and Experimental Testing of Thermo-Chemical Structural Health Monitoring of Composites

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Composite structural systems are becoming more and more widespread across industries and the capability to finding and tracking internal defects before they have grown to major deterioration is of paramount importance

in regard to safety, economy and maintenance. We are exploring a novel method of internal damage detection and tracking in composite material using thermo-chemical sensing. A micro-size network of strings is interwoven into the composites. Each string consists of a pair of tubes, containing one of two different non-polar reactants. A local defect within the composites causes straining and cracking of the tube shell, resulting in direct contact of the two non-polar reactants. The latter undergo a chemical reaction resulting in a polar product. Our preliminary investigation shows that a polar product, when exposed to a microwave energy source, heats up dramatically in comparison to the ambient composite material or the non-polar reactants. This very localized thermal signature can be visualized by an infrared camera. The key characteristics of this embedded structural health monitoring technology is that it allows wide area monitoring and does not require embedded wiring or power source. Various types of composite materials with this structural health monitoring technology embedded are investigated experimentally and computationally. This paper sheds light on the physics enabling detection and monitoring, including the microwave heating and subsequent cooling of the composites material, and undertakes a sensitivity study of the technology. Further, findings of an extensive parametric study, targeting a prioritization of parameters, such as electrical and thermal conductivity, relative permittivity, relative permeability and heat capacity at constant pressure, are presented.

522: Computational aspects of Morphological Instabilities

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Instabilities due to compressive stresses in materials lead to variety of folding patterns. In general, potential sources of compressive stress that can result in morphological instabilities are mechanical loading, confined thermal loading, and confined or differential material growth and swelling. Common examples of instabilities in biological tissues include folding of the brain and asthmatic airways. Malformation of folding in brain or asthmatic airways can signal abnormal evolution of the tissue, often related to serious fatal diseases. Not only controlling instability is important in biological tissues, but it is also important for recent applications of soft materials in electronic skin, stretchable electronics and material characterization. From the continuum mechanics perspective this problem can be modeled as a thin film growing on a substrate. Recent studies show that the parameters such as the stiffness ratio of the film to the substrate, the thickness of the film and the growth rate influence the onset of the instability as well as its pattern. As the film grows, the instability forms sinusoidal wrinkles on the surface for a compliant substrate. However, we observe crease formation when the substrate is stiffer than the film. Sinusoidal wrinkles and creases are referred as primary instability modes. The onset and the pattern for these instabilities can be accurately captured using the eigenvalue analysis [1] [3]. Further growth promotes the secondary and higher instability modes in the form of a ridge, period-doubling or folding [2]. The objective of this presentation is to establish a computational framework based on the finite element method and more advanced techniques such as isogeometric analysis to create a phase diagram predicting the instability modes and the onset of the instability. The eigenvalue analysis provides accurate results for the critical growth to observe primary instabilities. However, a perturbation technique is often required to observe the transition of the primary modes to the secondary modes. Our proposed framework may lead to a better understanding of the primary and higher instability phenomena in soft materials, and consequently, promote the diagnostic methods by investigating the morphogenesis in biological tissues and design of new devices by controlling the instabilities.

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676: Computational Cryo-Mechanics for Frozen Soil

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WaiChing Sun, Columbia University

We investigate the freezing-thawing effect of frozen soil using a stabilized thermo-hydro-mechanical (THM) finite element model. By applying mixture theory, frozen soil is idealized as a composite consistent of four phases, i.e., solid grain, air, unfrozen water and ice crystal. A generalized hardening rule is adopted to replicate how critical state evolves under a combination of non-mechanical loading, such as degree of saturation, temperature and phase transition. The enhanced particle interlocking and ice strengthening, and the cryo-suction effect in frozen soil are replicated. Meanwhile, mass-exchanges among constituents due to phase transition are considered. A stabilized equal-order finite element model that employs mass, momentum and energy balance laws as governing equation are used. Inf-sup tests are conducted to ensure the spatial stability of the numerical models. The frost heave problem and triaxial compression tests at different temperatures are used to benchmark and validate the numerical schemes.

500: Computational Design of Interconnected, Polymer Composites for Impact Resistant Applications

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Use of polymer composites as energy absorbing material has constant demand in defense and aerospace applications. In order to safely resist the high rate of loading such as blast waves, the constituent materials need to have sufficient stiffness and damping capacity simultaneously. Use of viscoelastic materials can enable the composite to dissipate energy, thus acts as good damper. In the present study, focus has been given on designing micro-architectured material consisting of interconnected stiff and soft polymers. To design such micro-architecture, inspiration has been drawn from natural materials. The interconnected, micro-architecture has significant advantage over layered composites. Firstly, the interlocking between stiff and soft materials renders no use of adhesive in the interface. Secondly, stiffness enhancement is achieved over layered composites. In the present study, two sets of materials are taken. One set consists of PMMA and soft gel type material, while the other set has PMMA and Polyurethane. The optimum design of the micro-architecture has been found through finite element analysis. Several case studies are performed to assess the performance of the material. A sinusoidal loading is applied to the designed micro-architecture to determine its rate dependent stiffness and damping response. Also, stress wave mitigation is studied by applying a high rate impulse to the micro-architecture. In order to design architectured materials with multi-functionality such as high stiffness and damping, a mathematical framework needs to be developed for characterizing the constitutive response of constituent polymers. A physically motivated model to characterize these materials in conjunction with design optimization would lead to efficient manufacturing. The proposed constitutive models have been developed in finite deformation framework to incorporate both large deformation and rate dependent behavior of constituent polymers.

564: Computational Evaluation of the Role of Aggregate Shape Parameters on the Mechanical Performance and Degradation of Asphalt Mixtures

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Eyad Masad, Texas A&M University at Qatar

Aggregate shape parameters (i.e. form, angularity and texture) are recognized to impact the mechanical performance of hot mix asphalt (HMA) materials. However, there are limited works dealing with the actual influence of those properties on the mechanical response and degradation of the material. This work quantifies such an impact through the random generation of HMA microstructures that share the same geometry and volumetric properties but that have different aggregate form and angularity indexes. These microstructures are composed by three phases: 1) air voids, 2) coarse aggregates, an 3) a fine aggregate matrix (i.e., the combination of binder and aggregates with a diameter smaller than 1.18 mm) The microstructures are used as model geometries in finite elements, and are subjected to mechanical loading using a non-linear viscoelastic continuum damage mechanics formulation for the matrix phase. The overall response and the magnitude of the internal degradation of the mixtures is quantified and compared. One relevant aspect of this work is that, since several HMA replicates are computationally tested in each case, the influence of the aggregate shape parameters on the response of the mixture is analyzed using probabilistic principles. The results from the simulations demonstrate that these shape parameters do play an important role in defining the mechanical behavior of asphalt mixtures. Simulations like the ones conducted in this study could be efficiently used to define threshold values for aggregate shape and angularity indexes that guarantee a proper performance of the mixtures, as well as minimum acceptable levels of the structural reliability of these materials.

677: Computational Fluid Dynamics Simulation of Potential Risk Factors in a Mouse Model of Pediatric Cerebrovascular Disease

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Mutation in ACTA2, encoding smooth muscle alpha-actin, leads to stenosis, occlusion and pathological straightening of cerebral arteries, particularly in the Circle of Willis (CoW) territory and some of these changes are similar to what occurs in Moyamoya disease. We developed healthy and pathological CoW vascular models and performed computational fluid dynamics (CFD) analysis to evaluate scenarios potentially affecting disease severity and progression. A 3D image stack of the mouse CoW was acquired using a small animal micro-CT scanner. Following segmentation, a surface representation of the arterial network was created, which was then processed through a computer-aided design (CAD)-based vascular modeling pipeline to generate a 24-patch hexahedral NURBS (Non-Uniform Rational B-Splines) mesh for analysis. Under a continuum-based approach, blood flow was assumed to be governed by the unsteady incompressible Navier-Stokes equations subjected to appropriate boundary conditions. A finite-element based isogeometric analysis framework was employed to simulate realistic blood flow features, driven by a pulsatile inflow condition, within the authentic CoW vasculature. To investigate the influence of vessel geometry on local hemodynamics, wild type (WT) and Acta2-/- (KO) mouse model, representative of healthy and pathological conditions, respectively, were analyzed. Symmetric bilateral flow was observed under normotensive and hypotensive conditions. In both cases, wall shear rate (WSR) remained largely below the threshold pathological value (<5000 s-1) for clot formation, suggesting that vessel straightening in the KO mouse alone may not lead to increased stroke risk. A careful study of KO mouse imaging datasets (n=8) revealed increased incidence of obstructions or malformations in the superior cerebellar artery (SCA) branch. Blood flow simulations of a KO model with an occlusion in the right SCA showed a 98/2 flow-split between left and right SCA. Regions with critical WSR values in the left internal carotid artery (ICA) and the left SCA was observed, signifying increased probability of clot formation in vessels contralateral to the occlusion. Retrograde flow was also detected in the right posterior communicating artery (PCOMA), thus helping to maintain sustained flow in the presence of the occlusion. Our simulation results indicate possible scenarios for transient ischemic attacks and strokes, which are common with ACTA2 mutations and moyamoya disease. The presented computational approach could potentially be used to predict risk for strokes in these patients.

215: Computational Free-Surface FSI with Applications

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Yuri Bazilevs, University of California, San Diego

We propose a computational free-surface fluid-structure interaction framework using finite element and isogeometric analysis, which enables the simulations of the interaction between free-surface flow and floating structures like offshore floating wind turbines with great efficiency, accuracy and robustness. The free-surface flow is modeled by two-phase Navier- Stokes equations with assistance of level set method. ALE-VMS is employed to discretize the Navier-Stokes equations and level set convection equation. The structural motion is described by isogeometric rotation-free shell, beam and cable formulation. Non-matching discretization is employed at fluid-structure interface. The kinematic compatibility between fluid and structure is weakly enforced at fluid-structure interface. Quasi-direct coupling strategy with matrix-free technique is adopted to handle the large added mass. The mathematical formulation is discussed in detail. A number of offshore engineering applications are shown.

555: Computational FSI with Applications

Yuri Bazilevs, University of California, San Diego

Fluid-Structure Interaction (FSI) has been receiving increased attention in Civil Engineering due to recent emphasis on the ability to model and analyze extreme events arising due to natural or man-made disasters. The presentation is focused on the computational framework that involves coupling of flow and structures undergoing large deformations. The formulation of fluid mechanics on the moving domain is presented, and efficient solution strategies for the underlying coupled mechanical systems are discussed. Basics of Isogeometric Analysis are also shown. The fluid-structure interface discretization is assumed to be nonmatching allowing for the coupling of standard finite-element and isogeometric discretizations for the fluid and structural mechanics parts of the FSI problem, respectively. FSI coupling strategies and their implementation in the high-performance parallel computing environment are also discussed, and computational challenges presented. Simulations ranging from full-scale wind turbines to structures under blast loading are presented.

238: Computational Health Monitoring of 3D Concrete Simple T Girders to Identify Objective Health Index Measure

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The structural decay of aging infrastructure systems presents itself as an increasingly important issue worldwide. To compound the issue, economic strains limit the resources available to confront this problem. Over the past several decades, structural health monitoring (SHM) has proven a cost-effective method for detection and evaluation of damage in structural infrastructure. Visual inspection and condition rating is one of the most commonly applied structural health monitoring techniques, but the effectiveness of this method suffers due to the fact it relies on the availability of experienced personnel and the reliability of largely qualitative damage evaluations. A significant amount of research has been conducted regarding the utilization of dynamic characteristics in damage detection as an alternative SHM technique. However, fewer studies focus on the potential applications of static characteristics or on damage evaluation and quantification. The artificial neural network (ANN) approach presented in this study attempts to provide a method of crack-induced damage quantification for reinforced concrete bridge girders requiring only the results of limited field measurements. A large number of simply-supported, three-dimensional, reinforced concrete T-beams with varying material, geometric, and crack properties were modeled using Abaqus finite element analysis software, and each beam's relative stiffness, between healthy and cracked states, was measured at multiple locations along the beam (stiffness nodes). Two feedforward ANNs utilizing backpropagation learning algorithms were then created with the beam properties serving as inputs for both neural networks. The outputs for the first network include the relative stiffness ratios at each node, and the sole output for the second ANN was a health index parameter based on the nodal relative stiffness distribution normalized across the length of the beam. The ANNs achieved excellent prediction accuracies with R^2 values exceeding 0.99 for both networks. The preliminary results of this study indicate that ANNs trained with static characteristics can provide accurate, quantitative damage evaluations for reinforced concrete beams using 3D finite element analysis.

70: Computationally Efficient Modeling of Axially Reinforced, Inflatable, Braided Beams and Tori

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William Davids, University of Maine
Andrew Goupee, University of Maine
Joshua Clapp, University of Maine

The Hypersonic Inflatable Aerodynamic Decelerator (HIAD) being developed by the National Aeronautics and Space Administration (NASA) has the potential to significantly increase payload delivery capacity from orbit to the surface of a planet with an atmosphere, such as Mars. The HIAD system consists of a series of stacked, concentric tori covered with a flexible heat shield that forms a relatively low mass cone shape decelerator with a large surface area. The tori consist of a braided fabric shell with integrated reinforcing cords. The textile structure gains its stiffness from the internal inflation pressure; the integrated cords and the braided fabric shell are pre-stressed during the inflation process and provide the axial and bending rigidity of the members. There are significant challenges associated with modeling the relatively compliant, inflatable structure. Component and structure level modeling to date has focused on high-fidelity shell-based finite element (FE) models with reasonable success, although these models can be time consuming to develop and computationally intensive to run. Previous work has shown that the behavior of the slender, inflatable members can be accurately captured using beam FE models. As a computationally efficient alternative to the high-fidelity shell-based FE models, a beam-based FE model formulation has been developed to model the slender, inflatable textile members and the HIAD system. The modeling tools that have been developed necessarily include geometric and material

nonlinearities in three-dimensional space. The development of the computationally efficient beam-based FE modeling approach will allow for the exploration of the HIAD design space as well as more formal HIAD optimization studies. In this presentation the development of the modeling methodology and analysis tools are detailed including the element state determination process and the determination of model constitutive properties from material testing. Validation studies on component level testing of straight beams and single torus structures, both of which demonstrate significant nonlinearities, are presented. The beam FE model response was found to agree well with both the measured test data and high-fidelity shell based FE models.

308: Computing the Value of Information in Sequential Decision Making: An Auction-Based Formulation

Milad Memarzadeh, Carnegie Mellon University
Matteo Pozzi, Carnegie Mellon University

Operation and maintenance of infrastructure systems depend on the information collected on their components. Information is usually expensive to acquire due to limited resources available for data collections. The Value of Information (VoI) is a consistent approach for ranking the available information, measuring uncertainty and risk that is relevant to the maintenance policy and impacts the decision-making. VoI of an observation is defined as the difference between the value of the management process with and without that specific observation. While VoI is a rational metric for assigning priorities in inspection scheduling, assessing the VoI is computationally intractable for most real-world applications, as it suffers from the so-called curse of dimensionality. In this work, we propose an approach for integrating the adaptive maintenance policy based on partially observable Markov decision processes (POMDP) and information gathering through inspections based on a tractable approximation of VoI. The proposed method uses auction-based formulation to make assumptions about the availability of the future inspections at system level. In details, the assumption is that future inspections will be available for each component ready to cover a specific cost. In some sense, the components compete in an auction to get future inspectors. The method is able to mimic the actual future allocations and decomposes the complicated system-level optimization problem into component-level optimization problems. The complexity of method is linear with respect to the number of components on the system and can be used for real-time inspection scheduling of infrastructure systems. We validate the performance of the auction model in several simulated scenarios.

778: Conceptual Building Design: Density and Ground Structure Topology Optimization Solutions

Igor Torres,
Sara Brandão,
Sylvia Almeida,
Glaucio Paulino, Georgia Institute of Technology

Topology optimization provides design solutions to several engineering applications and density methods are the most popular approach in this field. However, when it comes to building design, the dimension of the extended domain related to the high of the building provides material concentration at the basis of the building. On the other side, the ground structure method provides desirable grid solutions using a highly connected truss in an approach close to size optimization techniques. We address a prospective study about the application of both density methods and the ground structure method to conceptual design of buildings and explores desirable manufacturing constraints such as patterns repetition and symmetry. Simulations are developed both in two-dimensional and three-dimensional building configurations, illustrating the potential future applications of this

work in the context of building layout optimization.

714: Consequence-Based Management of Railroad Bridges Networks Enabled by Wireless Smart Sensors

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Billie Spencer, University of Illinois
Douglas Foutch, Professor Emeritus
Sandro Scola, Canadian National Railway

To increase overall profitability, add capacity to rail operations, and comply with new federal regulations on bridge safety, North American railroads are exploring means to improve the management of their bridge networks. Current maintenance, repair, and replacement (MRR) decisions are informed by bridge inspections and ratings, which recommend observing the response of bridges under trains. However, an objective relationship between bridge responses, bridge service state condition, and the associated impact to railroad operations has yet to be established. If the consequences of MRR decisions could be better determined, then the railroads could more effectively allocate their limited resources. This paper develops an approach for consequence-based management of bridge networks, adopted from the field of seismic risk assessment, for making MRR decisions on a network-wide basis. The proposed framework employs fragility curves to relate service condition limit-states to transverse displacement caused by traffic. The operational costs associated with these service conditions can estimate the total costs of a given MRR policy. In this way, optimum MRR decisions can minimize the total network costs. Additionally, measured bridge data can be used to update periodically the fragilities. This framework provides a consistent approach for the prioritization of railroad bridge MRR decisions.

4: Constitutive Model for Steel Reinforcement Under Cyclic Loading

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The hysteretic stress-strain response of steel reinforcement can significantly affect the performance of reinforced concrete (RC) structures. Additionally, the possibility of inelastic buckling and fracture of longitudinal bars can have a negative impact on the ductility of RC flexural members. This study presents a uniaxial material model to describe the inelastic behavior of reinforcing steel, accounting for all the aforementioned phenomena. As a starting point, an existing hysteretic law is employed, which is capable of capturing the material behavior in the absence of buckling and rupture. This law is enhanced to eliminate the need for an iterative stress update procedure and yield a closed-form expression for the material tangent stiffness, which was not feasible in the original model. Validation analyses demonstrate that the non-iterative version of the model gives practically identical stress-strain response as the original, iterative version. The enhanced material law is also provided with the capability to efficiently account for the effect of inelastic buckling using a simple, yet physically meaningful approach. Furthermore, the hysteretic model is supplemented with a low-cycle fatigue and rupture criterion, based on the accumulation of inelastic work under tensile axial stress. The buckling and low-cycle fatigue criteria are generic, in the sense that they can be combined with any hysteretic law for reinforcing steel.

546: Constitutive Models for Mortar of Bonded Anchors

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The efficient and permanently safe design of anchor system requires a thorough understanding of complex load carrying mechanisms and processes. Considering the required design life time of at least 50 years in combination with the demanded small failure probability, especially for the ultimate limit case, a suitable framework for the service-life prediction and assessment is critical. In general, accurate modelling concepts for all involved materials and processes, taking into account the associated model and prediction uncertainties, should be utilized. In case of bonded anchors three basic components - steel rod, mortar and concrete – are of relevance. In this paper, constitutive models of two different types of mortars (epoxy or vinyl-ester based) are presented. According to the preliminary experiments, the investigated epoxy based system is characterized by a pronounced ductile behaviour whereas the vinyl-ester based system is quite brittle. The proposed numerical approach, formulated in the framework of discrete particle and continuum models, is utilized to capture the aforementioned characteristics. The numerical results obtained by the proposed models are compared with the available experimental data.

178: Continuum Mechanics with Violations of Second Law of Thermodynamics

Martin Ostoja-Starzewski, University of Illinois

The entire field of continuum mechanics has been developed subject to the Second Law of thermodynamics requiring a non-negative rate of irreversible entropy production. However, the results of contemporary statistical physics indicating that, on short time scales (…indeed, up to 3 seconds in some liquids) and very small space scales, the entropy production rate may be negative, motivate a generalization of continuum mechanics. Thus, the Second Law is replaced by the fluctuation theorem with the irreversible entropy evolving as a submartingale, so the thermomechanics is built from stochastic functionals of energy and entropy. Problems studied so far include: (1) diffusion-type problems with random field constitutive coefficients with violations of positive definiteness; (2) thermoviscous fluids with with parabolic or hyperbolic heat conduction; (3) random fields possibly including spatial fractal and Hurst effects; (4) spontaneous random fluctuations of the microrotation field in Cosserat-type fluid mechanics; (5) permeability in systems with nanoscale pores; (6) acceleration wavefronts randomly encountering regions with negative viscosity coefficient.

598: Coupled Thermo-Mechanical Behavior of Hydronically-Activated Concrete Structures: Consideration of Material Damage Due to Mechanical Loading and Temperature Cycling

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Hongyu Zhou, The University of Alabama in Huntsville
Qiuhai Zuo, The University of Alabama in Huntsville

Building sector accounts for 40% of the primary annual energy consumption in the United States, and nearly half of which is used for space conditioning. Currently, the dominant mode of building heating and cooling is air-based HVAC; however, air isa poor medium for distributing thermal energy. The emerging thermally-activated building system (TABS) uses hydronic technology to convey and distribute thermal energy within its structural backbone, utilizing the structural components of buildings (e.g., walls and roofs) to simultaneously serve as active thermal masses. Due to their superior energy efficiency, TABSs have been increasingly implemented in business structures and public facilities. The dual functionality of TABS system (i.e., structural load-bearing and thermal-

load management) calls for a thorough understanding of the coupled thermal -mechanical behaviors of construction materials and structures. In the case of hydronically-activated reinforced concrete structures, microdamages initiated by mechanical stresses may propagate under temperature cycling; on the other hand, the evolving material damage will lead to changes in the thermal conductivity, and thus, affects the thermal gradient near the convective channels. In this light, the current research carries out a combined experimental and numerical program to investigate the coupling effects between mechanical- and thermal-induced material damages and how they impact the structural and conductive behavior of TABS structures. Concrete specimens with and without reinforcements were exposed to mechanical loading and temperature cycling. The deteriorations in stress-strain behavior as well as thermal conductivity were investigated as functions of the material damage-state. In addition, numerical simulations were performed based on a thermoelastic-damage framework. Concrete damage is considered using the microplane model, and the damage evolution is formulated as a function of accumulative microplane strain. Numerical simulation has shown good match with the experimental data, and the results indicated that temperature cycling within the convective channels of TABS system may lead to damage of surrounding concrete material. Microcracks develop in the vicinity of hydronic heating and cooling pipelines due to high thermal gradient and stress-concentration within these areas. The accumulated damage (induced by either mechanical stresses or thermal cycling) has two-fold impacts on both mechanical and heat conductive behaviors of the structural components. First, damage causes a change in the stress-strain behavior of the material (reduction in the stiffness); secondly, the thermal conductivity of the material also decreases as micro-damage accumulates.

548: Coupling Behavior of Shear Deformation and End Rotation of Elastomeric Seismic Isolation Bearings

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Takuya Nishimura, Shimizu Corporation
Ian Aiken, SIE

The mechanical properties of elastomeric seismic isolation bearings depend on the interaction between shear and axial forces. The horizontal stiffness of elastomeric bearings decreases under large shear deformation and high compressive load, and the decrease in the horizontal stiffness eventually causes isolator buckling. The critical load of buckling is one of the most important issues to investigate when considering safe conditions for isolators. In the case of column top isolation, the isolators are subjected to not only shear and axial deformation but also end rotations. In this case, the additional bending moment caused by P-Delta effects is distributed asymmetrically in the vertical direction because of end rotations. The varying load and deformation conditions have to be considered in time history analysis. The authors have developed a mechanical model to predict the behavior of elastomeric seismic isolation bearings subject to combined end rotations and shear deformation. The model consists of a series of axial springs at the top, mid-height and bottom of the bearing to vertically reproduce the asymmetric bending moment distribution in the bearings. The model can take into account end rotations of the bearing, and the overall rotational stiffness includes the effect of the variation of vertical load on the bearing and the imposed shear deformation. Static loading tests under various combinations of vertical load and shear deformation were conducted to identify the mechanical characteristics of the bearings. The test results indicate that the bearing rotational stiffness increases with increasing vertical load but decreases with increasing shear deformation. The end rotation of the bearings greatly affects the shear hysteresis properties. Simulation analyses were also conducted to validate the proposed model. The results of analyses using the model show very good agreement with experimental observations. A series of seismic response analyses were performed to demonstrate the dynamic behavior of column top isolation structures, in which end rotations of isolation bearings are expected to become larger. The results suggest that the end rotations of elastomeric bearings used in practical column top isolation structures do not reduce the stability limit of isolation systems.

529: Cross-Entropy Based Adaptive Importance Sampling and its Application to High-Dimensional System Reliability Analysis

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Junho Song, Department of Civil and Environmental Engineering, Seoul National University

In this talk we present a recently developed cross-entropy-based adaptive importance sampling technique and discuss its application to system reliability problems in which the number of random variables is large (more than 50). The cross-entropy-based adaptive importance sampling technique is specially developed for high dimensional reliability analysis by employing a von Mises-Fisher mixture (vMFM) as the sampling density model. Using a few rounds of pre-sampling, the sampling technique finds a near-optimal sampling density by minimizing the Kullback-Leibler cross entropy between a vMFM model and the absolute best importance sampling density. The method is proved to be applicable to both component and system reliability problems. In this presentation the focus will be on system reliability problems, and issues on how to efficiently find the optimal sampling density using pre-sampling in system reliability analysis will be discussed. Finally, system reliability analysis examples with simple explicit limit-state functions and implicit limit-state functions defined by finite-element algorithms are presented to discuss various aspects of the sampling method.

274: Crowdsourcing-Based Structural Health Monitoring Using Smartphones

Ekin Ozer, Columbia University
Maria Q. Feng, Columbia University

This paper presents an innovative structural health monitoring (SHM) platform in terms of how it integrates smartphone sensors, the web, and crowdsourcing. The ubiquity of smartphones has provided an opportunity to create low-cost sensor networks for SHM. Crowdsourcing has given rise to citizen initiatives becoming a vast source of inexpensive, valuable but heterogeneous data. Previously, the authors have investigated the reliability of smartphone accelerometers for vibration-based SHM. This paper takes a step further to integrate mobile sensing and web-based computing for a prospective crowdsourcing based SHM platform. An iOS application was developed to enable citizens to measure structural vibration and upload the data to a server with smartphones. A web-based platform was developed to collect and process the data automatically and store the processed data, such as modal properties of the structure, for long-term SHM purposes. Finally, the integrated mobile and web-based platforms were tested to collect the low-amplitude ambient vibration data of a bridge structure. Possible sources of uncertainties related to citizens were investigated, including the phone location, coupling conditions, and sampling duration. The field test results showed that the vibration data acquired by smartphones operated by citizens without expertise are useful for identifying structural modal properties with high accuracy. This platform can be further developed into an automated, smart, sustainable, cost-free system for long-term monitoring of structural integrity of spatially distributed urban infrastructure. Citizen Sensors for SHM will be a novel participatory sensing platform in the way that it offers hybrid solutions to transitional crowdsourcing parameters.

82: Crystal Plasticity Finite Element Based Modeling of Deformation-Twinning Induced Failure in Magnesium Alloy

Jiahao Cheng, Johns Hopkins University
Somnath Ghosh, Johns Hopkins University

Extensive formation of deformation twinning is promoted by lack of easy slip systems in Magnesium's hexagonal crystal structure, which leads to intricate holistic material response including strong plastic anisotropy, tension-compression asymmetry, local material softening and trigger early brittle-like failure at room temperature, otherwise Mg and its alloys would be ideal lightweight structure material with high specific strength that can have significant applications in automotive industry, aerospace, army and other fields. The understanding of underlying mechanism of twinning as well as the ability to predict twin formation and its induced crack-initiation is critical for the future utilization of Mg. In this work, a novel physics-based crystal plasticity (CP) constitutive model for the deformation-twinning-induced microstructure evolution and failure in magnesium alloys AZ31 is developed. The model accounts for dislocation slips, geometrically necessary dislocations (GNDs) accumulations, stress concentration near grain boundaries, and the unique feature of explicit micro-twin nucleation and propagations. It predicts the twin-evolution-induced material responses at multi-scales, including at macroscopic scale the tension-compression asymmetry and the dramatic change of hardening rates due to twin saturation, as well as at microscopic scale the dislocation density distribution and deformation localization in twin bands, which are potentially responsible for short-crack initiation. The model implementation in finite element analysis is facilitated by a robust subcycling algorithm to accelerating the CPFE simulation developed by authors. Without acceleration, the CPFE simulation of high fidelity microstructure with the existence of strong deformation localization in twin bands will not be feasible. In the last part of presentation, the model is utilized to analysis the effect of polycrystalline microstructure on twin formations, including the effect of grain size, grain crystallographic orientation, grain boundaries misorientation, geometrically dislocation densities on twin bands formations, which bring insights into understanding deformation twinning-related failure mechanism and provided the base of modeling such failure events in Mg.

154: Damage Assessment of a Two-story Masonry-Infilled RC Building from Vibration Data

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This paper presents linear finite element (FE) model updating of a two-story masonry infilled reinforced concrete building for damage identification. The building, located in El Centro California, was damaged due to the 2010 Baja California Earthquake and it was planned to be demolished following a number forced vibration tests. The tests were performed using an eccentric mass shaker, operated by NEES at UCLA, which produced harmonic excitations including sine sweeps, sine dwells, and sine steps. Acceleration response of the building was measured using an array of 55 accelerometers. Between the dynamic tests, damage was induced to the building by sequentially removing a number of the exterior walls. This type of damage could impact the lateral load resisting mechanism of the structure and the strength of the structure. A system identification method has been employed to estimate the natural frequencies and mode shapes of the structure using the ambient vibration measurements in both the undamaged and damaged states. Due to the pre-existing damage of the structure, developing a model to simulate its state prior to the tests is a rather challenging task. Hence, an initial FE model of the structure, created based on site inspections, geometry measurements, and material test data, was updated by adjusting the equivalent stiffness of the infill walls at each story to match the identified modal parameters. The same procedure was repeated at each damage state. The calibrated models, at undamaged and damaged states, are validated using a different set of low-amplitude forced vibration measurements. Damage identification results are finally compared with the induced damage in the structure.

104: Damage Decision Support Synthesizing Inspected Structural Health

Mark Groden, University of Michigan
Matthew Collette, University of Michigan

Responding to incidence of acute damage to marine vessel structures is presently a challenge for the maritime industry. Especially in incidents where the vessel survives the initial incident, bringing the vessel to safe harbor successfully has proven challenging. In several incidence such as the Prestige, Castor, and Maritime Maisie, a central concern has been the progressive failure of the vessel's hull structure in days and weeks after an incident. Large-scale fatigue crack growth is one of the central mechanisms for such progressive failure. Current shipboard damage control systems (DCS) presently operate with limited awareness of the structural integrity of the vessel and have focused primarily on stabilization activities for visible areas of the structure. To move beyond such approaches the ability to performing fatigue monitoring, diagnosis and prognosis in such post-incident responses is essential. This work proposed a novel decision graph approach using Bayesian network updating to refine an estimate of the fatigue damage process active in a post-incident structure and optimal return-to-port routing. In the proposed approach, a Dynamic Bayesian network is used to track both crack growth and the loading process over time. Load sensor reading and crack length estimates are used to update both the loading process model and a Paris-law fatigue crack growth model. A real time course decision support system to minimize the risk of vessel loss is then constructed by extending this Bayesian network into a decision graph. This extension adds decision nodes that allow specific speed and heading to be selected for the vessel, and utility nodes that examine both the predicted probability of structural fracture and the total time to safe port. Optimal policies are then found for speed and heading based upon initial damage estimates and updated damage estimates as data is gathered and supplied to the network. This approach is demonstrated for a test case with different evidence scenarios.

318: Damage Detection and Localization Using Multifunctional Cement Composites and Electrical Impedance Tomography

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Jesus Gonzalez, University of California, Davis
Kenneth Loh, University of California, San Diego
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The development and application of multifunctional cementitious composites have gained significant attention in recent years. In particular, an aim of achieving multifunctionality is to extend their primary load bearing properties to also include the ability to sense damage in the material. Significant advancements have been made in this area, primarily by incorporating conductive additives and/or nanomaterials (e.g., carbon fibers, steel fibers, and carbon nanotubes (CNT), among others) in the cement matrix. In doing so, the electrical properties of the cementitious composite have been shown to be sensitive to applied loads/deformation and damage. However, major challenges associated with this approach are poor fiber dispersion, impact on mix workability, need for high concentrations, and associated high capital and raw material costs. The result is that most efforts are confined to laboratory or small-scale implementations. In this study, a novel approach of designing and fabricating multifunctional cementitious composites was developed. Instead of directly dispersing CNTs in the cement matrix, the cement-matrix interface was modified with CNT-based thin films. CNT-latex films were spray-coated onto fine and/or coarse aggregates, and once dried, the film-enhanced aggregates were used as is for casting. It was hypothesized that the electrical conductivity (and sensitivity to loads, deformation, and damage) are enhanced since electrical

current could flow through the cement-matrix interface through a percolated network formed by film-coated aggregates in close proximity with one another. This reduced by orders of magnitude the amount of CNTs used (thereby significantly reducing costs), while CNTs remained dispersed at the interfaces. The results showed that the electrical properties of bulk cementitious composites were enhanced. In addition, the electrical properties of specimens also exhibited sensitivity to applied stresses/strains. Since the entire material was sensitive to damage, this study also implemented an electrical impedance tomography (EIT) algorithm for determining the spatial conductivity distribution of film-enhanced cementitious composites. Spatial conductivity distribution was obtained using input-output electrical measurements obtained along specimen boundaries. To validate damage detection and localization, various types, shapes, and severities of damage were introduced to specimens (e.g., by drilling holes at different locations or by cutting surface slits). The proposed method was verified by inflicting damage to small-sized concrete plates and by fatigue testing of beam specimens.

188: Damage Detection in Composite Plates Subjected to Large Deformations

Han-Gyu Kim, University of Washington
Richard Wiebe, University of Washington
Michael Motley, University of Washington

There has been a significant attention paid to damage detection in composite structures in the past two decades. In particular, dynamic characteristics such as natural frequencies, damping, or mode shapes have been probed as possible indicators of delaminations within carbon fiber reinforced polymer beams and plates. Given the inherent uncertainty in composite materials, there remains a need for additional numerical and experimental results. Additionally, there remain many unknowns in the study of damage progression under large (nonlinear) deformation. In this work we present the results of a combined numerical and experimental study of the natural frequencies and nonlinear dynamic response of quasi-isotropic composite plates with seeded delaminations. The plates are fabricated in-house and seeded with damage of various sizes, and locations relative to the plate boundaries. Natural frequencies and mode shapes are then obtained experimentally for both cantilever and fully-clamped boundary conditions. Subsequently, plates are also subjected to large amplitude harmonic loading in order to induce nonlinear dynamic response. This is done for both initially flat, and post-buckled plates. The distinction between these two cases is significant in the study of delaminations, as post-buckled plates are subjected to significant in-plane compressive loading during snap-through events, while flat plates see only tensile hardening. Numerical models are developed and validated against the experimental data using the commercial finite element solver ABAQUS. Both undamaged and damaged specimens are modeled, with seeded delaminations included numerically, and initial validation of specimen frequencies and mode shapes are performed. The natural frequencies and mode shapes are also reexamined at various run times (of the large amplitude response) to interpret the effects of delamination growth. The context, and much of the impetus for the work, may be found in the increased interest in using composites in engineering applications, including marine applications such as energy harvesting devices or ship components as well as aerospace applications such as airplane or wind turbine construction. These structures are typically flexible, and are subjected to large hydrodynamic and/or aerodynamic loads, which may lead to large deformations and regions of significant compressive loading in critical locations. Despite these challenges, the weight, strength, and corrosion resistance of composite materials make them a potentially critical step forward in the development of composite technology. Ultimately, this small-scale experimental and numerical program can help inform large-scale numerical models used in the design and analysis of composite structures.

156: Data-Driven Modeling of Full-Field Pressure Measurements for Aeroelastic Response Predictions

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Ricardo Perez, Universal Technology Corporation
Benjamin Smarslok, AFRL Structural Sciences Center

Design of a reusable hypersonic vehicle requires a strong understanding of complex fluid-thermal-structural interactions. As the aircraft structure is exposed to aerodynamic heating and acoustic loading, causing thermo-acoustic deformation, which in turn alters the flow. To investigate the fluid-thermo-acoustic response during high-speed flight, a series of wind tunnel experiments were conducted at Air Force Research Laboratory (AFRL) to observe the dynamic response compliant panels subjected to a shock impingement. Observing aerothermoelastic coupling is particularly challenging and requires advanced full-field measurement techniques, such as pressure sensitive paint (PSP), digital image correlation (DIC) for strain measurements, and infrared cameras for temperature field measurements. To measure the short time scales of these aero-thermo-acoustic interactions and accurately quantify the frequency response spectra, these full-field measurements require high sampling rates and spatial densities. Accordingly, these tests have yielded a large quantity of high dimensional pressure and deflection measurements. Analysis of this data is desirable to complement ongoing modeling efforts at AFRL; however, traditional analysis techniques are confounded by the size and dimensionality of the data. Therefore, it is beneficial to take advantage of parallelization to avoid crippling computation times. This research develops a data-based statistical model of a large, high dimensional, full-field pressure data set from the RC-19 wind tunnel experiments. The mean pressure signal is simulated by adding noise to the phase angle of the signals and transforming to the time domain with an inverse fast Fourier transform. This ensures that simulated signals have the desired frequency content for coupling with structural models. The spatially correlated signal noise is modeled using a pairwise Gaussian random field (PGRF), which is a subset of random fields that are particularly useful for continuous-valued data recorded on a regular grid. The unique structure of the PGRF allows for piecewise, parallel, parameter estimation and parallel sampling. The PGRF surrogate is constructed for a pressure field acting on a panel in a wind tunnel with Mach 2.2 flow. To assess the quality of the PGRF, the statistical properties of the simulated data are compared with those of holdout validation measurements. Quantitative validation metrics are then computed. Additionally, the frequency response of a structural model prediction using loading from the simulated pressure data is compared with validation data. Clearance # 88ABW-2015-4964

335: Data-Driven Resiliency Management of Bridges in a Rail Network under Multiple Hazard Exposures

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Mohammed Ettouney, Weidlinger Associates

Transportation networks including highways and railroads must ensure continuous and safe operations even during exposure to extreme hazard events such as earthquakes, hurricanes, blasts, and collisions, just to name a few. The weakness of system components (for example, bridges) fundamentally introduces vulnerabilities into the transportation network. Current management methods used by infrastructure asset managers is based on ensuring the health of their individual components through visual inspection followed by structural assessments. In this work, remote wireless sensing is proposed a powerful means of providing owners of transportation networks quantitative and objective data from which more rigorous risk and resiliency analyses can be conducted. A resiliency management framework is proposed for bridges in a rail network based on the availability of network load data obtained from in-network load detectors and bridge response data collected from wireless monitoring systems. A network of rail bridges along the same rail division in the vicinity of Memphis, TN are instrumented with dense wireless sensor networks for continuous monitoring. The study evaluates automation of load and

bridge response data to ascertain the demands and capacities of critical bridge components. Combination of component and span reliability with consequences provides a basis for quantitatively evaluating the risk of bridges and in-turn the rail network at-large. The role of bridge reliability and risk assessments are defined in the broader context of resiliency estimation.

102: Deformation and Failure Modeling of Polycrystalline Ti Alloys across a Range of Strain Rates

Xiaohui Tu, Johns Hopkins University
Ahmad Shahba, Johns Hopkins University
Somnath Ghosh, Johns Hopkins University

Ti alloys are widely used in design and manufacturing of various industrial applications ranging from military, automotive and aerospace components to biomedical devices. Failure of these alloys have been observed in low strain rate deformations such as dwell fatigue loading due to redistribution of stress in hard grains due to plastic deformation of the neighboring soft grain. On the other hand, their failure under high rates of deformation is attributed to strain localization in narrow micron-size bands, namely adiabatic shear bands (ASBs). It is evident that the material properties such as the significant anisotropic mechanical response along with the morphological and crystallographic features such as grain size and orientation distributions play a significant role in failure of these alloys. In this respect, crystal plasticity finite element method is an appropriate tool for modeling failure as both material and microstructural details are explicitly taken care of in its framework. In this work, a unified dislocation density-based rate sensitive crystal plasticity (CP) model is developed in a stabilized locking-free large deformation finite element framework to model deformation of Ti alloys across a range of strain rates. This model has been calibrated and validated against various experiments such as creep and quasi-static and dynamic constant strain rate tests. Modeling dwell fatigue loading scenario, the results of the proposed CP model are used along with an experimentally-validated crack nucleation model to predict the number of cycles to crack nucleation. For high rate simulations, temperature increase due to adiabatic heating is considered which results in further thermal softening of the material and formation of hot spots, serving as the precursor for nucleation of ASBs.

660: Degradation of Materials and Structures Due to Temperature and Moisture: Semi-Analytical Solutions, Computational Framework, and Numerical Solutions

Can Xu, University of Houston
Kalyana Nakshatrala, University of Houston

According to 2013 ASCE's report card, USA infrastructure is given a grade point average of D+ (which is between poor and mediocre). An estimated investment of $3.6 trillion is needed by the end of 2020 to at least raise/restore America's infrastructure to a decent quality [1]. Sustainability, resilience, and ongoing maintenance are identified as one of the three key solutions by the leadership to improve the current conditions of various infrastructural systems. Hence, a detailed understanding of material and structural degradation plays a vital role in curtailing the loss in either serviceability or functionality of these systems. Degradation is a coupled phenomena involving deformation, transport, temperature, and chemical reactions. The objective of this talk is to present a general thermodynamically-consistent mathematical model and a computational framework for coupled chemo-thermo-mechano degradation analyses. First, the thermodynamically-consistent mathematical model is constructed based on balance laws and by appealing to maximization of rate of entropy production. Various special cases of the proposed general degradation model are discussed. Non-dimensional parameters measuring

the strength of coupling are proposed and specialized parameters proposed in literature are recovered. As the deformation under consideration is finite, the governing equations for the proposed model are strongly coupled and highly non-linear. Semi-analytical solutions for several representative and popular boundary value problems are obtained to illustrate the important effects resulting from chemical and thermal degradation. Second, a robust computational framework based on a stable staggered scheme is presented. A comparative study between the semi-analytical and numerical solutions is performed, which highlights the limitations of employing semi-inverse methodology. Finally, implication of the results from our study on degradation are discussed within the context of better design codes for infrastructural systems.

Reference:[1] ASCE's 2013 report card for America's infrastructure. http://www.infrastructurereportcard.org/.

114: DEM Simulations of Failure Process of Continuum Based on Principle Stress Analysis

Shunying Ji, Dalian University of Technology
Yongjun Li, Dalian University of Technology

To simulate the failure process of continuous materials with discrete element method (DEM), the bonded-particle method has been developed using an inter-particle bonding strength and a breaking criterion in the previous studies. In the traditional failure criterion of bonded particles, the maximum tensile and shear stresses are calculated in normal and tangential directions separately. In fact, the maximum tensile and shear stresses are not always in the normal and tangential directions according to the principle stress analysis. To improve the traditional failure model of bonded particles, the principle stress analysis is introduced in this present study. The Mohr-Coulomb failure criterion is also adopted to determine the breakage of bonded particles here. Considering the loading and un-loading process, a damage factor between bonded particles is also applied to describe the internal damage state. With this improved failure criterion above, two bonded particles can be broken under uniaxial compression besides the shear and tension loading patterns. Moreover, the uniaxial compression, three point bending and Brazilian disk tests of sea ice, as a typical brittle material under rapid loading rate, are simulated with this bonded-particle method. The influences of inter-particle sliding friction coefficient and bonding strength on the failure processes and strengths of sea ice are discussed. The results simulated with DEM are compared well with the physical experimental data of sea ice.

197: Dense Array of Soft Elastomeric Capacitors for Feature Extraction on Wind Turbine Blades

Austin Downey, Iowa State University
Simon Laflamme, Iowa State University

Structural health monitoring (SHM) of civil infrastructure presents many challenges, often inherent to the size of the monitored systems. Existing sensing technologies enabling SHM are difficult to scale over large geometries due to technical and or economic obstacles. Recent advances in conductive polymers have enabled the fabrication of flexible sensors capable of covering large areas, a possible solution to this mesoscale challenge. The authors have previously proposed a novel thin film sensor consisting of a soft elastomeric capacitor (SEC) acting as a large strain gauge. Arranged in a dense array configuration, the SECs are analogous to sensing skin, where local changes can be monitored onto large areas. Here, we present results from experimental validations of the sensing method for applications to SHM of wind turbine blades. In particular, we study the capacity of a dense array of SECs at extracting SHM features, such as local damage, strain maps, and deflection shapes, from a large-scale surface.

396: Design Component and System Reliability in Low-Rise Cold Formed Steel Framed Commercial Buildings

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Sanjay Arwade, University of Massachusetts, Amherst
Benjamin Schafer, Johns Hopkins University
Cristopher Moen, Virginia Tech

Target structural reliabilities are implicit in most modern design codes and yet efficiency of design and construction as well as the presence of constraints on the design space mean that structural components in a building system may have as-designed reliabilities that differ from the target reliabilities. This paper presents an investigation of this phenomenon through a detailed examination of the two story cold formed steel framed building designed and tested as part of the CFS-NEES project. Specifically, for the gravity load system of the second floor and the lateral force resisting system the demand to capacity (D/C) ratios and reliabilities (□) are calculated. The results of these calculations illustrate the excess and highly variable D/C ratios and reliabilities that result from efficient design procedures. Since the ultimate goal of structural design is to ensure performance of the structural system at a target level of reliability the influence of excess and variable component reliability on reliability of the lateral force resisting system is examined by making assumptions about series and parallel-type interaction of the floor diaphragm and shear walls. Finally, discussion is presented about the role of load combinations and their associated coefficients of variation in determining component and system reliability in a cold formed steel framed building. Future considerations include more robust, high fidelity, modeling of the system effects and evaluation of excess capacity and variability of reliability across suites of other building designs and structural systems such as roof trusses.

784: Design for Resilience Based on Computational System Reliability Analysis

Zhen Hu, Vanderbilt University
Sankaran Mahadevan, Vanderbilt University

As an emerging concept, resilience is becoming more and more important for engineering applications in many fields, such as civil infrastructure and business supply chains. Significant efforts have been recently devoted to the qualitative and quantitative evaluation of resilience in engineering systems. Current resilience researches, however, have mainly focused on the development of new resilience metrics and performing resilience assessment from the overall system perspectives. How to effectively design an engineering system with high resilience is a challenge yet to be explored. This work proposes a new resilience metric for the design of engineering systems to bridge the gap between resilience and engineering design, by investigating the effects of recovery activity and system failure modes on system resilience. The defined resilience metric is connected to design through time-dependent system reliability analysis. This connection enables us to design a system for a specific resilience target in the design stage. Based on the time-dependent system reliability analysis using computational simulation models and a recently developed reliability analysis method, dominant system failure modes are enumerated and then the system resilience is estimated. The connection between the proposed resilience assessment method and design is investigated through sensitivity analysis and component importance measure (CIM). A roller clutch and a cantilever beam-bar system demonstrated the effectiveness of the proposed design for resilience method.

165: Design of a Bi-Stable Airfoil Using Topology Optimization

Anurag Bhattacharyya, University of Illinois
Kai A. James, University of Illinois

Morphing aircraft are multi-role aircraft, which, through the use of advanced materials, computational tools and design concepts, aim to accomplish more efficient performance under multiple flight conditions. One way to achieve this is through active airfoil shape morphing which aims to eliminate discrete moving parts on the wing, subsequently reducing mass and increasing aerodynamic efficiency. A novel approach to the design of a morphing airfoil and its internal mechanism will be presented. The key component of the proposed methodology is the solid isotropic material with penalization (SIMP) method for performing topology optimization of the design domain, incorporating geometric nonlinearity to simulate large, continuous changes in the airfoil camber and the section aerodynamic properties. Additionally, an analytical adjoint method is used for evaluating the sensitivities. The design aims to utilize a single actuating force for morphing of the airfoil, and snap-through instability to achieve two distinct equilibrium configurations, thus making the structure lightweight and bi-stable. This will also ensure a seamless integration of the actuating mechanism with the structure of the airfoil, making it multi-functional in nature. The airfoil will be covered with a pre-tensioned Elastomeric Matrix Composite (EMC) skin surface. The motivation for exploring this novel concept comes from treating the morphing as a structural problem instead of a materials problem, and utilizing the snap-through property of structures in the design of bi-stable airfoils to make them lightweight and simple. The concept will be investigated on a NACA 0012-based airfoil. A comparison will be made between a NACA 0012 baseline airfoil with a plain trailing edge flap, and the same baseline airfoil with a morphing trailing edge design as proposed.

782: Design of a New Experimental Facility for Simulating Wind-Induced Damage on Solar Systems

Elena Dragomirescu, University of Ottawa
Zhe Xiao, University of Ottawa
Derek Eden, University of Ottawa

The fields of wind-induced hazard mitigation and sustainable energy infrastructure were harmoniously combined for developing an inter-disciplinary experimental facility which can simulate damage induced by high-intensity and multi-directional winds, such as shear and gusty winds, wind storms and tornadic flows, to structural components and energy collecting systems exposed to these phenomena. Thus the Wind-induced Damage Simulator (WDS) will re-create the way the structure sees the effect of the generic wind storms. The prototype consists of a 5.0 m x 5.0 m x 3.0 m hollow structure (enclosure), large enough to house full scale PV solar panels, with four 300 mm inlet on the bottom right corner of each side-wall and a 750 mm outlet on the roof uplifting the air through the enclosure. Laminar CFD simulations were performed on the system both with and without solar panels, for outlet speeds ranging from 0 – 40 m/s. The Solar Panel array consisted of three 2m x 1m panels angled at 20 degrees from the horizontal. The results obtained were analyzed to characterize the dynamics of the fluid in the structure as a whole and around the solar panels. The directional vector field of the wind speed within the enclosure was found to have a symmetric pattern and this increased with the gradual increase of the velocity magnitude through the roof outlet. The introduction of the solar panel array into the enclosure was found to, with reasonable predictability, alter the flow through all the inlet velocities; measurements taken from key locations showed that the original wind component velocities were reduced by an average of 20%. The solar panels that were tested experienced large uplift forces of up to 4.0 kPa, with a very large distribution throughout the panels' surface. Because this uplift was produced by induced wind lateral currents, rather tan the uplift suction, this simulation method represents realistically the way the phenomenon is produced in nature. The results obtained from the newly designed Wind Damage Simulator can provide important information and data, which will be used to quantify the maximum wind loads that structures can withstand. Furthermore, such experimental results

can be used to prepare sound and practical design codes such as ASCE, 1998, NBCC, 2005, CHBDC, 2006, etc., required by structural engineers.

440: Design of Experiments for Uncertainty Quantification on Sparsly Sampled Discrete Random Functions In Multiple Dimensions

Justin Winokur, Sandia National Laboratories
Vicente Romero, Sandia National Laboratories

We investigate the treatment and quantification of uncertainty from discrete, sparse, and random samples in multiple dimensions. We are specifically concerned with uncertainty from variation in experimental characterization of stress-strain curves but make use of a surrogate problem of discrete samples in order to investigate, develop, and validate our results. Past work has identified two promising approaches to estimating the uncertainty with sparse samples: Statistical Tolerance Intervals and the Pradlwarter-Schueller Kernel Density Estimations. We first characterize the appropriate choice of effective tolerance-interval factor for samples in multiple dimensions derived from the combination of discrete inputs. We then investigate methods to choose an optimal combination of samples in multiple dimensions when additionally limited by computational resources. Proposed is a space-filling simulated-anealing approach to experimental design where care is taken to ensure no a priori assumptions are enforced for the final design. The performance of this and other approaches are characterized on simple test problems with respect to the dual objective of accuracy as well as margin of safety in the final uncertainty estimation.

129: Design Optimization of 3-D Woven Micro-Lattice Materials

Seunghyun Ha, Korea Maritime & Ocean University
James Guest, Johns Hopkins University

This talk will discuss the design of porous metallic lattice materials manufactured using a 3-D weaving process. The woven material is characterized as having wires positioned orthogonally in three-directions. Topology optimization is applied using a ground structure approach to optimize the wire architecture with the goal of maximizing combinations of the effective properties of the bulk material, including mechanical, fluid, and thermal properties. Effective properties are estimated using homogenization. Several design examples are presented for the case of 3D woven materials manufactured from 200-micron diameter wires. Optimized designs are manufactured and experimentally tested and shown to offer combinations of properties not achievable with more conventional micro-lattice systems.

488: Designing Better Structural Materials by Understanding Nanoconfinement and Nanoscale Interfaces

Sinan Keten, Northwestern University

Natural and engineered structural (load-bearing) nanocomposites often try to exploit microphases that are confined in nanoscale dimensions to achieve remarkable mechanical properties. However, the emergent performance of these materials depends strongly on both the chemistry of the interfaces and the microstructure of the material system, which complicates their design. In this talk, I will present a new computational materials-by-design paradigm for understanding phenomena occurring at such disparate scales. I will discuss several cases where the coupling between nanostructure and chemical structure will lead to intriguing phenomena, such as

polymers with more or less identical bulk properties exhibiting contrasting behavior under nanoconfinement in thin films. Drawing an analogy between thin films and nanocomposites, I will illustrate how understanding thin film simulations help us design better load-bearing nanocomposites with graphitic and nanocellulosic fillers.

558: Detecting Building Occupancy with Vibration Sensors and Machine Learning

Roya Cody, University of Waterloo
Shounak Mitra, University of New Hampshire, Durham
Tat Fu, University of New Hampshire, Durham
Sriram Narasimhan, University of Waterloo
Nicholas Kirsch, University of New Hampshire, Durham

Occupancy detection is important in buildings because it can improve energy efficiency (by reducing unnecessary lighting, heating, cooling, etc.) and security (by identifying areas that should not be occupied). Common detection methods involve motion sensors, heat sensors and cameras that require a dedicated sensing system or have privacy concerns. This paper aims to study vibrations created by occupants' footsteps and movements and leverage the use of vibration sensors installed for structural health monitoring. In such a system, building vibrations will be analyzed for the dual proposes of detecting occupancy and structural issues. The proposed method aligns with the recent trend of "big data" in which a complex set of data is studied for multifaceted proposes and sometimes for purposes not originally intended. In this paper, the authors propose to analyze vibration data using machine learning methods in determining occupancy and localization in buildings. More specifically, experiments were conducted in two settings: classrooms and hallways. The proposed sensing methods were able to detect the number of people walking in the hallways as well as tell whether a classroom is being occupied. Various machine learning algorithms such as Neural Networks, Generalized Linear Modeling, K-means clustering, and Support Vector Machine approaches were compared for this study. The data from the vibration sensors was divided into training and test sets in the ratio of 0.7:0.3. It was observed that Support Vector Machines worked the best for detecting whether a classroom is occupied or not, whereas, the best predictive indicator for classification of the number of people walking in a hallway was Neural Networks. There were 144 events in the dataset for people walking in a hallway that were generated using combinations of 1 to 6 persons walking individually and in groups. For people sitting in a classroom, the sample space was generated with 13 students in the room seated for a duration of 15 minutes at a time and the events were divided into occupied and unoccupied. The accuracy of detecting whether a classroom is occupied or not is almost 100%, every time, and the average accuracy of detection of 1 to 6 persons walking, individually as well as in groups is about 80%. It is estimated that with the increase in number of datasets, the accuracy of the predictive classification of the system would improve further.

2: Determination of Stresses in Step-wise Cylindrical Steel Storage Tanks Under Hydrostatic Loading

Eyas Azzuni, Purdue University
Sukru Guzey, Purdue University

A design method to determine the shell thickness of steel liquid storage tanks with flat bottoms is variable-design-point method (VDM). This method is based on membrane theory with Kirchhoff-Love kinematic assumptions, and was adopted by API Standard 650 "Welded Tanks for Oil Storage" and other national and international steel tank design standards. However, when shells are filled with liquid, the bottom plate under the shell yields and adds moment on the bottom edge of the shell. This additional bending moment is not accurately captured by VDM. The bending moment due to the restraining effect of the base plate creates circumferential stress which has a sinusoidal nature. In shorter and wider tanks this bending moment can increase the circumferential stress beyond the allowable stress and designs based on VDM. API 650 requires linear analysis instead of VDM to address the inaccuracy of VDM for short tanks with wide diameters. The provisions in API 650 do not provide a suggested linear analysis approach to be used. Finite element analysis is one way of obtaining the stresses in the tank, but it might be time consuming for general design purposes. Linear analysis obtained by an analytical solution that is relatively easy to implement may be more suitable for design purposes. This presentation introduces an analytical approach to calculate the circumferential stress in step-wise storage tanks using thin shell theory. The approach identifies boundary conditions of the joints of shell courses, and takes into consideration the plastic yielding moment of the bottom plate. In this work an analytical solution is discussed and a systematic approach of deriving the stress values in the shell is explained.

720: Determining the Critical Chloride Threshold for Corrosion of Steel Reinforcing Rebars in Synthetic Concrete Pore Solution

Michael Kubista, Rensselaer Polytechnic Institute
David Duquette, Rensselaer Polytechnic Institute
Mohammed Alnaggar, Rensselaer Polytechnic Institute

Steel reinforcement is widely used throughout the construction industry to provide the required tensile strength in concrete structures. However, this strength can be compromised if active corrosion of the reinforcement occurs which results in loss of tensile capacity due to cross section reduction and loss of bond due to degradation of surrounding concrete under corrosion induced expansive pressure. In the absence of activating species, typically chlorides introduced either as setting accelerators or through de-icing salts, the high pH environment of the concrete pore solution protects the embedded steel from corrosion by maintaining the metal in a passive state. The presence of chloride ions reduces the ability of the pore solution to protect the steel rebar by preventing the steel from repassivating, resulting either in localized corrosion or completely depassivating the steel. In this study, corrosion resistance of steel rebars is investigated by conducting anodic polarization sweeps on samples of rebars surrounded by a synthetic concrete pore solution. Polarization curves are generated as a function of chloride concentration in the pore solution to determine the critical concentration of chloride at which the steel begins to lose passivity. The pore solution used contains 0.1M sodium hydroxide, 0.3M potassium hydroxide, 0.03M calcium hydroxide, and 0.002M calcium sulfate dehydrate with a pH ranging from 13.20 to 13.10. The chloride concentration of this solution is adjusted through the addition of sodium chloride. When the experimental setup was tested using a neutral salt solution composed of 0.1M sodium sulfate with a pH near neutral, active corrosion of the sample was observed at slight increases in circuit potential. A current density of 0.1mA/cm2 was reached at 20 mV above open circuit potential, and a current density of 10.0 mA/cm2 was reached at 250 mV above open circuit. In the synthetic pore solution with no added chlorides, the steel exhibited passive corrosion behavior and resisted corrosion throughout the polarization sweep. The current density remained below 0.1 mA/cm2 up to an applied potential of 825 mV above open circuit potential. After this point, the rise in current density can be attributed to oxygen evolution. This presentation will show the results obtained from different chloride ions concentration in the pore solution up to full breakdown of passivity is obtained. The conclusions drawn from this research will be used in the implementation of numerical models to predict the deterioration of reinforced concrete elements due to corrosion induced by chloride ions exposure.

452: Development of a Regional Performance-Based Seismic Assessment Framework for California's Highway Bridges

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Ertugrul Taciroglu, University of California, Los Angeles

The objective of this research is to develop a Regional Performance-Based Seismic Assessment (PBSA) framework for highway bridges. The framework will be provided to its users through an open-access website, and will use data that are harvested continuously from the public domain. It will provide structure- and site-specific seismic risk and loss estimates for a range of probable seismic events at an unprecedented level of granularity. The Regional PBSA framework is planned to offer a state-of-the-art user-interface that is well integrated with a free GIS tool (Google Earth Pro), and will be both informationally flexible and updateable. While primarily operating on automatically harvested image data and existing databases, this tool will also accommodate progressively granular sources of user provided information. By design, both lay-users and experts will be able to contribute to or update data sources of the tool. In developing its predictions, the framework will make use of state-of-the-art and open-source public-domain performance-based earthquake engineering tools that provide ground motions estimates for specific locations (OpenSHA), high-fidelity structural response estimates (OpenSees), and loss estimates for structural components (FEMA PACT). The quality of risk estimates from less-resolved metadata will be validated through comparisons with those from more resolved data, including actual as-built drawings, specifications, and responses recorded at instrumented bridges during past seismic events. A beta-version of the framework is currently being applied to I-10/I-215 Interchange Bridge in Colton City, as well as the Napa River Bridge on Sears Point Road. These two case studies will enable method verification and validation. Subsequently, the framework's database will be extended—as further demonstration—to the freeway segment from US-101/I-405 interchange to the Port of Los Angeles.

279: Development of Fiber-Reinforced Polymer Composites with Superelastic Shape Memory Alloys

Sherif M. Daghash, University of Virginia
Osman E. Ozbulut, University of Virginia

Fiber reinforced polymer (FRP) composites have been increasingly used in civil engineering applications due to their lightweights, relatively high strength, and high corrosion resistance. However, the conventional FRPs exhibit brittle failure, low toughness, limited fatigue strength, and relatively low ultimate tensile strains. Shape memory alloys (SMAs) are a class of metallic alloys that can recover large strains upon load removal with minimal residual deformations. Besides their ability to recover large strains, SMAs possess excellent corrosion resistance, good energy dissipation capacity, and high fatigue properties. This study explores the use of superelastic SMA fibers to reinforce a thermoset polymer matrix to produce a polymer composite with enhanced mechanical properties. Nickel-Titanium wires with a diameter of 500 micrometer are used as fibers. SMA coupons with different reinforcement ratios are fabricated using the vacuum assisted hand lay-up technique. The uniaxial tensile tests are conducted under monotonic and cyclic loading. The results of the tests are assessed in terms of ultimate strength, ultimate strain, residual strain, toughness, and failure modes of the composites.

360: Direct Evaluation of Stress Intensity Factors for Curved Cracks Using Irwin's Integral and a High-Order Extended Finite Element Method

Yongxiang Wang, Columbia University
Haim Waisman, Columbia University
Isaac Harari, Tel Aviv University

This study presents a successful implementation of Irwin's crack closure integral, within a high-order extended finite element method (XFEM), for direct evaluation of mixed mode stress intensity factors (SIFs). SIFs are computed in closed-form directly from enriched degrees of freedom, thereby significantly simplifying post-processing procedures. To improve the accuracy of XFEM-based Irwin's integral for curved cracks, we address some relevant numerical aspects including the singularity integration, enrichment scheme, and definition of angle in asymptotic enrichment functions. The present study serves as an important complement to our previous work. The accuracy and convergence rate of the proposed approach are studied on several benchmark examples involving circular and parabolic arc cracks. With an appropriate enrichment scheme, striking accuracy is observed even on coarse meshes. Furthermore, while the popular interaction integral (a variant of the J-integral method) requires special auxiliary fields for curved cracks and is also limited in cases of cracks in close proximity, the proposed approach shows none of those limitations and the results are very promising.

737: Discrete Element Modeling of Heat Transfer in Granular Systems with Experimental Insight

Jason Marshall, California Institute of Technology
Jose Andrade, California Institute of Technology

In this presentation, we will highlight recent work on the simulation of heat transfer in granular systems. Numerical systems are investigated using a recently developed level set discrete element method (LS-DEM). A key feature of this method is that the exact particle morphology of individual grains can be captured from 3D x-ray computed tomography images (3DXRCT). The multiphysics (mechanical, thermal) computational code is 3D and scalable for high performance computing. We implement, explore, and present multiple models of heat transfer between grains. The code is veri ed and validated against a simple 2D table top experiment of a granular material comprised of circular grains subjected to thermal boundary conditions. We conclude with a case study investigating the e_ect of a penetrator from the InSight rover on the in-situ thermal conductivity of a martian soil.

571: Discretisation Sensitivity of Voxel-Based Bone Models

Martin Ruess, University of Glasgow

Numerical models used for the patient-specific prediction of the vitality of human bone, its elasticity properties and elastic response to loading are generally based on modern biomedical imaging techniques such as quantitative computer tomography (QCT) or magnetic resonance imaging (MRI). It is a common approach in the framework of a finite element analysis to derive discrete models with elements covering each voxel or chunks of voxels of the tomography scan data. Various strategies have been favoured over the years to assign CT-data-derived material properties to the elements often accepting averaged or highly discontinuous distributions of the elasticity parameters. Furthermore, boundary-fitted, unfitted and embedding element technologies have been developed and considered for an appropriate use in the clinical routine which is driven by a fast, simple and reliable model generation and a reasonable analysis time. In this contribution the model sensitivity of voxel-derived analysis models in the framework of the finite element method is studied. Different modelling aspects will be highlighted and discussed with regard to different modelling strategies including material models and boundary conditions. Furthermore, the granularity of the analysis model with regard to element size and element type including standard finite elements and embedding elements is considered and assessed to reveal a clear picture about the main factors, their sensitivity and influence in a modelling & analysis procedure tailored for clinical use. The presented analysis results are based on experimentally tested bone models to provide a fair basis for verification and validation.

769: Distributed Real-Time Hybrid Simulation of Connected Base Isolated Buildings Author Information

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The use of base isolation to provide seismic protection of buildings is a well understood practice that has continued to increase. The behavior of a base-isolated structure during an earthquake is highly affected by the characteristics of the base isolation system. To effectively filter out the high frequencies of long-period earthquakes, more flexible isolation systems are needed. This increased flexibility in the isolation layer can lead to large horizontal base displacements, requiring large seismic gaps. This paper proposes the use of semiactive Magneto-Rheological (MR) fluid dampers connecting two adjacent base-isolated building structures to provide for effective isolation and limited horizontal base displacements. Real-time hybrid simulation (RTHS) is used to conduct a series of experiments with the MR dampers as physical components in order to characterize the system-level performance of the system. With MR dampers located at both the University of Connecticut and Purdue University, the RTHS are conducted as distributed RTHS (dRTHS) tests. The experimental setup and network time delay compensation are described in this paper along with a comparison of the results to a single site RTHS test.

288: Dynamic Characterization of Civil Structures Based on the Variational Mode Decomposition Method

Abdollah Bagheri, University of Virginia
Osman Ozbulut, University of Virginia
Devin Harris, University of Virginia

In this paper, a new method based on the variational mode decomposition (VMD) is proposed to identify the dynamic characteristics of engineering structures via measured ambient vibration data. The VMD is a decomposition algorithm that has been presented to overcome to some limitations of the empirical mode decomposition method such as sensitivity to noise and sampling. The VMD algorithm searches to find a set of modes and their respective center frequencies, such that the summation of modes reproduces the original signal. In the study presented in this paper, the measured acceleration time history at a given degrees of freedom is decomposed into different modes using the VMD. Then, the Hilbert spectral analysis is applied to compute the frequency of each mode, which represents the fundamental frequencies of the structure. In order to demonstrate the efficiency of the method, the ambient vibrations of a footbridge with three spans and a total length of about 50 meters are measured using 10 wireless sensors. Comparing numerical and experimental modal data of the footbridge, it is shown that the proposed method gives accurate results and is a novel approach for the system identification of structures.

471: Dynamic Instability and Sidesway Collapse Analysis of Framed Structures

Kevin Wong, National Institute of Standards and Technology
Steven McCabe, National Institute of Standards and Technology

Nonlinear dynamic analysis has increasingly been used in performance-based seismic engineering to analyze new and existing structures, especially for tall buildings or other complicated structures where current prescriptive design codes and standards have limitations. One important aspect of performing nonlinear dynamic analysis is that modeling and simulation requires accurately capturing structural dynamic behavior up to collapse, which in turn requires that the analysis be able to handle large displacement responses. Currently, only sophisticated finite element software packages use large-displacement formulation, while typical structural analysis software packages are developed based on small-displacement theory. In addition, framed structure will experience significant nonlinear response prior to sidesway collapse, and this nonlinear response requires the inclusion of both geometric nonlinearity and material nonlinearity in the analysis. Structural analysis software packages based on small-displacement theory possess both geometric and material nonlinearity capabilities for analyzing framed structures. However, these capabilities are in essence superimposed and not based on a common, integrated formulation. In typical application, analysis is first handled by considering material nonlinearity through a plastic reduction matrix, which represents the change in stiffness due to inelastic system behavior. This reduction matrix is derived using principles from the theory of plasticity and assumes an appropriate yield surface. It is then numerically "combined" with the theoretically-derived geometric stiffness matrix that accounts for geometric nonlinearity, and the structural response are calculated incrementally by solving simultaneous linear algebraic equations to arrive at a solution. Thus, in many cases one algorithm for performing material nonlinearity analysis and another separate algorithm for performing geometric nonlinearity analysis are used to derive the complete (i.e., combined) nonlinear response. This approach leads to potential problems with how this coupling between geometric nonlinearity and material nonlinearity is numerically combined. To improve the accuracy for small-displacement-based structural analysis software packages to simulate large displacement responses, this research investigates the dynamic instability of framed structures through the use of basic principles of nonlinear engineering mechanics. The objective is to develop an analysis method based on a new stiffness approach that considers geometric nonlinearity coupled with material nonlinearity from the beginning of the formulation. Numerical simulations via nonlinear dynamic analysis will be presented to demonstrate the feasibility of the method. Response history results using this methodology will be compared with those obtained from other analytical platforms to demonstrate the reliability of the proposed method in analyzing near-collapse structural response.

326: Dynamic Interaction of Soil – Structure Cluster

Feng Xiong, Sichuan University
Qi Ge, Sichuan University

With the rapid progress of urbanization, more and more structure clusters are being built in major cities and small towns, where the spacing of buildings is becoming smaller and smaller. The cluster effect among buildings in the system of soil and structure cluster interaction (SSCI) emerges during an earthquake. The concept of cluster effect of SSCI is presented in this paper. This work investigates and fully presents the cluster interaction in the context of SSCI using a shaking table test based on the finite element method (FEM). Several cases are studied: a single building and a structure cluster, with various loading conditions, such as the El Centro ground record and Shanghai artificial wave. The Davidenkov foundation model is used as the constitutive soil model, and this model describes the dynamic nonlinearity of soil and is conducted using an ANSYS parameter design language and a restarting command. The numerical simulations of the shaking table test are in good agreement with the experimental records. Extensive analyses on parametric analyses of SSCI are conducted to determine the influence of some parameters of SSCI, including structure spacing, soil property and structure number. Considering the cluster effect under the similar conditions with the experiment, the laws and the influences of soil and structure cluster interaction are fully summarized as follows: the natural frequency of the system of SSCI is less than that of soil and structure interaction (SSI). Under earthquake excitation, the structures in different

locations have different responses, and this is the cluster effect of SSCI. Cluster interaction reduces the acceleration responses of structures, while velocity may be larger or less than that of the single building (SSI), and this is related with the earthquake input and the structure location. The displacement of the central building reduces, but these of the surrounding structures along the vibration increase, and the buildings farthest from the center have the largest displacements. The maximum absolute value of the influence coefficients of the cluster effect for displacement reaches 770.94%. The building number is the most significant factor that affects the cluster effect in SSCI system. The cluster interaction constantly reduce when the structure spacing increase and disappears when the clear spacing is larger than 1.32 times as the size of the building foundation, and the cluster effect is weak. Last, the mechanism of SSCI is studied by the laws of the displacement.

315: Dynamic Modeling of Urban Transportation System with Application to Resilience Planning

Ruda Zhang, University of Southern California
Roger Ghanem, University of Southern California

Recently emerging data sources at urban scale, especially in transportation and communication systems, has led to deeper understanding of human mobility patterns. But these research efforts are mostly data-driven, lacking a modeling strategy with concrete and interpretable meaning. Here we propose a dynamic model based on the master equation of the probability distribution over a configuration space, which represents the possible macroscopic states of an urban area. This model integrates transportation infrastructure with population dynamics by including macro-variables for both sectors. Previous works in sociodynamics generally lack enough empirical data to calibrate neither the full probabilistic model nor the parameters of the corresponding quasi-meanvalue equations. Our work leverages open data for the New York City metropolitan area to calibrate the mobility and utility terms that appear in system transition rates. We then applies our model under hypothetical changes of the transportation system to analysis their influence on the stationary distribution of marcro-variables. Implication of different transportation scenarios are then served as recommendations for future planning purposes.

43: Dynamics of Wind Turbine Structures Subjected to Hurricane Winds

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Sungmoon Jung, Florida State University

Aerodynamic forces and responses of the wind turbine structures subjected to hurricanes are investigated in this study. Wind turbine structures are subjected to various loads such as earthquake, lightening and hurricanes. Much research has been done to investigate wind turbine's behavior versus these loads. These studies proposed new methods to make the design more efficient and reliable. Structures, including wind turbines, in the Southern and Southeastern United States are often affected by hurricanes. During the last decade, various studies and observations have been conducted in order to explore the nature of hurricane winds such as energy spectrum, vertical profile and non-stationarity. These studies showed that characteristics of hurricane surface winds can be different from those of regular boundary layer winds. Based on hurricane characteristics in recent observations, there is a need to establish a detailed analysis framework for wind turbine structures subjected to hurricanes. This study, first, discusses the nature of hurricanes according to recent observation and compares them with regular boundary layer winds. Next, we use a time-domain framework to address wind-structure interaction of the tower and blades. In this part, a coupled blade-tower analysis is formulated considering unsteady buffeting forces. Also, the self-excited forces are taken in to the account using aerodynamic flutter derivatives. In the time domain framework, we use rational functions to address the frequency dependent parameters of unsteady state. Initial

results show that the dynamic responses of wind turbines subjected to hurricane winds would be different from those subjected to regular surface boundary layer winds.

36: Earthquake-Induced Falling Debris Hazard Analysis and Emergency Shelter Design of High-Density Tall Building Areas: A Case Study of Beijing Central Business District (CBD)

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Zhen Xu, University of Science and Technology Beijing
Xinzheng Lu, Tsinghua University

A rational prediction of earthquake-induced secondary hazard can assist in the design of emergency shelter and evacuation route, therefore, mitigates the risk of casualty and enhances community resilience. Falling debris from exterior non-structural components are a significant threat to the sheltering and evacuation of numerous people gathered in high-density tall building areas. However, such type of hazard has rarely been studied in existing literatures. Thus, a novel simulation method based on physical process and probability analysis is proposed herein, which consists of three major components: (1) Calculation of the distribution of falling debris. Based on the nonlinear multiple-degree-of-freedom (MDOF) flexural-shear model and time-history analysis, the seismic responses of tall buildings can be obtained. Together with the damage criteria of exterior non-structural components, the falling statuses and initial velocity of falling debris can be acquired, which facilitates the further calculation of the falling debris distribution. (2) Uncertainty analysis of ground motion. A set of ground motions are used to consider the uncertainty of the ground motions; meanwhile, incremental dynamic analysis (IDA) are conducted to obtain the distribution probabilities of falling debris within the design period. (3) Design of emergency shelters and evacuation routes. The hazard region of falling debris in a tall building area can be acquired by overlapping the hazard regions of different individual buildings, based on which the emergency shelters and evacuation routes can be designed reasonably. Finally, the proposed method is applied to analyze the distribution probabilities of falling debris in the Central Business District (CBD) of Beijing over the design period. The results are used for selecting a safer site for emergency shelter and a safer route for evacuation. This study is expected to provide a useful reference for the seismic emergency response and disaster management of high-density tall building area.

20: Effect of Actuator Delay on Uncertainty Quantification for Real-Time Hybrid Simulation

Kai Chen, San Francisco State University
Weijie Xu
Cheng Chen, San Francisco State University
Tong Guo

Analysis of uncertainties in numerical substructure is necessary to estimate the variance of structural response obtained from structural experiments through the hybrid simulation technique. In a real-time hybrid simulation the servo-hydraulic actuators apply the desired responses to the experimental substructures in a real-time manner. It has been observed that actuator delay could be reduced but cannot be eliminated. In this study, the effect of actuator delay on uncertainty quantification is investigated for real-time hybrid simulation through polynomial chaos expansion. Responses of a single-degree-of-freedom system are projected on a basis of orthogonal stochastic polynomials and represented using simple polynomial. The mean and variance from polynomial chaos expansion are compared for the cases of with and without delay. Actuator delay in a real-time hybrid simulation

is observed to result in the increases of mean and variance for the structural responses. Sensitivity analysis also indicates that actuator delay affects the variance of structural response under uncertainty in real-time hybrid simulation.

87: Effect of Creep on the Behavior of Flush Endplate Connections at Elevated Temperatures

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Elie Hantouche, American University of Beirut
Mohammad Ali Morovat, University of Texas

The objective of this study is to investigate the effect of thermal creep of steel on the behavior of flush endplate beam-column connections subjected to elevated temperatures due to fire. Creep refers to the time-dependent inelastic deformation of structural steel at high temperatures. Very limited experimental and analytical studies have been conducted on the influence of creep on flush endplate connections. To address this issue, finite element (FE) models using ABAQUS are first developed to validate the load-rotation characteristics of the connection under combined shear and tension forces during a fire. Then, parametric studies are conducted to investigate the effect of some major geometric parameters (beam length, load ratio, endplate thickness, and beam depth) on the behavior of flush endplate connections in fire with and without creep effect. These parametric studies are first performed under steady-state temperature conditions to investigate the failure modes of the flush endplate connections at different temperatures without taking into consideration the effect of creep. Then, creep effect is added to the FE models under steady-state temperature conditions to investigate the time-dependent or creep response of beam-column connections when applied stresses and temperatures are kept constant. The results show that, creep tends to relax the beam by increasing its deflection and reducing the thermal-induced axial compressive force. This increase in deflection generates higher catenary forces in the beam-column connection. Disregarding creep effect may result in an unsafe prediction of the overall response of steel frame systems subjected to fire.

428: Effect of Particle Shape and Particle Size Ratio on the Packing Density of Very Dense Binary Mixtures

Tang-Tat Ng, University of New Mexico

Packing density of binary mixture has been studied in ceramic and pharmaceutical industries for a long time. Analytical and empirical models for packing density of various fine contents have been developed. In this study we employ the discrete element method to examine the effect of particle shape and the particle size ratio of the large and small particles on packing density and the performance of these models. The granular binary mixture contains large and small similar ellipsoids of different sizes. The ratios of major axis and minor axis of these ellipsoids are 1.2, 1.5, and 1.7. The particle size ratio between the large and small ellipsoids is either 5 or 10. Segregation is possible when particles settle by gravity for these particle size ratios. Therefore, samples of various fine contents were created by particle growth method without gravity. We prepare these samples as dense as possible. The general behavior between packing density and fine content is similar to those observed in laboratory of binary granular mixtures. We observe some interesting effect of particle size ratio and particle shape on packing density.

493: Effect of Relative Humidity on Basal Spacing and Stiffness of Stack of Clay Layers

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Sébastien Brisard, Laboratoire Navier, IFSTTAR
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Clayey soils and clay-based rocks are known to be sensitive to water: this sensitivity mostly stems from the clay minerals they contain. Here, we focus on the sensitivity to water of nanometric stacks of clay layers. We aim at determining what their hydromechanical behavior is, at a given relative humidity and under a given state of stress. We consider stacks of montmorillonite clay layers at constant temperature. Simulations at a given chemical potential and under a given state of stress can be inefficient, as both the number of water molecules and the dimensions of the simulation box vary over the run. As an alternative, we perform two series of simulations: 1) simulations in the grand-canonical ensemble (i.e., at given chemical potential of water and dimensions of the simulation box), which provide adsorption isotherms; and 2) simulations in the isobaric ensemble (i.e., at given amount of water and stress applied to the system), which provide swelling curves. From those two series of simulations, we aim at inferring the behavior of the stack at a given relative humidity and under a given state of stress. We show how, from the simulations performed, the equilibrium states and their stability can be inferred. In particular, we retrieve that, under a given stress and at a given relative humidity, only a few equilibrium states can be observed: this fact is well known experimentally, and the states are referred to through the number of layers of water in the interlayer spacing. We identify the range of relative humidities over which each state (i.e., 1 layer of water in the interlayer, 2 layers…) can be observed. We show that the basal spacing associated to each state is not a constant value, but instead depends on both the relative humidity and the applied load. For any equilibrium state, two types of stiffnesses (i.e., elastic properties) can be defined: so-called drained ones (i.e., at constant relative humidity) and so-called undrained ones (i.e., at constant amount of water). Undrained stiffnesses can readily be obtained from the isobaric simulations. We show that, in theory, the drained stiffnesses can be calculated from the simulations performed in this study. However, this calculation proves to be noisy.

189: Effect of Soil Heterogeneity on Nuclear Facility Soil-Foundation Interaction

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Justin Coleman, Idaho National Laboratory
Benjamin Spencer, Idaho National Laboratory

There are many uncertainties involved in modeling the site response at a nuclear facility site. Current site response analyses assume the soil layers to be horizontally aligned and calculate the response at the soil surface (for an input applied at the rock outcrop) using a simplified 1D equivalent linear or 1D non-linear analysis. While this 1D analysis might provide sufficient results at sites where soil layers can be divided into uniform horizontal layers, it may introduce additional modeling uncertainty when analyzing complex heterogeneous soil sites like the INL site. We use the INL soil site as a prototype to assess the effect of 3D soil heterogeneity on the surface response. The 3D nonlinear soil model is constructed using data from boring logs with the soil material models matching those obtained from experiments conducted on the different soil types. This soil model is then analyzed using MOOSE, which is an open source finite element software developed at INL. Results from this analysis will be compared against the 1D analysis for vertically propagating shear waves. Additionally, the effect of non-vertically propagating waves and soil porosity on the response a simplified block model of a non-embedded nuclear facility foundation will also be studied using this model.

650: Effect of Temperature and Performance of Stabilized Formulations for Viscous Fingering and Mixing in Porous Media

Mohammad Shabouei, University of Houston
Kalyana Babu Nakshatrala, University of Houston

Viscous fingering and miscible displacement in porous media can be found in a wide range of industrial and environmental applications such as carbon-dioxide sequestration and enhanced oil recovery. In this talk, the influence of temperature on viscous fingering, which can be interpreted as double diffusive effects, is presented. Temperature effects on fingering phenomena and miscible displacement can be observed by altering thermal log-mobility (R), Lewis number (Le), and Péclet number (Pe). We will consider an incompressible single-phase miscible flow with two components. The flow is governed by the Darcy model, which describes the flow of an incompressible fluid in a rigid porous media. We also consider temperature effects and include thermal equations. The governing equations for transport and thermal are transient in nature, while the governing equations of flow are quasi-static. This gives rise to a coupled flow-transport-temperature system, which is solved numerically. To complete the coupled model, the viscosity is assumed to depend exponentially on the values of concentration and temperature. By utilizing the finite element method, it will be shown that the temperature has significant effect on the initiation and development of finger-like patterns, and on the interactions of neighboring fingers. We will also characterize the effect of temperature on the mixing, concentration profile, and contamination spreading. This comprehensive quantitative investigation is performed with respect to mixing progress, mixing rate, total, and average concentration. The secondary objective of current study is to understand the impact of violation of non-negative constraint on the development of viscous fingering instabilities. In particular, we will show that employing stabilized formulations (e.g., SUPG and GLS), which are commonly employed to control numerical instabilities, can also suppress physical instabilities (e.g., viscous fingering). This means that stabilized methods should be employed with care in the numerical simulations of physical instabilities.

395: Effect of Thermal Fields on Interface Strength in Fibrous Composites: A DG method with Consistently Evolving Stabilization

Pinlei Chen, University of Illlinois
Arif Masud, University of Illlinois

A stabilized Discontinuous Galerkin method with consistently evolving stabilization at finite strains is developed for modeling the effects of thermal fields on the fiber-matrix interfaces. Starting from a thermo-mechanically coupled formulation, a Lagrange multiplier method along the interface is developed. Employing ideas for VMS based stabilization [1], the interfacial fine-scale problem is expended via edge bubbles and resolved locally to extract an analytical expression for Lagrange multipliers. The derived expression is a function of evolving mechanical and thermal fields and therefore the derived stabilized formulation contains the numerical flux and stability tensor which are free from user-defined parameters. The coupled thermomechanical method is applied to interface problems with strong discontinuities such as debonding at the fiber matrix interface due to both thermal and mechanical effects. The evolution of the debonding parameter is modeled through internal variables such as an inelastic gap at the interface [2]. Several test cases are presented to validate the method.

Reference: [1] Truster TJ, Chen P, Masud A. Finite strain primal interface formulation with consistently evolving stabilization. International Journal for Numerical Methods in Engineering 2015 102(3-4):278-315 [2] Truster TJ, Masud A. 2013. A Discontinuous/continuous Galerkin method for modeling of interphase damage in fibrous composite systems. Computational Mechanics. 52:499–514-499–514

422: Effective Implementation of Real-time Hybrid Simulation: Stability and Performance

Amin Maghareh, Purdue University
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Real-time hybrid simulation (RTHS) is a powerful cyber-physical technique that is a relatively cost-effective method to perform global/local system evaluation of structural systems. Predictive stability and performance indicators (PSI and PPI) were initially established for single degree-of-freedom systems. The PSI and PPI assess the impact of partitioning choices (substructurability) on the stability and performance of a global RTHS response and enable RTHS users to quantitatively examine the sensitivity of an RTHS configuration to any de-synchronization at the interface. These indicators also assist the users to choose an appropriate control/compensation technique for any configuration choice. PSI is extended to linear multi-degree-of-freedom, piecewise linear, and nonlinear systems. Moreover, we demonstrate how PSI can be used as an effective design metric in implementation of successful RTHS. The design of partitioning choice is a primary and fundamental step in implementation of a successful and safe RTHS. Also, the PSI sets the minimum transfer system performance. Based on the PSI and available transfer system performance, prior to conducting an experiment, alternative partitioning choices can be sorted, on the basis of system instability likelihood, from an extremely challenging partitioning choice to an unconditionally stable one.

447: Effects of Centrifuge Testing Condition on the Dynamic Response of a Dry Sandy Slope

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Mourad Zeghal, Rensselaer Polytechnic Institute

Centrifuge modeling is an efficient experimental tool to test reduced scale soil systems. The associated scaling laws are well established and depend on the corresponding centrifugal force field. However, the effects of some of the associated experimental conditions are still not adequately clear, or at least not fully quantified. For instance, what are the effects of a radial centrifugal force field on a soil system deformation, and how to counter these effects? Also, how do embedded sensors affect the soil response, especially when using a small soil model under a high centrifugal force field? These concerns are difficult to explore using physical testing. In this study, the discrete element method is used to assess the response of a reduced scale model of a dry sloping granular soil deposit under a range of dynamic loading conditions that mimic centrifuge testing. The conducted simulations showed that a radial centrifugal force field induces a lower confining within the middle zone of the model (compared to a parallel force field such as in the case of natural gravity) leading to larger permanent displacements. These lower stresses and larger displacements cannot be counteracted fully by replacing planes surfaces by cylindrical ones (normal to the force field) as commonly used in practice. On the other hand, sensors embedded with the deposit (such as accelerometers to measure accelerations) may behave as soil inclusions that reduce permanent displacements. The sensor size, arrangement and loading condition affect these displacements. For the analyzed sloping deposit, the effects of the centrifugal force field and sensors were found to be relatively small and acceptable from practical engineering prospective.

685: Effects of Foundation Gapping and Sliding on Seismic Risk of Nuclear Structures

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Justin Coleman, Idaho National Laboratory

Soil-structure interaction (SSI) analysis is now routinely performed in the seismic probabilistic risk assessment of new and existing nuclear structures. Soil-structure interaction analysis of nuclear structures in the United States

is currently performed using linear analyses in the frequency domain using codes such as CLASSI or SASSI, assuming that the in-structure response increases linearly with the ground motion intensity. Nonlinear effects of SSI, which can be significant in beyond-design basis events, are mostly ignored in these calculations. Estimates of seismic hazard at nuclear facility sites have been increasing in recent years as more data is gathered on seismic sources and events, leading to more intense ground motions used for design and performance assessment. Nonlinear SSI effects therefore become more relevant in the seismic probabilistic risk assessment (PRA) of nuclear structures. Nonlinear effects of SSI include material nonlinearities in the soil and the structure, and geometric nonlinearities, namely, gapping and sliding of the foundation. The study presented in this paper is a part of a larger study to incorporate nonlinear SSI effects in seismic PRA of nuclear structures. The current study involves performing the PRA of a sample nuclear power plant (NPP) structure using traditional and advanced (including nonlinear SSI effects) approaches and comparing the results to examine the effect of nonlinear SSI on seismic risk. Only the effects of gapping and sliding are investigated in the current study. A simple, BWR type NPP structure is chosen along with an idealized soil profile and seismic hazard representative of those at the Advanced Test Reactor (ATR) site at Idaho National Laboratory. The structure is assumed to be surface-founded in order to exacerbate gapping and sliding. The seismic PRA is performed for a real plant system at the ATR site. Realistic probabilistic distributions are assumed for the modulus and damping of the soil, modulus and damping of the superstructure and the coefficient of friction of sliding at the soil-foundation interface. Thirty instances of the SSI model are calculated using Latin Hypercube sampling and the SSI analysis are performed for thirty ground motions at four intensities. The linear SSI analyses are performed using CLASSI and the nonlinear analyses are performed using the commercial finite-element code, LS-DYNA. Preliminary calculations (made from six instances instead of 30) of the seismic fragilities of various components showed a decrease in the conditional probabilities of failure due to the effects of gapping and sliding.

401: Effects of Grain Boundary on the Sources of Size Effects

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The present paper investigates the effects of grain boundary on the sources of size effects. Up to now, several studies have been conducted to address the role of grain boundaries in size effecs from the atomistic point of view. However, a study which addresses a transition between different governing mechanisms of size effects has not been presented yet. Here, samples with different length scales are studied to capture the role of grain boundary in size effects as the grain size changes. The reponse of single and bi-crystal Ni thin films with different sizes are studied during nanoindentation experiment using large scale atomistic simulation. Next, in each sample, the sources of size effects are analyzed using the atomistic information obtained from the simulations. Various symmetric and asymmetric tilt grain boundaries are incorporated to study the effects of grain boundary geometry on the response of samples during nanoindentation. The results show that the sourzes of size effects changes from dislocation nucleation and source exhaustion to the forest hardening mechanism as the grain size increases. In the case of small bi-crystal samples, dislocation nucleation and source exhaustion govern the size effects. The grain boundary eases the dislocation nucleation beneath the indenter which reduces the strength of sample by providing required dislocations to sustain the imposed plastic deformation. Increasing the indentation depth, however, some of the dislocations are blocked by the grain boundary which induces some local hardening. In the case of large bi-crystal samples, the dislocation interaction with grain boundary induces hardening and forest hardening mechanism governs the size effects. It is observed that the dislocations firstly absorbed by the grain boundary. Increasing the indentation depth, they start dissociating into the next grain. The observed hardening varies for each graing boundary type and depends on the indentation depth at which dislocations start dissociating into the next grain. In other words, if the dislocations are blocked for a longer time, the induced hardening will be higher.

271: Effects of Material Spatial Randomness on Dynamic Fracturing in Rocks

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There is an increasing demand to employ probabilistic models in the simulation of rocks; as many other heterogeneous brittle materials, the fracture of rocks is highly sensitive to the random distribution of defects and inhomogeneities. Rocks have significant inherent material randomness at different scales. Micro-cracks and granular microstructures describe rocks at small grain scale while different rock types, faults and randomly-oriented natural fractures characterize them at large mass scale. In this study, we utilize two approaches to address rock inhomogeneities in dynamic fracture simulations. One is based on considering fractures explicitly with random size, location and orientation as the natural pre-existing crack-like defects. In the other one, a probabilistic nucleation technique is applied to implicitly model initial randomness in material and to enable creation and extension of new cracks during the course of analysis. Both approaches can be employed for rocks in which the natural fractures are oriented in a specific angle, which is applicable to the simulation of sedimentary rocks. For the first approach, there will be a bias in initial crack orientations, while for the second one nucleation and extension strengths will be functions of spatial position as well as the angle of a potential crack extension. Herein, an interfacial damage model implemented in a Spacetime Discontinuous Galerkin (SDG) finite element method is utilized to simulate fracturing in rocks. This robust tool utilizes a powerful mesh adaptivity to track cracks with element boundaries. Besides, the employed model tackles the transitions between different contact modes using a dynamically consistent damage-contact model fitting for rocks under compressive and shear loadings. We will present examples from hydraulic fracturing and rock fracturing under dynamic compressive loading.

170: Efficient Incremental Dynamic Analysis via Stochastic Averaging

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André Beck, University of São Paulo

Incremental dynamic analysis (IDA) has been a well-established methodology in earthquake engineering for assessing the performance of structural systems under a suite of ground motion records, each scaled to several levels of seismic intensity. Nevertheless, the need for performing nonlinear dynamic analyses both for various excitation magnitudes and for a large number of seismic records renders the IDA methodology potentially a computationally highly demanding task. In this paper, an efficient stochastic IDA methodology for nonlinear/hysteretic oscillators is developed by resorting to nonlinear stochastic dynamics concepts and tools such as stochastic averaging and statistical linearization. Specifically, modeling the excitation as a non-stationary stochastic process possessing an evolutionary power spectrum (EPS), an approximate closed-form expression is derived for the parameterized oscillator response amplitude probability density function (PDF) as a function of the excitation EPS intensity magnitude. In this regard, an IDA surface is determined providing the PDF of the engineering demand parameter (EDP) for a given intensity measure (IM) value. In contrast to an alternative Monte Carlo simulation (MCS) based determination of the IDA surface, the herein developed methodology determines the EDP PDF at minimal computational cost. Further, an approximate closed-form expression is derived for the parameterized nonlinear oscillator response EPS as well; thus, a conceptually novel IDA surface is determined where the EDP relates to the nonlinear oscillator response EPS. Note that the technique can account for physically

realistic excitation models possessing not only time-varying intensities but time-varying frequency contents as well. Numerical examples include a bilinear/hysteretic single-degree-of-freedom (SDOF) oscillator, whereas comparisons with pertinent MCS data demonstrate the reliability of the developed stochastic IDA methodology.

655: Efficient Model Order Reduction of Problems with Material Nonlinearities Using a Localized Discrete Empirical Interpolation Method

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There are widely used procedures in computational mechanics, such as parameter sensitivity analysis or parameter estimation for inverse problems, which remain computationally expensive despite constant advances in computing power. Model Order Reduction (MOR) techniques have been successfully applied in various fields to reduce the computational cost of a simulation by breaking the analysis into a computationally expensive offline part and a relatively inexpensive online part. Despite these advances, MOR techniques have only been able to efficiently reduce the complexity of the linear part of a system. Recently, some of these methods have been extended by suitable approximations of the nonlinear part [1,2]. In the light of the cumulative effort of these improvements, and in particular of the Discrete Empirical Interpolation Method (DEIM), it is now possible to consistently address the construction of an efficient nonlinear reduced model. In this contribution, we show the application of a variant of the DEIM-based Proper Orthogonal Decomposition to a strain-softening continuum viscoplasticity model. Our experience indicates that the decay of the singular values of the corresponding solution is slow. Therefore, the reduced subspace, in which the system solution lies, is not significantly smaller than that of the system space. As a result, the expected significant reduction of complexity of the system is not possible. To tackle this problem, as proposed in [3], we collect the snapshots which are ``close" to each other into clusters using machine learning techniques such as the k-means, the k-nearest neighbors classification rule and the feature extraction [4]. We show that with appropriate modifications of these clustering techniques, it is possible to construct a consistent and efficient nonlinear reduced model. References:[1] S. Chaturantabut and D. C. Sorensen (2010). Nonlinear model reduction via discrete empirical interpolation. SIAM Journal on Scientific Computing, 32(5), 2737-2764.[2] N. C. Nguyen, A. T. Patera and J. Peraire (2008). A 'best points' interpolation method for efficient approximation of parametrized functions. International Journal for Numerical Methods in Engineering, 73(4), 521-543.[3] B. Peherstorfer, D. Butnaru, K. Willcox and H. J. Bungartz (2014). Localized discrete empirical interpolation method. SIAM Journal on Scientific Computing, 36(1), A168-A192.[4] C. M. Bishop (2006). Pattern Recognition and Machine Learning. Springer.

764: Efficient Multiline Anchor Systems for Floating Offshore Wind Turbines

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Charles Aubeny, Texas A&M University
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Over 60% of U.S. offshore wind energy potential is in water depths greater than 60 m, where floating offshore wind turbines (buoyant structures individually anchored to the sea bed by at least 3 mooring lines and anchors) are economically, environmentally, and aesthetically favorable. The high capital cost of offshore wind energy is

a primary barrier in development. For existing FOWT technology, the materials and installation cost of the station keeping support structure inclusive of the mooring system and anchors typically accounts for 27% of capital costs. The core concept of the proposed solution is a novel, integrated, and networked multiline mooring system in which anchors are shared among many turbines, instead of each turbine being moored separately by its own set of anchors. The goals of this research are to evaluate the feasibility of this concept and propose preliminary design guidelines for optimization of mooring line geometry and anchor placement in multiline systems. An exploration of the geometric design space will determine the water depths, mooring geometries, and spatial organizations that are feasible for the multiline concept. Multiple geometric configurations adhering to unit cell arrangement will be generated, and candidate wind farm layouts will be developed with 3D visualization tools. To predict forces on the anchors, probabilistic, spatially and temporally correlated models for wind and wave conditions over the spatial extent of a typical wind farm will be developed. An optimization, and reduction in number, of anchor locations has the potential to provide significant capital cost savings for geotechnical site investigation, installation, and materials, and a reduction in ecological footprint with fewer disturbances to the seabed.

345: Eigenstrain based Reduced Order Homogenization for Polycrystalline Materials

Xiang Zhang, Vanderbilt University
Caglar Oskay, Vanderbilt University

Microstructural morphology significantly affects the mechanical performance of structures made of polycrystalline metals and alloys. Crystal Plasticity Finite Element Method (CPFE) has the flexibility to leverage available constitutive formulations and relies on discretization of the realistic polycrystalline microstructure, providing satisfactory performance on the microstructure scale. Multiscale computational methods (such as computational homogenization, variational multiscale enrichment, heterogeneous multiscale method, multiscale finite element method) on the other hand, provide the computational framework to upscale the microstructure scale response to the macroscopic scale. However, the high computational complexity of a CPFE simulation performed over a representative volume element (RVE) typically prohibits straightforward application of these methods to homogenize polycrystal response. In this talk, we will present an eigenstrain based reduced order homogenization method for polycrystalline materials, where model reduction is achieved through reduced order modeling of the RVE simulations and provides an approximation to the microscale problem with orders of magnitude computational efficiency. A two-scale asymptotic analysis is used to decompose the original equations of polycrystal plasticity into micro- and macroscale problems. Eigenstrain based representation of the inelastic response field is employed to approximate the microscale boundary value problem using an approximation basis of much smaller order. The reduced order model takes into account the grain-to-grain interactions through influence functions that are numerically computed over the polycrystalline microstructure. The proposed approach is also endowed with a hierarchical model improvement capability that allows accurate representation of stress and deformation state within subgrains. The proposed approach was implemented and its performance was assessed against crystal plasticity finite element simulations. Numerical studies point to the capability to efficiently compute the mechanical response of the polycrystal RVEs with good accuracy and the ability to capture stress risers near grain boundaries. The capability of efficient macroscale modeling of the proposed model is also demonstrated.

568: Elasticity and Fracture of Clay-Based Materials at the Nano-Scale

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Christian Hoover, Massachusetts Institute of Technology

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Roland Pellenq, Massachusetts Institute of Technology
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The productivity of source rock recovery is strongly dependent on how cracks propagate during the fracking process. The rock properties such as the elasticity, the anisotropy, and the fracture toughness, greatly affect the crack propagation and thus the frackability. A significant part of the valuable organic matter is contained within the porous clay matrix. Among the minerals composing this matrix, the phyllosilicates constitute the main inorganic components, which evolve with respect to the increases in temperature and pressure. This process occurs concomitantly to the organic matter maturation that leads to oil and gas expulsion. Therefore, understanding the impact of the phyllosilicate phase transformation on the mechanical response of the clay matrix is of prime importance to the fracking industry. In order to address this problem, we evaluate the evolution of elasticity, resistance to plastic deformation, ductility and fracture toughness of 2:1 phyllosilicates with respect to their interlayer interactions. Specifically, five single crystal phyllosilicates, representative of octahedral composition and a wide range of layer charges, were studied using nanoindentation and nanoscratching. The results showed a strong dependency of the mechanical properties to the interlayer interactions of these minerals. The ductility (M/H) of the phyllosilicates appears to be controlled by i) the long-range electrostatic attractions between the layer and the interlayer cations and ii) the atomic bonds within the octahedral sheets. The interlayer interactions also control the apparent fracture toughness (Kc), and therefore the critical energy release rate (Gc) in the directions of interest. The proposed investigation also seeks to extend this understanding to more complex geomaterials. Work under progress on clay films reveals a complex network of toughening mechanisms. These mechanisms can provide insight to the applicability of linear elastic fracture mechanics (LEFM) models in transversally isotropic and heterogeneous solids. The implications of these results for predicting the macroscopic mechanical performance of clays bearing geomaterials, such as economically valuable source rocks, will be discussed.

489: Elastoplastic and Geometrically Nonlinear Analysis of Frame Structures based on Generalized Total Potential Energy Functional

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In a great variety of engineering simulations, including collapse analysis of structural systems, consideration of nonlinear effects is indispensable. In this work, a beam-column element for nonlinear analysis of skeletal structures is presented that allows for efficient modeling of complex problems, concurrently exhibiting elastoplastic behavior and large displacements. The Total Potential Energy (TPE) functional is minimized by implementing primal-dual nonlinear optimization concepts. Specifically, the TPE functional is generalized by adding constraint terms to ensure compatibility through Lagrange multipliers, and evaluated at collocation points within each element. This procedure results to an exact-type finite element, having the curvature □ along the element as the only internal approximated field, derived by Lagrange polynomial interpolation. The stress resultants at each collocation point are determined by discretization of cross sections into fibers and the solution scheme employs the standard Newton-Raphson and arc-length numerical methods to derive the equilibrium paths. One of the main features of this formulation is that large displacement theory is precisely followed without any kind of simplifications, either for curvature or axial deformations. Validation of the resulting element is performed through comparative analyses with other state of the art beam-column finite elements, solving well documented benchmark nonlinear problems cited in the literature. Applications of large, realistic frame structures are analyzed and compared as well, primarily focusing on collapse simulations. Overall, numerical results demonstrate that the

presented formulation is very efficient and effective. That is, it allows for coarser discretization and reduced structural degrees of freedom, for a given level of accuracy, compared to other formulations, including force-based elements, and surpasses them in providing demanding equilibrium paths without ending the solution process prematurely.

349: Embedded Interface Problems with Quadratic X-FEM: A Nitsche Approach

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Yingjie Liu, Duke University
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The extended finite element method (X-FEM) coupled with a weighted Nitsche approach [1] has proven to be an accurate, robust method for solving embedded interface problems. The Nitsche approach provides an effective means to develop an optimally convergent and stable method for embedded interfaces while circumventing the difficulties associated with generating an LBB stable multiplier space. However, with some exceptions ([2, 3]), the method has been mostly used in conjunction with linear or bilinear elements. The main difficulty for higher-order elements lies in the definition of the stabilization parameter. While exact closed-form expressions for this parameter can be derived for linear triangular and tetrahedral elements, no such expressions are apparent for higher-order elements and an (often expensive) eigenvalue computation needs to be performed. Here, we generalize the weighted Nitsche's approach of Annavarapu et al. [1] to higher-order simplex elements. In particular, we provide closed-form expressions for the Nitsche's stabilization parameter for simplex elements of an arbitrary polynomial order $p \geq 1$. We also prescribe a weighting for the Nitsche consistency terms that minimizes the stabilization parameter while ensuring coercivity. The proposed formulation is expected to yield well-conditioned discrete systems in the presence of both large heterogeneities and elements with arbitrarily small volume fractions. Furthermore, to ensure optimal rates of convergence, we employ a hierarchical local refinement approach [2] for an improved geometrical representation of the curved interface. Numerical experiments for quadratic triangles demonstrate the effectiveness of the presented approach.
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639: Energy Dissipation Strategies Inside the Mantis Shrimp's Dactyl Club: Hypotheses and Biomimetics

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Nick Yaraghi, University of California, Riverside
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Pablo Zavattieri, Purdue University

The smashing stomatopod (mantis shrimp) has been known for its heavily smashing blow creating the velocity

and acceleration equivalent to a .22 caliber bullet with the forces up to 1.5 kilonewtons and the load-bearing part of its raptorial appendages, so-called dactyl club, having a capability of withstanding such tremendous forces. The focus of this research is on this extraordinary damage tolerant dactyl club. The success of the dactyl club's mechanical response lies in its multi-regional and hierarchical composite architecture. In this talk we will discuss the role of the hierarchical architecture of three important regions: the impact, the periodic and the striated region. Each region exhibits distinct features that characterize their functionalities. In our approach we employ analytical/computational models and mechanical tests done at various scales. In this talk I will briefly discuss some of the current efforts to elucidate the most relevant energy dissipation strategies of these regions.

751: Engineering Interpretations of Various Buckling Methodologies Used in Nuclear Design Code Evaluations of Rigid Strut Assemblies

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Shrikant Nargund, LISEGA Inc.

This paper discusses the prescribed requirements contained within the ASME B&PV Code, Section III, Subsection NF that specifically address the considerations of the stability and buckling load capacities of linear piping restraints (i.e., struts). The analytical modeling of various strut geometries and the results of the buckling analyses of a slender (slenderness ratio Kl/r $\geq$ 100) structural members using various finite element solution techniques are presented herein. Specifically, three types of finite element analysis are conducted in an effort to define the critical buckling load for the subject structural members, and include the traditional linear (Eigen value) Euler method; the nonlinear, second order large deformation method; and finally, the nonlinear large deformation method that incorporates nonlinear elastic-plastic material behavior. These techniques are employed for a hollow cylindrical structural member (i.e., a strut assembly) with varying cross sections along its length. The critical buckling load is calculated in each case, thereby predicting the load at which instability will occur in the structural member. The results obtained from the aforementioned techniques are then compared both numerically and qualitatively with an appropriate explanation of the purpose and usefulness of each particular result with respect to the intent of the ASME B&PV Code, Section III, Subsection NF requirements. The results show significant variations (as expected) based on differences in the assumptions and techniques employed in the respective analyses.

400: Engineering Validation of Simulated Ground Motions for Building Damage Assessment

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Carmine Galasso, University College London

Synthetic ground motion signals (hereinafter, "ground motions" or "GMs"), simulated at fine grid spacing, represent an attractive option for loss estimation purposes. Among stakeholders the general concern is that simulated GMs may not be equivalent to real (e.g., recorded during past earthquakes) records in estimating seismic structural demand, and hence, in estimating the induced damages to structures and losses. To overcome this, several recent studies and research efforts are developing and implementing testing/rating methodologies for simulated GMs via collaboration between GM modellers and engineering users. This study addresses, on a statistical basis, whether simulated GMs for four historical earthquakes lead to biased estimates of the seismic structural demands and expected damage levels for relevant building types in comparison with real records. In particular, the study considers the Graves and Pitarka’s (2010) hybrid broadband ground motion simulation methodology for the following historical events: 1979 M 6.5 Imperial Valley, 1989 M 6.8 Loma Prieta, 1992 M

7.2 Landers, and 1994 M 6.7 Northridge. The considered building types are selected based on the predominant structural systems encountered in the regions of the historical events (i.e., California). The seismic structural demand is assessed using the recently developed FRACAS (Fragility from Capacity Spectrum Assessment) methodology, recommended in the guidelines for Analytical Vulnerability developed within the Global Earthquake Model (GEM) Project. The capacity curves for the studied building types and the damage states definitions are derived from the HAZUS package developed by the Federal Emergency Management Agency (FEMA). For each earthquake and building type, a color-coded map representation of the analysis results is developed to also allow verification of whether or not there is a systematic directionality in the over- or underprediction trends of the simulations relative to recorded data. The results from this study highlight the similarities and differences between synthetic and real records. These similarities should provide confidence in using the simulation methodology for engineering application, while the discrepancies, if statistically significant, should help in improving the generation of synthetic records.

744: Ergodicity and Linear Response of Thermostats for Single Degree of Freedom Systems: Towards Improved Temperature Control

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Baidurya Bhattacharya, Indian Institute of Technology Kharagpur

Over the years several deterministic molecular dynamics thermostats have been proposed. Each of them possesses unique characteristics and advantages of the other. In this article we illustrate and contrast several important physical properties of basic kinetic, configurational and full phase space thermostats, as well as those that use thermostat chains or control higher order temperatures. In particular, we present our newly developed C1,2 thermostat that controls the first two orders of configurational temperatures. We start by highlighting the similarities in the equilibrium properties due to the different thermostats. Subsequently, we critically analyse the ergodic characteristics of these thermostats from the perspective of the dynamical-systems theory and statistics. Subsequently, we look at the linear-response of the six thermostats both due to mechanical and thermal perturbation. It is interesting to note that despite the near-equivalence of macroscopic properties due to these thermostats at thermodynamic limit in equilibrium, the linear response of our prototypical single degree of freedom system is considerably different.

171: Estimation and Rectification of Model-Form Errors in Transonic Reynolds-Averaged Navier Stokes Simulations

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Jaideep Ray, Sandia National Laboratories
Srinivasan Arunajatesan, Sandia National Laboratories
Lawrence Dechant, Sandia National Laboratories

We present results from a study performed to estimate and reduce model-form errors in Reynolds-Averaged Navier Stokes (RANS) simulations of a supersonic jet interacting with a transonic crossflow. After performing a calibration of the RANS model to experimental data, we find that the main source of error lies in being able to reproduce turbulent stresses in the numerical simulation; this is the largest contributor to the model-form error. That, in turn, is ascribed to the simplicity of the linear eddy viscosity model (LEVM) that is typically used in such simulations. We consider the case of enriching the LEVM model with higher-order terms to reduce the model-form error. Such high-order models exist, e.g., cubic eddy viscosity models (CEVM), but are calibrated using low-speed curved-channel flows. We use shrinkage regression, specifically LASSO, on the CEVM to attempt to

span the gap between numerical predictions of the turbulent stresses and their limited experimental measurements. The regression shows that the experimental data only supports the retention of one out of the seven quadratic and cubic terms that the CEVM contains. It also provides a rough estimate of the improvement that the enrichment of the eddy viscosity model can provide. The CEVM is then implemented in our RANS simulator and we recalibrate it to jet-in-crossflow experimental data. We identify the feasible space i.e., the parameter space where the RANS simulations are physically realistic and perform a Bayesian calibration to estimate three RANS parameters (one of them being the enriching term in the eddy viscosity model). We check the improvement that the enriched eddy viscosity model provides over the original linear one, for various mean-flow and turbulent flow quantities.

631: Estimator and Closed-Loop Performance of Wireless Control Systems Under Intermittent Observations

Lauren Linderman, University of Minnesota

As traditional wired feedback control systems move towards wireless sensor networks, consideration of intermittent observations is essential to understand the closed-loop control performance. Typically, a complete set of measurements or states are not available, so the structural system states are estimated for feedback control. With centralized, wired control systems estimation performance and error can be determined and limited with proper assumptions of measurement and modeling error. However, with wireless sensor feedback systems, packet loss can lead to estimator and controller instability. The total performance of the controller is a function of both the estimator and regulator. Poor performance, or instability, of either component ultimately dominates the closed-loop system. An error performance index will be used to characterize the Kalman estimator performance with intermittent observations from multiple sensor channels and the resulting closed-loop Linear Quadratic Gaussian (LQG) response. A jump system approach used for lossy systems to approximate the estimate error for a static Kalman gain is expanded to account for partial observations from multiple sensor channels. Three states will be considered: all observations received, partial observations, and no observations. The separability of the estimator and regulator are used to relate the estimator error performance to the LQG closed-loop performance for a specific control design. The goal is that an error performance index and closed-loop performance can be used in a reliability-based analysis of wireless feedback control systems. The wireless control benchmark, which incorporates non-deterministic packet loss in the measurement feedback, is used as an analytical test-bed for the indices under intermittent observations.

625: Evaluation of Coarse Grained Models for Cellulose NanoCrystals (CNCs)

Mehdi Shishehbor, Purdue University
Pablo Zavattieri, Purdue University

Understanding the CNC-CNC and CNC-polymer interaction is of a great interest in cellulose based nano-composite materials context. However, representing an accurate model for interaction of crystalline cellulose particles at the mesoscale still remains challenging due to the complexity of chemical interactions between atoms inside the crystal and large length/time scale of the system. In this work we propose a coarse-grained model for CNC-CNC interaction. First the effect of bonded and non-bonded interactions on mechanical properties have been studied and then a coarse-grained model has been built up based on transferring the important chemical-mechanical properties. Finally we are able to study the mechanical properties of CNC-based structures.

313: Examining the Dependencies of a School Building on Critical Physical Infrastructure for a Community Subjected to Tornado

Hassan Masoomi, Colorado State University
John van de Lindt, Colorado State University

Today's world is a complex system including highly coupled networks. A malfunction in a network or component can result in a cascading failure, which in turn can cause a loss of functionality in the system. For example, the Northeast blackout of 2003 was a widespread power outage affecting eight U.S. states and the Canadian province of Ontario. There are more than 1200 tornado touchdowns a year in the United States, resulting in risk to communities in the Midwest and Southeast. In this study, structural fragilities of an archetype masonry school building subjected to tornado loading were developed for an array of damage states and structural functionality (repair). Then, the school fragilities were used in an illustrative risk and resilience study of a simple community that includes water, power, and building networks. In order to study the resilience of the community, a randomly generated tornado path was modeled based on historical statistics of U.S. tornadoes. A set of rules for when groups of individuals could attend the school, the functionality of the school itself (both structural and dependencies on water and power), and the surrounding community are modeled.

92: Experimental and Numerical Analysis of Perforation Process for Selected Aluminum Alloys - Defining Friction Coefficient and Failure Criterion

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Amine Bendarma, Universiapolis, Ecole Polytechnique d'Agadir
Alexis Rusinek, University of Lorraine
Tomasz Jankowiak, Poznan University of Technology

Experimental analysis on standard and recent aluminum alloys have been carried out using a high pressure gas gun. Perforation tests have been done for a variety of projectile shapes to investigate friction effects. Numerical simulations using Abaqus have supported the experimental study. Proper application of the constitutive relation have been discussed for alloys of different ductility. Friction coefficient has been proposed to reflect projectile-plate contact behaviour. Failure criteria are based on energetic considerations.

278: Experimental and Numerical Development of Material Constitutive Properties for Marine Mammals

Molly Grear, University of Washington
Michael Motley, University of Washington

Tidal energy has an immense potential for creating renewable energy and various devices are currently being investigated worldwide. In this emerging field, the potential environmental consequences of installing tidal turbines must be investigated. The goal of this study is to quantify the soft tissue response of marine mammals during a collision with a tidal turbine. To accurately model this response, appropriate biomechanical properties of the whale's skin and blubber are needed to implement a finite element model determining the extent and severity of a turbine blade strike. Initial models of projectile impact on marine mammals have assumed that the material behaves isotropically, however initial experiments have shown that this is not the case. The anisotropic nature of the skin and blubber creates complexities in developing an appropriate model of most marine mammals, and proper development and refinement of these numerical models is nontrivial. Researchers at the University of Washington's Friday Harbor Labs have access to marine mammal skin and blubber specimens for post-mortem

examination of their constitutive properties, including Southern Resident killer whale (Orcinus orca), harbor porpoise (Phocoena phocoena), and harbor seal (Phoca vitulina). Tensile tests of both the skin and blubber layers were performed on several of these specimens to determine tensile stiffness and tensile strength, as well as the strain rate effects on these quantities. The samples were taken in different orientations (0°, 45° and 90°) to the longitudinal body axis to investigate anisotropy present in the tissue. Both types of tissue exhibited a large plastic region, showing non-linear behavior with the amount strain expected in a turbine collision. Further, compressive spherical indentation tests were performed with the composite skin and blubber layer and on the blubber layer alone to assess the appropriateness of extrapolating tensile data for compressive behavior. It was found that the compressive stiffness was approximately an order of magnitude lower than corresponding tensile data. These experiments were subsequently recreated using the commercial finite element solver ABAQUS to validate the numerical material constitutive models. Ultimately, the numerical models can be extrapolated to full-scale, realistic models of marine mammals to assess their susceptibility to injury from turbine blade impact or similar phenomena.

733: Experimental Inference of Inter-Particle Contact Forces in Granular Media under Shear Deformation

Eloïse Marteau, California Institute of Tecnhology
Jose Andrade, California Institute of Technology

By providing a connection between continuum and granular scales, assessment of inter-particle contact forces is of major interest for the development of multiscale methods. We report here a set of experiments performed on a novel mechanical device that focuses on the microstructural scale. This mechanical device allows a specimen composed of a two-dimensional analogue granular assembly to be subjected to quasi-static shear conditions over large deformation. The shear cell consists of a horizontal deformable parallelogram of size 50 cm by 50 cm in the undeformed configuration. We use the Digital Image Correlation (DIC) technique to measure displacement and strain field at the laboratory scale (centimeters). On the other hand, the Granular Element Method (GEM) enables the inference of inter-particles forces in opaque granular materials, provided that average particle strains are measured and that the location of contact points in the array is known. This new technique enables us to reconstruct the force distribution. We present here experimental results that shed light into the multiscale mechanical behavior of granular assemblies under shear loading.

640: Experimental Investigation into the Deformation and Failure of a Magnesium Alloy under Dominant Shear Loading

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Ali Ghahremaninezhad, University of Miami

There has been an spurt of research activities in the ductile fracture of polycrystalline metallic alloys, especially under a dominant shear loading. Traditional ductile fracture models such as the Gurson-Tvergaard-Needleman (GTN) model have been developed on the basis of void growth due to volumetric strain, and subsequent void coalescence leading to fracture. It has now become evident that these models are not able to capture the fracture processes in dominant shear deformation conditions, which occur in the form of shear localizations in ductile metallic materials. In this presentation, we report an experimental investigation of deformation and failure mechanisms in a magnesium alloy under a dominant shear loading. Deformations at the grain and subgrain scales were measured in a scanning electron microscope by in-situ tracking of the changes in grain size and morphology, and at the macroscale using digital image correlation (DIC). High strain heterogeneity at the grain and subgrain scales was observed and quantified. The relation between the strain and grain size and morphology is discussed.

63: Experimental Model Updating with Frequency Response Function Considering Damping Effect

Yu Hong, Southwest Jiaotong University; Georgia Institute of Technology
Yang Wang, Georgia Institute of Technology

In structural engineering, finite element (FE) model updating generally refers to the process of refining certain parameters of a FE model, so that the model can more accurately represent the actual structure. Many studies on FE model updating do not consider updating of damping parameters, partly due to the difficulty in damping update. Some researchers have studied a model updating approach that intends to minimize the difference between analytical and experimental frequency response functions (FRF). While the analytical FRFs are obtained from the updated FE model, the experimental FRFs can be obtained by measuring dynamic structural response under controlled excitations. In this research, the approach is extended to update mass, stiffness, and hysteretic or viscous damping parameters. The effectiveness of the presented FRF model updating method is validated through laboratory experiments on a four-story shear-frame structure. To obtain the experimental FRFs, shake table tests and impact hammer tests are performed. The proposed FRF model updating approach is shown to successfully update the stiffness, mass and the two different types of damping parameters in matching the analytical FRFs with the experimental FRFs.

478: Experimental Study for a Double Skin Façade Damper System

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Tat FU, University of New Hampshire

A double skin façade (DSF) system consists of two “skin” layers of glasses with a cavity between the skins. The skins and cavity help insulate and ventilate buildings (air is allowed to flow in the cavity).This project integrates mass dampers and double skin façades by enabling movements in the outer skin. The DSF dampers can dampen structural vibrations during earthquakes and strong winds without adding extra weight (i.e., separate mass dampers) to the structure. Additionally, by being able to adjust the gap size between the two skins, ventilation rate can be controlled to improve energy efficiency.In this study, both numerical optimization and experimental study were performed. The numerical study optimized damper parameters (stiffness and damping coefficients) to minimize structural response under stochastic earthquake excitations. In the experimental study, a façade damper system with optimized damper parameters was installed on a six-story shear structure. This six-foot steel structure was placed on a shake table and shake tests were performed on the DSF damper, a conventional tuned mass damper (TMD) and an uncontrolled system. Various DSF damper configurations were tested: one-, two- and three-damper configurations. In the one-damper configurations, the facade spanned and connected to all six floors and, thus, moved as an entire piece. In the two- and three-damper configurations, each of the DSF dampers spanned three or two floors, respectively. The DSF damper system had a 10% damper-mass ratio relative to the primary structure and the TMD system had the same damper-mass ratio.The DSF, TMD and uncontrolled systems were subjected to four historical earthquake records (1992 Erzincan, 1994 Northridge, 1999 Jiji, and 2011 New Hall) using the shake table. Both acceleration and displacement were recorded on each floor of the structure. Acceleration was recorded via wireless accelerometers; and displacement was obtained by digital image correlation (DIC) technique and interstory drift was then derived. The experiment result showed that various DSF damper configurations significantly reduced structural vibration and interstory-drift compared to the uncontrolled system and outperformed the TMD system.

298: Experimental Study on A Discrete-Time Compensation Technique for Real-time Hybrid Simulation

Wei Song, The University of Alabama
Saeid Hayati, The University of Alabama

Real-time hybrid simulation (RTHS) provides a cost-effective means to evaluate the behavior of large-scale structural system under realistic loading condition. A primary challenge in developing RTHS applications is to accurately compensate for the time delay and lags caused by servo-hydraulic system and its interaction with the attached structural system. The performance of servo-hydraulic compensation is crucial to the success of RTHS, and can be influenced by the chosen structures/models, noise contamination level, and experimental setup error. In this study, a discrete time based compensation technique for RTHS is introduced. The goal is to provide guaranteed compensation performance to applications with a wide range of frequency bandwidth. A series of command inputs with various frequency bandwidth are applied to examine the behavior of the compensation technique. Experimental testing results are presented and compared to demonstrate the performance and effectiveness of the proposed compensation technique.

56: Experimental Verification of Common Assumptions Used in the Analysis of the Rocking Motion of Rigid Bodies

Raphael Greenbaum,
Andrew Smyth, Columbia University
Manolis Chatzis, University of Oxford

According to the U.S. Federal Emergency Management Agency (FEMA), "nonstructural failures have accounted for the majority of earthquake damage in several recent U.S. earthquakes". The dynamic response of many of these nonstructural elements when subject to ground accelerations is governed by rocking motion. Despite the increasing number of theoretical and simulation studies of rocking motion, few experimental studies exist. Of those that have been published, most are focused on a constrained version of the complete problem introducing modifications to the physical problem which may significantly affect the rocking response. The intent of this presentation is to describe experimental studies of unconstrained rocking of rigid bodies which demonstrate two important phenomena. First, it will be demonstrated that a two dimensional analysis, which is common in the literature, may not capture the failure responses of a body. Second, it will be shown that the rocking initiation criteria of the commonly accepted inverted pendulum model which states that a body will only rock if the coefficient of friction between the body and its support medium is greater than the ratio of the body's width to the body's height may not hold true in all circumstances. These two outcomes will demonstrate that the current state-of-the-art may result in potentially non-conservative analyses.

697: Exploration of Error Rate Criteria to Decide Bounds for Model Falsification

Subhayan De, University of Southern California
Patrick Brewick, University of Southern California
Erik Johnson, University of Southern California
Steve Wojtkiewicz, Clarkson University

To characterize dynamic structural systems, typically one must choose model(s) or model class(es) from the variety of possible models and model classes, and reject other model(s) and model class(es), based on dynamic response measurements. In structural control, the design of a controller is only as good as the modeling of the system; in health monitoring, the modeling of the structure is important as the damage detection is often performed by identifying changes in the model parameters. One approach for determining which models to eliminate is the use of "model falsification" based on hypothesis falsification. This notion of model falsification originated in the 1930s from Popper's "The Logic of Scientific Discovery" (2002), asserting that scientific models cannot be fully validated by data and can only be falsified. The error domain model falsification approach (Goulet et al., 2013 MS&SP, 2013 Adv. Engrg. Inf.) specifies a bound for errors in measurements based on combining uncertainties from different sources, and uses these bounds to falsify models. The error bounds have been chosen based on the Sidak (1967 J. ASA) correction for multiple comparison test to keep the family-wise error rate (FWER) among all comparison points (i.e., measurements) at a fixed value. This approach was developed and applied to a series of structural modeling and monitoring investigations. In the present study, the Bonferroni and Sidak corrections for multiple comparison test to control the FWER are explored, along with the Benjamini and Hochberg (1995 J. Royal Stat. Soc. B) procedure for multiple comparison tests for controlling the false discovery rate (FDR), which has been shown to be beneficial for exploratory studies. The aim of using the FDR is different than that of FWER: FDR tries to maintain, on average, the rate of falsely rejecting a valid model relative to the rate of rejection of all (valid and invalid) models; in contrast, FWER simply maintains a rate of false rejections. Error bounds for model falsification are chosen using these three different approaches and implemented for some testbed structural dynamical systems. It is shown that there are clear advantages, as well as some disadvantages, of each of the approaches.

465: Fabric Evolution during Soil Liquefaction

Usama El Shamy, Southern Methodist University
Yasser Abdelhamid, Southern Methodist University

During earthquake shaking, saturated loose granular deposits experience a decrease in void space and a rise in pore-fluid pressure, which leads to a degradation in soil stiffness and strength properties and ultimately liquefaction. Liquefaction is an instability phenomenon that is generally associated with a site loss of bearing capacity and flow failure along with lateral displacements and excessive settlements. Several studies have shown that tracking the evolution of fabric during loading of granular soils can shed light on induced anisotropy and its effect on soil behavior. These studies, however, considered element level behavior and focused on either the drained or constant-volume behavior of granular soils without representation of pore-fluid. In this presentation, we introduce results of a novel coupled pore-scale model of pore-fluid interacting with discrete particles. A mircoscale idealization of the solid phase is achieved using the discrete element method while the fluid phase is modeled at a mesoscale using the lattice Boltzmann method. The fluid forces applied on the particles are calculated based on the momentum exchange between the fluid and particles. The proposed approach is used to model liquefaction of a saturated soil deposit subjected to seismic excitation. Results of conducted simulations reveal that liquefaction is due to reduction in void space during shaking that leads to buildup in pore-fluid pressure. The results also indicate that the level of shaking-induced shear strains plays a major role in the onset of liquefaction and the rate of pore-pressure buildup. In addition, variations of the fabric tensors at different locations along the deposit depth were monitored to trace the changes of the structural anisotropy of the deposit. Near the surface of the deposit where liquefaction took place, the structural anisotropy of the soil increased dramatically. At deeper depth locations that did not liquefy, minimal change in soil structure was observed.

392: Fatigue Reliability of Vibratory Systems Using a Nonlinear Damage Model

Vasiliki Tsianika, Oakland University

Zissimos P. Mourelatos, Oakland University
Monica Majcher, Oakland University

Fatigue life estimation, reliability and durability are of paramount importance in acquisition, maintenance and operation of vehicle systems. Different fatigue damage models are used in practice mainly relying on simplicity assumptions such as the Miner's linear damage model and simple cycle counting techniques based on peak stress counting. Fatigue life is random because of the stochastic load, the inherent variability of material properties, and the uncertainty in the definition of the S-N curve. It has been shown that a linear damage accumulation model is often not adequate to estimate accurately the fatigue life under variable amplitude load. To address this issue, we propose using a nonlinear damage model under variable-amplitude, wide-band loading. Based on either analytical or experimental stress signals, we calculate the cumulative damage according to a four-point rainflow counting technique. In addition to the stochastic load, we account for the uncertainty in material properties and the S-N curve. The probability density function of the fatigue life is calculated using Latin Hypercube sampling and a saddlepoint approximation approach. A vibratory beam example demonstrates all developments.

663: Field and Laboratory Testing of Levee Structures in Southwest Louisiana to Mitigate Storm Surges and Protect the Shoreline

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Evan Geerts, Duplantis Design Group, PC
Ning Zhang, McNeese State University

Coastal erosion is significant in southwest Louisiana (SWLA) due to the wave action and hydrodynamics of the Gulf of Mexico and the surrounding water systems. The erosion causes loss of both private and public land and roads as well as loss of barriers to flood damage, thereby jeopardizing the ability of residents and emergency responders to safely evacuate and access areas during times of emergency. The goal of this research is to examine erosion at coastal structures in SWLA, which are constructed for mitigating storm surges and preventing the loss of coastal land caused primarily by the local wave-structure interaction. In order to meet the goal of this study, we performed both in-situ measurements and laboratory experiments. Specifically, two levee sections were built 4.6 miles east of Holly Beach in Cameron Parish, Louisiana, for evaluating alternative substrate material having high strength and relatively low cost. For the substrate two different materials were utilized; clay material and the OPF42 Synthetic aggregate manufactured at various circulating fluidized bed boilers, both supplied by a local company, LA Ash, a division of Headwaters Resources, Inc. Continuous monitoring of the levee section included (1) recording of the pressure at different locations in the front and lee side of the levee for calculating the wave forces; (2) surveying of the levees for determining the erosion rates; (3) capturing the wave via digital cameras permanently installed at the site; (4) post-processing the collected data and use them for validating simulation models. Further, laboratory experiments were performed in a wave tank to better examine the wave actions on a small-scale levee within a controlled environment. Laboratory measurements included 3-dimensional, point velocity measurements using an Acoustic Doppler Velocimenter by SonTek and calculations of turbulent intensities. The results of this project will determine the potential benefits to the State of Louisiana from the utilization of alternative substrate material in coastal structures to minimize erosion damage to the levees and adjacent roadways due to the wave surges. This could result in a significant savings to the state since most of the coastal structures are susceptible to erosion.

62: Finite Element Model Updating with Noisy Data through the Modal Dynamic Residual Approach

Xinjun Dong, Georgia Institute of Technology
Yang Wang, Georgia Institute of Technology

In order to identify a more accurate finite element (FE) model for an as-built structure, selected FE model parameters can be updated based on experimental data collected from the actual structure. This process is termed as FE model updating. However, in practice, experimental data is inevitably contaminated by measurement noises, which, in general, will decrease the model updating accuracy. Among various model updating approaches, the modal dynamic residual approach aims to minimize the residuals of the generalized eigenvalue equation, where analytical structural matrices are used in combination with experimentally measured resonance frequencies and mode shapes. In this research, a minimum variance estimator of the FE model parameters is proposed while maintaining the modal dynamic residuals as minimization objective. The noises existing in the experimental modal properties and the model parameters are treated as random variables with appropriate distributions. The proposed estimator intends to minimize the variance of the updating parameters in the process of model updating. The performance of the proposed approach is evaluated through numerical studies. Monte Carlo simulation is performed to generate noise-contaminated modal properties. The results of the numerical studies demonstrate that the proposed statistical model updating approach can successfully update the FE model parameters with an acceptable accuracy.

696: Finite Element Modeling for Optimal Design of Bridge Pot Bearings

Najib Bouaanani, Polytechnique Montreal
Kimiya Zakikhani, Polytechnique Montreal
Tarik Fethi Saichi, Polytechnique Montreal

Pot bearings were developed in the early 1960s and are used to support a bridge superstructure and accommodate its movements independently from the supporting elements, i.e. piers and abutments. They are considered as High Load Multi-Rotational bearings since they can (i) transmit large force demands from the superstructure to the substructure, and (ii) accommodate rotation about any horizontal axis as a function of the applied loads. This type of bearings can also accommodate translational movements thanks to an added PTFE/stainless steel slider. Pot bearings have usually been designed according to a mix of empirical and theoretical procedures. Some of these rules were validated by experimental tests, and others are only based on theoretical considerations, engineering judgment or in-house practice of various bearing manufacturers. In this paper, we investigate the structural response of more than 40 pot bearings with various dimensions (eg. diameters and heights of the pot, piston and elastomeric pad), designed according to ASHTOO (2015). The pot bearings are modeled using 3D finite elements including nonlinear contact between the pot and the piston and are subjected to horizontal and vertical loads. The results of the finite element analyses are examined mainly in terms of stresses within the piston and pot, as well as the contact forces between the two components. In particular, we investigate the central angle corresponding to the arc-length along which contact between the pot and piston is effective considering various horizontal to vertical load ratios. The results confirm that the angle of contact between piston and pot is generally different from 180 degrees as assumed in most design specifications of pot bearings. The results from finite element models are also discussed in light of predictions of available analytical formulations (eg. Hertz and Persson contact theories). A nonlinear regression analysis including the most important design parameters is conducted to better estimate the angle of contact between pot and piston in lieu of assuming distribution of contact forces along half of bearing perimeter as stated in most design specifications. Implications of the results of this study on the design of pot bearings are discussed.

253: Finite Strain Wave Propagation Analysis in the Micromorphic Media

Farhad Shahabi, University of Colorado
Richard Regueiro, University of Colorado

This presentation establishes a three-dimensional (3D), large deformation finite element analysis (FEA) framework accounting for material microstructure by way of micromorphic continuum mechanics (in the sense of Eringen). The fundamental assumption of this theory is that material microstructure satisfies the classical continuum mechanics equations within a ``micro-element" or ``representative volume element (RVE)." The micro-element deformation with respect to the centroid of the macroscopic continuum point is governed by an independent micro-deformation tensor $\bm{\chi}$. Assuming proper constitutive models can be formulated, and material parameters calibrated, the theories may fill the gap between the RVE-microstructural-length-scale and the macroscopic continuum scale. The aim of this presentation, therefore, is to provide more insight into the dynamics behavior and wave propagation analysis in the micromorphic media. The focus of our simulations is to show macroscopic wave propagation as well as the wave associated with the additional micromorphic degrees of freedom which we call them "`micro-wave". The differences in the micro and macro wave speed will be highlighted and the effect micro inertia tensor on the micro-wave profile and total macroscopic dynamic response will be investigated. Note that a comparison is done to demonstrate the finite strain against small strain analysis on the wave propagation simulations in the micromorphic media.

706: First Order Sampling Approach for Time-Dependent System Reliability Analysis

Zhen Hu, Vanderbilt University
Sankaran Mahadevan, Vanderbilt University

Time-dependent reliability gives the probability that a component or system fulfills its intended function over a time period of interest without failure. Current time-dependent reliability analysis methods mainly focus on component reliability analysis and are based on the Poisson assumption of independent upcrossing events. Even if efforts have been made to estimate the time-dependent system reliability, currently available methods cannot be applied to systems with more than five components and the accuracy and efficiency of these methods are not satisfactory. This paper proposes a novel and efficient first order sampling approach for time-dependent system reliability analysis of systems with multiple limit-state functions of random variables, stochastic processes, and time. Since there are correlations and variations between components and over time, the overall system response is formulated as a random field with two dimensions: component index and time. Directly model the system response random field is computationally prohibitive because computer simulation models are usually used as component response functions. In order to overcome this difficulty, an equivalent Gaussian random field is constructed based on the probability equivalency between the equivalent Gaussian random field and the original response random field. The first-order reliability method (FORM) is employed to obtain important features of the equivalent random field. The Kriging surrogate model is used to reduce the computational effort in modeling the equivalent random field. By performing simulation on the equivalent random field, the time-dependent system reliability is estimated from Boolean functions defined according to the system topology. Since the system response is directly simulated at the system output level instead of at the component input level, the efficiency of time-dependent system reliability analysis is increased significantly. Using one system reliability analysis, the proposed method can get not only the entire time-dependent system probability of failure curve up to a time interval of interest but also two other important outputs, namely, the time-dependent probability of failure of individual components and dominant failure sequences. In addition, since the proposed method is independent from the system topology, it can be applied to systems with complicated system configurations. Three examples featuring series, parallel, and combined systems demonstrated the effectiveness of the proposed method.

256: Floor Pressures below Dry and Submerged Layered Vertical Granular Columns

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Hubert Vollmer, Lawrence Livermore National Laboratory
Victor Hepa, Lawrence Livermore National Laboratory

Floor-loads under vertical columns of dry and submerged sand and gravel are examined and compared to expected behavior. Analytic expressions for the expected floor-load vs height are compared to measured floor-loads. The vertical stress distribution produced when a top-surface load is added to a granular column, and stress distributions in multilayered granular columns, are examined by differential-slice analysis, laboratory measurements, and discrete element method simulations. For submerged systems the behavior is found to be very similar to the usual Janssen [1895] predictions for dry materials, except for the addition of a fixed hydrostatic head, and a buoyancy correction to the effective density of the submerged granular material. When a top-surface load is added to a granular column of a fixed height, modified boundary conditions in Janssen's analysis result in a predicted linear increase in floor pressure proportional to the top-surface pressure applied to the fixed-height granular bed. The proportionality ratio varies with the existing height of the granular bed, and is nearly the same as the fraction of the asymptotic Janssen floor pressure achieved before the addition of the top-surface load. The slope of the resulting floor pressure vs top-surface load curve is a linear extension of (i.e., tangent to) the Janssen floor-load vs granular-material-load curve for the pre-existing granular bed. Measured floor-loads and simulations generally confirm this linear relation between the top-load added and the floor-pressure measured. In measurements with large top-surface loads (applied over a smaller-than-pipe-diameter area) the slope of the top-load vs floor-pressure curve became smaller – perhaps indicating a change in the k-value of the material (i.e., its lateral to axial stress ratio) due to the stress state reaching a failure surface. The top-load analysis result is used to construct analytic expressions predicting the floor-loads produced by two-layer, or multilayered granular columns. The resulting predictions indicate that if the bottommost layer has a height on the order of two pipe-diameters or greater, then its properties are likely to dominate the determination of the ultimate floor pressure created, with only a small sensitivity to the material properties of the material added above that bottommost layer. Most of the laboratory test results were similar to expectations; however, wider than anticipated variability was exhibited in some configurations and one anomalous result remained incompletely explained, but may have been the result of a thin over-consolidated layer at the bottom of the sand column in that submerged test.

739: Fluid-Structure Interaction Using the Domain Free Discretization (DFD) Method

Yang Zhang, Vanderbilt University
Haoxiang Luo, Vanderbilt University
Chunhua Zhou, Nanjing University of Aeronautics and Astronautics

Fluid-structure interaction (FSI) is common in many biological flows, such as bird wings, fish fins, blood vessels, and heart valves. The conventional approach for solving these FSI problems is the Arbitrary Lagrangian-Euler (ALE) method. However, for objects going through large and complex deformations, the interpolation error between old and new meshes could be excessive, and the frequent update of the mesh could drastically reduce the computational efficiency. In comparison, the immersed-boundary (IB) method is advantageous for many of such FSI problems due to its easy mesh generation without the need to achieve conformity between the mesh and the fluid-structure interface. In this work, a partitioned approach for simulating FSI problems involving both rigid and flexible bodies has been developed. A local domain free discretization (DFD) method that belongs to the family of sharp-interface IB methods is used to solve the fluid flow. In the local DFD, the discrete form of governing equations at an interior node near the solid body may involve some nodes outside the solution domain. The functional values of flow variables at the exterior dependent nodes are updated at each time step via the

approximate form of solution near the boundary, which is constructed through extrapolation and the simplified momentum equation along the normal direction to the boundary. For solid bodies, either rigid-body dynamics or thin-walled nonlinear elastic structures has been incorporated. The fluid and solid solvers are combined with each other in a strong-coupling manner at the fluid-structure interface to improve numerical accuracy and stability. For objects experiencing large displacements, a mesh adaptation technique based on prediction and correction is employed to obtain higher resolution around the solid body. Several FSI problems involving 2D rigid and flexible objects have been simulated by using the current numerical method to demonstrate its accuracy and efficiency. For rigid objects, the classic vortex-induced vibration of elastically-mounted circular cylinders has been performed to verify the fidelity of the present method. Other applications include free-falling cylinders and tumbling cards. For flexible objects, a flapping wing performing hovering flight has been simulated to study the effect of wing inertia on the wing deformation and on the aerodynamic performance.

599: Foundation Structure Interaction for Wind Turbine Towers

Sukhvarsh Jerath, University of North Dakota
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Foundation Structure Interaction for Wind Turbine Towers S. Jeratha* and S. Austinb a Professor of Civil Engineering b Graduate Student in Civil Engineering University of North Dakota, Grand Forks, ND, USA *corresponding author: sukhvarsh.jerath@engr.und.edu Abstract: The electric power generated by the wind throughout the world is increasing as an alternate source of energy. In 2014, 51 GW wind power was added bringing the total installed capacity close to 370 GW. This growth has resulted in the expansion of wind turbines into the seismic zones and has contributed to the greater interest in the design of wind turbines subjected to earthquake loads. This paper studies the natural frequencies of the truncated cone steel wind towers when they are supported by different foundations: spread foundation, mono pile, pile group and anchored foundations. Three wind turbines of capacity 65 kw, 1 MW, and 5 MW are investigated by the finite element method using ANSYS computer program. The foundation soil structure interaction is considered by using the K model and the explicit soil model. In the K model soil behavior is simulated by a series of elastic springs under foundation which results in the soil pressure being linearly proportional to the foundation settlement. Stiffness of these springs is called modulus of subgrade reaction, K. In the explicit soil model the soil is modeled as mesh of finite dimensions, this method is more accurate. First 20 modes were found for each turbine. The first mode has the predominant effect on the turbine's dynamic behavior and the first three modes include for the 85% of the effective mass. Hence the dynamic response to an earthquake load is predominantly governed by the first few modes. The natural frequencies variation in Hz for different turbines resting on various foundations is given below: For 65 kW turbine the natural frequencies varied as 1.52 - 1.56, 1.59 - 1.64, and 1.70 - 2.52 for modes 1, 2, and 3 respectively. The frequency variation for 1 MW turbine for modes 1, 2, and 3 is 0.42 - 0.42, 0.42 -0.42, and 1.41 – 2.29, respectively. In the case of 5 MW turbine the frequency variation for modes 1, 2, and 3 is 0.23 – 0.23, 0.23 – 0.24, and 0.95 – 1.10, respectively when resting on different foundations. In this study the natural frequencies obtained for the tower, foundation and soil combination are comparable from both the K models and the explicit soil models. Hence the soil can be modeled by K model instead of the explicit soil model, thus saving the analysis time. The present investigation shows that the effect of a type of foundation on the soil structure interaction is small. Hence the behavior of wind turbine towers subjected to earthquake loading is not likely to be affected by the type of foundation.

270: Fracture Analysis of a Quasi-Brittle Material Based on a Random Field Representation of Micro-Cracked Domain

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Philip Clarke, University of Tennessee Space Institute
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Pavan Kumar, Indian Institute of Technology

The material failure and post-instability response is greatly influenced by the microstructural architecture and energy absorption mechanisms; for ductile materials large inelastic deformations re-balance microscale stress field and retard fracture while for brittle and quasi-brittle materials–e.g., bone, concrete, rocks, high explosives, beryllium alloys, ceramics, and many composites–even the same geometry and loading condition can give quite different fracture patterns. The high dependence of their fracture progress on microstructural defects results in wide scatter in their ultimate strength and the so-called size effect. Our approach for incorporating randomness in quasi-brittle materials is based on the modeling of stochastic volume elements (SVEs). Representative volume elements (RVEs) are commonly used in practice to homogenize the properties of materials with different constituents at microstructure. However, the sizes of RVEs are intentionally chosen large enough so that the homogenized values such as elastic moduli are spatially uniform for a statistically homogeneous material. The use of SVEs in this work ensures that the material randomness is maintained upon "averaging" of microscale features. To create the random field we generate several realization of a material, for example by having a certain overall crack density. By choosing the center of SVEs at a given spatial position on these random realizations and using the moving window approach, where the center of SVE translates in these random realizations, we obtain first and second moments of the target random field. We employ the created random field for the fracture simulation of brittle materials. We use the spacetime discontinuous Galerkin finite element method for our dynamic simulations. Cracks can nucleate from any spatial position based on the corresponding fracture strength, which in turn is obtained from the SVE analyses of microcracked domains.

304: Fracture Investigation of Organic Rich Shale: Microscopic to Macroscopic Scale

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2016 Conference of the ASCE Engineering Mechanics Institute, May 22 – 25, 2016 Vanderbilt University, Nashville, TN Over the last decade, there has been a great deal of emphasis placed on organic-rich shale also called black shale, gas shale or unconventional shale. This is in part due to the relevance of the material in major energy-related applications such as hydrocarbon recovery for oil and gas wells, carbon dioxide geological sequestration or nuclear waste store in depleted wells. Gas shale is a porous multi-scale material that consists essentially of clay, silt inclusions, air voids and kerogen which is gaseous organic matter. At the macroscopic scale, it appears as a layered system as a result of the geological sedimentation history over several million years. Despite breakthrough in the science and technology of hydraulic fracturing, which is a common well stimulation technique also known as fracking, little is known of the fracture behavior of gas shale, especially at the micron and sub-micron length scales. Therefore, our research objective is to investigate the fracture behavior at the granular and nanometer level using a combination of advanced theory and cutting-edge experiments. We focus our study on materials system coming from major shale plays in both the United States and France: Barnett (Bend Arch-Fort Worth Basin, Texas), Antrim (Michigan Basin, Michigan, Ohio and Indiana), Woodford (Ardmore Basin, Oklahoma) and Toarcian shale (Paris Basin, Southeast France). First, we implemented grinding and polishing procedure so as to carry out microstructural observation. Electron probe microanalysis and optical microscopy reveal a porous composite with micron-sized grains. Next we assess the elastic-plastic properties using nano-indentation, which consists in pushing against a soft material with a diamond conical probe and it is widely used in several fields of science and engineering. Furthermore, we characterize the fracture toughness by carrying out microscopic scratch tests in which a sphero-conical diamond probe is pulled across the material under a linearly increasing load. An in-situ acoustic emission sensor is employed to track and record fracture processes. In addition, a microscopic observation of the residual groove after testing shows micro-cracking and chipping mechanisms. We investigate the anisotropy of the fracture response by considering three crack orientations with respect to the crack plane. The fracture toughness is calculated by application of nonlinear fracture mechanics and a toughening behavior is observed at the microscopic. The multi-scale theoretical-experimental approach presented here is a major step towards the quantitative prediction of the fracture properties of gas shale materials.

257: Fracture Mechanisms of Microparticulate Composites via Macroscopic Scratch Testing

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Ange-Therese Akono, University of Illinois

Despite several experimental and theoretical investigations, the prediction of the effective fracture properties of composite materials remains a challenge. In this investigation we focuses on particulate quasi-brittle materials with spherical inclusions. The objective is to model the effect of the reinforcement volume fraction on the fracture behavior using advanced theory and controlled experiments. To this end, we manufactured soda lime glass-reinforced wax composites with a mean inclusion size of 20μm, different filler volume fractions, 0%, 5% and 10%, and by considering both strong and cohesion at the glass-polymer interface. A macroscopic scratch testing equipment built-in house is employed to characterize the fracture properties. Scratch tests consist in pushing across the surface of a soft material with a straight hard prism blade at a constant speed while recording the resulting forces. Scratch testing is relevant in several engineering applications including strength characterization of rock, strength assessment of ceramics and quality control of thin films and coatings. In this study, we performed scratch tests with different blade widths and at different depths of penetration. For each specimen synthesized, the fracture toughness was calculated by application of a nonlinear fracture mechanics model. The fracture toughness was found to increase with the particle volume content; also, strong interfaces led to better fracture resistance. In parallel, we built a theoretical model that integrates fracture mechanics and micromechanics to estimate the macroscopic fracture toughness. Our analytical model predicts a coupling between the elastic and fracture properties that depends on the morphology, that I whether we have a dilute, cast or polycrystalline system. An excellent agreement was found between fracture toughness values predicted by the theory and the experimental measurements. In order to test the generality of our method, we examined the case of porous ceramics materials. The model was able to quantitatively reproduce the loss in fracture toughness caused by the presence of pores. In the future, we plan to incorporate the effect of extensive plastic dissipation into our analytical approach. In brief, the current findings provide a framework to upscale the fracture resistance of composites. As such, this work is an important development in the field of fracture mechanics, materials science and multi-scale modeling.

771: Free Form Finding of Grid Shell Structures

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The general shape of a shell structure can have a great impact on its structural performance. This presentation addresses a numerical implementation that finds the funicular form of grid shell structures. Two methods are implemented for the form finding: the potential energy method (PEM) and the force density method (FDM). The

PEM, inspired by the 3D hanging chain model, find the funicular form by minimization of the total potential energy. On the other hand, the FDM find the funicular form by solving a linear system, in which a geometric stiffness matrix is constructed with the force density and nodal connectivity information. The form finding process is nonlinear, because the nodal loads are calculated with the rationale of tributary area and evolve with the structural form. Apart from the form finding, a member sizing procedure is implemented for a preliminary estimation of the member cross sectional area. In the member sizing, the stress-ratio method is used to achieve a fully-stressed design. Finally, three numerical examples are examined to demonstrate the effectiveness of the current implementation.

251: Free Surface and Non-Newtonian Flow using Lattice Boltzmann Method: An Application in Wellbore Cementing

Matthew Grasinger, University of Pittsburgh
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John Brigham, University of Pittsburgh

The cementing of oil and gas wellbores is a complex physical process. Cement slurry is pumped downhole and is pushed up through the annulus formed by the steel casing and drilled rock formation. The purpose of the slurry is to fill the annulus completely and seal different zones in the wellbore from each other; the cement annulus acts as a barrier protecting the water table and atmosphere from contamination. In order to design the cement slurry properly, new modeling approaches need to be investigated, developed, and implemented that can capture the multiphysics of the cementing process. Included in the physics that needs to be considered in such a simulation are the non-Newtonian flow and free surface flow of the cement slurry as it fills the wellbore annulus. A novel approach for modeling the cementing of a wellbore annulus will be presented. The modeling approach centers on the use of the Lattice Boltzmann method (LBM), as the LBM has nuances that are well suited for non-Newtonian, free surface, and multiphase/multicomponent flows. An overview of the approach will be given, which includes: the constitutive model for the slurry and its implementation, the derivation and implementation of the free surface flow model, an overview of the computational algorithm, and a discussion of ways in which the algorithm can be improved. Several case studies of simulated cement jobs will then be shown for different cement slurry constitutive properties, pump velocities, and irregularities in the wellbore annulus geometry. Conclusions will be drawn from the results as to which cement slurry constitutive properties and pump velocities are most desirable for a given wellbore geometry. Lastly, there will be discussion of future research and developments to cementing modeling approaches.

716: Freezing/Thawing Rate Effects on Concrete Strength with Different Moisture Contents

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As a current target of USA and many other countries to push the design period of infrastructures to 100 years, deterioration due to freeze/thaw gains much more significance. Despite the fact that standard tests for evaluating freeze/thaw susceptibility of concrete exist, many have reported the deficiency in upscaling these test results to real structures and realistic environmental conditions. One major shortcoming of these tests is their extremely

accelerated nature. The tests involve rapid freezing/thawing cycles of concrete cylinders that are frozen in ambient air conditions or in water then thawing by means of water bath. The reduction in strength (usually compressive strength) is correlated to the number of cycles and this serves as an index of the specific concrete freeze/thaw resistance. As has been illustrated early in the 50's by T. C. Powers, the presence of large pores in concrete that are filled with water is the main driving reason for damage as water in these pores expand while freezing and expels unfrozen water into smaller pores along with the creation of large internal expansive pressures. In addition, diffusion of water in concrete is generally a slow process as the pores are not fully interconnected, which means, that higher freezing rates will create higher pressures as far as these rates are higher than real ones achieved by natural environmental freezing and thawing. Additionally, structures that are directly exposed to air will have different humidity conditions. Finally, the size of the structure can play a significant role as the macroscopic water diffusion in concrete is proportional to the square of its thickness. To understand these effects, a series of freezing and thawing experiments are conducting. Concrete prisms are cast and cured at high temperature (55°C) for 4 weeks to guarantee high degree of cement hydration to reduce the effects of freeze/thaw cycles of reaction. Different specimen sizes are brought to uniform humidity levels between 70% to 100% at 23°C in an environmental control chamber then sealed with aluminium wrap during freezing. Thawing is done also in the chamber up till 20°C then specimens are brought back to the same humidity levels and a new cycle is started. After multiple cycles, both compression and fracture strengths are characterized using uniaxial compression and three point bending tests. Results of the experimental program are used to calibrate a new meso-scale model for freeze/thaw effects implemented within the Lattice Discrete Particle Model framework.

332: From Diffuse Damage to Sharp Cohesive Cracks: A Coupled XFEM Framework for Failure Analysis of Quasi-Brittle Materials

Yongxiang Wang, Columbia University
Haim Waisman, Columbia University

Failure of quasi-brittle materials is governed by crack formation and propagation which can be characterized by two phases: (i) diffuse material degradation process with initial crack formation and (ii) severe localization of damage leading to the propagation of large cracks and fracture. While continuum damage mechanics provides an excellent framework to describe the first failure phase, it is unable to represent discontinuous displacement fields. In sharp contrast, cohesive zone models are poorly suited for describing diffuse damage but can accurately resolve discrete cracks. The present work is devoted to a coupled continuous/discontinuous approach for modeling the two failure phases of quasi-brittle materials in a coherent way. The proposed approach involves an integral-type nonlocal continuum damage model coupled with an extrinsic discrete interface model. The transition from diffuse damage to macroscopic cohesive cracks is made through an equivalent thermodynamic framework established in multidimensional settings, in which the dissipated energy is computed numerically and weakly matched. The method is implemented within the extended finite element framework, which allows for crack propagation without remeshing. A few benchmark problems involving straight and curved cracks are investigated to demonstrate the applicability and robustness of the coupled XFEM cohesive-damage approach. Force-displacement response, as well as predicted propagation paths, are presented and shown to be in close agreement with available experimental data. Furthermore, the method is found to be insensitive to various damage threshold values for damage-crack transition, yielding energetically consistent results.

131: From Discrete Particles to Continuum Fields

Thomas Weinhart, University of Twente

A challenge related to particle simulations is to bridge the gap towards macroscopic continuum quantities (constitutive relations) and towards the application to large-scale processes. There are many methods to extract spatially resolved continuum quantities from dynamic particle simulations. In many formulations, however, inhomogeneities near boundaries, shear zones or interfaces cause an error in the mass and momentum conservation. We present a novel coarse-graining expression for the stress tensor of discrete mechanical systems that is applicable near boundaries and interfaces [1]. It is derived by coarse-graining the mass and momentum balance equations, and thus satisfies them exactly. Boundary interaction forces are taken into account in a self-consistent way and thus allow the construction of continuous stress and interaction force fields, avoiding problems many other methods have near boundaries. The resolution and shape of the coarse-graining function used in the formulation can be chosen freely, such that both microscopic and macroscopic effects can be studied. The method does not require temporal averaging and thus can be used to investigate time- dependent flows as well as static and steady situations. Discrete element simulations of granular chute flows are presented to illustrate the strengths of the new boundary treatment. We show how to obtain expressions for the macroscopic stress tensor as a function of microscopic parameters and hence perform the micro-macro transition. As a model system, the expressions are applied to the flow caused by a jet of granular material impinging on an inclined plane [2]. Three flow regimes are present, i.e.: (i) a highly kinetic supercritical flow immediately around the point of impact, stretching towards the downslope direction, (ii) a slowly sheared subcritical zone, separated from the supercritical region by a shock, and (iii) a stagnant layer away from the point of impact.

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669: Full Gibbs Sampling Algorithm for Sparse Damage Detection for the Phase II IASC–ASCE Structural Health Monitoring Experimental Benchmarks

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To exploit the prior knowledge that damage typically occurs at a limited number of locations in the absence of structural collapse, we have previously proposed a series of Bayesian methods for the stiffness loss inverse problem[1-3]. These methods build on developments in Sparse Bayesian learning (SBL)[4] where sparseness of the inferred structural stiffness loss is promoted automatically, allowing robust damage localization with high-resolution. A specific hierarchical Bayesian model is employed where the Bayesian analysis at the lowest level can be done analytically because it involves Gaussian distributions. However, the higher levels involve the evaluation of multi-dimensional integrals over hyper-parameters of the Bayesian model that are analytically intractable. Laplace's method of asymptotic approximation was used in our previously proposed SBL methods. The Laplace approximations that we used ignored the posterior uncertainty in the hyper-parameters, as well as in the identified system modal parameters and the stiffness parameters from the calibration stage[1-3], which has limited applications for real structural identification with large modeling errors. A goal of the work presented here is to provide a full treatment of the posterior uncertainty by employing Gibbs sampling (GS)[5] to efficiently sample the posterior probability density functions (PDFs) of the high-dimensional uncertain parameter vectors that arise in our sparse stiffness loss inversion problem. The effective dimension is kept low by decomposing the uncertain parameters into a small number of groups and iteratively sampling the posterior distribution of one parameter group conditional on the other groups and the available data. Analytical expressions for the full conditional posterior PDFs are derived in order to implement the GS method. The effectiveness of the proposed approach is illustrated with the IASC–ASCE Phase II Experimental benchmark studies.

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187: Functionality-Fragility Surfaces: a Tool for Probabilistic Resilience Analysis of Bridges

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Paolo Bocchini, Lehigh University

The topic of infrastructure and community disaster resilience has gained a substantial attention from academic and professional communities, as well as government officials. To this respect, recently several researches have focused on observing, assessing, improving, and optimizing the resilience of critical infrastructures, such as power grids, water supplies, and transportation networks. These studies mainly target the two fundamental "ingredients" of resilience, namely vulnerability, and recoverability of the infrastructures. Among several infrastructures, transportation networks are of significant importance as the operation of many other critical infrastructures is highly interconnected with these lifelines. In particular, the role of transportation networks is more prominent in the aftermath of an extreme event when the lack of functionality can result in extensive short- and long-term direct or indirect losses. Thus, a thorough study of resilience of transportation networks and their components is of utmost importance. This includes airports, highways, and bridges, in particular. Several techniques and methodologies have been proposed for the probabilistic assessment of the fragility of bridges, in which the extent of damage is expressed as a probabilistic function of the intensity of the extreme event. However, for a fully probabilistic resilience analysis of bridges and transportation networks, it is necessary to evaluate the probabilistic characteristics of the serviceability of bridges (as opposed to their damage state) at different stages of the post-disaster management, including the response and recovery phases. To this respect, this paper presents a framework through which a new dimension can be added to the fragility curves generated by common techniques available in the literature, which reflects the time-dependent probabilistic characteristics of the functionality of bridges. A simulation-based scheduling optimization algorithm is utilized to construct different realizations of the bridge post-event restoration construction process, considering the level of components initial damage, available restoration resources, and common construction considerations in practice. To showcase the application of the presented methodology, a fully probabilistic analysis is performed to generate the functionality-fragility surface of a bridge. This includes the seismic fragility and restoration modeling of the studied bridge. The possible expansion of the technique to probabilistic resilience assessment and optimization of transportation systems is discussed.

734: Fundamental Two-Stage Formulation for Bayesian System Identification

Siu-Kui Au, University of Liverpool
Feng-Liang Zhang, Tongji University

Structural system identification is concerned with the determination of structural model parameters (e.g., stiffness, mass) based on measured response data collected from the subject structure. For linear structures, one popular strategy is to adopt a 'two-stage' approach, where modal properties (e.g., natural frequency, mode shape) are identified in Stage I and then used to identify the structural parameters in Stage II. While Bayesian approach is seen to provide a fundamental means for the problem, deriving the posterior distribution of structural parameters

in Stage II conditional on information of modal properties in Stage I is highly non-trivial. Formulations so far have been inevitably heuristic in nature and they may distort the fundamental nature of the Bayesian approach. This presentation provides an answer to the two-stage problem and discusses its implications. Although motivated by structural system identification, the theory is applicable to general system identification problems.

490: Gauss's Principle of Least Constraint and Nonholonomic Dynamics

Karah Kelly, Duke University
Henri Gavin, Duke University

Gauss's Principle of Least Constraint provides a systematic approach to modeling constrained dynamical systems, regardless of the classification of the constraints. The Principle is reduces the equations of motion to the minimization of a quadratic constraint subject to a set of linear equality constraints. The objective need not be positive definite, as long as the null space of the Hessian is spanned by the range of the constraint gradients. These concepts are illustrated in the study of rolling isolation systems. Rolling isolation systems provide a simple and effective means for protecting components from horizontal floor vibrations. In these systems a platform rolls on four steel balls which, in turn, rest within shallow bowls. The trajectories of the balls is uniquely determined by the horizontal and rotational components of the rolling platform, and thus provides nonholonomic constraints. In general, the bowls are not parabolic, so the potential energy function of this system is not quadratic. In applying Gauss's principle of least constraint, the equations of motion are described in terms of a redundant set of constrained coordinates. In the absence of any modeled damping, the equations of motion conserve energy. Simulations and experiments show that responses are highly sensitive to small changes in the initial conditions; peak responses can be predicted only statistically.

261: Gaussian Process Models for Truncated Response Data

John McFarland, Southwest Research Institute

Gaussian Process regression is widely used to create fast-running response surface models as surrogates for computational models. One of the limitations of this method is that the usual formulation uses a stationary covariance function, which models the rate and scale of the response fluctuations in terms of parameters that are constant over the input space. This presentation discusses a particular scenario in which this modeling assumption becomes problematic, which is when the training data response values are truncated or censored at a lower or upper limit. As an example, fatigue or life-prediction models may truncate the life calculations at a fixed upper bound. This work proposes a hybrid two-part modeling approach. First, a classification model is used to classify inputs as to whether the associated response will fall above or below the cutoff value. Those data that fall below the cutoff value (in the case of an upper bound) are then modeled using the usual stationary Gaussian Process regression approach. Different approaches for the formulation of the classification model are discussed, including trees, support vector machines, and Gaussian Process classification using latent functions. The proposed method will be demonstrated on fatigue life prediction data obtained from the DARWIN® software. DARWIN is used for probabilistic risk assessment of gas turbine engine rotating components. As part of DARWIN, a deterministic fracture mechanics module predicts fatigue life as a function of initial flaw size, stress multiplier factor, and other inputs. The demonstration study will compare different methods for creating a response surface that predicts fatigue life, with the challenge being that some of the fatigue life training data are truncated at an upper limit.

415: General Elements for XFEM Using Physically-Based Enrichment Parameters

Iman Asareh, University of South Carolina

A general and local extended finite element method for modelling arbitrary dynamic cracks is presented with a new formulation for element-by-element crack propagation in explicit methods. The proposed method allows the enrichment parameters to be chosen based on physical quantities of interest such as a crack jump and the relative movement of a crack inside the element. A methodology is developed to construct local enrichment functions that encapsulate the enrichment within the element and vanish outside the element domain. This encapsulation leads to a significant simplification in object oriented programming. By describing the enrichment parameters independent of the element type, the crack can propagate through different element types requiring minimal changes in explicit methods. For specific element types, we show that the results are equivalent to the XFEM method with shifted sign enrichment functions. The approach also dissociate the finite element nodes from the enrichment function definitions so that the critical time step can be easily reduced using mass lumping techniques. The proposed method is applied for several numerical examples to demonstrate the robustness and utility of the method.

583: Generation of Conformal Finite-Element Meshes from 3D Measurements of Microstructurally Small Fatigue-Crack Propagation

Ashley Spear, University of Utah
Jacob Hochhalter, NASA Langley Research Center
Albert Cerrone, GE Global Research Center
Anthony Ingraffea, Cornell University

In an effort to computationally reproduce the observed evolution of a microstructurally small fatigue crack (MSFC) within a polycrystalline alloy, a method has been developed for converting 3D measurements of MSFC propagation into geometrically explicit finite-element (FE) volume meshes. The method relies on a voxel-based description of the microstructure and leverages the surface-meshing capabilities in an existing software called DREAM.3D. The final set of volume meshes contains traction-free surfaces that conform to incrementally measured 3D crack shapes. Grain morphologies measured using near-field high-energy X-ray diffraction microscopy (HEDM) are also represented explicitly within the FE volume meshes. Proof-of-concept simulations are performed to demonstrate the utility of the mesh-generation method. The proof-of-concept simulations employ a crystal-plasticity constitutive model and are performed using the conformal FE meshes corresponding to successive crack-growth increments. The crystal orientation of each grain, as measured from HEDM, is included as an input to the constitutive model. Although the proof-of-concept simulations are carried out independently of one another (i.e. without maintaining material-state history throughout crack growth), it is possible to transfer material state variables from one crack-increment mesh to the next in a relatively straight-forward manner. The material-state transfer approach will be discussed. The mesh-generation method that we present was developed by using post-mortem measurements of MSFC propagation, yet it is general enough that it can be applied, with little to no modification, to in-situ measurements of 3D MSFC propagation.

322: Generation of Higher-Order Stochastic Material Morphologies Using Bispectral Representation Method

Hwanpyo Kim, Johns Hopkins University
Michael Shields, Johns Hopkins University

Many macroscopic properties (e.g. mechanical and/or transport properties) of random heterogeneous media are strongly dependent on the stochastic properties of the morphology – many of which go beyond the conventionally modeled 1st and 2nd order properties (i.e. mean and correlation structure). There have been a number of efforts to generate random media over the past 20 years. However, the majority of these efforts consider only 2-point correlation functions, which are often insufficient to ensure that the reconstructed media match the target and possess the correct material properties. Those methods that do incorporate higher-order features require the solution of complex non-unique inverse problems and, in addition to being complex, they can be very computationally expensive. To incorporate higher-order properties of these media in stochastic simulations, we propose the Polyspectral Representation Method – which is an analytically derived extension of the classic Spectral Representation Method (SRM) that expands the field from higher-order spectra (polyspectra). A specific formulation, the Bispectral Representation Method (BSRM) for simulating stochastic media with 3-point correlation (3rd order cumulant) is considered in this presentation. The presented simulation methodology for random media with BSRM is computationally affordable and extension of the method to capture the desired n-point correlation will be discussed. The 1 and 2-dimensional realization of material media with BSRM will be discussed.

277: Global sensitivity analysis for time-dependent, multidisciplinary simulation

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Sankaran Mahadevan, Vanderbilt University
Benjamin Smarslok, AFRL - Structural Sciences Center

Identifying and tracking critical sources of uncertainty in transient multidisciplinary analyses (such as predicting the aerothermoelastic response of airframe components) presents a unique challenge due to having multiple models operated in succession and several outputs of interest evolving through time. The first step in identifying dominant uncertainty sources lies in a quantitative sensitivity analysis of each model output to the various candidate uncertainty sources. These candidate uncertainty sources include: (1) natural variability in model inputs (e.g., aerodynamic loads and geometry); (2) data uncertainty from measurement variability, experimental errors, and sparse data; and (3) model errors due to simplified or poorly understood physics and numerical approximations. Several sensitivity analysis methods are available for simplified linear and single-discipline problems. This presentation will explore efficient sensitivity analysis strategies for multi-physics, time-varying simulations. Sobol's variance-based sensitivity indices quantify the share of the variance in a particular model output contributed by each individual uncertainty source as well as groups of uncertainty sources. These indices are traditionally estimated using Monte Carlo sampling based methods which are often computationally expensive due to a large number of model calls required for forward propagation. Often meta-models, or surrogates, are used to reduce the computational expense and make sensitivity analysis affordable. For time-dependent, multidisciplinary analyses with several interacting models and parameters, constructing an overarching surrogate model may not be computationally feasible or accurate. The problem becomes more complicated in the case of simulation over time. Therefore, intelligent sampling of the input uncertainty parameter space is needed to propagate through the multidisciplinary physics models. This has been done in the past using optimal Latin-Hypercube sample designs and FAST methods. The proposed methodology borrows concepts from experimental design techniques to iteratively and sequentially select the optimum samples for uncertainty propagation, and minimizing errors in global sensitivity estimates. The developed method will be illustrated for the efficient sampling to compute Sobol's sensitivity indices for a hypersonic vehicle panel simulation that involves four disciplinary analyses to predict the panel's aerothermoelastic response, namely aerodynamics, aero-heating, heat transfer, and structural deformation models.

756: Grain Size-Effect in Granular Micromechanics

Payam Poorsolhjouy, University of Kansas
Anil Misra, University of Kansas

In this presentation the non-linear damage-plasticity granular micromechanics method previously proposed for cementitious materials is enhanced by incorporating the effects of grain sizes in the formulation. In the method of granular micromechanics, the continuum behavior of the material is derived by considering the inter-granular behavior of all grain-pair interactions within the material. The non-linear damage-plasticity model presented previously for cementitious materials1, demonstrated many characteristic features of the behavior of these materials at the macro-scale by utilizing simple microscopic force laws defining the force-displacement relationship of grain-pair interactions. The derived thermodynamically consistent model was able successfully describe macro-scale tension-compression asymmetry, effect of confinement in the material behavior and failure pattern, load path dependence in the material response, and loading induced anisotropy.In the enhanced method to be presented, the effect of grain size is incorporated into the method of granular micromechanics by considering its influence at the micro-scale in terms of grain- interaction behavior. As a result, the method is able to predict the grain-size effects on the macro-scale of granular media. In particular, simple proportional relationships are utilized to model the effect of grain size on inter-granular displacements, volume density of inter-granular interactions in an RVE of the granular material. Further new formulations for grain-interaction behavior are introduced that incorporate the grain-size effect upon inter-granular stiffness coefficients, and inter-granular failure behavior. Using these relationships, size-effect relationships for macroscopic response of the material (macroscopic stiffness tensor and the Cauchy stress) are predicted. These results are calculated for parameters that are calibrated using experimental data available in the literature. Results from the implementation of the model into commercial finite element codes for solution of large-scale problems will also be demonstrated. The proposed model represents an alternative approach to model grain-size effects on the macro- scale behavior.1 Misra, A. and Poorsolhjouy, P. (2015), "Granular Micromechanics Model for Damage and Plasticity of Cementitious Materials Based upon Thermomechanics" Mathematics and Mechanics of Solids, DOI: 10.1177/1081286515576821

722: Grainsize Effects in the Comminution of Granular Materials: A Micromechanical Interpretation

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Giuseppe Buscarnera, Northwestern University
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The yielding pressure of brittle granular soils is known to depend on the size of the constituting particles. Such grainsize effect is important for a variety of problems, such as pile driving in sand, the design of rockfill dams, and the assessment of borehole stability. At the grain scale, fracture mechanics and Weibull statistics are useful tools to characterize the crushing potential of single particles. At the sample scale, the Breakage Mechanics theory offers physical insights on the macroscopic response of crushable granular assemblies. However, gaps still exist between these approaches, since they describe particle breakage process at widely differenct length scales.This contribution aims at bridging such descriptions through energy arguments1. First, the single particle crushing energy under uniaxial loading conditions is derived in analytical form by using fracture mechanics and the Weibull weakest link theory for a range of contact laws (i.e. flat, spherical and conical contacts) and failure modes (i.e. contact, center and random cracks). A simple liner scaling law is then proposed to link the fracture energy of individual particles with the energy threshold required to initiate collective grain crushing in the Breakage Mechanics theory2. Such threshold plays indeed a central role in quantifying the size of the yield surfaces, thus affecting the stresses at the onset of comminution. The validity of this hypothesis is finally assessed against datasets of crushing pressures reported in the literature3, showing that the link between particle-scale fracture and sample-scale energetics enhances the predictions of the theory by capturing correctly the grainsize dependence of the yielding pressure. This approach can be readily applied to extrapolate the yielding stresses measured from small-scale laboratory samples to the actual particles used in railway engineering and rockfill dams. It also opens new avenues to infer the macroscopic effects of particle-scale characteristics, such as the fracture toughness of the constituting minerals, thus enabling the analysis of the effect of the environmental agents that may alter such properties (e.g., water vapor, pore fluid chemistry).

33: Harmonic Analysis of Elliptical Hollow Section Tubes in Bending

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Leroy Gardner, Imperial College London

The bending of tubular members leads to flattening towards the axis of bending, thus reducing the second moment of area. Eventually, a limit point is reached whereupon the initial stability of the system is lost and unstable equilibrium prevails, thus reducing the load-carrying capacity of the member. This effect was originally described by Brazier in 1927 for circular tubular members. In the present study, the analysis of Brazier is adapted for elliptical hollow section members, taking into account the additional geometric complexities inherent in ellipses. An analytical method is presented whereby the initial geometry and the displacement functions of the system are replaced by superpositions of harmonic functions of the angular coordinate (Fourier series), thus reducing the analytical complexity of the problem. After formulating the potential energy functional, use of a variational method allows for the amplitudes of the constituent harmonics of the Fourier approximations of the displacement functions to be solved, providing estimates of the deformed geometry of the cross-section and the associated moment. In keeping with the analogy of Brazier for circular sections, a limit point is observed. These analytical predictions are then compared with the results of a complementary finite element analysis, whereupon it is found that for smaller longitudinal curvatures there is close agreement between the analytical and numerical methods. For larger curvatures and moments beyond the limit point some divergence is observed between the predictions of the two methods, which can be attributed to the lower-order approximations assumed in formulating the potential energy functional in the analytical method.

370: Heavy Tailed Distributions in Diffused Wave-Fields: A New Tool for Imaging through Scattering Media?

Salvatore Buonocore, University of Notre Dame
Mihir Sen, University of Notre Dame
Fabio Semperlotti, Purdue University

In recent years, the development of non-intrusive imaging techniques have seen a rapid expansion in many fields of engineering, applied science, and medicine. Many of these techniques leverage the attenuation, scattering, and diffusion mechanisms associated with field transport theory. Regardless of the diffusive or propagating nature of the field transport process, this class of problems has been typically modeled using analytical and numerical tools of the classical continuum theory that are rooted in integer order differential or integral models. Numerous experimental results have recently confirmed the existence in nature of many phenomena that do not behave exactly in a purely diffusive or propagating way. In particular, several studies have shown the occurrence of anomalous diffusion associated with wave-like propagating fields in inhomogeneous scattering media. In this context, fractional calculus models have provided a powerful tool to accurately capture the nature of the anomalous propagation process. The present study concentrates on the anomalous diffusion process arising from

the propagation of an initially collimated wave-field through a highly scattering medium. By using both stochastic molecular and fractional continuum models, we numerically explore the transition between the purely propagating and the diffusive mechanisms with particular attention to the formation of heavy-tailed distributions of the field intensity. The study also tries to identify a connection between micro- and macro-scale behavior in order to clarify the role of fractional continuum models. Our results suggest that the ability to interpret the information available in the tails of distributions could provide a valuable tool for novel techniques that are able to image through scattering media.

202: Hierarchical Upscaling to Inform Continuum Constitutive Models of Soils

Erik Jensen, University of Colorado
Richard Regueiro, University of Colorado

Funded by an Office of Naval Research (ONR), United States Department of Defense, Multidisciplinary University Research Initiative (MURI) grant, the primary goal of the project is to use state-of-the-art multiphase and multiscale modeling tools to model partially saturated soil failure under buried explosive loading. Concurrent high strain rate experimentation using split Hopkinson pressure bars, shock tubes, and modified triaxial cells conducted on a variety of soils as well as geotechnical centrifuge blast experiments are being conducted to be used for verification and validation of the numerical model. In addition, the soils used for the experimentation are a sand and clay extracted from the ground rather than the more homogeneous "laboratory" soils typically used in geotechnical research in an effort to capture the behavior of a "real" soil or soil mixture.This work focuses on the hierarchical upscaling algorithms that will be used for the multiscale modeling component of the overall project. A two scale numerical model is being developed for the project. The gain-scale will be a combination of four coupled modeling methods: discrete element method (DEM) with added grain crushing for the sand particles, peri-dynamics to model clay fracture (PD), smooth particle hydrodynamics (SPH) for the liquid water, and computational fluid dynamics (CFD) for the background air and water vapor. This complicated grain-scale model will be coupled to a macroscale material point method (MPM) continuum model (developed in Uintah) using a hierarchical upscaling procedure. The MPM model will implement a new high-strain rate, elasto-plastic soil constitutive model (Arena) currently being developed for the project. Arena also includes a void disaggregation algorithm, the effect of temperature changes on the material properties, and Duvaut-Lions viscoelasticity. Currently, efforts have focused on using small cubes of DEM particles representing Colorado Mason sand to replace continuum constitutive models embedded within a finite element code. The finite element formulation contains full finite strain and dynamic kinematics, and the Mason sand is modeled using ellipsoidal particles. In general, the finite element code is used to calculate the strain at each integration point within the problem domain, which is then passed to DEM assemblies representing the Mason sand at each integration point. The DEM program applies the calculated strain via displacement boundary conditions and after the DEM simulation is completed, the homogeneous stress and stiffness of the assembly is passed back to the finite element code. This stress and stiffness are then used to calculate the strain at the next time step. The following are results from a two element mesh generated to model the aforementioned split Hopkinson pressure bar results for the sand.

505: High Performance Computing in the Modeling of Recycled Water Release Infrastructure in the City of Gold Coast, Australia

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Daniel Grimwood, Pawsey Supercomputing Centre

Population growth is placing increased pressure on the City of Gold Coast's recycled water release system, which is approaching hydraulic capacity. For almost a decade, DHI has supported investigations commissioned by Gold Coast Water (GCW) designed to assess short- and medium-term options for managing excess recycled water releases from the Gold Coast Seaway. GCW is investigating long-term staged solutions for upgrade and design of new recycled water release infrastructure. DHI has continued to support this effort through the development and calibration of a three-dimensional hydrodynamic and transport model. The model was designed to inform the environmental assessment of release options given the system's proximity to the highly sensitive estuarine Broadwater system and Moreton Bay Marine Park. In order to meet these goals, the spatial scale of the model needed to be extensive to capture regional hydrodynamics, while at the same time maintaining resolution fine enough to resolve local scale flow structures in the Seaway and the placement of diffuser infrastructure. These requirements necessitated an investigation into computational solutions beyond desktop computing. DHI's MIKE3 software has three types of parallelization: a shared memory approach (OpenMP, introduced R2008), a distributed memory approach (MPI, introduced R2011) and a multi-GPU approach (introduced R2016). Solutions using MPI and GPU architecture were investigated for suitability in terms of the project needs and timeline. Testing on HPC systems at the Pawsey Supercomputing Centre in Perth, Western Australia indicated that the model scalability lent itself to an efficient HPC solution to meet project goals. In the first phases of this project, DHI originally made use of a Hewlett Packard cluster delivering 87 TeraFLOPS of compute power. The recent addition of a petascale supercomputer to the Pawsey Centre allowed DHI to initiate the first compilation of the MIKE source code on a Cray OS. The efficiency and speed of the new system allowed the model to run at almost twice the speed of the original system. Access to the computing and human expertise of the Pawsey Centre allowed the project to proceed with much more advanced and highly resolved models than had been employed in prior phases of the project, which has been instrumental in the decision making process for the design of future excess recycled water release infrastructure.

670: Homogenization of Inter-Granular Fracture Towards a Transient Gradient Damage Model

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It is well documented that standard damage models become ill-posed during strain softening, leading to numerical results which are mesh dependent. One remedy is to incorporate higher-order enhancements to regularize the softening behavior, with the associated length scale parameter collectively characterizing the various micro-processes underlying the localized deformation. However, a clear physical interpretation and decomposition of the length scale parameter is often lacking. In many higher-order damage models, a constant length scale parameter is adopted, which may result in spurious damage growth at high deformation levels – instead of localizing into a single crack, the damage region expands with deformation. In view of this anomaly, a strain-based transient gradient damage model was proposed by Geers et al (1998), where the nonlocal interaction is controlled by a gradient activity parameter through a phenomenological evolution law. In this contribution, we focus on the failure of polycrystalline materials which are dominated by inter-granular cracks. At the meso scale, the fracture process can be modelled by inserting cohesive elements at the grain boundaries. For a typical engineering problem, however, having such a detailed resolution can be computationally expensive. Motivated by the need for a more efficient model that adequately describes the failure process, we proposed a homogenization theory that consistently translates the fine-scale inter-granular fracture model onto the macro level. For simplicity, a uniaxial problem is considered. Through the scale transition, a Helmholtz-type homogenized microforce balance is extracted, which resembles a generalized micromorphic continuum. In addition, the non-local interaction in the microforce balance has a transient nature, hence avoiding the spurious damage growth naturally. A 1D spectral analysis reveals that the softening response is well-regularized, with a vanishing localized bandwidth at complete failure. Moreover, the homogenized material response compares well with reference solutions obtained from direct numerical simulations. The contribution of the work is highlighted: in contrast to the many gradient damage models in literature which are formulated top-down, our homogenized damage model is obtained bottom-up. Constitutive assumptions at the macro-level are thus minimized, since the fine-scale properties (e.g. grain size, surface modulus) propagate and naturally manifest themselves in the length scale parameter at the macro level.

410: Hydro-Thermal Coupled Multiphysics Simulation for Health Monitoring of Embankment Dam

Chung Song, University of Nebraska-Lincoln
Tewodros Yosef, University of Nebraska-Lincoln

Seepage induced temperature profiles in embankment dams may indicate a leakage or high permeability zone in the dam body. A Multiphysics approach that coupled seepage and heat transfer was used in this study. Numerical analysis was performed using VS2DH1 for an actual dam with continuously measured temperature data. From this research it is shown that the high temperature profile at deep depth of the studied dam could be caused by hot water inflow from surrounding area, not from piping or other issues. It is also shown that the temperature stabilization time of the dam could be much longer than usually expected – temperature was not stabilized even in 10 years for the dam analyzed in this study. This finding may impose a new light in analyzing long term behavior of earthen dams.

693: I(mmer)sogeometric Design and Analysis of Artificial Heart Valves

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Austin J. Herrema, Iowa State University
Josh Mineroff, Iowa State University
Michael C. H. Wu, Iowa State University
Fei Xu, Iowa State University

In this presentation we focus on an isogeometric design-through-analysis platform developed to help design engineers and analysts make more effective use of IGA to improve their product performance. The platform takes input design parameters, generates appropriate geometric models, performs mechanical analysis, post-processes the solution fields, and executes optimization packages, all within the same CAD program. This design-centric combination of parametric modeling and IGA offers truly seamless design-and-analysis iteration and the ability to gain a high degree of knowledge about the parametric design space and inherent optimal design tradeoffs. The presentation concludes by discussing a recently proposed geometrically flexible technique for fluid–structure interaction (FSI). The proposed immersogeometric method immerses complex design objects into an unfitted discretization of the surrounding fluid domain and weakly enforces boundary conditions on the objects' surfaces. We show that this immersogeometric capability can be integrated into our platform and serve as an apt vehicle for high-fidelity multidisciplinary parametric optimization for the purpose of artificial heart valve design.

665: Identifiability Assessment of Nonlinear Structural System Identification Problems

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Robert Bitmead, University of California, San Diego

Identifiability of parametric models investigates the question of existence and uniqueness of the solution of the associated parameter estimation problem. The identifiability problem is closely related to the experimental design and optimal sensor placement problems, which respectively aim at designing the input excitation and sensor locations to measure the most informative data about the parameters to be estimated. This paper investigates the problem of model identifiability in structural system identification based on nonlinear mechanics-based finite element (FE) models. Recently, a new approach for nonlinear system identification of civil structures that can be applied for post-disaster structural health monitoring and damage identification of real-world civil structures has been developed. In this approach, the measured input excitation and output response of a civil structure during a potentially damaging event are utilized to update in the time domain an advanced mechanics-based nonlinear FE model of the structure of interest using Bayesian inference methods. The nonlinear FE model of the structure depends on a set of unknown model parameters including but not limited to the parameters characterizing the nonlinear material constitutive laws. The model parameters are estimated by minimizing the discrepancy between the time histories of the FE predicted and measured structural responses during the potentially damage-inducing event, accounting for the various sources of uncertainty. As for any parametric system identification problem, the accuracy and robustness of the underlying parameter estimation procedure depends on the information contained in the measurements about the model parameters. It is therefore crucial to provide a systematic process to select the model parameters and the sensors arrangements to harvest the maximum possible information about the parameters. In this study, a statistical metric is proposed to quantify the information contained in every individual measurement channel about every individual model parameter. This one-to-one identifiability measure is developed by evaluating the difference between the Shannon entropy of the prior and posterior probability distribution functions (PDF) of the model parameters. The presented approach provides a measure of identifiability of nonlinear structural FE models, which can have immediate applications in parameter selection, optimal sensor placement, and design of experiment. Moreover, the framework presented in this study offers a generic one-to-one identifiability measure that can find useful applications in nonlinear system identification problems from various engineering disciplines. The application of the proposed identifiability approach is illustrated in this paper through a 3D 5-story 2-by-1 bay reinforced concrete (RC) frame building model subjected to bidirectional horizontal earthquake excitation.

139: Identification of High-Resolution Vibration Modes of Structures from Video Camera Measurements Only

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Tyler Mancini, State University of New York at Buffalo
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Experimental or operational modal analysis traditionally requires physically-attached wired or wireless sensors for vibration measurement of structures. The sensor instrumentation could result in mass-loading on lightweight structures, and is costly and time-consuming for large civil structures, especially for long-term applications (e.g., structural health monitoring) that require significant maintenance and labors for cabling (wired) or energy supply

(wireless). In addition, these sensors are discrete point-wise, providing low spatial sensing resolution that is hardly sufficient for larger structures. Non-contact optical methods such as scanning laser vibrometers provide high-resolution sensing capacity without the mass loading effect; however, they operate sequential measurement that requires considerable acquisition time. As an alternative non-contact method, digital video cameras are relatively low-cost, agile, and provide high spatial resolution, simultaneous, measurements. Combined with vision based algorithms (e.g., image correlation or template matching, optical flow, etc.), video camera based measurements have been successfully used for experimental and operational vibration measurement and modal analysis, such as the digital image correlation (DIC) and the point-tracking techniques. However, they typically require speckle pattern or high-contrast markers instrumented on the surface of structures, which raises the instrumentation issue when the measurement area is large or inaccessible. This work explores advanced computer vision and video processing algorithms to develop a novel video measurement and vision based operational modal analysis method that removes the need of structural surface preparation in existing vision based methods. By manipulating the motion encoded in the video measurements only, the proposed method efficiently and accurately extract frequency, very high-resolution mode shapes, and damping ratio of the structure, and is validated by laboratory experiments.

302: Image Processing for Damage Diagnosis and Uncertainty Quantification

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Sankaran Mahadevan, Vanderbilt University

Digital image processing techniques have been studied in the context of non-destructive testing (NDT) of structures and materials. Current image processing techniques for concrete damage diagnosis mainly focus on detection of cracks on the surface of the structure. We investigate an image processing technique for concrete internal damage diagnosis based on thermal imaging. The method is based on Sobel operator and statistical learning, and is capable of detection, localization, and quantification of the damage. A particular feature of the proposed methodology is uncertainty quantification in the damage diagnosis result, by aggregating various sources of uncertainty introduced at each step of the image processing. Further, global sensitivity analysis is applied to identify the dominant contributors to diagnosis uncertainty. Based on the results of uncertainty quantification and global sensitivity analysis, a maximum likelihood technique is formulated to identify the optimal parameters at each step of the image processing, in order to minimize the uncertainty in diagnosis. An illustrative example of damage diagnosis of concrete slabs is used to demonstrate the effectiveness of the proposed approaches for damage diagnosis, uncertainty quantification, and parameter selection. The damage diagnosis procedure using thermal imaging consists of four steps: cropping, smoothing, feature calculation, and diagnosis decision-making. In each step, the analyst has to select values for different parameters. First, in the cropping step, we need to select proper geometrical coordinates to crop the images. Secondly, in the smoothing step, we need to determine the selection of filters and their parameter-settings. Third, in the feature calculation step, we need to choose and calculate features, which are sensitive to internal damage. Lastly, in the diagnosis decision-making step, we need to select appropriate criteria to judge the condition of the structure. Our proposed methodology considers the uncertainty in the choice of parameters at each stage, and quantifies the overall uncertainty based on Monte Carlo simulations. Thereafter, based on experimental observations, the proposed methodology provides optimized parameter settings for further damage diagnosis and prognosis.

485: Image-based Multi-scale Modeling and Simulations of High Energy Ball Milled Porous Composites

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To identify shock conditions under which materials with tailored properties can be synthesized is a key challenge in materials design. Shock-induced synthesis of high-energy ball milled composites is a very promising technique for new material production. Modeling and simulations may provide key insights on the synthesis processes, towards definition of optimal material properties and operation conditions. Simulations however are computationally feasible only if modeling is guided by localized physical phenomena and by the material morphology. This approach is here termed image-based multi-scale modeling. It encompasses hierarchy of spatial and temporal scales as well as constitutive models. Subdomains in which scale separates will be identified, allowing ensemble averaging via computational homogenization approaches. The morphology of the micro-scale computational domain, usually termed representative unit cell, is reconstructed from experimental data, so to respect the statistical distribution of material characteristics at each scale (particles, layers, crystals). In this regard, recent research highlighted the significance of accurate higher-order statistical description of heterogeneous materials to predict effective thermo-mechanical properties with high fidelity. Uncertainty quantification provides a platform for model selection and propagation of uncertainties through the computational framework. In this contribution, multi-scale simulations will be carried out under quasi-steady and shock conditions. At the micro-scale, representative unit cells will be constructed based on experimental observations, which will dictate particle packing - by controlling geometrical features, distribution of particles, and percolation paths - as well as the morphology of two-phase Ni-Al particles that are generated during the high-energy ball milling process - up to crystals distributions. Crystal plasticity constitutive laws will be adopted. Numerical solution of space-time adaptive micro-continuum problems in a high-performance computing environment will show the effectiveness and robustness of the approach.

146: Impact of Boundary Conditions and Modeling Assumptions on the Coupled Response of Structural Panels in High Speed Flow

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Accurate characterization of the long time record coupled response of aircraft structures in extreme environments is an important challenge in the development of reusable air-breathing hypersonic vehicles. In particular, response of thin gauge structural panels to high speed turbulent boundary layers and shock impingements represents an extreme loading condition due to the potential for material degradation and damage. There are numerous practical challenges in reproducing the extreme environments and the associated fluid-structure interactions in a laboratory setting. High fidelity modeling tools that reliably predict the physics are computationally prohibitive when conducting long time record (trajectory-level) studies. Consequently, state-of-the-art strategies in this emerging area of research rely on approximate formulations and reduced order modeling methodologies that are benchmarked using a limited amount of test data to capture the relevant multi-disciplinary interactions. In this context, understanding the impact of modeling assumptions on the coupled response is crucial in providing guidance for subsequent modeling improvements and testing efforts. The current work investigates the impact of thermal boundary conditions and assumptions in modeling the unsteady fluid loads on the coupled fluid-thermal-structural-material response of thin gauge structural panels in supersonic flow. The studies are conducted using a moderate fidelity fluid-thermal-structural computational framework that was developed in recent studies by the authors. Preliminary results indicate that the initial thermal state of the panel has a significant impact on both the coupled static and dynamic response of the panel. For a fixed initial thermal state, the coupled response of the panels was sensitive to the correlation present in the turbulent boundary layer pressure loads. The proposed study builds on these findings and aims to quantify the uncertainty in structural response due to uncertainties in multiple inputs or modeling assumptions. This study is intended to aid the creation of an uncertainty-informed multidisciplinary computational framework that represents an essential step in achieving the overall objective.

457: Impact of Vehicle Speed and Traffic Flow on Pavement-Vehicle Interaction Emissions at the Network Level

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Rolling resistance has been shown to be a significant contributor to the use-phase environmental impact of roadway networks [1]. It is therefore essential to take into account and minimize this impact when making network level decisions for sustainable design and maintenance of pavement infrastructure. Recently developed mechanistic pavement vehicle interaction (PVI) models quantify this impact by relating pavement properties, vehicle characteristics, speed and temperature to fuel consumption [2,3,4]. In this presentation we consider two distinct PVI models accounting for two different dissipation mechanisms; (i): deflection induced PVI model that takes into account the dissipation of energy within the pavement material and (ii): roughness-induced PVI model that quantifies the dissipation of energy within the suspension system. To have more accurate estimations of the network level fuel consumption, the variation of vehicle speed and the state of traffic flow (jam versus free flow) are taken into account. We study the impact of distribution of vehicle speed and the variation of traffic flow over time on deflection- and roughness-induced energy dissipation and--to evaluate the benefit gained from a more detailed analysis--compare the results with the fuel consumption estimates that are obtained using annual average daily traffic data readily available to state and federal agencies.

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700: Impact Response of Steel and Aluminum Foams

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For metal foams to be used in engineered systems subject to impact, the strain-rate dependent properties of the materials must be characterized and the deformation mechanisms fully understood. An open-cell aluminum and closed-cell steel foam have been tested using a drop-impact test protocol to assess dynamic material properties such as elastic modulus and yield stress as well as wave propagation speeds and energy absorption characteristics. High speed video footage of the impacts allows preliminary assessment of deformation mechanisms present in the materials. Comparisons between the dynamic properties and the quasi-static properties of these materials are made, based on previous work by one of the authors, to characterize the quasi-static material properties. Properties measured in the experiments are used to develop constitutive models that are then used within a finite element

analysis context to model the dynamic response of impact absorbing systems that use the metal foams as energy sinks and to demonstrate the potential application of metal foams as energy absorbers in infrastructure applications such as crash and blast protection of critical infrastructure components.

719: Implantable Magnetic Nanocompsites for Cancer Treatment

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Nima Rahbar, Worcester Polytechnic Institute
Wole Soboyejo, Princeton University

163: Implementation of Functionally Graded Materials in Compliant Mechanism Design using Topology Optimization

Cian Conlan-Smith, University of Illinois
Kai A. James, University of Illinois

In recent years compliant mechanisms have frequently been proposed for aerospace systems due to their advantages over traditional rigid-link mechanisms, such as low weight, low wear, and the elimination of the need for lubricants and assembly. Compliant mechanisms achieve motion and force transmission through the deflection of flexural members. However, stress limitations in these mechanisms produce restrictions on the design for the higher load applications frequently experienced in aerospace missions. These stress limitations result from high stresses at thin hinge-like junctions, which are necessary to allow the mechanisms to achieve large deformations. This research will use topology optimization to create feasible designs that are free of thin flexural hinges. More specifically, the solid isotropic material with penalization (SIMP) method will be used in conjunction with adjoint sensitivity analysis methods to produce an optimal material layout within the mechanism. To achieve hinge-free designs we look to nature for inspiration. For hinge joints in the human body, stiff structural bones allow load transmission while movement is achieved by the presence of compliant cartilage and ligaments at the center of the joints. This integration of compliant and stiff materials to achieve large deformations while allowing high load transmissions is implemented through the use of functionally graded materials (FGMs). FGMs produce a smooth continuous variance in material properties throughout a structure, allowing a stronger material form to be focused towards the input and output ports of the mechanism, with a rubber-like material form focused towards joints. By replacing thin joints with thicker rubber-like joints, stresses will be more evenly distributed, thus reducing the design limitations and broadening the potential for complaint mechanisms in aerospace applications. These mechanisms are fabricated using 3D printing and so appropriate methods are incorporated to convert the digital material gradients from topology optimization results to physical FGM mechanisms. Several examples of optimized functionally graded compliant mechanisms will be presented, and their performance will be compared with that of conventional homogenous mechanisms.

736: Implications of Grain Morphology on the Rheology of Dense Granular Flows

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José E. Andrade,

The non-smooth contact dynamics (NSCD) method is applied to the simulation of particle me-chanics. This method treats particle as being perfectly rigid; small elastic wave propagation and deformation are neglected due to the fact that the overall deformation of a particle system is majorly due to particle rearrangement. In this paper, the contact law integrated as a linear optimization problem with inequality constraint (complementarity formulation), an implicit algorithm based onimpulse-momentum law in determining inter-particle force and an explicit algorithm for systemcon guration evolution are presented. We then use this method to analyze the quasi-static loadingbehavior of a given particle assembly such as force transmission and distribution of deformation.In the meantime, the e_ects of particle shape, inter-particle friction coe_cient on its loading re-sponse are also analyzed. We show that this method is capable of handling the simulation of aparticle system with arbitrary shape and capturing its loading behavior without introducing non-physical parameters as being done in other explicit methods. Lastly, issue of solution existence andrestitution coe_cient e_ect is discussed.1

115: Improvement of Contact Force Model and Failure Criterion of Bonded Dilated Polyhedral Elements

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Shunying Ji, Dalian University of Technology

The dilated polyhedral element is constructed based on the Minkowski sum theory in this study. The dilated element is constructed via sweeping over a sphere on the surface of the basic polyhedral element. The normalized Hertz contact force model is introduced to calculate the contact force considering the various contact modes between dilated polyhedral elements. A bonding-failure model with the elastic force acting on the shared common plane between contacted elements is adopted to simulate the breaking process of continuum. The elastic force is calculated with the elastic modulus, the element shape and the contact area. The breaking process on the shared common plane can be modelled with the given inter-particle bonding strength. Meanwhile, the detached plane method is used to speed the detection of elements. Moreover, the bonded dilated polyhedral elements are adopted to simulate the failure process of sea ice via the Brazilian disk test. The simulated results are compared with the physical experiments to validate the failure criterion of the bonded elements. As a typical engineering application, the interaction between sea ice and ship is simulated with dilated polyhedral elements to determine the ice loads on the hull. The influence of ice thickness, velocity, ice floe size on the ice loads are discussed based on the numerical results.

479: In Situ Material State Monitoring Using Embedded Cadmium Selenide Quantum Dots

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Talitha Frecker, Vanderbilt University
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Kane Jennings, Vanderbilt University
Douglas Adams, Vanderbilt University

Traditionally, many structural health monitoring (SHM) and nondestructive evaluation (NDE) systems and applications have relied on the use of external sensors to communicate and localize damage in a variety of structures and materials. Though many of these systems have proven to be effective at detecting and communicating the occurrence of external forces acting on a system, they are inherently hindered by their requirements for continuous data collection and power consumption. This research seeks to develop a novel damage detection methodology focused on the direct incorporation of sensing capabilities within a material, where damage can be detected and communicated without the need for external sensors or power. To accomplish this goal, this research is focused on the implementation of ultrasmall Cadmium Selenide (CdSe) white light emitting quantum dots to probe and detect changes in the material state intrinsically within composite materials. In previous work, a baseline emission spectrum for undamaged epoxy samples containing CdSe quantum dots has been established. In this work, epoxy samples containing varying %-weights of CdSe quantum dots, ranging from 0.5% - 5%, will be exposed to external loads and the corresponding shift in emission spectra will be analyzed. It is hypothesized that the light emission spectra of samples with embedded CdSe quantum dots will show a continuous decrease with the application of damaging loads being applied to the system. The response of samples containing CdSe quantum dots will be tested for various external loading states including, but not limited to: compression, tension, cyclic, chemical and thermal forces. By correlating and analyzing the difference in emission spectra between the damaged and undamaged samples, the effectiveness of using ultrasmall CdSe quantum dots to detect and communicate changes in material state intrinsically after the application of external loads will be evaluated.

497: Inelastic Base Shear Reconstruction from Sparse Acceleration Measurements of Buildings

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Henri Gavin, Duke University

This paper presents a novel method for recovering base shear forces of building structures with un-known nonlinearities from sparse seismic-response measurements of floor accelerations. The method requires only direct matrix calculations (factorizations and multiplications); no iterative trial-and-error methods are required. The method requires a mass matrix, or at least an estimate of the floor masses. A stiffness matrix may be used, but is not necessary. Essentially, the method operates on a matrix of incomplete measurements of floor accelerations. In the special case of complete floor measurements of systems with linear dynamics and real modes, the principal components of this matrix are the modal responses. In the more general case of partial measurements and nonlinear dynamics, the method extracts a number of linearly-dependent components from Hankel matrices of measured horizontal response accelerations, assembles these components row-wise and extracts principal components from the singular value decomposition of this large matrix of linearly-dependent components. These principal components are then interpolated between floors in a way that minimizes the curvature energy of the interpolation. This interpolation step can make use of a reduced-order stiffness matrix, a backward difference matrix or a central difference matrix. The measured and interpolated floor acceleration components at all floors are then assembled and multiplied by a mass matrix. A sum (or weighted sum) of the resulting vector of inertial forces gives the base shear. The proposed algorithm is suitable for linear and nonlinear hysteretic structural systems.

35: Inelastic Coupled Yield Surface Development for Standard Steel Sections

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Tathagata Ray, New Mexico State University

The shear stress and strain distribution in inelastic range was modeled for the steel cross sections by satisfying the equilibrium to the shear force and the boundary conditions of the shear strain. This model captured the finite element based shear stress and strain distribution responses from ABAQUS/CAE with considerable agreement. The standard inelastic moment-curvature response and the newly developed shear stress-strain distribution was then applied in modeling axial, shear and bending moment interaction for steel sections. The resulting macroscopic stress resultant based yield surface is based on the section integration of the mutually interacting microscopic normal and shear stress components. The interaction of the microscopic stresses was based on the von Mises criterion. Newton-Raphson iteration method was used to implement the algorithm for updating the

stress and stress resultants. The application of the proposed yield surface has been demonstrated numerically for a typical frame structure.

289: Infill Strut Model Class Uncertainty of Seismic Response of Reinforced Concrete Masonry Infilled Frames

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This paper assesses the effect of incorporating uncertainty related to infill strut model class selection on the probabilistic seismic demand analysis (PSDA) of a reinforced concrete masonry infilled frame. The work is based on a novel modeling approach that is proposed to estimate the response of the infilled RC frames. The proposed modeling approach makes use of fiber-section force-based elements for columns and beams, experimentally calibrated phenomenological strut models that account for infill-frame interaction, zero-length linear spring that simulate strain penetration at column ends, and a newly implemented empirically based limit-state nonlinear zero-length shear spring at column ends. The limit-state shear springs consider the effect of axial force on the lateral strength degradation of the RC columns. Validation of the modeling approach is achieved using one-bay one-story infilled frame experimental results available in the literature. The validation process outlines the complex nature of frame-infill interaction and load redistribution among the components as the structure deforms. In addition, in this work, the effects of modeling uncertainties in building responses are estimated using three state-of-the-art infill strut model classes. Both nonlinear static pushover and nonlinear response history analysis are used to estimate the response. Uncertainty in the parameters defining the model classes is also considered. A 6-story building of the Dhaka Medical College Hospital in Bangladesh is selected as a case study. This building is an infilled RC frame structure that was designed to ACI 318-08 and ASCE7-05 standards. Two-dimensional nonlinear structural models of the case study building, which consider the modeling uncertainties, are then subjected to a multiple stripe analysis (MSA). In the MSA performed herein, records are selected using conditional spectra at twenty intensity levels of ground shaking. At each intensity level, thirty ground motions are selected. Results indicate that incorporating uncertainties of the infill strut model classes and lateral degradation of column strength is critical to the prediction of the variability in the response. The variability parameters for the response estimated here are especially important to inform the proposed FEMA P-58 and new Chapter 16 of ASCE 7-16.

358: Influence of Particle Morphology on 3D Kinematic Behavior and Strain Localization of Sheared Sand

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Boning Zhang, University of Colorado
Richard Regueiro, University of Colorado

Many researchers utilized a broad number of experimental and theoretical approaches to derive constitutive stress-strain relationships for granular materials. According to Bagi (1996), researchers mostly adopt well-known continuum or discrete micro-structural approaches to calculate strains within granular materials. Despite extensive research, neither of the two approaches can fully capture the behavior of granular materials, but rather they are considered as complementary to each other where each has its own strength/limitations in solving granular mechanics problems. Zhang and Regueiro (2015) proposed continuum-based finite strain measures to measure local strains in granular material subjected to large deformations. They used 3D discrete element method data to

validate the proposed strains measures. This paper presents an experimental validation of Zhang and Regueiro (2015) approach using 3D images of sheared Ottawa sand specimens. Eulerian finite strains were calculated for representative element volumes (REV) within the specimens. The presentation will show the changes of Eulerian octahedral shear strain and the volumetric strain for REV's along with the global averaged values.

7: Influential Parameters on the Probabilistic Seismic Demand Models of Irregular Bridges

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Reginald DesRoches, Georgia Institute of Technology
Jamie E. Padgett, Rice University

The observed damage from recent earthquakes (Northridge earthquake in 1994, and Kobe earthquake in 1995) affirmed that the bridges, with irregularities or geometric inconsistencies in the configuration, have higher chance of being damaged severely or even collapsed, in comparison with the regular, straight bridges. Probabilistic seismic demand model (PSDMs) is an essential tool to describe the seismic demand of various components of a bridge in terms of the ground motion intensity measures. In this paper, various parameters are considered and investigated for their influence on the resulting PSDMs, using statistical tools such as Analysis of Variance (ANOVA) and regression analysis. Later, the influential parameters are used as major variables in the fragility analysis, which is used for the reliability and risk assessment of structures. For the purpose of this study, single frame box girder bridge type has been considered, which accounts for the bulk of California bridges. The applied methods for the sensitivity of seismic responses of irregular bridges assessed the influence of parameters including number of spans, number of column bents, abutment types, the specifications of three different design eras (pre-1971, 1971-1990, and post-1990), and various ranges of geometric irregularities such as low to extreme skew angles. A suitable ground motion set was selected from PEER Next Generation Attenuation (NGA) that was representative of the seismic hazard in the area of interest. Extensive plan review of the bridge plans, collected from the Caltrans repository, was carried out to set up appropriate distribution of parameters, required for the finite element modeling generation. Using the response of non-linear time history analysis of the bridge models, PSDMs were developed. Based on the results of the probabilistic models and the sensitivity analysis implemented on the PSDMs, the influential parameters, with significant impact on each structural response, are proposed and can be used later for the development of fragility curves to estimate the potential damage of the irregular bridges.

255: Integrating Water and Electric Systems in a Post-Earthquake Fire Analysis

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Integrating water and electric systems in a post-earthquake fire analysis Negar Elhami Khorasani Assistant Professor, Dept. of Civil, Structural and Environmental Engineering, University at Buffalo, Buffalo, NY, U.S.A. negarkho@buffalo.edu Maria Garlock Associate Professor, Dept. of Civil and Environmental Engineering, Princeton University, Princeton, NJ, U.S.A. mgarlock@princeton.edu Analyzing components of the built environment (buildings, transportation, lifelines, and communication systems) without considering the interdependencies and cascading effects in the system does not provide a realistic performance evaluation of that system. Therefore, new approaches considering such dependencies are needed to better understand a community performance and reduce economical and social losses especially under increasing number of natural and man-made hazards. This research presents a proposal for integrating water and electric systems in the assessment of community response to post-earthquake fire scenario. Previous studies show that, depending on an earthquake scenario, a large number of fire incidents are probable in dense urban areas that could place demand on fire departments in excess of their capacity. The success of fire department and the key to avoid conflagration is largely related to the available water pressure. Historically, lack of water to fight the fire has been one of the main causes in cases that experienced extensive fire damage after an earthquake. In the mean time, fragility curves exist for individual elements of water network to study their performance after an earthquake. However, individual assessment of elements in the water network does not provide a truthful performance of the network. In addition, one critical link between the lifelines is the influence of electricity on functionality of other utility elements such as pumps in the water network. Therefore, the overall performance of the water network depends on the performance of individual elements as well as the interdependency between the water and electric networks. This presentation presents new research on a methodology to evaluate and quantify resiliency of a community to post-earthquake fires. The methodology integrates the performance of water and electric networks and their interdependencies with the community response to fire ignitions. Such an approach leads to better understanding the varying degrees of internal and external dependencies between the elements of built environment, which in turn provides more effective action plans to minimize risk and losses to the community.

222: Interaction Grand Potential Between Calcium-Silicate-Hydrate Nanoparticles at the Molecular Level

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Calcium-Silicate-Hydrate (or C-S-H), a phyllosilicate, is the major binding phase in cement pastes and concretes and a porous hydrated material made up of a percolated and dense network of crystalline nanoparticles of mean apparent spherical diameter ~5 nm that are each stacks of multiple C-S-H layers. Interaction forces between these nanoparticles are at the origin of C-S-H chemical, physical, and mechanical properties at the meso- and macroscales. These particle interactions and resulting properties may be affected significantly by nanoparticle density and environmental conditions such as temperature, relative humidity, or concentration of chemical species in the bulk solution. In this study, we combined grand canonical Monte Carlo simulations and an extension of the mean force integration method to derive the pair potentials. This approach enables realistic simulation of the physical environment surrounding the C-S-H particles. We thus constructed the pair potentials for C-S-H nanoparticles of defined chemical stoichiometry at 10% relative humidity (RH), varying the relative crystallographic orientations at a constant particle density of part ~ 2.21 mmol/L. We found that cohesion between nanoparticles is affected strongly by both the aspect ratio and crystallographic misorientation of interacting particles. This method and findings underscore the importance of accounting for relative dimensions and orientation among C-S-H nanoparticles in descriptions of physical and simulated multiparticle aggregates or mesoscale systems.

508: Interaction of Failure Modes in the Fatigue Life of Laminated Composites

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In this work, we investigate the roles of interacting failure mechanisms in the mechanical response of laminated fiber reinforced composite materials subjected to high cycle fatigue loading. The failure of laminated composites

is governed by damage mechanisms which initiate at the microscale of material heterogeneity and propagate to scale of the laminate. In layups with multiple ply orientations, the interaction of failure modes and the associated local stiffness loss leads to stress redistribution in the laminate and characteristic changes in the accumulation of damage in adjacent plies. The damage mechanisms which drive this behavior are investigated through both experimental X-ray images and computational models. Experimental data from stiffness vs. life, residual strength after fatigue, and X-ray images of damage accumulation are presented for a number of layup configurations. Eigendeformation based homogenization with reduced order models (EHM) is implemented to generate numerical models to compare with the experimental result. EHM employs a reduced basis representation of the microscale nature of the composite material which is able to maintain fidelity to local, microscale damage accumulation in a computationally efficient manner. These models are exercised to demonstrate the roles of damage accumulation mechanisms in the laminate, as well as the effects of artificially suppressing potential damage modes on the overall response of the composite.

359: Interfacial Debonding and Viscoelastic Behavior of Magnetorheological Nanocomposites

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Magnetorheological elastomers (MREs) as a class of polymer-based composites with dispersed magnetic particles fall in the class of smart materials since their rheological properties can be continuously, rapidly, and reversibly changed with the applied magnetic field. However, conventional MREs exhibit poor mechanical properties and MR effect as a result of its matrix material and third interface (the phase between the iron particles and the matrix). Here we report the development of MREs with the addition of multi-walled carbon nanotubes and acetones. To understand how MREs are affected by the inclusion of these fillers, research is conducted in characterizing the composition of elastomers. This is done through the visualization of the three-dimensional microstructure of the MREs. The results are used to characterize and quantify the main structural parameters of the MRE, such as the volume ratio of the three phases, distribution of iron particles, and density distribution of the matrix. The main structural parameters are then compared to the mechanical properties obtained via dynamic mechanical analysis (DMA) to determine how the structural parameters affect the mechanical performance of the MR nanocomposite. It is found that with a slight addition of carbon nanotubes and acetone, the mechanical performance and MR effect are improved when compared to conventional MREs.

39: Introducing an algorithm for training of Neuro-Skin model

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Neuro-skin or Neuro-membrane has been introduced by the authors in a recent paper. It is an advanced form of Dynamic Plastic Continuous Neural Network (DPCNN) which is comprised of neurons embedded in a plastic membrane. Trainability of the neuro-skin is studied here. In this paper a new algorithm based on sensitivity analysis for the process of training of Neuro-skin has been introduced. The neuro-skin is adaptive and has the capability of providing desirable response to inputs intelligently. Hence, after training, it responds as a smart medium and this way, the neuro-skin can be considered as a new type of neural network with adaptability and learning capability. The skin is modelled by nonlinear dynamic finite elements. Each finite element receives a feedback excitation from the neuron that is attached to it, as well as its neighboring neurons. So, the finite elements are called Finite Neuro-Elements (FNEs), where each finite element is considered as a cell of the neuro-skin. Each neuro-element is comprised of a neuron with its own activation function and four nodes. Output is defined

as the force of the middle support of the medium. The free parameters of the Neuro-skins are: 1) input-weights of the neuro-elements, 2) output-weight of the neuro-elements, 3) parameters defining the activation functions and 4) material properties of the neuro-elements. In this research, only the parameters corresponding to the neuro-elements are adjusted which include the material properties of the neuro-elements such as their elastic modulus as well as the output-weights of the neuro-elements.

287: Investigation of Bone Fragility at Microscopic Length Scales

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Bone fracture injuries are among the 20 most expensive medical conditions with an annual estimated medical cost of around $22 billion in United States alone. Osteoporosis- a disease common in the higher age groups that makes the bone brittle and susceptible to fracture, causes one fracture every three seconds around the world. With an increasing elderly population and unhealthy lifestyle the problem is only going to aggravate. Also, the rest of the population is estimated to have at least 2 fractures in their life time due to athletic injuries or accidents. To abate the number of fracture in bones, a profound understanding of the primary mechanisms of bone fracture, bone quality and the functioning of its individual components is necessary. This will aid in developing advanced medicinal remedies to treat bone disorders and help reduce the overall treatment expenses. Bone is a composite of five distinct length scales- nanoscale (mineralized collagen fibril), sub microscale (single lamella), microscale (lamellar structure), mesoscale (cortical bone) and macroscale (whole bone). This indicates that the nature of fracture is also hierarchical. The objective of this investigation is to assess the fracture toughness at both the sub-micron, microscopic and meso length scale using scratch tests. In our experiments, an axisymmetric diamond probe is pulled across the surface of the material under a linearly increasing vertical force, meanwhile the resulting horizontal force and penetration depth are measured using high-accuracy piezo-actuated sensors. The challenge lies in developing an experimental protocol that yield an intrinsic measure of the fracture resistance which is independent on external factors such as penetration depth, applied force or loading rate, while taking into account the heterogeneous and anisotropic nature of the material. Three crack orientations are considered with respect to the direction of the harversian canal. In parallel, micro-indentation tests are carried out to assess the fracture energy. Preliminary data is presented on cortical bone specimens harvested from bovine humerus. The quantitative data obtained from this research can potentially help establish accurate quantitative models to gain a fundamental understanding of bone fragility.

742: Investigation of Shear Bands in Granular Materials Using the Level Set Discrete Element Method

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The phenomenon of shear banding in granular ma-terials has been studied from a continuum stand-point [3], whereby the onset of a shear band and angle of a shear band can be predicted given the material's elastoplastic parameters. However, these parameters have micromechanical origins at the grain scale, and so further insights on the be-havior shear bands, including shear band thickness and strain rate upon localization, require scrutiny at the grain scale. There have been some exper-imental e_orts involving X-ray computed tomog-raphy (XRCT) imaging of real granular materi-als to investigate shear banding [1], and we con-tinue in this same vein by using a `tomography-to-simulation' approach using the level set discrete el-ement method to simulate computational `avatars' of grains obtained from XRCT images of real ex-periments [4, 2] to simulate shear banding in vir-tual specimens, which has the added advantage of being able to compute interparticle forces and lo-calized stresses, something XRCT imaging cannot do as it is only able to track strain-based quantities from particle kinematics. We then compute, from the grain scale, the evolution of continuum plastic variables friction and dilatancy, which are integral to shear band formation [3] and inves-tigate their micromechanical origins. Finally, we continue to probe the micromechanics of the shear band once it has been formed.

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448: Investigation of Stress-Induced Martensite Transformation in A Large-Diameter NiTiNb Bar For Self-Stressing Applications

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Nickel-Titanium-Niobium (NiTiNb) alloys are a class of shape memory alloys that are distinguished by a wider hysteresis than conventional Nickel-Titanium (NiTi). The NiTiNb alloys can be pre-strained below the forward martensitic transformation start temperature and remain deformed until heated well above room temperature. Hence, they are considered for civil engineering applications that utilize stresses generated during constrained shape memory effect (SME) recovery via heating. This paper explores thermomechanical characterization of a large diameter NiTiNb bar for their use in self-stressing applications. Recovery stress tests are conducted under quasi-static uniaxial tensile loading at room temperature. An infrared camera is employed to measure the temperature of the specimens. The distributions of the temperature on the NiTiNb sample surface and temperature profiles along the length of the specimen length are obtained. Full field strain and displacement fields are documented using a non-contact optical measurement system. The formation and growth of the martensite are characterized. Finally, a pre-strained NiTiNb bar is embedded in a concrete beam and activated by electrical heating. The developed recovery stresses and pre-stress losses over time are monitored.

426: Investigation of the Impacts of Coastal Waves on Erosion of Coastal Structures

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Louisiana coast experiences significant erosion due to wave actions. There are wetlands and marshes located in the coastal areas. Wetland loss is a major threat to the coast areas. Although coastal waves and floods cause erosion, they also carry much-needed sediments to the wetlands which can counter-act some of the wetland losses. A balanced shoreline protection solution of wave reduction and sediment retention will be very beneficial to coastal Louisiana. Traditional shoreline protection design intends to stop the flow to reduce the erosion. However, sediments are not able to pass through if the flow is stopped. In this research, numerical simulations were used to investigate the effects of flow and wave on coastal erosion, and identify the more dominant factor. The results can lead to innovative shoreline protection design that reduces the erosion and increases the volumes of sediments

passing through.

218: Isochoric Creep of Hydrate Gel Needles Explains Macroscopic Creep of Cementitious Materials

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Hydrates are typically the only creeping constituent of cementitious materials. We here identify universal creep properties of hydrate gel needles. To this end, we exploit results of a comprehensive early-age creep testing series on hydrating cement pastes, with initial water-to-cement mass ratios amounting to 0.42, 0.45, and 0.50, respectively. Tested specimens were subjected, once every hour, to a three-minutes creep test. The first test was carried out 21 hours production, and hourly testing was continued until the specimens reached an age of 8 days. During three minutes, hydration does not proceed significantly. Therefore, three-minutes creep tests provide access no non-aging creep properties of cement pastes with specific microstructures. Results from more than 1000 three-minutes creep tests are used for top-down identification of two universal creep constants of hydrate gel needles. This is carried out in the framework of continuum micromechanics and based on the correspondence principle, i.e. based on (i) Laplace-Carson transformation, (ii) quasi-elastic upscaling, and (iii) numerical back-transformation. The identified creep properties of hydrate gel needles allow for predicting creep properties of weeks-long creep tests on very mature cement pastes. This underlines the predictive capabilities of the proposed multiscale model. Finally, we report on upscaling of creep properties from the cement paste scale both to the mortar and to the concrete scale.

185: Issues in Generating Response Surfaces for Reliability Analysis of Large Complex Dynamic Systems

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Limit state equations or performance functions are expected to be implicit for large complex dynamic systems and their reliability evaluation become very demanding. One attractive option is to represent them explicitly with the help of the response surface-based methodology and then the classical first or second order reliability method (FORM/SORM) can be used to evaluate the reliability. Although the basic concept of response surface method (RSM)-based reliability evaluation method is relatively simple, its implementation for the structural reliability evaluation could be challenging. The required response surfaces and the corresponding limit state functions are generally generated using deterministic responses at sampling points around a center point. The total number of required sampling points or deterministic analyses will depend on the mathematical form of the response surface and the sampling scheme used. The authors observed that the total number of required sampling points could be very large, in some cases prohibitive, to satisfy the accuracy requirements in the estimated reliability information. The authors studied several basic approaches to generate a response surface including advanced factorial schemes, Kriging method, and the moving least squares method. The major objective is to extract reliability information using only tens of deterministic evaluations at very intelligently selected points. The initial phase of the study indicates that using the available basic schemes, a response surface that will satisfy the accuracy requirements can be generated using thousands of deterministic evaluations. However, it may be impossible to

estimate reliability of large complex dynamic systems using only tens of deterministic evaluations. The authors are now considering several schemes to reduce the total number of deterministic analyses. They subdivided the sample points in to basic and edge points. Basic sampling points cannot be changed. Fortunately, they are not numerous. Edge points are numerous and they can be manipulated to obtain reliability information with tens of deterministic analyses without compromising the accuracy. Some of the strategies when used together are expected to produce compounding beneficial effects. They will be discussed during the presentation and will be clarified with the help of several informative examples and case studies. This study is based on work supported by the National Science Foundation under Grant No. CMMI-1403844. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the writers and do not necessarily reflect the views of the sponsor.

680: Joining of Cu-Nb Multilayered Nanocomposites

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Marcus Rutner, Stevens Institute of Technology

Multilayered metal nanocomposites have gained interest in science and industry due to their unique properties. Enhanced properties of these nanocomposites compared to conventional metallic materials, such as radiation damage resistance, electrical and magnetic properties, strength and indentation hardness, ductility, and fatigue resistance, make them attractive for novel applications in nanotechnology. An essential step towards industrial usage of multilayered nanocomposites is to be able to joining them. However, conventional joining processes cause localized heating around the joint and may compromise the integrity of the nanolayered composite cross section. In this research, Cu-Nb multilayered nanocomposites are synthesized by dc magnetron sputtering at room temperature on Si substrate. Various joining processes are introduced and performed and the advantages and drawbacks in regard to the processing and the nanomechanics of the joint are discussed. The nanostructure of the sputter-deposited Cu-Nb joint zone and adjacent heat affected zone is investigated by Scanning Electron Microscope imaging. Further, the hardness and strength of the joint area is studied by Atomic Force Microscopy.

683: Large Coverage, Direct Sensing and Monitoring of Corrosion in Reinforced Concrete Structures

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There is a tremendous need for reliable, yet simple corrosion damage detection techniques coupled to life cycle performance and failure risk analysis. It is further mentioned that reliable lifetime models and life cycle cost assessment methodologies are not yet developed beyond their infancy stage. A literature review of current state-of-the-art sensing technologies of corrosion in reinforced concrete structures reveals that most approaches have wires embedded in the concrete cover, which compromises the structure integrity. Further, most approaches only enable localized measurement, and wide coverage corrosion sensing would only be possible with a dense array of sensors which is infeasible due to the wires and electronics required per sensor. A further drawback of some technologies is that corrosion is actually not measured directly, but through dummy reinforcing bars or other indirect measurements, such as moisture content, conductivity, etc. The industry is in need of non-contact and maintenance-free sensing technology which allows high-resolution direct corrosion measurement. The proposed approach addresses these needs by providing (1) an accurate assessment of the material-, component- and system-level performance affected by corrosion through a sensing and monitoring technology which entails unmatched advantages compared to existing embedded technologies, and (2) establishment of a cost and risk metric system defining the relation between life cycle performance and costs (timely repair, late repair, reduced service life, etc.) accounting for corrosion.

182: Large-Eddy Simulation of Atmospheric Boundary Layer Winds for Structural Engineering Applications

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Wind loads on structures can be estimated by using analytical, experimental, and/or numerical simulation approaches. In view of the limitations of the analytical approach, the experimental approach using wind tunnel testing has been widely used, in spite of its relatively high costs, measurement limitations, and scaling issues. As an alternative, with the development of computer and numerical techniques, the numerical approach using CFD (Computational Fluid Dynamics) simulations has drawn the attention of wind/structural engineers. The UK Design Manual for Roads and Bridges (BD 49/01 2001) and the Eurocode (prEN 1991-1-4 2005) allow the use of proven CFD procedures to provide additional design guidance. However, this is not the case for the ASCE 7 Standard (2010), as wind/structural engineers in the U.S. are not convinced that CFD is ready for use in design. The National Institute of Standards and Technology is currently engaged in an effort aimed to develop CFD algorithms for use in structural engineering. As part of that effort, the authors performed three-dimensional simulations of turbulent Atmospheric Boundary Layer (ABL) flows over open terrain using the open source OpenFOAM software, and investigated the quality of the simulated flows from a wind/structural engineers' viewpoint. The simulation employed the k-equation eddy-viscosity LES (Large-Eddy Simulation) turbulence model with a wall function at ground level. The characteristics of the fully developed turbulent flow in the low part of the ABL height, which is of interest in most applications, were analyzed and compared with their theoretical and experimental counterparts, as well as with relevant provisions of the ASCE 49-12 Standard (2012) for the wind tunnel testing of structures. In addition, our paper discusses challenges that arise in numerical simulations for wind engineering applications.

126: LARS-based ARX PCE metamodel for computing seismic fragility curves

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In the field of civil engineering, the framework of seismic risk assessment has been of particular interest in the last few decades. A fundamental component of this framework is the computation of seismic fragility curves. In practice, due to the prohibitive computational cost of non-linear transient analysis of structures, only a limited number of analysis is used. Thus, the computation of fragility curves is done by parametric methods that are based on simplified assumptions (e.g. use of a lognormal shape), which however induce significant effects. In this context, metamodelling appears as the solution that allows one to overcome the problem related to the prohibitive cost of structural analysis. Using metamodel as a substitute of the actual numerical (e.g. finite element) model, one can afford a large number of analysis at a reasonable computational expense. This allows the computation of fragility curves by means of non-parametric methods. Among different metamodelling techniques, polynomial chaos expansions are proved effective in various applications. However, it is well known that PCE (as well as other metamodelling techniques) fail to represent the non-linear dynamics of structures, i.e. the time dependent response quantities. Recently, Spiridonakos et al. [1] proposed the use of autoregressive with exogenous input (ARX) model and PCE to model non-linear structures. ARX is used to capture the dynamics, whereas PCE is used to propagate uncertainties. This powerful approach allows one to take into account uncertainties from seismic

excitations and structural properties. However, its performance depends strongly on the appropriate selection of ARX and PC terms. In this paper, we propose the use of least-angle-regression (LARS) [2] for more effective selection of the mentioned terms. LARS proves reliable and fast to detect the relevant ARX terms from the experimental analysis. The representation of ARX coefficients as a function of uncertain parameters also relies upon the LARS-based sparse adaptive PCE scheme [3]. The applicability of the LARS-based ARX PCE model is illustrated for computing seismic fragility curves of non-linear structures subject to stochastic seismic excitations.

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581: Lattice Discrete Particle Modeling of Shear Failure in Reinforced Concrete Beams without Stirrups

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The size effect on the shear strength of reinforced concrete (RC) beams is affected by the relative size of the fracture process zone (FPZ) with respect to the effective depth. The Lattice Discrete Particle Model (LDPM) realistically simulates concrete heterogeneity by placing randomly-generated coarse aggregate particles in the volume consistent with the actual particle size distribution, and uses vectorial constitutive relations based on cohesive crack theory to simulate tensile fracture, thereby simulating size effects related to FPZ size. To date, while the literature reports on LDPM calibration and validation vis-à-vis experimental data for deep RC beams, no evidence has been disseminated on slender RC beams. This presentation discusses the calibration of LDPM concrete parameters, and model validation for the case of shear failure in scaled slender RC beams without stirrups. The LDPM geometric parameters were defined based on the concrete mixture design. The mechanical parameters were first computed based on a literature database of meso-scale parameters, and then refined to attain best fitting of experimental compressive stress-strain curves obtained by testing concrete cylinders per ASTM C469. Through this process, the effect and importance of each model parameter was studied. In addition, as a means to offset the limitations of relying on uniaxial compression test data, numerical simulations of fracture tests were performed to ensure that the simulated fracture energy is representative of experimental values found in the literature. The calibrated LDPM concrete model was used to simulate the response of scaled RC beams without stirrups. These beams were designed to fail in shear, fabricated using the concrete mixture based on which the LDPM was calibrated, and load tested in a four-point bending arrangement. The beams were internally reinforced with either ductile (steel) or non-ductile (glass fiber-reinforced polymer) longitudinal bars, and had a shear span-to-effective depth ratio of 3.1 and an effective depth in the range 146-292 mm. It is noted that this range had been previously reported as yielding evident size effect on shear strength, in addition to changes in the failure mode (i.e., from diagonal cracking to flexural failure with bar rupture) depending on the maximum aggregate sizes. The results of numerical simulations served for model validation through a comparison with evidence from physical experiments. The different responses of the beams having ductile or non-ductile reinforcement are discussed based on relevant criteria, including elastic response, post-cracking stiffness degradation and damage progression, shear strength and failure mode.

432: Length-Scale Effect on Wave Propagation in Periodic Micro-Lattices

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Recently there has been a considerable amount of interest in the engineering and materials science communities in developing novel metamaterials by designing material layout at the microstructural level. For example, it is well known that dispersive waves occur in elastic solids due to the interaction between the material microstructure and an impending wave front, and thus dispersive properties of materials depend directly on the topology of the microstructure. To describe the dispersive properties of metamaterials at such small scales, however, care needs to be taken to account for the microstructural length-scale effect in the constituent materials. This effect, which is typically reflected as an enhancement of mechanical properties corresponding to a decrease in physical dimension, has been well documented [1]. In this study, length scale effect on wave propagation in metamaterials consisting of periodic micro-lattices is investigated. To this end, lattice-type metamaterials are modeled as periodic assemblages of micro-beam elements and numerical methods are employed to analyze their dispersive properties. The micro-beam elements are developed based on a modified couple stress theory [2] and Bloch's theorem is used to analyze wave propagation in periodic micro-lattices. The effect of length scale on the dispersive properties of these metamaterial is carefully investigated and results are presented for a number of different lattice topologies. It is shown that the inclusion of length scale effect in the analysis significantly alters dispersive properties of these metamaterials and should be carefully considered in their design.

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517: Life-Cycle Reliability Assessment of Corroded RC Bridges under Multiple Hazards

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This paper presents a probabilistic framework for the life-cycle reliability assessment of existing RC bridges under multiple hazards. The life-cycle reliability of a bridge girder under the traffic and airborne chloride hazards is compared with that of a bridge pier under the seismic and airborne chloride hazard. When estimating the life-cycle reliability of the existing bridge girder and pier, observational data from inspection and/or non-destructive testing methods could be used to estimate the current material corrosion level. In this paper, the mean and variance associated with steel weight loss are estimated. The parameters to estimate the steel weight loss incorporating the spatial variability in steel corrosion are derived from previous experimental results used to visualize the steel corrosion in RC members by X-ray technology. In addition, random variables associated with the prediction of time-variant steel weight loss are updated by using sequential Monte Carlo simulations (SMCSs). In an illustrative example, the bridge components with the lowest life-cycle reliability depending on the hazard levels associated with seismic, traffic and airborne chloride and inspection results are identified. KEYWORDS: Reliability assessment, steel corrosion, updating, inspection data, spatial variability, seismic hazard, airborne chloride hazard, traffic hazard.

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Greece; 2009.

93: Limit-State Surrogate Based Reliability Estimation Under Uncertainty

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Practical reliability analyses are affected by different types of epistemic uncertainty, due to inadequate data and modeling errors, along with aleatory uncertainty in input random variables. When the original physics-based model is computationally expensive, a surrogate has often been used in reliability analysis, introducing additional uncertainty due to the surrogate. This work presents a framework to include statistical uncertainty and model uncertainty in surrogate-based reliability analysis. Inadequate data causes uncertainty regarding the statistics (distribution types and distribution parameters) of the input variables, and also regarding the system model parameters. Model errors include model form and solution approximation errors, surrogate model uncertainty, and also Monte Carlo sampling (MCS) error due to limited sampling during reliability analysis. Two types of surrogates have been considered in the literature for reliability analysis: (1) general response surface models that compute the system model output over the desired ranges of the random variables; and (2) surrogates that concentrate only on modeling the limit state. This work focuses on the latter type, using Gaussian process (GP) surrogates for performing both component reliability (single limit state) and system reliability (multiple limit states) analyses. Traditional approach for the construction of a limit-state surrogate in the presence of a model discrepancy is to construct the surrogate for the simulation model and the model discrepancy is later added as an additive term. This traditional approach works well for component (single limit state) reliability analysis but cannot be extended for system reliability analysis. Therefore, a systematic procedure for the inclusion of model discrepancy terms (for component and system reliability analyses) in the limit-state surrogate construction is developed using an auxiliary variable approach. An efficient single-loop sampling approach using the probability integral transform is used for sampling the input variables with statistical uncertainty. The variability in the GP model prediction (surrogate uncertainty) is also included in reliability analysis through correlated sampling of the model predictions at different inputs. The Monte Carlo sampling (MCS) error is quantified through a Gaussian distribution and included in the reliability analysis. Two mechanical systems – a cantilever beam with point-load at the free end and a two-bar supported panel with point load at its center, are used to demonstrate both component and system reliability analyses using the proposed techniques.

71: Local-Global Mode Interaction in Thin-Walled Rectangular Hollow Section Struts

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Compression members made from slender metallic plate elements are vulnerable to a variety of different elastic instability phenomena. In order to take advantage of thin-walled struts efficiently, post-buckling strength should be included in design guidance. However, the triggering of various buckling modes simultaneously can alter post-critical behaviour profoundly. In particular, it may cause a violent destabilization of the response after the maximum load is reached. The current work focuses on such a problem using an analytical approach, the methodology of which has been well established in previous works on sandwich struts and I-section beams and columns. An analytical model describing the interactive buckling of a thin-walled rectangular hollow section member under pure compression is formulated based on variational principles. For the member in question, the interaction is between global (Euler) buckling about the weak axis in combination with local buckling of the most

compressed regions of flange and web simultaneously, where a semi-rigid joint is modelled using elastic rotational springs. By minimizing the total potential energy, a system of governing differential and integral equations are derived that are solved within the numerical continuation software, AUTO-07p. This software can not only solve nonlinear problems numerically but it also maintains the intrinsic bifurcational structure of the solutions and is able to switch between, as well as trace, equilibrium paths. A progressive buckling mode change arising from the mode interaction between the weakly stable global mode and the strongly stable local buckling mode is observed. The interaction between the web and the flange and its effect on the post-buckling is also analysed. A series of finite element (FE) models are also established within the commercial package ABAQUS to validate the analytical model. Comparisons between the analytical and FE models show that the behaviour of the members is represented particularly well in the post-buckling range and that the fundamental mechanics have been captured excellently.

321: Long Duration Blast Loading and Debris Distribution of Masonry Structures

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Considerable research has been historically conducted towards conventional high-explosive blast loading and its dynamic interaction with structures. Typically, the positive phase duration of the conventional case is less than 100msec and in most cases, nearer 20msec; whereas, long-duration blast can be an explosive event in which the comparative duration substantially exceeds 100msec. This type of blast load radically increases structural damage and consequently, analytical complexity due to the high impulse or energy deposition resulting from a long wavelength, powerful drag winds and sustained dynamic pressures. As part of a funded on-going research study to develop a set of predictive algorithms, this paper investigates the geometric dependence of segmental masonry panels on the breakage patterns and debris distribution of common structures when subject to long-duration blast. Key experimental trials have been conducted using the national UK Air Blast Tunnel, a specialised facility for long-duration blast. The trials have been designed to benchmark high fidelity computational models developed using the new Applied Element Method (AEM) demonstrating good agreement for a wide range of scenarios. This research provides a valuable insight for both practitioners and academics towards the failure modes of masonry structures and the subsequent debris distribution when subject to high-power, long-duration air blast.

17: Long Wave Instability for Progressive Collapse of Tall Steel Moment Frames

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During the last decades, new super-tall and slender buildings have appeared with an increased trend, posing a great challenge from the engineering mechanics point of view. Apart from the challenging design of the intact structure, the progressive collapse analysis of such buildings is also extremely important mainly due to the undesirable and immense consequences of a potential collapse. It has been shown that the loss of a member can degrade the stability of an entire structure and lead to its ultimate collapse and this phenomenon can be profoundly more important in the case of super-tall and slender buildings especially when their aspect ratio is very high. This paper examines the response of tall and slender buildings to the unexpected appearance of an extreme local damaging event. The damage scenario follows the widely accepted notion of key element removal as described in the Unified Facilities Criteria of the Department of Defense [1]. The results demonstrate that this type of structures are vulnerable to a progressive collapse mode which has not received the adequate attention from the community. The complete absence of any individual component failure prior to collapse makes the detection of this collapse mode very difficult, because traditionally progressive collapse methods focus on individual member safety rather than overall system safety. [1] DoD (2009). Unified Facilities Criteria (UFC). Design of buildings to resist progressive collapse. Department of Defense, USA.

543: Long-Term Deformations of Fastening Systems Under Sustained Loads

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Fastening elements are used to connect structural members with each other and with appliances. In general post-installed fastening systems are characterized as either mechanical anchors or so called bonded or chemical anchors. The working principle of the former is friction or mechanical interlock while the performance of the latter is based on the adhesive properties of polymer mortars – mostly epoxy or vinyl-ester based. Both mechanical as well as chemical anchors undergo an approval process during which their performance is certified. These tests are performed according to strict guidelines. In recent years two prominent disasters created significant concerns regarding the performance of bonded anchors under sustained loads. Thus, current approval guidelines regarding the qualification of bonded anchors systems are being challenged and the introduction of penalty factors for sustained loads is being discussed. Interestingly, all long-term deformations are being attributed to the adhesive only, neglecting contributions from concrete as well as damage and system effects. In this contribution we attempt to quantify the effect of (a) concrete creep, and (b) stress redistribution and damage mechanisms based on state of the art numerical simulations, calibrated by material tests and validated by system tests. Specifically, an epoxy based and a vinyl-ester based system are investigated and compared to the performance of headed-studs. The numerical framework is able to model the coupled problem of heat- and moisture transport, hydration, ageing of material properties, shrinkage and creep in a rate-type, pointwise form. For the constitutive model the Lattice Discrete Particle Model (LDPM) is used.

514: Mean-Strain 10-Node Tetrahedron with Energy-Sampling Stabilization

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Petr Krysl, University of California, San Diego

Recently, several methods for stabilizing mean-strain hexahedral elements by hourglass control were introduced. In the latest contribution, the energy-sampling stabilization was used to develop a mean-strain eight-node hexahedron, which resulted in quite good coarse-mesh accuracy and robust convergence under element-level constraints (incompressibility, reinforcement with stiff fibers). However, high quality hexahedral meshes are difficult to create for arbitrary and complex shaped volumes. In contrast, tetrahedral elements are easy to generate automatically and fit well within an arbitrary domain. In this work, a new mean strain 10-node tetrahedral element (T10MS) is developed using the energy-sampling stabilization. The proposed 10-node tetrahedron is composed of the several four-node linear tetrahedral elements, four tetrahedra in the corners and four tetrahedra that tile the central octahedron in three possible sets of four-node linear tetrahedra, corresponding to three different choices for the internal diagonal. We formulate a mean-strain element with stabilization evaluated on the four corner tetrahedra. The proposed element naturally leads to a lumped mass matrix and does not suffer from contact pressure oscillations because of the unequal distribution of equivalent nodal forces when a pressure acts on the face of the element. Furthermore, the mean-strain tetrahedron also works for relatively thin structures. The stabilization energy is here assumed to be generated by a quadratic form whose coefficient matrix (i.e. the material constitutive matrix) is taken in the isotropic form and hence there are two input parameters to define. An argument

is developed that avoids locking by fixing the value of the Poisson ratio away from 1/2, and links the Young's modulus of the stabilization material to the input properties of the real material and (crucially) also to the geometry of the element (edges and heights of tetrahedron). While the Poisson ratio can be chosen practically arbitrarily, the Young's modulus is matched to both the material and the geometry of the element. The accuracy and convergence characteristics of the present formulations compare favorably with the classical 10-node tetrahedral elements. The numerical results show that the present element performs well for solid, shell, and nearly incompressible structures.

206: Measuring and Managing Resiliency in Facilities

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Buildings and infrastructure are exposed to a wide range of natural and man-made threats. How they respond in the face of these threats is of critical importance to facility owners, occupants, users, and the communities in which the facilities are located. A facilities response to threats can be measured by evaluating resiliency - the ability to reduce the effects of the magnitude and duration of disruptive events. Assessing a facility's exposure to various threats can be a difficult and complicated process subject to the vagaries of approach and the experience of the assessor. To achieve consistent and meaningful results, a structured process that can be implemented by a wide range of organizations and individuals is needed. Through application of the interconnected concepts of risk, resiliency, high performance and an all hazard approach, the Department of Homeland Security's Integrated Rapid Visual Screening (IRVS) Tool provides a systematic approach to identify facility resiliency and provide a framework for its management. With a tool that produces comprehensive, objective and consistent measures, options for mitigating vs. accepting risk can be established and applied. The resulting differences in relative risk and resilience are the basis for a framework for objective decision-making. Through scenario analysis, options with varying risk and resilience can be compared towards selecting the best fit for the situation. The role of life cycle cost evaluation to support decision-making will be established. How the process and tool work, and can be used to improve overall safety and security of existing facilities will be demonstrated in this presentation.

64: Mechanical Behavior for Submarine Pipelines Crossing Active Strike-Slip Fault

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With the development of ocean engineering, the seismic safety issue of submarine pipelines has been gradually arousing widely concern especially when the pipelines cross earthquake faults. However, the understanding for dynamical performance of submarine pipelines when crossing active strike-slip fault is still limited. This paper presents a comprehensive analysis on the mechanical behavior of submarine steel pipeline subjected to strike-slip fault displacement loads. The investigation is based on rigorous numerical simulation of soil-pipe system, accounting for nonlinear material behaviors and large strains of both pipeline and the surrounding seabed soil. With the bucking and the fracture of the pipeline included, the paper employs the strain-based criterion to estimate the safety performance of submarine pipeline throughout the analysis. The effects of various diameters, diameter-to-thickness ratios and internal pressures are examined. The influences of different soil conditions as well as intersection angles between pipeline and soil are also investigated by considering soil stiffness and burial depth. Furthermore, the new phenomenon of reciprocating fault movement is considered and the corresponding effects on pipeline are analyzed. The results are presented in diagram form, which depicts the critical fault displacements of the pipeline under different parameter conditions. Finally, a set of recommendations has been made regarding design of submarine pipelines based on the analysis.

67: Mechanical Modeling of Steel Top and Seat angle Connections with and without Web Angles Subjected to Elevated Temperatures

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Elie Hantouche, American University of Beirut

The finite element (FE) simulations and the experimental results are used to develop a mechanical model to predict the beam axial force-temperature and rotation-temperature of top and seat angle connections with and without double web angles when exposed to elevated temperatures. First, FE models are developed and validated against experimental results available in the literature at elevated temperature. Second, FE models are developed to conduct an extensive parametric study to investigate some major geometric parameters such as load ratio, beam length, initial cooling temperature, angle thickness, beam depth, gap distance, that impact the behavior of these connections when exposed to fire. Third, a mechanical model, that considers the major geometric and material properties, is developed to predict the thermal axial force and rotation response. The proposed mechanical model provides important insights into fire-induced thermal forces and deformations and their implications on the design of steel bolted top and seat angle connections with and without double web angles under fire.

759: Mechanical Systems' Reliability to Enhance Monte Carolo Simulation

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Calculating the reliability of realistic mechanical systems by using conventional reliability theoretical techniques can be exceedingly difficult. There are many tech- niques for approximate calculations, but they are often complicated and difficult to implement. This paper describes the development of a new method for efficient calculation of system reliability, based on Monte Carlo simulation. Standard Monte Carlo simulation forms a simple and robust alternative for calculating system re- liability. If one can generate large samples, the law of large numbers ensures that the result will be accurate as well. This may, however, be a very time consuming operation. The method introduces a parametrized system that corresponds to the given system for set parameter values. By using regularity of system reliability as a function of the introduced parameter, the system reliability for our original sys- tem can be predicted accurately with relatively small samples. Results obtained with the method are promising - simulations with 105 generated random variables were able to estimate system failure probabilities of the order 10−6 to 10−7 with good accuracy. This applies in particular to dependent systems with common cause and cascading failures. Examples are given to demonstrate the performance of the proposed method.

393: Mechanics of Damage, Healing, Damageability, and Integrity of Materials: A Conceptual Framework

George Voyiadjis, Louisiana State University
Peter Kattan, Louisiana State University

In this work several new and fundamental concepts are proposed within the framework of Continuum Damage Mechanics. These concepts deal primarily with the nature of the two processes of damage and healing along with introducing a consistent and systematic definition for the concepts of damageability and integrity of materials.

Towards this end, seven sections are presented as follows: Section 1 introduces the new concepts of the damage field and the integrity field. Section 2 introduces the healing field along with the integrity index. In section 3 a new formulation for damage mechanics is presented in which the two angles of damage-integrity and healing-damageability are introduced. It is shown that both the damage variable and the integrity variable can be derived from the damage-integrity angle while the healing variable and damageability variable are derived from the healing-damageability angle. Section 4 deals with various issues related to damage and integrity of materials. Section 5 introduces the new and necessary concept of unrecoverable damage or non-healable damage. In section 6 generalized healing is presented where a distinction is clearly made between linear healing and nonlinear healing As an example of nonlinear healing the concept of quadratic healing is derived. Finally in section 7 a complete and logical/mathematical dissection is made of the healing process. It is hoped that these new and fundamental concepts will pave the way for new avenues in research in damage mechanics and characterization.

527: Meso-Chemo-Mechanics of Calcium-Silicate-Hydrates

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Hamid Valipour, University of New South Wales
Mohammad Javad Abdolhosseini Qomi, University of California, Irvine

With the bloom of computational physical chemistry methods, researchers in cement and concrete community have vastly exploited these techniques to explore molecular structure and physical properties of different phases present in cementitious systems. These methods have been fruitful in providing a consistent textural and chemo-mechanical picture of cement paste at the nano-scale. Despite their success, these methods are restricted to small length and short time scales due to spatial and temporal resolutions required for proper description of motion of atoms and inter-atomic interactions. These limitations give rise to the orders of magnitude difference between physical properties measured via atomistic simulations and experiments. While mean-field homogenization techniques enable us to bridge this gap, they fail to provide a physical understanding of the underlying mechanisms behind such sheer differences and plausible solutions that might help close these gaps. This motivates us to develop physics-based models to transfer chemo-physical signatures of materials hierarchically across length scales. In this work, we propose a realistic set of meso-scale models of calcium-silicate-hydrates (C-S-H) with characteristic length scale of 100 nm at varying ca-to-silicon (C/S) ratio and environmental conditions. Our approach is based on the potential of mean force (PMF) that stems from the perturbation theory. PMF quantifies the inter-lamellar interactions at variable interlayer spacing, humidity level and temperature. This method enables us to quantitatively analyze the screening effect of water molecules in meso-pores with different saturation degrees. Subsequently, we employ Bayesian statistics to construct a parametric course-grained free energy landscape with a posteriori uncertainty estimates. These uncertainties arise from the statistical nature of atomistic simulations as well as the polymorphic structure of C-S-H. We employ these stochastic parametric models in a reverse Monte Carlo scheme to construct meso-scale structures of C-S-H at varying stoichiometry. This has enabled us to fully reproduce intensity and structure factors measured in small angle neutron scattering and to escape entrapment in unwanted jammed states. Furthermore, we validate our models against existing experimental measurements available at the meso-scale in the literature.

337: Mesoscale Material Properties Fields; Partitioning Strategies and Probabilistic Descriptions

Sarah Baxter, University of St. Thomas
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Composite materials are often characterized by the effective properties of an equivalent homogeneous material. Determination of these properties depends on the identification and justification of an appropriate representative volume element (RVE). RVEs should be large enough to represent the material microstructure accurately, but small enough to offer a computational advantage. Effective properties of an RVE, however, remove all information about material property variations. These variations are important to accurate predictions of certain composite behaviors, e.g., damage and failure. Therefore, composites with random morphology are increasingly being analyzed at a mesocale. Statistical Volume Elements (SVEs), which are partitions of an RVE, represent one way to construct such a mesoscale material representation. The apparent homogenized properties of each SVE are calculated and the resulting distribution of properties then used to statistically characterize local property variation. Even using SVEs, however, the discrete material properties of the composite are smoothed; this smoothing depending largely on the choice of SVE. Therefore, central questions in the development of mesoscale representations are partition geometry and partition size. Typically, square or rectangular partition geometries have been used. Recent work suggests that a better approach is to choose SVE boundaries based on material microstructure. Voronoi tessellation is such an approach. Under this method partition boundaries can be constructed that do not intersect any of the inclusions. When the relatively stiff inclusion phase lies on the boundary, local stress concentrations occur and artificially increase SVE apparent properties. In the current work, partition shape, square or tessellated, and partition size are varied to investigate their effects on probabilistic descriptions of material properties in a mesoscale analysis. Mean values, based on the apparent properties of the SVEs, are compared; illustrating a hierarchy of bounds on material properties and the relative effects of partitioning. In addition, probability density functions (PDFs) of apparent SVE properties are generated using the Principle of Maximum Entropy. PME-generated PDFs are compared for several microstructural morphologies. Three main cases are considered: uniformly randomly distributed circular inclusions, a composite with clustered randomly distributed circular inclusions, and a composite with uniformly randomly distributed elliptical inclusions. In each case, the effect of phase contrast ratio is also examined. Results show that when a Voronoi tessellation partitioning scheme is used, tighter material property bounds are observed, the effect of contrast ratio in significantly reduced, partition size plays a lesser role, and the distribution of properties is more sensitive to changes in the microstructure.

137: Mesoscale Thermomechanical Modeling of Energetic Material Interfaces Under Transient Loading

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Caglar Oskay, Vanderbilt University

We present the formulation and implementation of a mesoscale thermomechanical model for analysis of interface damage and associated temperature rise of energetic material under transient loading. We propose a fully coupled thermomechanical cohesive finite element approach to properly account for the interface debonding, traction separation relation, heat flux generation and interface temperature increasing. The coupling roots from the fact that the energy released by decohesion and the heat flux generated due to the friction in post interface debonding directly contribute to the temperature rise at interface, on the other hand the binder material typically shows temperature dependent constitutive behavior and the thermal strain becomes an important factor in the displacement field around the interface neighborhood. A linear cohesive law is employed to describe the traction separation relation. The penalty method is used to suppress the interpenetration and a damage dependent regularized Coulomb's law is applied to account for interface post damage friction. The phase materials used in this study are HTPB for binder and HMX for particles, respectively. A viscoelastic constitutive law is employed for HTPB, and HMX particles are modeled as brittle material with damage evolution law. The finite element model of the energetic material system is solved with fully coupled explicit thermomechanical dynamic solver.

467: Micro-Macro Experimental Study of Remolded Clayey Materials on Drying path

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The aim in this research is to provide a better understanding of the relation between the macroscopic and microscopic behavior of a remoulded clayey materials. Kaolin, which is a little swelling “nearly pure” kaolinite, was studied in this research; the influence of mineralogical properties was then introduced through a mixture of kaolinite and montmorillonite (more swelling clay). The investigations were conducted at micro and micro scales; the approach at the macroscopic scale consists in measuring the water content, void ratio and degree of saturation versus suction (s) during drying. This part of the study allows to specify the relationship between shrinkage and desaturation and highlights the characteristic phases of behavior. At the microscopic scale, the analysis of the orientation of the clay particles was carried out by scanning electron microscope picture analysis under different suctions. On drying path, the observations show a systematic isotropy of the microfabric. The evolution of the porosity derived from mercury intrusion porosimetry tests is confirmed by SEM image observations

658: Micro-Polar Discrete-Continuum Coupling Method for Fluid-Infiltrating Porous Media

Kun Wang, Columbia University
WaiChing Sun, Columbia University

A scale-bridging model has been established to couple the micro-scale fluid-solid interaction simulation with macroscopic finite element models for higher order porous continua. Based on the effective stress principle, a hierarchical coupling approach is established in which grain-scale discrete mechanics simulations are used as constitutive laws for updating macroscopic effective stress and couple stress, while the grain-scale fluid-solid interaction is captured explicitly via a DEM-network coupling model. To improve computational efficiency, we adopt a semi-implicit predictor-multi-corrector scheme that splits the internal force into an implicit elastic component and an explicit plastic component. By inferring effective stress measure and poroplasticity parameters, such as porosity, effective permeability, Biot's coefficient and Biot's modulus from micromechanics of RVEs, the multiscale model is able to predict effective poro-elasto-plastic responses by intrinsically incorporating material length scales without introducing phenomenological laws. The performance of the proposed framework is demonstrated via a collection of representative numerical examples at specimen- and field-scales. The dual-scale model is shown to have good convergence rate, and is mesh independent, stable and robust. In addition, it has potentials in solving a wide spectrum of finite strain poroplasticity problems across spatial length scales.

469: Micromechanical Characterization and Modeling of Mechanical Property of Long-Term Aged Asphalt Binder Based on Inclusion Based Boundary Element Method

Gan Song, Columbia University
Huiming Yin, Columbia University

The mechanical response of aged asphalt binder under different mechanical load have been studied through both experiments and numerical modeling. The asphalt binder is considered as a particulate composite consisting of asphalt binder matrix and mineral aggregate. To interpret the experimental results, an inclusion method based

boundary integral equation for viscoelastic problem has been proposed. The effect of the material mismatch between the aggregate particles and the asphalt matrix can be simulated by an eigenstrain rate, which is a fictitious nonmechanical strain rate. Due to the interaction between particles and boundary effect, the eigenstrain rate on a particle is not uniform. An asymptotic analysis shows that a quadratic distribution of the eigenstrain rate over each particle provides very good accuracy. Since the discretization of particles is not needed due to applying an analytic form of eigenstrain rate field, a large number of aggregate inhomogeneities can be simulated and the local field can be calculated in aged asphalt binder sample. The formulation has been implemented in a software package for the simulation of material samples and has been verified with the finite element method. The simulation results based on idealized microstructure exhibit very good agreement with the experimental results of the effective viscosity of the aged asphalt binder.

323: Micromechanical Damage Model for Mode I Fracture of Fiber Composite Under static Loading

Rudraprasad Bhattacharyya, Vanderbilt University
Caglar Oskay, Vanderbilt University

Composite structural components of aircrafts and aerospace structures degrade during operating conditions, the progression of which may be complicated due to the complex microstructural mechanisms. In this study, we present a micromechanics-based delamination model for fibrous composites to predict delamination without resorting to traditional cohesive zone modeling approaches. The primary purpose of the proposed approach is to alleviate the increase in computational cost and numerical convergence difficulties associated with explicitly accounting for ply delamination using discrete modeling techniques, and idealizing delamination as coalescence of microstructural damage. The ply delamination due of mode I fracture under static tensile loading is modeled through simulating the double cantilever beam experiments performed on IM7/977-3, a graphite fiber reinforced epoxy composite. The modeling approach employed in this study is the eigendeformation-based reduced order homogenization, due to its computational efficiency and its ability to incorporate distinct damage modes. The reduced model is designed such that the delamination could be interpreted directly from the damage state in the material microstructure (modeled in an approximate fashion due to model order reduction). The spurious residual stresses that occur in the reduced model are alleviated by using the concept of compatible eigenstrains, derived based on the Mura's impotent eigenstrain concept. The capabilities of the proposed approach in approximating the mode I crack propagation is compared to delamination based on cohesive zone modeling. The sensitivity of the proposed approach to element shape and size are investigated.

608: Micromechanical Stiffness Estimation of Tissue Engineering Scaffolds Composed of Hydroxyapatite Granules, Considering Bone Regeneration

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Vladimir Komlev, Russian Academy of Sciences
Alexey Gurin, Central Scientific Research Institute of Dentistry and Maxillofacial Surgery
Christian Hellmich, Vienna University of Technology

Bone replacement materials have to fulfill various different requirements, including adequate mechanical properties. Designing such materials with the just right stiffness occurs standardly through a (potentially inefficient and expensive) trial-and-error approach. Here, a micromechanics-based modeling tool is presented, which may contribute to improving the efficiency of the design of bone replacement materials. In particular, a three-step homogenization scheme is derived for a granular, hydroxyapatite-based scaffold material that has been developed as bone replacement material in the human mandible. Notably, the homogenization scheme takes into account all significant morphological features observed on the relevant observation scales: hydroxyapatite crystals are the main constituent of the material, while nano-pores, micro-pores, and cracks „weaken" the material. Furthermore, bone regeneration is considered, i.e. newly formed bone tissue may envelope the scaffold material, whereas the model is also able to take into account scaffold resorption, as it occurs in its physiological environment. Numerical studies show, qualitatively, the adequacy of the model. Finally, a potential application of the homogenization scheme is presented, highlighting how it could provide support during the design process of a new bone replacement material. Through prescribing suitable evolution laws that describe the development of the scaffold material composition after insertion, the model allows for computing the corresponding stiffness evolutions. Additionally, the elastic limit of the scaffold material can be predicted, providing valuable insights regarding the onset of cracks that could potentially harm the material's load-carrying capacity.

61: Micromechanics of Incremental Stress Probes of a Granular Material

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The bulk behavior of granular materials is known to depend upon details of the contact mechanism between particles. Simulations of two mechanisms are explored: a standard linear-frictional spring and a full Jager implementation of the Hertz-Mindlin-Cattaneo contact. A large assembly of non-convex sphere-cluster particles was initially configured in a dense isotropic packing and was then subjected to monotonic triaxial compression loading. The initial loading was periodically halted so that a series of loading probes could be implemented. The incremental probes involved loading in many stress directions: both in the pi-plane and in the Rendulic plane. Very slow loading rates were applied so that rate-effects could be minimized. The following questions were investigated. Does all sliding between particles cease during incremental unloading? In which directions is sliding preferentially favored in different probe directions? How do these results depend upon the particular contact mechanism?

760: Micromechanics of Plastically Sliding Interfaces: Theoretical Foundations and Application to Bone

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Christian Hellmich, University of Technology

In this study, we consider fluids as a source of plastic sliding events of hydrated polycrystals in (bio-)materials, comprising heterogeneous microstructures and fluid-filled porosity at small length scales. In this context, fluid-filled interfaces are typically considered to act as a lubricant, once electrically charged solid interfaces start to glide along fluid sheets, while the fluid is typically in a liquid crystal state, which refers to an "adsorbed", "ice-like", or "glassy" structure of fluid molecules.The intimate bounding of fluid or water molecules to electrically charged solid surfaces stabilizes the interaction between mineral crystals: the hydrated crystals do not break or detach one from another once a critical stress threshold is reached, but when the intra- and intercrystalline loads accumulated up to the elastic limit, will be maintained through the crystals starting to glide upon each other, along the ice-like features, which prevent the sliding crystal surfaces from disintegration. Disintegration of porous polycrystals is also prevented by the collagen fibrils interweaving the extracellular bone matrix. This vision is consistent with an elastoplastic interface behavior between hydroxyapatite crystals. Bridging liquid crystal physics with continuum micromechanics of materials, we employ recently proposed micromechanical formulations for influence and concentration tensors valid for phases of arbitrary shapes and orientations [3], specific choices of which lead to the well-known transformation field analysis [1, 2]. Then, interfaces are regarded as zero-thickness limit case of spheroidal phase inclusions translating the inclusion plastic strains into displacement discontinuities (or ”jumps”) across the interfaces, and the inclusion stresses into traction vectors acting on the interface planes [4]. Thereafter, we introduce an elastoplastic constitutive law for these interfaces, which links the traction vectors acting in the interfaces to corresponding plastic displacement discontinuities. The resulting rigid-plastic problem is solved through a new variant of the algorithmic strategy of ”return-mapping”. Finally, we integrate these new developments into an multiscale elastoplastic model for bone [5]. [1] Dvorak G., Benveniste Y.: On transformation strain and uniform fields in multiphase elastic media. Proceedings of the Royal Society London, Series A (437), 291-310, 1992. [2] Pensee V., Kondo D., Dormieux, L.: Micromechanical analysis of anisotropic damage in brittle materials. Journal of Engineering Mechanics 128 (8), 889-897, 2002. [3] Pichler B., Hellmich C.: Estimation of influence tensors for eigenstressed multiphase elastic media with nonaligned inclusion phases of arbitrary ellipsoidal shape. Journal of Engineering Mechanics 136 (8), 1043-153, 2010. [4] Shahidi M., Pichler B., Hellmich C.: Viscous interfaces as source for material creep: A continuum micromechanics approach. European Journal of Mechanics A/Solids 45, 41-58, 2014. [5] Fritsch, A., Hellmich, Ch., Dormieux, L.: Ductile sliding between mineral crystals followed by rupture of collagen crosslinks: experimentally supported micromechanical explanation of bone strength. Journal of Theoretical Biology 260, 230-252, 2009.

408: Micromechanics-Based Elastoplastic Behavior of Functionally Graded Materials with Particle Interactions

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A micromechanics-based elastoplastic model is developed for a particulate functionally graded material (FGM). The FGM was recently designed as a key component of a multifunctional building envelope for high performance of energy efficiency, which was realized by using spherical aluminum particles and fine High-Density Polyethylene (HDPE) powder through a vibration-sedimentation process. In this model, the FGM is microstructurally divided into two distinct zones: particle-matrix zone and the transition zone. In the particle-matrix zone, pair wise interactions between particles are employed using a modified Green’s function, and the particle phase (metal) is assumed to be linearly elastic while the matrix phase (polymer) is elastoplastic. In the transition zone, a transition function is constructed to make the homogenized elastic fields continuous and differentiable in the gradation direction. The ensemble-volume averaging procedure is employed to micromechanically derive the effective yield function based on the probabilistic spatial distribution of spherical particles and the particle-matrix influences. Accordingly, the overall elastoplastic stress-strain responses of the FGMs with different volume fractions of aluminum particles under uniaxial loading/unloading histories are derived. Corresponding laboratory tests are conducted and test results are compared with the predicted solutions to validate the presented model.

757: Micromorphic Model Including Grain Spins Based Upon Granular Micromechanics

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Many materials with engineered micro-structure can be described as granular materials. These cover a wide range of materials, including materials with distinct grain boundaries (such as grain assemblies) and materials in which

identification of grains and their boundaries is not so straightforward but are formed of grain precursors. Granular micromechanics provides a practical and beneficial approach for continuum modeling these materials. In this approach, the material representative volume element (RVE) is modeled as a collection of grains which are interacting with each other through different inter-granular mechanisms. In the proposed presentation, the kinematic field within the material point considers not only grain displacements but also their spins. Furthermore, to better describe the rich kinematics within a material point additional non-classical terms are incorporated as discussed in 1. Thus, we include not only the classical macro-scale strain tensor (first gradient of the average displacement field), but also tensors that describe the fluctuations from average displacement gradient and the second gradient of the displacement fluctuations. The grain spins are also considered in defining the kinematics, including both the average and fluctuations from the average grain spin. The enhanced macro- scale kinematic measures are identified with the micro-scale kinematic measures that define grain-pair relative movements. Conjugate to the aforementioned kinematic measures, force (or moment) measures are defined at the micro-scale. Similarly, the macro-scale stress measures are defined as the work conjugate to the macro-scale kinematic measures. By equating internal free energy density of the RVE to the volume average of all the deformation energies of all grain-pair interactions within the material point, the macro-scale stress measures are calculated based upon inter-granular force (or moment) measures and material microstructure. Expressions for the elastic stiffness tensors corresponding to the aforementioned macro-scale kinematic measures are then derived assuming quadratic form of grain-pair deformation energies. A practical approach for obtaining the elastic stiffness tensors is then demonstrated. The need for additional macro- scale deformation measures for the continuum modeling of granular materials becomes evident in this identification process. Moreover, the effect of grain spins on the macro-scale behavior is clarified.1 Anil Misra and Payam Poorsolhjouy, "Granular micromechanics based micromorphic model predicts frequency band gaps" Continuum Mechanics and Thermodynamics (2015) DOI: 10.1007/s00161-015-0420-y

413: Microscale Modeling of Strain Localization in Bleurswiller Sandstone

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Granular rocks deformed under laboratory conditions exhibit complex pressure dependent stress–strain responses and strain localization processes. Such class of quasi-brittle materials is in fact characterized by various forms of fine-scale heterogeneity, which generate macroscopic patterns that can be traced back to a range of micro-structural processes, such as crack initiation; crack propagation along complex three-dimensional paths; interaction and coalescence of distributed multi-cracks into localized continuous cracks; and interactions between fractured and unfractured material. While usual constitutive approaches describing the macro-scale response of porous rocks neglect such rich variety of microscopic processes, discrete numerical models allow the incorporation of material heterogeneity directly at the scale where such processes take place. This paper discusses a new computational tool for the analysis of inelastic processes in granular rocks subjected to varying levels of confinement. The purpose is to provide a flexible and efficient computational tool for the analysis of failure processes in geomechanical settings. The proposed model is formulated within the frame of Lattice Discrete Particle Models (LDPM), which is calibrated to capture the behavior of a porous rock widely tested in the literature: Bleurswiller sandstone. It is shown that the model allows one to explore the effects of heterogeneous microstructures on the development of pervasive faulting and strain localization. Most notably, it is discussed how LDPM analyses can be interpreted from a macroscopic perspective, deriving a detailed description of inelastic deformation patterns at the continuum scale. It is further discussed how the combined use of LDPM analyses, continuum modeling, and bifurcation theory can enable one to assess predictive capabilities and limitations of the usual elastoplastic models for sandstones, thus suggesting possible enhancements of their

formulation.

547: Microstructure and Nanomechanical Properties of the Interfacial Transition Zone in Geopolymer Concrete with Different Molar Ratios of SiO2/Na2O of Alkaline Activator

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Many studies have intensively investigated cementitious products resulting from various alkali activated materials and their global mechanical properties, but there is not many studies that have explored the Interfacial Transition Zone (ITZ) between the alkali activated materials and aggregates. Using class F fly ash as an alternative alkali activated binder to supplement and/or replace traditional Portland cement requires better understanding of the effects of ITZ on overall mechanical properties of concrete mixtures. To this end, scanning electron microscopy (SEM) and nanoindentation tests are conducted to examine the microstructure and nanomechanical properties of the ITZs between class F fly ash paste and aggregates. Effects of different mortar ratios of SiO2/Na2O of alkaline activator on the development of ITZs are also studied. The research results on micro and nanoscale are expected to improve the understanding of the mechanical properties of the alkali activated materials on macroscale behavior and performance of concrete mixtures and structures.

136: Mitigating Mesh Dependence of Stochastic Finite Element Analysis of Quasibrittle Fracture

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Damage localization is one of the most salient features of quasibrittle fracture. The size of the localization band is a material property independent of the structural size and geometry. This leads to the spurious mesh dependence issue in the finite element (FE) simulations of quasibrittle fracture. Over the past three decades, various approaches, such as crack band models, nonlocal integral models, and gradient models, have been proposed to overcome this mesh dependence issue. All these models were developed for deterministic calculations. In this study, we investigate the effect of damage localization on the stochastic FE simulations of quasibrittle fracture. It is shown that the simulated probability distribution of nominal strength is strongly dependent on the mesh size using the conventional crack band model. In view of this, a probabilistic crack band model is developed. Based on the finite weakest link model, the probability distribution function of material strength of each finite element is formulated to be dependent on the element size as well as the damage extent of the adjacent elements. The model is incorporated into a simple continuum damage constitutive model for analysis of both tension and bending specimens. It is shown that the proposed model provides an effective means to suppress the spurious mesh subjectivity for the stochastic FE analysis of quasibrittle fracture.

234: Mitigation of Structural Response Due to Near-Field Seismic Ground Motion Using an Optimized Innovative Rotational Inertia Damping Device

Abdollah Javidialesaadi, University of Tennessee
Nicholas Wierschem, University of Tennessee

This study investigates the use of an innovative light-weight rotational device for the passive protection of structures from the effects of near-field seismic ground motion. The rotational devices studied are connected to a small supplemental mass and convert the relative translational motion of this mass into the localized rotational motion of a single or group of rotating masses. These devices can passively protect a structure via two main mechanisms: the modification of the overall dynamic properties of the structure due to the increased effective inertial mass caused by the rotational device and the conversion of energy contained within the structure into the rotational kinetic energy of the rotational mass and dissipation of this energy. A key factor in the effectiveness of these devices is that a relatively small mass can be used to create a device that has massive effective inertial mass and substantial potential for kinetic energy storage. In this work, numerical simulations are performed on a system consisting of a rotational inertia damping device connected to a multiple degree-of-freedom base structure, which is representative of a mid-rise structure. Using this system, a numerical optimization study is perform to select the parameters of the rotational inertia device which best mitigates the response of the structure due to a generalized representation of a near-field seismic ground motion.

604: Mixed-field Meshfree Method for Modeling Munitions Penetration in Soils

Sheng-Wei Chi, University of Illinois at Chicago
Thanakorn Siriaksorn, University of Illinois at Chicago
Ashkan Mahdavi, University of Illinois at Chicago

We introduce a mixed-field meshfree method based on the reproducing kernel (RK) approximation for modeling munitions penetration into soils. To handle contact, extreme deformation, material separation, the semi-Lagrangian RK formulation is employed, in which the RK shape function is constructed following the material point while the influence of kernel function is fixed in space [1]. The contact between the penetrator, soils, and soil debris is naturally simulated by the interaction of kernels in the present method. The stick-slip condition on the contact surface is imposed by a lay of artificial material that mimics the Coulomb's frictional law, and a level-set algorithm is utilized to identify the contact surface [1]. A pressure-displacement formulation, extended from Biot's theory, is incorporated in the meshfree framework to describe the porous nature of geomaterials. Stabilized nodal integration schemes under the variationally consistent integration [2] are developed for the mixed field formulation to ensure the stability and accuracy of solutions. A Drucker-Prager plasticity with damage model is adopted to account for material hardening, softening, and damaged for the solid phase. The proposed method is verified with several benchmarks. The simulation results of penetration processes is compared with the results from literature.[1] S. W. Chi, C. H. Lee, J. S. Chen, and P. C. Guan, "A level set enhanced natural kernel contact algorithm for impact and penetration modeling," International Journal for Numerical Methods in Engineering, vol. 102, no. 3-4, pp. 839-866, 2015.[2] J. S. Chen, M. Hillman, and M. Rüter, “An arbitrary order variationally consistent integration for Galerkin meshfree methods,” International Journal for Numerical Methods in Engineering, vol. 95, no. 5, pp. 387–418, 2013.

585: Model Updating of a 10-Story Concrete Building Using Hierarchical Bayesian Framework

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In this study, a Bayesian framework is used to calibrate a Finite Element (FE) model of a ten-story concrete frame building located in Utica, NY. Ambient vibration measurements were collected from the building before and after the removal of six of building's exterior walls, which were removed to simulate the effects of damage. The first three identified natural frequencies and mode shapes at the reference state are used to update the material parameters of the FE model and estimate the uncertainties of the FE model in calculating the first three frequencies/mode shapes of the building. To this end, the misfit between the FE model-calculated and the identified modal parameters is defined by a Gaussian probability distribution with unknown parameters. The parameters of the misfit/error functions (e.g., means and variances) are updated in addition to the structural model parameters. Four updating cases are performed based on different selection of structural parameters and different definition of the error functions. It is shown that the inclusion the FE-model parameter uncertainties as well as modeling errors (probability model of the error functions) in the updating process improves the model accuracy, especially when used to simulate the data used in model calibration. The considered four models are also used to predict the modal parameters of the structure at the damaged states. The probability model of the error functions, obtained from the updating process at the reference state, is used to propagate model uncertainties into the predicted frequencies/mode shapes at the structural damaged condition. The model predicted modal parameters are compared with the measured counterparts and good agreement is observed between the two. The proposed updating approach of this study is a good alternative to both deterministic and probabilistic FE model updating techniques that are based on minimizing the discrepancies between the identified and FE-model modal parameters. The results of the deterministic model updating framework can be obtained if no probability model is considered for the error functions. The results of Bayesian FE model updating can also be obtained if no variability is assumed for the structural model parameters. By accounting for both the test-to-test variability of identified modal parameters and modeling errors, the probability of predicting the real structural behavior from FE models increases and more accurate damage identification or response predictions to future loads are expected.

466: Model Updating of Compressive Strength Constitutive Models for Cement Paste

Yohanna Mejia, University of South Carolina
Juan M. Caicedo, University of South Carolina
Fabio Matta, University of South Carolina

Constitutive models available in the literature typically describe the compressive strength of ordinary Portland cement (OPC) paste in a deterministic fashion, as a function of relevant parameters such as porosity, water-to-cement ratio, and in some instances chemical composition of clinker. In this presentation, representative compressive strength models for OPC paste are analyzed and updated from a probabilistic perspective. Due to the diversity of sources of error in a given model, the updating process is addressed as a problem of statistical inference, which aims to enable a more accurate strength prediction as well as provide a quantitative assessment of such accuracy. Statistical inference is performed by applying Bayes' theorem to model updating, using the parameters with greater uncertainty. Here, the models selected were updated using experimental data collected from the literature. Then, the models were comparatively assessed based on the calculated Bayes factor. This Bayes factor is used to determine the probability ratio of one model compared with the other, giving engineers an idea of which model is more probable given the data available in the literature.

314: Modeling Agents and Environments at the Built-Human Interface

Paul Torrens, University of Maryland

Modeling dynamics at the human-built interface has always been a challenge. The task becomes particularly daunting for critical scenarios, such as dynamics of building damage, collapse, and evacuation following earthquake. In such situations, the interface between people and the urban substrate fundamentally transforms in often extraordinary and unexpected ways that defy any usual norms of behavior or planning. The dynamics are also usually massive in impact and fleeting in process. This leaves us with quite a conundrum: modeling critical interfaces with huge amounts of uncertainty and intricate requirements for detail in a vacuum of ground truth. In this presentation, I will demonstrate a preliminary solution for beginning to address these issues: a virtual geographic environment, replete with realistic-behaving and realistically-represented agent-characters that can be embedded in high-detail virtual urban models with high-resolution physical and social processes. Together, they offer a sandbox for experimenting with what-if scenarios and data as they become available. I will show the usefulness of the scheme in modeling hypothetical earthquake scenarios in Salt Lake City, UT, proven on a high-performance computing and data management platform that can accommodate 100,000 agents and their interactions with the built environment at details that scale from a few millimeters through to a large areas of a downtown setting.

151: Modeling Anisotropic Grain Boundary Energy and Morphology in Polycrystal-Level Simulations

Brandon Runnels, University of Colorado

Grain boundaries (GBs) are known to be key players in a variety of mesoscopic processes, such as solidification, recrystallization, grain boundary migration, and severe plastic deformation. Though grain boundary energy (per unit area) is frequently treated as having a constant value, numerous experimental and computational studies indicate that grain boundary energy is strongly dependent on the geometric character of the interface; that is, the 5-dimensional space of the crystallographic orientation relationship and orientation of the interface. Additionally, although grain boundaries are frequently modeled as planar, it has been observed frequently that many interfaces exhibit a tendency to form complex microstructure. Such grain boundaries with complex morphology have been observed to play a crucial role in many micromechanical phenomena such as grain boundary migration, stability, and twinning. In this work, a new model for interface energy and morphology is formulated that is fast, general, and dependent on only three material parameters, and is verified by comparison with more than 40 molecular dynamics datasets for multiple types of symmetric/asymmetric tilt and twist boundaries, as well as experimental measurements, for FCC and BCC materials. In order to account for non-planar interfaces (e.g. with facets) it is necessary to extend the model by means of relaxation. A relaxation algorithm is presented that is able to efficiently compute the optimal facet pattern and corresponding relaxed energy. It is shown that the algorithm, used in conjunction with the grain boundary energy model, is able to predict the experimentally observed faceting patterns as well as thermally activated facet/de-facet transitions. Finally, the grain boundary model is implemented as an interface model in a polycrystal simulation to observe the effects of grain boundaries in conjunction with elastic and plastic deformation. The simulations for basic and realistic test cases are compared with those using an isotropic grain boundary model, and the effect of the grain boundary isotropy on the bulk properties of the sample as well as the microstructural evolution is determined. The results have immediate application towards, e.g., improved grain boundary models in polycrystal simulations, determining the relationship between GB energy and void nucleation, and techniques for optimal GB engineering.

728: Modeling Dynamic Fragmentation of Heterogeneous Structural Materials

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Nitin Daphalapurkar, Johns Hopkins University
Lori Graham-Brady, Johns Hopkins University

Extreme high-rate loading conditions in structural materials trigger a complex process of fragmentation involving probabilistic, energetic and mechanical aspects. In this work we discuss a one-dimensional approach based on the model suggested by Zhou et al. [1] to study dynamic fracture and fragmentation in glass, concrete and masonry, with particular interest in the higher strain rate regime (103 to 105 /s). The model considers a one-dimensional bar under a uniform tensile initial strain rate, with a stochastically varying strength. Two preliminary steps are considered as part of the model: (i) the Bayesian information criterion is used to select the best type of distribution and (ii) a parametric study is performed to capture the impact of the heterogeneity of the materials in some of the variables of the model. The results show the fragment size, fragment mass and time of formation distributions for the three materials studied. The relationship between average fragment size and strain rate show good agreement with shock tube experiments for all the materials studied. However, the predicted distribution of fragment size exhibits a smaller variance than that observed in the experiments. Future work will evaluate this difference in the results, which could be the result of the one-dimensionality of the model, heterogeneity of strain rate in the shock tube tests, experimental measurement errors, or a combination of all of these. Corresponding models in two and three dimensions will also be investigated as a means of verifying the 1D results.

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110: Modeling Hydraulic Fracture of Ice Shelves Using Continuum Damage Mechanics

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Ravindra Duddu, Vanderbilt University
Jeremy Bassis, University of Michigan
Haim Waisman, Columbia University

The propagation of water filled cracks (crevasses) in glaciers is a phenomenon that contributes to accelerated failure of glaciers. Cracks in ice shelves may be filled by surface lake water, ice melt and/or ocean water. Continuum damage models have been previously proven to be promising techniques for the analysis of iceberg calving; however, hydraulic effects have not been considered in these models. In this research study, we propose a new approach to incorporate hydraulic fracture into a viscoelastic ice model within a damage mechanics framework. To this end a new damage term is proposed which corresponds to the ratio between the pore fluid pressure and the solid matrix pressure of a given damage state. This novel approach allows for modeling the propagation of multiple water filled cracks along with the non-linear viscoelastic ice flow. The developed model is used to analyze the calving of idealized rectangular grounded and floating ice slabs subjected to different loading conditions. In this study, we investigate the propagation of isolated surface crevasses as well simultaneous propagation and interaction of surface and basal crevasses. The results are comparable to the results previously presented in the literature which were retrieved from analytical Nye-zero stress model and linear elastic fracture mechanics models.

446: Modeling Kinematic and Inertial Interaction Effects on Buried Structures Through Reduced Order Models

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Ertugrul Taciroglu, University of California, Los Angeles

Soil structure interaction problems are generally analyzed by either the direct or the substructure methods. In the

former (the one-step method), the soil extent as well as the structure is modeled and analyzed together. On the other hand, in the latter (the two-step method), the surrounding soil is first replaced by impedance functions---a set of force- displacement mapping functions---that not only replicate the effects of soil dynamic properties, but also, by being convolved with the scattered motion at the soil-structure interface, translates the effects of excitation sources embedded within the soil, e.g. seismic excitations. Then, the resulting reduced order model, which replicates the kinematic interaction effects, is coupled with the system of equations that represents dynamic properties of the structure to evaluate inertial interaction effects. Almost all existing reduced order models to take the effects of kinematic and inertial interaction into account are limited to on-ground structures such as buildings and bridges. In this study, we explore the possibility of modeling these effects for buried structures such as tunnels. To this end, we use our in-house code to compute soil impedance functions and scattered motions along the interface at which the buried structure interacts with the soil. The toolbox features perfectly matched layers and the domain reduction method to efficiently absorb/inject outgoing/incoming waves from/into the semi-infinite media. The resulting reduced order model is used to obtain the response of tunnels with different shapes and flexibilities when subjected to seismic excitations. The accuracy of these models is examined by comparing the computed responses against those obtained from direct modeling of the same problems.

629: Modeling of Aging Effects on Concrete Creep/ Shrinkage Behavior: A Lattice Discrete Particle Modeling Apporach

Mohammed Abdelatif, Rensselaer Polytechnic Institute
Giannis Boumakis, University of Natural Resources and Life Sciences Vienna
Roman Wendner, University of Natural Resources and Life Sciences Vienna
Mohammed Alnaggar, Rensselaer Polytechnic Institute

The currently aging and deteriorating infrastructures both in the US and all around the world have been a major cause to extend the current design provisions for concrete structures to 100 years of design lifetime. During such a long period, concrete exhibits a well-known time dependent behavior that is a function of multiple factors including both rheological aspects of the concrete mix as well as the effect of environmental conditions, which contribute to its time dependent aging. While initial conditions (e.g. concrete mix design parameters) can be well controlled, much less knowledge is available on the type and extent of the environmental conditions that will affect the structure. Using macroscopic homogeneous models results in an averaged creep deformation that neglects internal creep/relaxation at lower scales due to internal self equilibrated stresses. Such a short-coming of all continuum based creep models is naturally over come by the explicit implementation of the previously formulated solidification-microprestress (SM) theory within the Lattice Discrete Particle Model (LDPM). LDPM is a discrete model capturing various features of concrete internal heterogeneity and it has demonstrated superior modeling and predictive capabilities under a large variety of loading conditions, both quasi-static and dynamic. The new model entitled Solidification-Microprestress Lattice Discrete Particle Model (SM-LDPM) is uniquely capable of representing creep due to nonuniform shrinkage or thermal strains even under zero external loading. This is thanks to the formulation of creep deformations at the aggregate interface as a function of the inter-aggregate stresses. In this work, the SM theory is numerically approximated through an aging Kelvin chain and the resulting rate-type constitutive equations are integrated with an explicit time integrator. Temperature, humidity and reaction degree of concrete are obtained through a multi physics model evolving temperature, humidity and cement degree of reaction in full coupling over time and space. This leads to an elegant and simple implementation within the LDPM framework through an imposed eigenstrain, which leaves the features of the LDPM constitutive equation simulating material strength and toughness completely unaltered. Aging of the Kelvin chain is formulated as a function of a global aging degree of concrete. Simulations of elastic stiffness evolution over time are perused using different aging functions and the results are compared to the engineering code provisions. The presentation is completed with multiple numerical simulations of experimental data from

literature to show the superiority of the proposed model.

268: Modeling of Groups of Standing People Over a Structure Using a Closed Loop Controller Model

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Juan M. Caicedo, University of South Carolina

The interactions between people and structures could create significant vibration problems in many structures occupied by crowds. Traditionally, humans have been modeled using mass or mass-damper-spring systems. Recently, a new type of model has been proposed based in control theory. These models consist of a feedback closed loop system where the human act as a controller and the structure is the plant. Although control inspired models have been demonstrated to be effective in modeling single occupancy, models have not been fully tested for groups of people. This limits their application to structures occupied by one person at the time, which are not very common in Civil Engineering. This research discusses the implementation of control inspired models to groups of people. Each person is first modeled independently. Then, the expected dynamics of the structure plus the group of people is estimated using the numerical models. Results are validated using experimental results for groups of three people.

557: Modeling of Heterogeneous Quasi-brittle Solids with Viscoelasticity, Interface, Nonlinear Fracture, and Multiphysical Phenomena

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Keyvan Rami, University of Nebraska-Lincoln
Taesun You, University of Nebraska-Lincoln

This paper presents a microstructural damage modeling of heterogeneous quasi-brittle solids where viscoelastic deformation, rate-dependent fracture, and interfacial degradation due to moisture diffusion are significant sources of energy dissipation and failure-associated phenomena. Complex geometric characteristics of mixture microstructures are represented by a 2-D or 3-D image technique, and individual mixture constituents such as elastic particles, surrounding viscoelastic matrix, and interface between the particles and matrix are characterized for their material properties. In addition, viscoelastic cohesive zones are embedded in the microstructure to account for rate-dependent fracture within the mixture microstructure. A series of laboratory tests were performed to obtain properties of the component phases (i.e., micro-scale) and overall damage-associated performance of the entire mixture (i.e., meso-scale). The computational microstructure modeling was validated by comparing simulation results with the experimental test results available. The results presented in this paper clearly indicate that the effect of microstructure and individual component material properties on the entire damage-associated multiphysical behavior of the heterogeneous mixtures. The microstructure modeling was then extended to a two-way coupled multiscale modeling so that micro-scale component properties are directly used for predicting homogenized structure-level damage-induced performance (i.e., macro-scale).

361: Modeling of Leadership Behavior with an Extended Social Force Model for Crowd Evacuation in Buildings

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Crowd evacuation in buildings under various emergencies, such as earthquake, fire, or terrorist attack has long been recognized as an important but challenging issue. This has attracted considerable attention in the field of civil and architectural engineering over the last years. During crowd evacuation, how to efficiently assign the evacuation leaders is regarded as a critical problem especially when the evacuee crowd is not familiar with the internal layout of the building. In this study, an extended social force model is developed to simulate the leadership behavior during crowd evacuation in rooms with limited visibility range. The simulation results show that: (i) For a large evacuee crowd, a small proportion of the evacuation leaders is already sufficient to guide the whole crowd efficiently, even if the visibility range of the room is very limited. And the smaller the crowd size, the larger the proportion of the leaders is needed to achieve satisfactory evacuation guidance. (ii) The optimal proportion or number of the leaders in an evacuee crowd to achieve a satisfactory guidance is related to the visibility range of the room and the distribution range of the evacuee crowd. (iii) Leadership is not always positive to the crowd evacuation. It may have a negative effect on crowd evacuation when the visibility range of the room and the size of the evacuee crowd are large enough. These results provide a new insight into the effects of leadership on crowd evacuation. The results are also helpful for developing effective evacuation strategies and optimizing the building design.

574: Modeling of Pipeline Corrosion Deterioration Mechanism with a Lévy Process Based on ILI (In-Line) Inspections

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Mauricio Sánchez-Silva, Universidad de Los Andes

According to databases such as CONCAWE (Europe) and PHMSA (USA), onshore pipeline failure caused by corrosion represents about 16% of the overall number of incidents during the period from 2004 to 2011. In pipelines, the main testing procedure used to evaluate the effects and evolution of corrosion with time is the In-Line Inspection (ILI) assessment. It provides detailed information about aspects such as the inner and outer condition of the pipe and the pipe wall thickness variations, among others. Often this test is carried out every other year providing information about the pipe condition evolution with time. This information can be used with advantage to develop degradation models that can, in turn, be used to predict the failure time and to schedule maintenance activities. In this paper, we present a steel-pipe degradation model based on the so-called Lévy processes. The model combines progressive deterioration due to corrosion with sudden changes on the system condition. The parameters of the mix process are determined through optimization with a copula joint probability approach. The results of the model allow making accurate estimations of the lifetime distribution and the mean time to failure (MTTF) of the pipeline. Furthermore, the model takes into account the spatial variability of corroded defects along the pipeline, which allows determining the sectors that are more vulnerable and on which a preventive monitoring should be performed. The model was tested on an actual segment of an oil pipeline and the results were used to establish a preventive maintenance program.

116: Modeling of the Mechanical Properties of CNTs Reinforced Concrete Based on Element-Free MLS Method

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A new formulation to model the mechanical properties of carbon nanotubes (CNTs) reinforced concrete with arbitrarily oriented short fibers is presented. Each component of the composites, concrete material and reinforcing CNTs, are modeled by different constitutive relations. Under the assumption that any infinitesimal volume is occupied by all the components in their corresponding given volume fractions, the mechanical behaviors of the composites are simulated by combining these component models together. The mixture theory is applied to define the overall free energy of CNTs reinforced concrete, which is assumed to be homogeneously constituted. The present numerical methodology is assessed by simulating a selected set of experimental tests. In order to obtain the load-deflection diagram, displacement control procedure is applied. Due to damage of the composites, such as cracking or void growth, strain softening is considered via continuum based model. The element free Galerkin method based on moving least-squares (MLS) approximation is implemented to derive the discretized equation system. Finally, the numerical examples proves the viability and accuracy of meshless method to capture a number of mechanical phenomenon interacting at the macro- and mesoscale and leading to failure of CNT reinforced composites.

747: Modeling Projectile Penetration Mechanics in a Meshfree Computational Framework

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Material and structure response to extreme events like explosive detonation and projectile penetration is an area of significant interest to the engineering and scientific communities. The analysis of system response necessitates robust methods to accurately model the complex phenomena that dominate these extreme events. For projectile penetration and perforation, the target and penetrator failure mechanisms, coupled with the material response to high-rate impact loading, are crucial parts of the penetration mechanics. The ability to accurately model this complex behavior: 1) is critical for reliable analysis and design, and 2) presents unique challenges for the development of accurate and robust numerical techniques. The actively developing class of meshfree methods provides new capabilities in this field by naturally capturing large deformation and material separation without nonphysical treatments required by other approaches. To advance computational capabilities for high-rate penetration modeling, a new Reproducing Kernel Particle Method [1] impact and penetration formulation [2] has been developed. A stabilized semi-Lagrangian formulation is utilized for accurate numerical integration in the presence of material fragmentation, and evolutionary contact conditions between target and penetrator are addressed through a contact algorithm that obviates the need for a priori contact surface definitions. Penetration into concrete is of specific interest, so a multiscale material damage model [3] that links continuum-scale damage with microstructure fracture is also implemented. Projectile impact experiments into materials with differing strength and ductility are simulated for comparison of energy attenuation and failure modes as a function of the penetration event parameters (geometry, velocity, and target material properties). Results cumulatively validate the formulation accuracy for these type of extreme events.
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614: Modeling Resilient Infrastructure Combining Physical Damage and Loss and

Restoration of Functionality: The Case of a Water Network

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The large-scale disastrous events occurred worldwide in the past years show the extreme vulnerability of our society and its infrastructure. Civil infrastructure (e.g., transportation network, water systems, electrical power network, etc.) are critical to communities and their disruption has a direct impact on the economy of the damaged region and on the well-being of its inhabitants. Moreover, in the aftermath of a damaging event, their availability is crucial both for minimizing the societal impact of the event itself and for the recovery processes. In this context, the concepts of risk and reliability analysis allow us to define probabilistically different damage scenarios and to quantify the safety and performance of civil engineering asset. The paper propose a methodology for the evaluation of the infrastructure resilience, coupling the analysis of direct and indirect physical damage to the network components with loss and restoration of functionality. The method is general and able to model the resilience of different networks, with their dependencies and inter-dependencies, and different hazards. In this work, we apply the methodology to a water network subject to seismic event. The first step consists in a baseline deterministic hydraulic analysis of the network in the undamaged scenario, where it is crucial the individuation of meaningful functionality metrics. In the case of the water network, these could be the pressure at the demand nodes, the flow in the pipes and the quality of the water. Successively, a reliability analysis of the network is performed in the aftermath of the damaging event. Vulnerabilities and fragilities of the main elements of the network are taken into account to evaluate their performance level and damage state. Finally, a probabilistic analysis of the water network functionality is conducted to evaluate how the physical damage and the recovery time of each component affect the loss and restoration of the functionality metrics.

183: Modeling Stiffness and Damping in the Dynamic Analysis of Stranded Conductor Cables

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Cables are widely used in the power industry as essential components of the electrical transmission network. These are usually designed to meet electrical standards rather than structural performance requirements, but several past earthquakes have shown that the seismic response of interconnected substation equipment is significantly influenced by the dynamics of the conductors. Due to the complexity of this interaction, there are deficiencies in how this effect is accounted for in current seismic design and qualification standards. The seismic qualification procedures in the IEEE 693-2005 Standard are limited to individual equipment, with recognition that additional forces due to conductor dynamics have to be accounted for separately. However, the evaluation of these forces is based on experimental measures on specific conductor configurations that do not exhaust all the possible configurations in the field. The dynamic behavior of interconnecting flexible conductors is highly nonlinear, characterized by large displacements and rotations, and impulsive forces. Moreover, due to their construction, the dynamic properties and energy dissipation capacity of stranded electrical conductors are not easy to determine and model. Recent experiments on electrical conductors, under three-dimensional seismic excitation at the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at the University at Buffalo, have shown that stiffness and damping in these conductors are dependent on the amplitude of motion. This nonlinear effect can be explained by sticking and slipping of strands relative to each other. Due to friction,

both stiffness and damping decrease with increasing amplitude of motion. Energy dissipation by friction is also evident from quasi-static experimental measurements. A 3D finite deformation beam model and associated computational algorithms have been recently developed by the authors. These formulations already account for viscous and mass proportional forms of damping. The present study deals with experimental and analytical work towards the development, and inclusion within the current framework, of a plasticity model that can properly account for the strands stick-slip behavior. Three-dimensional connector elements are introduced to model the normal and tangential interaction between the helical wires composing the conductor. We then idealize that sliding between wires occurs when the magnitude of the tangential force becomes equal to a coefficient of friction times the compressive normal force. The numerical model is validated through experiments on conductors in typical field configurations.

516: Modeling the Force-Displacement Behavior of Passive Isolation-Layer Devices in a Four Story, Reinforced Concrete, Base-Isolated Structure through Bouc-Wen Hysteresis

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While full-scale testing of building specimens requires a substantial investment of time, money, and resources, the experimental results gained from these tests can offer researchers insight into the physical phenomena governing the building’s dynamics and mechanical behavior -- insight that simulations, no matter how complex, simply cannot provide. The necessity for such full-scale tests only increases when innovative technologies that enhance structural performance but exhibit nonlinear behaviors, such as seismic protective systems and base-isolation devices, are included in the building’s design. The researchers at E-Defense (a part of the Japan's National Research Institute for Earth Science and Disaster Prevention, NIED), a unique facility capable of testing full-scale structures, designed and constructed an asymmetric base-isolated building to test and study, in part, the performance of the isolation layer when subjected to strong impulsive and long period excitations. The composition of the isolation layer includes pairs of rubber bearings, elastic sliding bearings, and passive metallic yielding dampers, as well as (in some tests) controllable oil dampers with solenoids. The structure was constructed in late 2012 and early 2013, and underwent initial testing in March 2013. A variety of sensors, including displacement and force transducers and accelerometers, were mounted within the isolation layer to measure its response to the shake table excitations. Subsequent August 2013 tests, on which this study is based, included both random base motions and historical and synthetic ground motions. A model for the hysteretic behavior observed in the isolation-layer devices was created using the force and displacement sensing data from these tests. Since displacement data was available in both horizontal planar directions of table motion, a bi-axial Bouc-Wen model was assumed, using coupled nonlinear differential equations; the parameters in this model were fit based on the force and displacement measurements. It was found that the isolators exhibited generally linear behavior during the tests with random base motion, but behaved nonlinearly for the simulated earthquake ground motions, both historical and synthetic. For each simulated earthquake, a series of tests were conducted in which the input intensity, and thus ground motion amplitude, was gradually increased. Due to the well-documented amplitude dependence of nonlinear phenomena, the tests with the largest input amplitudes were primarily used for identification and the model with the resulting parameters was applied to the lower-intensity tests; however, lower-intensity tests were also used for parameter fitting as means of comparing performance. Further, cross comparisons of parameters from different earthquakes were conducted in order to gauge the generalizability of the identification results.

190: Modeling the Interactions between Cyber Capabilities and Critical Infrastructure-

Based Societal System Functioning in Disasters

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The resilience of critical infrastructure-based societal systems (CIbSSs) are necessary for community functioning. A CIbSS is comprised of interdependent buildings that together serve a community function and that are dependent on networks of critical lifelines (water, wastewater, power, natural gas, communications and cyber, and transportation). However, nearly every aspect of society has been affected by an increasing reliance on cyber capabilities, such as networked information systems, automation of processes, and a shift to electronic-only record keeping systems. These dependencies enhance productivity under normal conditions, but can significantly escalate the impact of a natural disaster. Escalation may have different causes. Loss of power at data centers (e.g., Health Information Exchanges, offsite hospital record stores) can disable information systems even when the hospital system remains functional. Loss of network connectivity can disable access to records stored at satellite offices, or to information systems that have been moved to offsite locations. Moreover, in emergency situations IT administrators may disable to bypass security protections information, making these systems vulnerable to escalations caused by follow-on attacks (e.g., deliberate cyber attacks or malware infection). The focus of this paper is modeling the interactions between cyber capabilities and CIbSS functioning in disasters. A significant vulnerability we have identified in our work is the vulnerability of existing Electronic Health Record (EHR) systems to communications failure or malicious exploitation during a natural disaster. This motivates the need for new security technologies to protect these sensitive records. In previous work, we have examined the use of encryption to protect sensitive health records. In this paper, a resilience-improving risk communication strategy based on "self-protecting electronic health records" is developed. These encrypted records remain both secure and accessible to healthcare providers, even when local and wide-area communication networks are unavailable. The developed approaches are demonstrated on a healthcare system, which we consider the perfect archetype of CIbSSs, because of its criticality in disasters, complexity in functioning, and interdependencies in physically distributed infrastructure networks. One key networked information link in the healthcare system is the system of electronic patient records. The vulnerability of Electronic Health Record to cyber attack, focusing particularly on the capabilities of this system in emergency scenarios, is investigated as it relates to overall system resilience. This work provides a deeper understanding of the interactions between cyber capabilities and CIbSS functioning in disasters, and develops solutions to prevent escalating and cascading failures in CIbSS functionality.

758: Modeling Thermal Softening Effects in Coupled THM Problems at Finite Strain

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In a number of geotechnical applications of relevant practical interest, a saturated soil mass is subjected to mechanical and thermal loading conditions, which induce solid skeleton deformations as well as water and heat flows. Recent experimental evidence on thermal behavior of fine-grained soils shows that temperatures changes can alter the shape and size of the yield surface, causing the development of so-called compensation yielding even at constant external loads. Understanding this coupled thermo-hydro-mechanical behavior from a qualitative, as well as quantitative point of view can be therefore very important. The purpose of this research is to describe these coupling processes within the framework of the theory of plasticity with extended hardening rules. A key feature of this approach is that evolution of the internal variables is governed by plastic deformations as well as by the change of temperature. An adaptively stabilized monolithic finite element model is proposed to simulate the fully coupled thermo-hydro-mechanical behavior of porous media undergoing large deformation. We first formulate a finite-deformation thermo-hydro-mechanics field theory for non-isothermal porous media. Projection based stabilization procedure is designed to eliminate spurious pore pressure and temperature modes due to the lack of the two-fold inf-sup condition of the equal-order finite elements. To avoid volumetric locking due to the incompressibility of solid skeleton, we introduce a modified assumed deformation gradient in the formulation for non-isothermal porous solids. Finally, numerical examples are given to demonstrate the versatility and efficiency of this model.

710: Modelling Post-Earthquake Recovery and Resilience of the Electric Power Supply Systems in Nepal

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Over the last decade, a significant shift in the focus of earthquake engineering research occurred – that from the seismic performance assessment of individual structures to the study of seismic resilience of engineered systems and communities. Critical infrastructure systems, for example, the water and the power distribution networks or the transportation network, play crucial roles in the seismic resilience of a community. The assessment of seismic resilience of a community is a complex task, due primarily to a) the complex interdependencies among infrastructure networks, b) a general lack of data that is most essential to create empirical models of different components and their functions, and c) the large-scale variations in the behavior of the different networks under the same hazard, and the behavior of the same network under different hazards. A review of recent research shows that the seismic fragilities and vulnerabilities of different infrastructure systems are better understood and estimated than the recovery of a community after a disastrous event. Modelling the recovery process is a challenging task, firstly because the recovery process is subjected to a large set of (interdependent) factors and variables, many of which are linked to organizational, socio- economic and political factors, that are difficult to quantify. Secondly, the lack of empirical data – especially at the community level – makes it extremely difficult to develop and calibrate analytical recovery functions for a specific infrastructure system-community-hazard combination. The primary objective of the present work is to adapt the component recovery model presented in Didier et al. 2015 for the recovery process in Nepal after the 2015 Nepal Earthquake Series. A first goal is to understand how the modelling assumptions for recovery functions affected and will affect the estimated seismic resilience of a community whose electrical power supply network has been damaged by an earthquake. The modelling assumptions that are analysed in this work are: a) the probability distribution type of the time-varying recovery functions, and b) the parameters of the recovery functions. The significance of modelling assumptions in these aspects are studied for the expected estimated time until recovery of the community (and its electric power supply system) and its variation. In addition, the effects on the mean and variation of the resilience of the combined system are also studied. The outcomes of this study will hopefully help to understand the possible long-term recovery process in Nepal and provide useful guidelines for its future seismic resilience.

612: Molecular Characterization and Adhesion Mechanics of Cancer Metastasis on Humanoid Tissue Engineered Scaffolds

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In the human body, invading cancer cells often migrate to distant organs and form 3D organized colonies through mechanisms of metastasis. Many cancers metastasize to bone and in most patients, cancer metastasis is unfortunately terminal. Prostate cancer cells are specifically inclined to metastasize to bone due to unique constituents of the bone microenvironment resulting in eventual death. Molecular mechanisms of metastasis are evaluated in invivo studies with animal models and in 2D invitro systems. Recently, 3D material systems are found to be useful for evaluation of cancer growth. In our previous studies we have developed novel nanoclay based polymeric scaffolds that develop bone mimetic tissue exhibiting hierarchy, mechanics and chemistry of human bone when seeded with human mesenchymal stem cells. These scaffolds also enable human mesenchymal stem cell (hMSC) differentiation. Here we describe the use of these bone-mimetic scaffolds for development of a test-bed to evaluate cancer cell metastasis as well as tumor formation. The nanoclay based bone mimetic scaffolds seeded with hMSCs create a new bone microenvironment conducive to growth and proliferation of prostate cancer cells. We observe presence of tumoroids with cancer cell proliferation on hMSCs. The cancer growth as evidenced by spheroid formation followed by tumoroids is similar to biological metastasis. Tumoroids are not formed on scaffolds seeded with mature bone cells followed by cancer cell seeding. We present here detailed microstructural and spectroscopic evaluation of the tumors and their evolution and growth. Nature of adhesion of cancer cells on new bone growth in scaffolds is described through electron microscopy. Fourier transform Infrared spectroscopy studies evaluate the molecular nature of the adhesion. Gene expression studies on these tumors are also presented that indicate genetic changes to cancer cells on adhesion and tumor formation on the scaffolds. The biomimetic scaffold system presented here represents an excellent bone-mimetic environment for study of tumor formation and cancer metastasis to bone.

645: Molecular Dynamics Simulation of the Melting of Pore Water for Understanding Phase Composition Behavior of Frozen Soils in the Extremely Low Temperature Range

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The phase composition behavior of frozen soils is a fundamental relationship in understanding permafrost and seasonally-frozen soils and thus of great interest in cold regions engineering. However, due to the complex interplay of adsorption and capillary effects, a clear physically-based understanding of the phase composition curves in the low temperature range is still absent. Especially, it is unclear whether the Young-Laplace equation corresponding to capillary still holds in nano-scale pores where adsorption could dominate. This paper employs molecular dynamics simulation to investigate factors that can possibly influence the complex physical process underlying the freezing of pore water. A monoatomic water model was adopted to depict interatomic potentials while a cylindrical nanopore with a face-centered cubic crystal structure was selected to represent the nano-size pores perforating the mineral matrix. The wettability of the nanopore was controlled by adjusting the water-nanopore interaction energy. A specific simulation procedure was presented for the determination of the melting temperature. A series of simulations was conducted to unravel the effects of the pore size and wettability on the freezing of pore water. It is observed that the melting temperature decreases slightly with the increase of nanopore wettability. Besides, the water confined in nanpores with a diameter of 1 nm and 2 nm could not form an effective ice crystal structure due to the molecular order caused by the dominant adsorption effect. The simulated melting temperatures of ice confined in nanopores with a diameter of 3 nm, 4 nm, 5 nm and 6 nm are 20-24 K lower than

those predicted using the Young-Laplace equation. It is therefore concluded that the adsorption effect may be significant in the low temperature range corresponding to nano-scale pores.

538: Multi- Scale Probabilistic Analysis of the Elastic Modulus of Concrete Using Digital Image Processing

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In the design of concrete structures, knowledge of the materials properties is required to conduct a proper, safe, and economical design. Young's modulus of concrete, denoted as (E), is in particular a key mechanical parameter utilized by engineers in the design and analysis of concrete structures. Design codes provide the engineers with relationships to estimate the elastic modulus of concrete of different strengths; these formulas relate (E) to its 28 day compressive strength. However, concrete is a highly heterogeneous material and extensive research shows that its mechanical properties are effected by the properties of its constituents. Several researchers provided composite models that relate the elastic modulus of concrete to the elastic modulus and volumetric fractions of aggregate, mortar, and interfacial zone (ITZ). However, these models interpret concrete as a homogeneous medium and use deterministic values for the elastic properties of the input variables (aggregate, mortar, and ITZ); thus, neglecting the effects of the spatial distribution of aggregates and the natural variation in the elastic properties of the input variables on the elastic modulus estimation. This study presents a probabilistic framework for estimating the modulus of elasticity of concrete while taking into consideration the uncertainties associated with the mix constituents and their spatial distribution. The variability of the characteristic of the mix constituents, i.e. elastic modulus and Poisson's ratio, is quantified by experimentally testing cylindrical core specimens of limestone and mortar. The tested specimens originate from different local sources for the case of the limestone and correspond to different mix design proportions for the mortar. This is specifically done to capture the possible range of variability for the input parameters. The spatial distribution of the aggregates and the volumetric fractions are captured by utilizing digital image correlation techniques to process scanned images of sections cut from concrete cylinders. Using Monte Carlo simulations, the probabilistic volumetric characterization of the mix constituents along with the quantified uncertainty in the mix constituent's characteristics are employed to stochastically predict the corresponding modulus of elasticity utilizing empirical models such as the Hirsch and Ramesh and Hashin models. The probabilistic representation of the elastic modulus of concrete is then compared to the elastic modulus measured experimentally in the laboratory.

689: Multi-Agent Decentralized Vibration Control of Large Building Structures using Bio-inspired Replicator Dynamics

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Active, semi-active, and hybrid vibration control of infrastructure has been the subject of significant research for the past twenty-five years. The goal is to develop a new generation of smart/adaptive structures equipped with sensors and actuators in which sensors measure the response of the structure in real time and actuators and damping devices apply the required forces to minimize the response of the structure. In order to accomplish this objective, various researchers have proposed an array of techniques and devices. Developed in the artificial intelligence community, an intelligent agent is an autonomous abstract or software entity that observes through sensors and acts upon an environment in an adaptive or intelligent manner. In the past few years agents have been

used in civil and structural engineering, for example, to build a flexible structural health-monitoring sensor network, to model homeowners' dynamic interactions with their neighbors following disasters, and to model crowd behavior. For any practical implementation of active and semi-active vibration control of large structures, energy consumption must be an important consideration when selecting a control algorithm. Hence, this research advances the idea of limiting the power available to each actuator or the total available power of an emergency generator should be included in the control algorithm formulation. This paper introduces three ideas to vibration control of structures: agent technology, replicator dynamics from evolutionary game theory, and energy minimization. It presents multi-agent replicator controller as a new intelligent control methodology for decentralized vibration control of structures subjected to dynamic loading such as seismic loading. A large structure is decomposed into a number of substructures with each substructure owning its own controller and set of actuators. The use of agents and a decentralized approach enhances the robustness of the entire vibration control system, as malfunction of an individual agent can be compensated for by nearby agents. The agents make decisions using the replicator dynamics. Recently, replicator dynamics was used for temperature control in energy efficient buildings. In this research, replicator dynamics is used to obtain vibration reduction while optimally allocating the available power. Optimizing the weighing replicator dynamic parameters: growth rate, population, and power available, a suitable global control can be achieved. The proposed control methodology is applied for vibration control of a 20-story steel benchmark building structure subjected to two sets of seismic loadings: Kanai-Tajimi and historic earthquake loads and is compared with a corresponding centralized and decentralized conventional control algorithm.

9: Multi-Criteria Design of Fluid Viscous Dampers Based on Life-Cycle Performance Criteria and Risk-Aversion Principles

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A probabilistic framework for the cost-effective design of seismic protective devices considering multiple criteria related to their life-cycle performance is presented in this contribution, focusing on application to fluid viscous dampers and on the incorporation of risk-aversion concepts within the design formulation. The framework is based on nonlinear time-history analysis for describing structural behavior, an assembly-based vulnerability approach for quantifying earthquake losses and on characterization of the earthquake hazard through stochastic ground motion modeling. In this setting life-cycle performance is described through the expected value of some properly defined risk consequence measure over the space of the uncertain parameters (i.e. random variables) for the structural system and the seismic hazard. The main objective considered for quantifying life-cycle performance is the expected life-cycle cost, composed of the upfront protective system cost and the present value of future earthquake losses. To offer greater versatility and incorporate risk-aversion attitudes in the decision making process, the consequences (repair cost or downtime) with specific probability of exceedance over the lifetime of the structure are additionally considered. This explicitly accounts for low likelihood but high impact events, and ultimately leads to a multi-criteria design setting, representing competing objectives to the life-cycle cost. To facilitate adoption of complex numerical and probability models, a computational framework relying on kriging surrogate modeling is established for performing the resultant multi-objective optimization. The surrogate model is formulated in an augmented input space, composed of both the uncertain model parameters and the design variables (controllable device parameters) and therefore is used to simultaneously support both the uncertainty propagation (calculation of risk integrals for the life-cycle performance) and the design optimization. As an illustrative example the retrofitting of a three-story building with nonlinear fluid viscous dampers is examined.

579: Multi-Field Meshfree Method for Landslide Simulations

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We introduce a mixed field reproducing kernel particle method to handle extreme deformation and material separation in the simulation of landslide processes. Due to the semi-Lagrangian nature of the approximations [1], the methods can naturally detect and enforce the contact conditions between bodies. Multi-field formulation extended from Biot theory is incorporated into the meshfree framework to capture the interactions between solid and fluid phases of porous media. We also incorporate the Drucker-Prager plasticity and damage models into the framework to account for material hardening, softening, and damaged. Stabilized nodal integration methods in conjunction with variationally consistent integration [2] are developed in the multi-field meshfree frameworks to enhance the stability of the methods and recover the consistency of the domain integration, and ultimately improve the accuracy of the solutions. The proposed method is verified with several benchmarks and is validated against landslide experiments; the results show that it is effective for the simulation of landslide. In addition, the von Neumann method is employed to study the stability of the methods. It is shown that the domain integration methods and influence domain of the meshfree approximations significantly affect the stability of the methods.
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86: Multi-hazard Resilient and Sustainable (or MRS) Bridges – Stronger, Taller, Wider, Smarter?

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The Louisiana Department of Transportation has constructed bridges stronger, taller, and wider since Katrina. Some coastal bridges are equipped with real-time laser sensors to measure the rising water elevation such that imminent hurricane vulnerability can be communicated to stakeholders. Recent flooding in South Carolina has washed out bridge supports/roads, and more than 150 bridges were closed due to the severe weather event. There needs a tool suitable to assess the resilience and vulnerability of the built infrastructure. The U.S. DOT Vulnerability Assessment Scoring Tool (VAST) assesses vulnerability of any combination of stressors and DOT asset types to extreme weather events. The result is a set of vulnerability scores that can be used to rank assets by vulnerability. In this approach, it is important to understand how to convert indicator values, which are certain characteristics of assets, to scores on a scale of 1-4. In evaluating hurricane vulnerability using this tool, the storm surge elevation becomes an important scoring factor; however, inconsistencies exist in the vertical control datum of existing bridges – some referenced NAVD88, some referenced temporary benchmarks, and some were not clear as to what the vertical control was. There requires a high-precision elevation measurement consistent with available surge data (e.g., NAVD88) provided by the NOAA's SLOSH model. Therefore, it is essential to make this information available in the national database such as NBI. Once storm surge and bridge elevations are determined, the vulnerability of coastal bridges is proposed to be assessed by generating a fragility function in terms of multiple environmental parameters such as wind and surge height though a development of metamodels. By evaluating the vulnerability this way, real-time surge elevations from the National Hurricane Center, possibly calibrated by USGS's laser sensors instrumented at selected bridge locations, can interact with the fragility function to provide a real-time evaluation of bridges such that resources may be allocated for safe evacuation routes and the most needed re-entry and recovery routes, establishing appropriate detours, allowing for debris clean-up, and facilitating repair and rebuilding activities so that residents can return to the road and business as usual, as quickly as possible. The Georgia Department of Transportation is considering an implementation of this modeling approach in the BridgeWatch software as it can simulate past or potential hurricanes along the Atlantic coast and assess the resilience of the built infrastructure.

72: Multi-Physics Simulation for a Strain Rosette Made of Slotted Patch Antenna Sensors

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Passive (battery-free) wireless patch antenna sensors have been developed in recent years for strain sensing, to provide convenient and low-cost instrumentation. In our previous work, strain sensing performance of a slotted patch antenna sensor has been demonstrated by numerical simulation and tensile testing experiments. This research presents a strain rosette made of slotted patch antenna sensors for measuring a general surface strain field. By closely deploying three strain sensors oriented at different directions, the average state of strain in that region can be determined. To achieve accurate measurement, the effect of transverse strain sensitivity of the antenna sensor is discussed. A calibration method for transverse sensitivity is proposed for actual application. Multi-physics coupled simulation is conducted to accurately describe the mechanical and electromagnetic behaviors of antenna sensors. Upon loading, the deformed shape of the patch antennas (bonded on a base structure) is simulated first. Then, the electromagnetic behavior of the antenna sensors is simulated based on the deformed shape. The electromagnetic resonance frequencies of the antenna sensors are identified using a partially air-filled cavity method. Finally, resonance frequency shifts of the antenna sensors are used to derive the three strain components in the plane stress scenario. Numerical analysis demonstrates that a general surface strain field can be measured by the rosette. The proposed calibration method for transverse sensitivity is shown to significantly reduce the error in the strain measurement.

569: Multi-Scale Experimental Chemo-Mechanical Testing on Quartz: From Elasticity to Fracture

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The Griffith criteria and Irwin's modifications are classical fracture mechanics relations that allow for calculating the critical energy release rate of a material from its fracture toughness and elastic properties, assuming it follows linear elastic fracture mechanics (LEFM). This theory was originally derived from experiments on amorphous isotropic glasses. In crystalline structures, the arrangement of atoms in an ordered pattern extending in all three spatial dimensions often leads to anisotropic properties. In this study, we seek to determine: 1) at what testing scale the anisotropy of the crystalline structure can be felt? 2) How do the mechanical test results compare with the classical fracture mechanics theory? To do so, we tested euhedral trigonal crystals of natural and synthetic

quartz that are chemically comparable to fused silica glass (SiO2). The exposed faces of these crystals form themselves because the surface orientations are more stable than others, due to a lower surface energy. In order to have a sense of the impact of these surface energies, we performed a set of experiments on three of the exposed faces of the samples, which relate to the underlying atomic arrangement, and one artificially exposed plane (0001). On the micro and nano scales, scratch testing gave us the fracture toughness of the material while indentation yielded the elastic modulus and hardness. A subsurface investigation of the scratches grooves was performed using optical microscopy and atomic force microscopy (AFM). This revealed a sequential process including significant contributions from friction and leading to a fracture dominated process. The focused ion beam (FIB) technique has been applied to prepare cross-sectional transmission electron microscopy (TEM) thin sections of the natural quartz sample parallel and perpendicular to the scratch trough. This technique enabled the visualization of subsurface microstructural deformation features. This investigation revealed a complex network of cracking, along with other energy dissipating mechanisms. Atomistic simulations were finally used to determine the surface energies on the surfaces tested and serve as a basis for comparison.

213: Multi-Scale Investigation of Damage-Fluid Flow in Porous Media with Cemented Microstructure

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Hydraulic Fracturing is used in unconventional gas reservoirs, notably tight gas or shale gas reservoirs where the permeability is extremely low. As such, it is important to understand the process by which the material fails through fracture formation to increase flow, and hence production. At issue is the understanding of both physical and numerical aspects of fracture initiation and propagation in quasi-brittle materials, including multi-phase flow. Various fracture regimes can be identified such as one which is diffuse (where fractures are tiny and ubiquitous) to an ultimate localized mode where certain micro-fractures coalesce into a macro-fracture. Conditions upon which the various fracture regimes occur as a function of loading (mechanical or fluid stimulation) type can be studied from the mechanics damage in a heterogeneous quasi-brittle material. In this paper, the fracture behavior of cemented materials such as rock consisting of arbitrarily distributed micro-cracks is addressed with coupled physics and in a Hydro-Mechanical (HM) framework. A multi-scale modelling approach is pursued where the average-field theory is utilized to formulate a continuum description of such heterogeneous material based on observed microscopic physical mechanisms. A representative volume element (RVE) of the medium is considered at the meso-level, and by investigating a detailed description of the micro-structure, the average quantities over the whole RVE and the underlying relations between them (constitutive equations) are determined at the continuum level, considering both solid and fluid phases. Hence, coupled fluid flow and deformation mechanisms of homogeneous porous medium is described by a novel closed-form formulation based on the intrinsic properties of solid and fluid phases at the micro-scale, where the physics are additive. The presence of heterogeneities in form of distributed micro-cracks is addressed here by formulating a one-way coupled problem. An anisotropic damage model is developed to capture the reduction in load bearing capacity with concomitant permeability evolution of the porous medium to help us predict the fracture occurrence in the reservoir under general loading condition. This model incorporates a crack density distribution tensor, the evolution of which is studied through a novel Fracture Mechanics-based micromechanical model and by formulating the strain energy release rate. In this manner, the induced anisotropy and the transition from diffused micro-cracks to an ultimate organized (localized) mode can be traced through describing the stable growth of micro-cracks under general loading conditions.

366: Multi-Scale Micromechanical Modeling for Electrical Conductivity of Cementitious-Based Composite with Multi-Walled Carbon Nanotubes and Moisture

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Carbon nanotube (CNT)/cement composites have been proposed as a multifunctional material for self-sensing and traffic monitoring due to their unique electric conductivity which changes with the application of mechanical load. However, environmental factors may significantly affect the potential application of this material. This paper investigates the effect of moisture on the effective electrical conductivity of CNT/cement composites. To prepare the specimens, multi-walled carbon nanotubes (MWCNTs) are well dispersed in cement paste, which is then molded and cured into cubic test specimens. By drying the specimens from the fully saturated state to the fully dry state, the effective electrical conductivity is measured at different moisture contents. As the water in the specimen is replaced by air voids, the electrical conductivity significantly decreases. Different ratios of MWCNTs to cement have been used in this study. Micromechanical models have been used to predict the effective electrical conductivities. A comprehensive model is proposed to take into account the effects of individual material phases on the effective electrical conductivity of CNT/cement composites with moisture.

347: Multi-scale Modeling of Adsorption-Induced Deformation of Micro-Porous Materials

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A multi-scale method is introduced to allow study the adsorption induced deformation of micro-porous materials. At the nanoscale a nano-size pore, embedded in a nanoscale solid matrix, is modeled using hybrid Grand Canonical Monte Carlo (GCMC) [1] / Molecular Dynamics (MD) [2] simulations. The mechanical and sorption behavior of this system is determined by subjecting it to a series of tests: (1) adsorption response to a chemical potential protocol under different mechanical loading conditions and (2) strain response to mechanical loading at different chemical potentials. A series of these nanoscale models is used as input to a mesoscale model employing the Dependent Domain Theory (DDT). Each domain in the DDT modeling is associated with a nanoscale system that is described by a coupling matrix, between the fields it experiences (chemical potential and stress) and it's response (moisture content and strain). This matrix is constructed from the results of tests (1) and (2) on the associated nanoscale system. The resulting DDT mesoscale model has adsorption-induced deformation and exhibits the mechano-sorptive effect, i.e., adsorption is influenced by mechanical loading. A particular feature of the mesoscale model is that it has mechanical and adsorption hysteresis that arises from the off-diagonal terms in the coupling matrices. A parametric study is carried out to examine the influence of different parameters on the coupling matrices. Special attention is given to the off-diagonal terms that induce hysteresis. It is demonstrated that this multi-scale modeling scheme introduced enables one to study the relationship between micro-structure and mesoscopic behavior. This modeling scheme can be extended for the simulation and optimization of many different micro-porous materials.
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81: Multi-Scale Modeling of Damage and Failure in S-glass/epoxy Fiber Reinforced Composite Subject to High Strain Rate Impact

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Somnath Ghosh, Johns Hopkins University

This work develops a computationally efficient multi-scale damage model for different composite systems that can be used for the structural design and meanwhile able to predict the damage behavior in micro-scale. First, dynamic micro-mechanical analysis of S-glass fiber reinforced epoxy composites is performed in conjunction with the phenomenon of stress wave propagation in the periodic RVE subjected to high strain rate deformation. The effect of strain-rate is modeled adopting a rate-dependent constitutive model for the composite system. Deformation and failure response of RVE model exhibiting fiber and matrix damage as well as inter-facial debonding, which is validated by cruciform experiment and micro-droplet experiment. With debonding model parameters calibrated from experiment, relation of micro-structure and damage properties is studied in various micro structure models by using a Voronoi cell characteristic method, e.g. cracking nucleation, growth and spacing decrease. Then macroscopic constitutive damage law is obtained through the homogenized response of micro-mechanical model. To connect the damage mechanism in micro-scale with macroscopic damage evolution, a fourth order tensor governing the initiation and evolution of the damage is introduced, and it is calibrated as a function of the macroscopic damage state in material. After this fourth order tensor is calibrated for specific composite system, the constitutive damage law can be obtained by this PHCDM model without performing micro-mechanical analysis. Finally this PHCDM model is incorporated in ABAQUS user-subroutine to describe the material behavior for the composite system, making the analysis of macro-scale structures computationally feasible.

365: Multi-scale Modeling of Mechanical Failure of Lithium-ion Battery

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Shriram Santhanagopalan, National Renewable Energy Laboratory
Michael Sprague, National Renewable Energy Laboratory
Ahmad Pesaran, National Renewable Energy Laboratory

Due to its high energy density, high voltage and low self-discharge rate, Lithium-ion batteries (LIBs) are currently the state-of-the-art power sources for a variety of applications, from consumer electronic devices to electric-drive vehicles (EDVs). LIB can be considered as a multi-layer stacked structure made of anodes, cathodes and separators. Modeling the mechanical deformation of a LIB is very challenging, due to very small thicknesses (from several micron to dozens micron), porosity induced differences in constitutive properties under tension and compression for the active layers and separators, interlayer sliding etc. There are limited studies in the literature on modeling the macro-scale structure failure of LIBs. Ali et al. (2013 and 2015) modeled the deformation pattern and load-displacement response of prismatic graphite/LiFePO4 pouch cells using macro homogenized material models and multi-scale buckling behavior under constrained compression using representative volume element (RVE) models. Sahraei et al. (2015) reported macro-scale isotropic and anisotropic homogenized models for fracture simulation of cylindrical and pouch cells with a maximum strain criteria. The anisotropic model presented advantages in predicting the location and orientation of cracks formed and corroborated with CT scan results.

Greve and Fehrenbach (2012) and Xu et al. (2015) studied the static and dynamic mechanical integrity of cylindrical lithium-ion battery cell using macro-scale finite element models. In our previous work, Zhang et al. (2015a and 2015b) developed a representative-sandwich (RS) model for fracture and a short-circuit model for a pouch cell under various indentation conditions. The existing computational models show capabilities in capturing the macro deformation and structure failure, but lack accuracy in modeling the internal failure mechanism (e.g. electrode cracking, bucking and dislocation). To address this problem, in this work, we propose a multi-scale finite element model in LS-DYNA with user-defined material models, where the number of through-thickness elements equals the actual number of RSs across the realistic geometry. The model is able to predict the damage initiation, progression and ultimate structural fracture of a LIB cell, which in turn provides valuable information for predicting the onset of internal short circuit, electrochemical reactions and thermal ramping behavior due to an external mechanical crush. Anisotropic constitutive mechanical properties for each of the individual components are implemented. Strain based failure criteria are defined for each component to simulate the progress of failure, and damage models implemented. Model validation is conducted by comparing with previous published experimental data under quasi-static compression and indentation loading conditions.

233: Multi-Scale Modelling of Segregating Granular Flows

Anthony Thornton, Univesity of Twente

Segregating granular flows (e.g. from snow avalanches, landslides, debris flows, pyroclastic flows to flows in rotating drum mixers, kilns and crushers). It is important to be know the degree of segregation in such flows as it is vital to predict the flow dynamics accurately. Continuum methods are able to simulate the bulk behaviour of such flows, but have to make averaging approximations reducing the degree of freedom of a huge number of particles to a handful of averaged parameters. Once these averaged parameters have been tuned via experimental, simulational or historical data, these models can be surprisingly accurate; but, a model tuned for one flow configuration often has no predictive capability for another setup. On the other hand discrete particle methods are a very powerful computational tool that allow the simulation of individual particles by solving Newton's laws of motion for each particle. With the recent increase in computational power it is now possible to simulate flows containing a few million particles; however, for 1mm particles this would represent a flow of approximately 1 litre, which is many orders of magnitude smaller than the flow volumes found in industry or nature. This talk will focus on a simplified example of bi-dispersed dry granular flows (varying in size and density) on inclined planes and in rotating drums. We will investigate this problem via the continuum modelling approach (both numerical and analytical solutions will be presented) and particle simulations, and conclude by discussing how both can be combined to reveal deeper insight.

101: Multi-Time Scale Coupled Transient Electro-Magnetic and Structural Dynamics Finite Element Analysis for Antenna Simulations

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This paper presents the wavelet induced multi-time scaling computational model using the Jacobian-Free Newton-Krylov algorithm for modeling functional materials with electro-magneto-mechanical couplings. Of special interest are microstrip patch antennas used in unmanned air vehicles (UAVs) for military applications and monopole broadcasting antennas which appear in mobile satellite communications. These types of antennas must operate in a wide spectral band and can be complex in geometry due to the ability of the antenna to conform to the surface of the structure on which they are mounted. While modeling of such antennas on large geometrically complex surfaces has a number of difficulties, one witnesses certain drawbacks in computational modeling aspects resulting to inadequate designs, which restricts their widespread engineering applications. For instance disregarding the vibration of the antenna structure under finite deformation principles and frequency domain simulations rather than time domain simulations may negate the radiation efficiency leading to small realized gain values. Their fabrication based on the current simulation techniques may become quite cumbersome, their attachment may limit the actual reduction in size, or their design may decrease the overall radiation efficiency. The fields governing the response naturally have large discrepancies in the frequencies viz. the ultrasonic electromagnetic field frequencies and the low mechanical vibration frequencies and this involves simulating a large number of electromagnetic cycles. A conventional single time-scale analysis proceeds in the time-scale of the highest frequency response and hence it is challenging to address issues related to the low frequency field. The present work addresses these issues by using the wavelet transformation based multi-time scaling method (WATMUS) for coupled transient electromagnetic nonlinear dynamical mechanical simulations in the finite element framework. This method is advantageous over conventional methods that fail because of assumptions of periodicity etc. The WATMUS method also provides an implicit framework to perform coarse scale integration and hence does not exhibit stability issues. The wavelet transformation projects the high frequency (fine time scale) transient electromagnetic potential response through translation and dilation of an appropriate set of scaling functions on the low frequency (coarse time scale) mechanical response with monotonic evolution. The method significantly enhances the computational efficiency in comparison with conventional single time scale integration methods. Furthermore, the Euler-Lagrange equations of the corresponding (Hamilton's) variational principle, i.e. Gauss' and Ampere's equations, are solved using the Jacbian-Free Newton-Krylov Method to improve the scalability of the system and accommodating large number of dofs.. The proposed computational model serves as a unified guide to the numerical implementation of the time dependent coupled electro-magneto-mechanical problems on a macroscopic temporal level.

383: Multi-yield Surface Modelling of Viscoplastic Materials

Hao Yan, Vanderbilt University
Caglar Oskay, Vanderbilt University

We propose a new multi-yield surface model to idealize the mechanical behavior of a viscoplastic solids subjected to cyclic loading. This model is then employed to characterize the response metals and alloys at high temperatures. The multi-yield surface model incorporates the evolution of nonlinear viscoplastic flow through a piece-wise linear hardening approximation. A kinematic hardening law is employed to account for the evolution of the backstress with respect to the viscoplastic strain rate. A new backstress evolution strategy is proposed to ensure all yield surfaces remain consistent throughout the viscoplastic process. The effect of rate dependent behavior on the evolution of the backstress is induced without violating Mroz's collinearity rule. The multi-yield surface model is implemented, along with a viscoelastic component to approximate relaxation behavior of high temperature metal alloys, using a mixed finite element approach, in which displacement and pressure are evaluated as independent unknowns. The model is validated against experiments conducted on the high temperature titanium alloy, Ti-6242S subjected to static, cyclic and relaxation conditions. A detailed presentation of the derivation and illustration of the multi-yield surface viscoplastic model is provided, as well as the finite element discretization, implementation and numerical investigations.

34: Multifunctional Nano Enhanced Materials for Infrastructure Protection

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Xiaobing Li, University of Mississippi
Hunain Alkhateb, University of Mississippi

Alexander Cheng, University of Mississippi

Multifunctional materials are highlighted by the National Academy of Engineering and the National Research Council as high-priority technologies/technical challenges [MF-1, MF-2]. There is a critical need to develop new multifunctional and hybrid materials that possess a diverse set of multimodal mechanical, electrical, thermal, acoustic, and chemical properties; such materials can be dynamic in responding to their environment and/or application demands. For example, multifunctional nanocomposites comprised of a matrix with 1+ nanoscale phases can be delineated from hybrid materials which are defined by the molecular-level integration of new atomic species that leads to novel material behaviors. Due to the inherent length scales of nanocomposite and hybrid materials, many of the innovations must necessarily occur at the nanoscale. Accelerating the pace of the discovery and deployment of multifunctional nanocomposites will therefore become crucial to achieving global competitiveness in the 21st century. This paper illustrates multi-functionality of nano-enhanced polymeric coatings for protection of infill masonry walls against multi-hazards (e.g. blast, fire, and lightening).

196: Multiple Floor Isolation Control System for Integrating Mass Damper and Seismic-Isolation Systems in Buildings

Hamidreza Anajafi Marzijarani, University of New Hampshire
Tat S. Fu, University of New Hampshire

Base isolation (BI) and tuned mass damper (TMD) systems are two of the most utilized seismic protective techniques in buildings. BI decouples the building motions from ground motions through isolators installed between the building and foundation layers. The isolators lengthen the periods of the overall structure and protect structure and its contents from severe damages. TMDs—consisting of an auxiliary mass and a spring-dashpot system—are generally designed to oscillate as the same frequency of the primary structure but in an opposite phase to mitigate the structural responses. Despite BI's and TMD's popularity, there are some practical limitations associated with these two techniques: BI systems are not ideal for high rise buildings because of the buildings' weight and the resulting large loading on the isolators while TMD systems require heavy damper masses added to buildings. In this study, the authors utilize a multi-floor isolation (MFI) system that addresses these two disadvantages. In the MFI approach, floor slabs are individually isolated from the primary structure such that the system can be simplified as a multiple TMD system using existing floor mass as an inherent damper mass. Unlike BI systems, the isolators are supporting part of a story instead of the entire building. The increased number of isolated units complicates the design. To address this issue, the authors performed optimization, using parametric study and Genetic Algorithm, over MFI system parameters (i.e., masses, stiffness, and damping coefficients of the isolated floors) to minimize structural responses. Unlike previous efforts in using floor slabs as isolation units, this study investigates the effect of different isolated mass ratios (IMRs) by recognizing the fact that different portions of a story can be isolated by appropriate architectural designs. Three structural models with 6, 20 and 40 stories are considered to present a low-, mid-, and high-rise building, respectively. These structural models are examined with BI, TMD and the proposed MFI systems. Simulation results indicate that MFI can effectively reduce the structural response of the primary building and isolated floors as well. The proposed MFI at low (5%) and large (95%) IMRs, behave similar to a TMD and BI system, respectively. In balancing performance objectives of the primary structure and the isolated floors, the authors find the most effective range at 20-30% IMR. Comparing the three structural models, the shorter 6-story model performs better at a higher IMR compared to the taller 40-story model that favors a lower IMR.

128: Multiple-Material Topology Optimization of Cellular Material Architectures

Josephine Carstensen, Johns Hopkins University
James Guest, Johns Hopkins Univeristy

Recent advances in manufacturing technologies, including additive manufacturing, have made it possible to control and manufacture periodic cellular material architectures with increasingly complex topologies. Cellular materials in this context refer to porous materials with a representative unit cell that is repeated in all directions. Topology optimization offers a means to leverage these new manufacturing capabilities though a systematic design framework. Topology optimization has previously been used for unit cell design of materials with elastic properties such as optimized Young's, bulk, or shear modulus, and for the design of auxetic materials. For unit cell design problems an upscaling law is required to connect the unit cell to the bulk material mechanics. For example, linear elastic mechanical properties can be estimated using homogenization. In this paper we look to extend these approaches to design material architectures consisting of multiple solid base materials. The proposed method uses an existing SIMP based multiple material design formulation and sensitivity analysis scheme as the backbone of the design algorithm. The Heaviside Projection Method controls the manufacturability and the Method of Moving Asymptotes is used as the gradient-based optimizer. Several new high performance topologies are presented and discussed.

588: Multiscale Finite Element Modeling for Nonlinear Wave Propagation

Negar Kamali, University of Illinois at Chicago
Sheng-Wei Chi, University of Illinois at Chicago

Nonlinear ultrasound techniques are capable of detecting microstructural damages with a length scale smaller than the ultrasound sound wave. The change in microstructure or the damage state corresponds to the nonlinearity parameter in the nonlinear acoustics, which is related to the amplitude ratio of the fundamental wave and higher order harmonics. However, the direct correlation between the microstructure and the nonlinearity has not yet been established. A multiscale finite element (FE) modeling framework is presented to predict and correlate the behavior of nonlinear acoustics due to different damage mechanisms. The framework first introduces enriched spectral functions within each element in order to address the computational challenge that excessively fine mesh is required in the standard FE for containing the dispersion and dissipation errors. The characteristics of the fundamental wave and higher harmonics are embedded as enriched functions in the FE; therefore, the method combines advantages of FE and spectral techniques while preserves the implement of the FE [1]. The proposed method has been implemented through the user defined element in ABAQUS™ and its effectiveness has been demonstrated through nonlinear acoustoelasticity problems. The second part of the framework consists of a multiscale homogenization approach [2], which incorporates the microstructural information into the constitutive model. Several microscopic FE models for different representative volumes element (RVE) are constructed from segmented micrographs, considering material heterogeneity and microstructure. The nonlinear effects due to finite deformation, material nonlinearity and self-contact in the microstructures are considered in detail in the RVE models. The load-displacement relationships in the RVE are then homogenized to construct a nonlinear constitutive model in the macro-scale FE model. Several enriched finite element simulations with different constitutive models created by aforementioned technic are conducted and the fundamental characteristics of ultrasonic waves are studied with which a guidance for interpreting the ultrasound profiles and the corresponding damage are provided. The results are validated with experimental tests.

References:[1] Ham S, Bathe KJ. A finite element method enriched for wave propagation problems. Journal of Computers and Structures 2102. 94–95 (0): 1–12[2] Ren XD, Chen JS, Li J, et al. Micro-cracks informed damage models for brittle solids. International Journal of Solids and Structures 2011.48(10): 1560–1571.

601: Multiscale Mechanics of Mechanochemically Responsive Elastomer

Qiming Wang, University Of Southern California

Mechanochemically responsive (MCR) polymers have been synthesized by incorporating mechanophores – molecules whose chemical reactions are triggered by mechanical force – into conventional polymer networks. Deformation of the MCR polymers applies force on the mechanophores and triggers their reactions, which manifest as phenomena such as changing colors, varying fluorescence and releasing molecules. While the activation of most existing MCR polymers requires irreversible plastic deformation or fracture of the polymers, we covalently coupled mechanophores into the backbone chains of elastomer networks, achieving MCR elastomers that can be repeatedly activated over multiple cycles of large and reversible deformations. This paper reports a microphysical model of MCR elastomers, which quantitatively captures the interplay between the macroscopic deformation of the MCR elastomers and the reversible activation of mechanophores on polymer chains with non-uniform lengths. Our model consistently predicts both the stress-strain behaviors and the color or fluorescence variation of the MCR elastomers under large deformations. We quantitatively explain that MCR elastomers with time-independent stress-strain behaviors can present time-dependent variation of color or fluorescence due to the kinetics of mechanophore activation and that MCR elastomers with different chain-length distributions can exhibit similar stress-strain behaviors but very different colors or fluorescence. Implementing the model into ABAQUS subroutine further demonstrates our model's capability in guiding the design of MCR elastomeric devices for applications such as large-strain imaging and color and fluorescence displays.

617: Multiscale Modeling of Scaffolds for Bone Regeneration: Bridging Molecular to Macroscale

Dinesh Katti, North Dakota State University
Anurag Sharma, North Dakota State University
Kalpana Katti, North Dakota State University

We have developed a novel biomimetic route to mineralize hydroxyapatite (HAP) using organically modified nanoclay (montmorillonite) (OMMT). Polymeric scaffolds are synthesized using the biomineralized HAP with polycaprolactone (PCL) for bone tissue engineering applications. These scaffolds are found to support mesenchymal stem cell viability, mediate their appropriate differentiation and make bone. We have conducted molecular dynamics simulations of modified nanoclay-HAP-PCL composite. The OMMT, HAP, and PCL show significant molecular interactions with each other in OMMT-HAP-PCL system. The interactions energy calculations reveal high attractive interactions of clay with PCL and HAP. The HAP has strong interactions with the functional groups and backbone of PCL chains. Our experiments show that the nanoclay based mineralized HAP with PCL has significantly improved nanomechanical properties as compared to pristine PCL polymer. Steered molecular dynamics simulations (SMD) have been performed to evaluate mechanical properties of these nanocomposite scaffolds. These properties are incorporated into finite element models of the scaffolds that were constructed using micro-CT imaging of experimentally prepared scaffolds. The mechanical properties of the cell-seeded scaffolds evolve over time because of the degradation of the scaffold, cell growth, and tissue regeneration. A new degradation/healing model has been developed to model the evolution of mechanical properties accurately with time. The combined multiscale model and the degradation/healing model allow us the ability to predict the response of implanted scaffolds over time.

119: Multiscale Modeling of Textural and Mechanical Properties of Clay

Davoud Ebrahimi, Massachusetts Institute of Technology

Andrew Whittle, Massachusetts Institute of Technology
Roland Pellenq, Massachusetts Institute of Technology

Clay minerals have a layered structure at the nanoscale. The interlayer galleries could be filled with confined water and affect textural and mechanical properties of clay. In this research we propose a multiscale approach to incorporate the effect of interlayer confined water at the atomistic scale on the formation of clay aggregates and mechanical properties of the clay water system at the mesoscale. We use free energy perturbation method to calculate potential of mean force (PMF) of the interaction between two clay platelets in face-to-face and edge-to-edge interactions. The two PMFs show oscillatory behavior and the local minima of the free energy curves are separated by distances comparable to the diameter of a water molecule (~ 3 Å). In other words, rearrangement of the water molecules determines favorable positions of the clay platelets. The two free energy functions are then used to calibrate the Gay-Berne (GB) potential that represents each platelet as a single-site ellipsoidal body to study formation of clay aggregates and their textural and mechanical properties at the mesoscale. We have parameterized Gay-Berne potential for different platelet sizes and studied microstructural and mechanical evolution of systems of clay platelets for selected ranges of clay particle sizes and confining pressures. Mechanical properties and compressibility of the systems agrees well with experimental measurements. The results show aggregate size of (3–8) platelets for sodium smectite in agreement with experiments (3–10). By increasing diameter of clay platelets, size of the aggregates and anisotropy of the system increases. Increase of confining pressure has similar effect on the system up to a pressure limit which decreases as platelet size increases. Further increase of pressure results in decrease of aggregate size while ordering (anisotropy) of the system remains constant due to sliding of platelets against each other with constant orientations. The proposed multiscale approach can be extended to study the effect of platelet charge (amount of isomorphous substitution) and pore fluid composition (salt concentration) on the microstructure and mechanical properties of the clay based materials.

462: Multiscale Monitoring and Health Assessment of Levees

Mourad Zeghal, Rensselaer Polytechnic Institute
Abdoun Tarek, Rensselaer Polytechnic Institute
Victoria Bennett, Rensselaer Polytechnic Institute

The integrity and reliability of levees and other earthen flood-control infrastructure are essential components of homeland safety. However, the national flood-control infrastructure is aging and its structural health is deteriorating. The ASCE's 2009 Report Card for America's Infrastructure gives the condition of our nation's dams a grade of D and levees a grade of D-. This paper presents a framework to assess the structural integrity and health of earthen levees. The framework relies on remote sensing and field monitoring data of levees during environmental loading conditions and natural processes of degradation. The monitoring data consists of levee displacements obtained using satellite-based interferometric synthetic aperture radar (InSAR), Global Position System (GPS) receivers, and Shape-Acceleration Pore Pressure (SAPP) Arrays. These measurements are used in an integrated fashion to localize internal zones of degradation within levees and quantify the corresponding level of weakening. Neural networks identification tools are first employed to assess the global (i.e., deteriorating or not) health of levees using remote sensing. The remote sensing and field measurements are used thereafter to localize and quantify any levee weakening. The framework is demonstrated using test data of small scale centrifuge levee models.

621: New Approach to Damage Mechanics through a Modified Finite Element Framework

Parisa Khodabakhshi, Texas A&M University

J.N. Reddy, Texas A&M University
Arun Srinivasa, Texas A&M University

Engineers are not just concerned with the design and construction of structures, but they also need to be able to give an estimate of the life-span of a structure and how and when the structure will be damaged. Due to the amount of uncertainty involved, damage mechanics is one of the most complicated concepts in computational mechanics, and at the same time one of the most critical areas. Researchers have long been engaged in modeling different modes of damage and methods of quantifying it. However, most of the methods in the literature are not practically applicable to everyday complex structures. To this end, in this study a new approach to damage analysis is proposed by introducing a modified finite element framework. Conventional finite element method is without doubt the most widely used computational framework in the field of applied mechanics and structural analysis. Several methods have been introduced in the literature on integration of damage analysis with finite element method. However, the complexity of these methods inversely impacts their applicability to everyday design problems. The modified finite element framework paves the way for a more straightforward study of damage in structures. In this study, it is shown that for hyperelastic materials nodal forces of an element (in a discretized domain) can be expressed in terms of the strains along the edges of the element (an edge is defined to be a line connecting any two distinct nodes of an element). This forms the basis for the modified finite element framework. One can determine the forces and strains along the edges, and place a damage criteria on the edge based on a displacement criterion or a force criterion. The modified finite element framework has the capability to be used in probabilistic damage analysis. In probabilistic methods, one can use the existing data from a structure to give an estimate on the probability of a given damage mode, its direction, etc. Similar to the concepts of machine learning, with increasing number of data from the structure the accuracy of this estimation improves with time. This is an extremely useful property of this method. Designers are not interested in the damage itself, but on the evolution and level of degradation of the structure. The ultimate goal is to assess the probable damage to take the required safety measures. Modified finite element framework can be integrated in probabilistic methods to provide this information.

125: New Euler-Type Progressive Collapse Curves for 3D Steel Frames

Panagiotis Pantidis, University of Massachusetts, Amherst
Simos Gerasimidis, University of Massachusetts, Amherst

Recent work [1], [2] on the area of structural response under extreme events has shown that stability induced collapse modes are critical for multi-story buildings. Although this has been clearly demonstrated for specific component removal cases of multi-story buildings, there are still cases for which the governing collapse mode is dictated by a series of yielding-type failures. The collapse mechanism depends strongly on the location of the component which is removed from the structure, or otherwise on the location at which damage is introduced in the structural system. Similarly to the Euler curve of a component under compression which describes the mode of failure, this paper introduces for the first time analytical descriptions for the derivation of new Euler-type collapse curves for buildings under a column removal scenario. The proposed new Euler-type curves provide practicing engineers with a valuable, easy-to-handle tool for predicting the collapse mechanism, without the necessity of performing rigorous FEM analyses. The outcome is verified by finite element analyses of the building under the same scenarios. [1] Gerasimidis S. Analytical assessment of steel frames progressive collapse vulnerability. Journal of Constructional Steel Research 2014; 95: 1-9. [2] Gerasimidis, S., Deodatis, G., Kontoroupi, A., Ettouney, M., Loss of stability induced progressive collapse modes in 3D steel moment frames, Structure and Infrastructure Engineering 2014; 11(3), 334-344.

692: Non Equilibrium Thermodynamics of Fault Gouge: Effect of Grain Contact Processes

Ahmed Elbanna, University of Illinois

Granular materials are ubiquitous in nature. They play an important role in the physics of many natural phenomena like earthquakes and landslides as well as many industrial application such as in food and pharmaceutical industries. In this presentation we present our latest progress in developing a nonequilibrium statistical thermodynamics framework for describing plasticity in amorphous materials such as the crushed rocks found in fault zone, commonly known as fault gouge.We show the in the limit of perfectly hard sphere, the material response is rate strengthening. The predicted shear strength exhibit weak rate dependence for low values of inertial number but it increases rapidly as the inertia number approaches a critical value nearly equal to 1. To reproduce rate weakening behavior, as well as non-monotonic rheology, observed in a variety of experiments additional theoretical components describing physical processes at the grain contacts must be introduced. We present a few candidates for these processes including flash heating at contact asperities, grain breakage, and friction in angular grains. We discuss the implications of non-monotonic rate dependence on stability of frictional sliding and stick-slip motion.

576: Non-Homogenenous Lévy Processes as a Degradation Model for the Efficient Reliability Estimation of Complex Systems

Javier Riascos-Ochoa, Universidad de Los Andes
Mauricio Sanchez-Silva, Universidad de Los Andes
Georgia-Ann Klutke, Texas A&M UNiversity

This paper presents an analytical and numerical framework to model degradation of systems and to perform their reliability estimation. The main assumption is that the constitutive components of the system degrade following a stochastic process with independent and monotone decreasing changes (without maintenance), i.e., an increasing non-homogeneous (NH) Lévy process (or a NH subordinator). With the additional assumption of independence between several sources of degradation on each component (e.g., shock-based and progressive degradation), but with possible dependence between the components (e.g., a common source of degradation), the framework allows the analysis of such systems with multiple degradation mechanisms. The numerical method proposed for the reliability estimation is based on inversion techniques of the characteristic function of the constitutive NH degradation subordinators, and is highly efficient and accurate. The framework is applied in a system with several components subject to combined degradation of a mainshock - aftershock sequences and a long-term progressive deterioration process.

649: Nonlinear Analysis of Concrete Members Exposed to Elevated Temperatures

Manar Al Fadul, University of Central Florida
Kevin Mackie, University of Central Florida

The response of structures under fire loading scenarios is difficult to perform experimentally, therefore, it is beneficial to develop numerical procedures for simulating the affect of fire on reinforced concrete members, as well as the corresponding nonlinear structural analysis of the system during and after the fire. A two-step nonlinear numerical analysis of concrete members exposed to elevated temperatures is presented. In the first step, a coupled heat and mass transfer analysis is performed to determine the transient temperature distributions over the concrete cross section. In the second step, the mechanical analysis is carried out, using the well-known sectional analysis approach, to predict the structural response of the concrete member under thermal and external applied loadings.

The results obtained from the heat and mass transfer analysis are utilized in the subsequent step to perform the structural analysis, where the transient temperature field is applied as thermal loading. In the coupled analysis, several phenomena have been taken into account, such as evaporation, condensation, and dehydration process. Temperature, pressure, and moisture content dependent properties of both gaseous and solid phases were also considered. A numerical case study that deals with the case of an extremely rapid heating condition of concrete is presented. The numerical results of both thermal and mechanical analysis are validated against experimental results with good qualitative agreement.

487: Nonlinear and Directional Effects of Waves in Areas of High Dissipation: Implications for Coastal Hazard Characterization

James Kaihatu, Texas A&M University
Ying-Po Liao, Texas A&M University
Samira Ardani, Texas A&M University

Recent studies of wave dissipation by dense vegetation has revealed the strong diffractive effects behind the region of dissipation. In this study we discuss the formulation of a new irregular wave spectral model which uses both the parabolic and angular spectrum approaches to simulate directional wave spreading and interaction in the lee of a region of high dissipation. In this case, the dissipation can be caused either by highly localized break or by a strong environmentally-induced dissipation. Comparisons to available data will be shown. Implications for characterization of coastal hazards in estuaries will be discussed.

294: Nonlinear Finite Element Model Updating and Seismic Response Reconstruction of Marga-Marga Bridge during the Mw 8.8 Maule, Chile Earthquake

Yong Li, University of California, San Diego
Rodrigo Astroza, University of California, San Diego
Joel Conte, University of California, San Diego

The seismic performance of isolated structures during recent earthquakes has shown the effectiveness of seismic isolators to mitigate and even avoid structural damage following strong events. Seismic isolation introduces a flexible horizontal interface with high internal damping between the sub- and superstructure. This results in an elongation of the effective fundamental period of the structure, which becomes significantly longer than predominant periods of typical earthquake ground motions, an increase of the energy dissipation capacity of the system, and concentration of the nonlinear behavior in the seismic isolators instead of the primary structural components (e.g., beams and columns). Nonlinear finite element (FE) modeling has been used widely to investigate the effects of seismic isolation on the response of seismically isolated structures subjected to earthquakes. Most studies on nonlinear FE modeling of isolated structures have made use of seismic isolator models calibrated using component test data. The accuracy of nonlinear FE models for seismic isolated highway bridge systems is rarely addressed using field data recorded from instrumented structures subjected to strong earthquakes. In this paper, nonlinear finite element model updating (FEMU) of the Marga-Marga Bridge, an eight-span 383 m long continuous seismically isolated highway bridge, is conducted using the data recorded during the Mw 8.8 Maule Earthquake in Chile. A detailed three-dimensional nonlinear FE model of the bridge is developed in OpenSees and multiple-support excitation is employed to account for the different excitations at the bridge ends and at the bottom of the bridge piers. FEMU aims to minimize the discrepancy between the FE predicted and recorded responses by formulating single-objective and multi-objective optimization problems and to obtain optimal seismic isolator properties for the isolator model used. The updated FE model is then used to reconstruct

the response quantities unrecorded during the earthquake and to obtain more insight into the effects of seismic isolation on the response of the bridge.

84: Nonlinear Finite Element Simulation of Seismic Response and Damage of RC Structures

Mohammadreza Moharrami Gargari, Virginia Tech
Ioannis Koutromanos, Virginia Tech

This presentation will describe a three-dimensional, continuum-based, finite element analysis framework to capture the hysteretic response and damage of reinforced concrete (RC) components and systems. The simulation framework uses three-dimensional continuum elements for the concrete and a recently developed material law which can capture the inelastic material behavior under multiaxial stress states. The reinforcing steel bars are modeled with beam elements which can naturally capture the nonlinear buckling under cyclic loading. The employed constitutive model for the reinforcing steel can also account for the rupture due to low-cycle fatigue. The analyses are conducted with an explicit finite element program, which efficiently accounts for material inelasticity and large deformations. The proposed framework is validated using experimental test data from two post-tensioned RC wall specimens subjected to quasi-static cyclic loading and a bridge column subjected to a sequence of earthquake ground motions. For both cases, severe damage and failure occurred by means of rebar buckling and subsequent rupture. The analytically obtained hysteretic response of the structures is in very good agreement with the corresponding experimental observations. Additionally, the concrete cover spalling, rebar buckling and rebar rupture, are very well captured. The validated methodology can be used for the analysis of prototype structures and for the calibration of simplified simulation tools.

176: Nonlinear System with Fractional Derivative Terms Parameter Identification Subject to Incomplete Non-Stationary Data

Ioannis Kougioumtzoglou, Columbia University
Ketson dos Santos, Columbia University
Liam Comerford, University of Liverpool

Most structural systems are likely to exhibit nonlinear and time-varying behavior when subjected to extreme events such as severe earthquake, wind and sea wave excitations. In such cases, a reliable identification approach is critical for efficient damage detection. In this regard, a novel identification approach for linear and nonlinear time-variant systems subject to non-stationary excitations was developed recently [1] based on the localization properties of the harmonic wavelet transform. According to [1] a single-input/single-output (SISO) structural system model is transformed into an equivalent multiple-input/single-output (MISO) system in the wavelet domain. Next, by utilizing measured (non-stationaty) input-output (excitation-response) data the unknown time and frequency dependent harmonic wavelet based frequency response functions, as well as related system parameters, are identified. This approach can be construed as a generalization of the well-established reverse MISO spectral identification approach [2] to account for non-stationary inputs and time-varying parameters. In this paper, the identification approach in [1] is further generalized to account for cases of highly incomplete/sparse measured data and for systems endowed with fractional derivative elements. The aforementioned generalization is especially important considering the recent utilization of fractional derivative modeling in a plethora of applications in engineering and materials science such as viscoelastic materials modeling and analysis. Further, available measured realizations may contain sampling gaps in the time domain, possibly occurring for reasons such as sensor failures, data corruption, limited bandwidth/storage capacity, and power outages. In this regard, a

recently developed L1-norm minimization procedure [3] based on the compressive sensing theory is applied for determining the harmonic wavelet coefficients to be used in the generalized MISO identification approach. Several linear and nonlinear time-variant systems with fractional derivative elements are used to demonstrate the reliability of the approach even in cases of noise corrupted and highly limited data.

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776: Nonlinear Topology Optimization Considering Plasticity through an Asymptotic Approach: A Polygonal Element Formulation

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We address the nonlinear topology optimization problem considering plastic material behavior by means of an asymptotic analysis using a fictitious nonlinear elastic model. The material nonlinear model is governed by von Mises criterion. We consider the topology optimization problem subjected prescribed energy, which leads to robust convergence in nonlinear problems. The objective function of the optimization problem consists of maximizing the strain energy of the system in equilibrium subjected to a volume constraint. The sensitivity analysis is quite effective and efficient in the sense that there is no extra adjoint equation. In addition, the nonlinear structural equilibrium problem is solved by means of direct minimization of the potential energy using Newton's method with a backtracking line search strategy. To illustrate the features of the implementation, we present numerical examples displaying convergent results for optimal structures in the plastic range using either quadrilateral or polygonal elements. The polygonal elements allow the solution of nonlinear topology optimization problems in arbitrary domains, rather than the prevailing Cartesian domains (i.e. box-type) of the technical literature.

68: Numerical Analysis on Continuous Impact Behavior of Cohesionless Soil with FEM-SPH Coupling Algorithm

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Cohesionless soil enters the hopper and soil box sequentially at certain impact velocity during centrifuge throw-filling equipment operation process. FEM-SPH (Finite Element Method & Smoothed Particle Hydrodynamics) coupling method is applied to simulation cohesionless soil continuous impact behavior of centrifuge throw-filling equipment. Centrifuge structural components are modeled using Lagrangian finite elements, and meshless smoothed particles are applied for cohesionless soil in the numerical simulation. Continuous impact process of cohesionless soil reappears in the FEM-SPH simulation results. Given soil impacting centrifuge hopper and soil box bottom at 5m/s, 10m/s speed respectively, stress distribution and equivalent impact load of the centrifuge are gained during soil continuous impacting process. The maximum stress is up to 292MPa on the cross section of centrifuge support device for soil 5m/s impacting hopper case. In order to reduce soil impact force, rubber layer cushion is placed on the box bottom to decrease impact amplitude when soil impacts the box bottom at speed of 10m/s. The rubber layer can protect box structure from soil continuous impact damage. Taking FEM simulation is with high computational efficiency and SPH method easily describe structure large plastic deformation into account, FEM-SPH coupling method can be applied to simulate soil-like material large deformation behavior. It contributes to improve numerical simulation’s fidelity and confidence coefficient.

375: Numerical and Experimental Analysis of Geogrid Reinforced Concrete Overlays

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Concrete overlays have been extensively used for the rehabilitation of the pavement’s structural capacity. One of the most serious problems associated with the use of thin concrete overlays is reflective cracking. This phenomenon is due to the horizontal and vertical movement of the underlying pavement layer caused by external loading and thus resulting in shearing and tearing of the overlay. Steel reinforcement is commonly proposed as a possible solution for this problem. However, the use of steel reinforcement in thin layers, where minimum concrete cover is not ensured, imposes problems like surface deterioration, steel corrosion and exposure, which creates great danger for on road vehicles. This study investigates the use of geogrids as main reinforcement in thin concrete overlays; geogrids possess favorable characteristics in terms of strength, ductility and ease of installation. The objective is to study the effect of geogrid reinforcement on mitigating the crack propagation and improving the overall design of overlays. For that purpose, three laboratory experiments were designed to simulate different failure modes of concrete overlays: (1) the direct tension test to simulate thermal loads, (2) the three-point bending to simulate flexural loads caused by moving traffic, and (3) the shear test to simulate the sliding resulting from traffic movement and causing in-plane shear loading. The outcomes from these experiments are then used to calibrate finite element mathematical models simulating the behavior of geogrid reinforced overlays. These models are then used to run sensitivity analysis to study the effects of varying the characteristics of the geogrid reinforcement (size, location, number of layers) on the strength of the overlays. The obtained results verify that the use of geogrid reinforcement significantly enhances the overlay performance; whereby geogrid reinforced models were more resilient to cracking than the unreinforced ones and demonstrated a reduction in the rate of crack propagation.

214: Numerical and Experimental Study of Fluid-Particle Flow

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Debris flow is one of the most destructive natural hazards, due to its features of high mobility (high velocity and long run-out distance) and impact forces. A typical debris flow event is a multiphase flow, which includes a viscous fluid phase with dynamic surface and solid grains with various particle sizes from fines to boulders. Complex interactions take place between the multiple phases. To better understand the micro-scale mechanism of fluid-particle flow, an extended Computational Fluid Dynamics and Discrete Element Method (CFD-DEM) model, with the Volume of Fluid (VOF) method incorporated, is developed [1] and applied to simulate a series of laboratory tests of fluid-particle flows on an inclined small-scale flume. The flume consists of a reservoir on the top and a wider horizontal container at the toe. The slope is 1m long and 0.2m wide, with adjustable slope angles ranging from 8 to 25 degrees. Semi-transparent liquids (CMC solutions) with varied viscosities are adopted for the calibration of rheological parameters and boundary conditions in the numerical simulations. Slurries are prepared to represent clay-water mixtures as homogeneous fluids with varied densities and viscosities, and colored glass beads with uniform sizes (0.5cm, 0.8cm, or 1cm) and mixed sizes are added to constitute fluid-particle flows. Velocity profile, flow depth and the final deposition of slurry and particles are measured in the lab tests and systematically studied with the extended CFD-DEM model. Many relevant mechanisms can be explored based on the experimental and numerical studies. The influence of rheological parameters (i.e. yield stress and viscosity) on the shape of final deposition is studied. It is found that at a given slope angle, either lower yield stress or lower viscosity will increase the frontal velocity at run-out, leading to an elongated fan-shape deposition. On the other hand, high yield stress results in a higher depth gradient as slurry is accumulated at the outlet. Another interesting finding is that the initial particle arrangements can influence the flow velocity (hence impact) and its final deposition. For instance, particles migrating on the edge of the flow may slow down the flowing mixture, as they increase the basal resistance of the front. And this mitigation of mobility is less significant when the particles are spreading more uniformly in the initial configuration, because there will be more particles left in the bulk of the flow, rather than transported to the edge.

References: [1] Jing, L., Kwok, C.Y., Leung, A.Y.F. & Sobral, Y. (2015) Extended CFD-DEM for free-surface flow with multi-size granules. International Journal of Numerical and Analytical Methods in Geomechanics. (published online)

364: Numerical Bifurcation Analysis of an Anisotropic Used Fuel Cladding Damage Model Incorporating Circumferential and Radial Hydride Responses

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At the completion of the nuclear fuel drying process, used fuel Zry4 cladding typically exhibits a significant population of hydride inclusions. These inclusions are in the form of small platelets that are generally oriented both circumferentially and radially within the cladding material, which are found to weaken the cladding materials and cause safety concerns during used nuclear fuel storage and transportation. In this work, efficient and robust numerical algorithms are introduced for the numerical bifurcation analysis of a recently developed high-fidelity anisotropic damage model for used fuel cladding with circumferential and radial hydride responses. The model treats the Zry4 matrix material as elastoplastic, and treats the hydrides as platelets oriented in predefined directions (e.g., circumferentially and radially). The bifurcation mode, bifurcation time and the corresponding bifurcation directions will be investigated and the computational performance of the numerical bifurcation algorithms will be evaluated.

768: Numerical Evaluation of Forces on Piled Bridge Foundations in Laterally Spreading Soil

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Chris McGann,
Pedro Arduino, University of Washington

In regions with high rate of seismic activity, liquefaction-induced lateral spreading causes considerable damage to the foundations of nearby structures. Piled foundation bridges that cross rivers in such areas are highly susceptible to damage due to the large loads induced by the moving ground material pushed into the foundation as lateral spreading happens. With the advances in computer technology in recent years, three dimensional numerical modeling of geotechnical engineering problems have become a viable option. In contrast to current

state-of-practice which uses simplified one or two dimensional numerical models –usually based on plane-strain assumptions– a three dimensional model is capable of capturing 3D effects that are neglected in simplified models. In this process, soil-structure interaction plays an important role in defining the bridge response. In this study, tools are developed to facilitate the modeling process of a bridge pier subject to lateral spreading. The results are compared with methodologies currently used in practice to investigate the validity of these methods in more complicated situations with inherent three-dimensional effects which cannot be captured using simplified methods. The Llacollén and Mataquito bridges located in Concepción, Chile were two of several bridges subject to lateral spreading during and after the 2010 Maule earthquake. Three–dimensional FE models of these two bridges are developed and used for the purposes of this study.

391: Numerical Evaluation of the Effects of Strain Localization and Asymmetric Damage Distribution on Damaged Rope Response

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The individual effects of the asymmetric damage distribution and strain localization on damaged static rope response are numerically studied and discussed in this paper. In this study, damage corresponds to the complete rupture of one or more rope components of a particular rope cross-section In order to account for the asymmetric damage distribution, the damaged rope is assumed to behave as a nonlinear beam under biaxial bending and axial load with Bernoulli´s kinematic hypothesis. Biaxial bending arises from the unbalanced radial contact forces within rope cross-section, which are related to the initial helical geometry configuration of the rope components, due to the asymmetric damage distribution. An iterative cross-sectional numerical algorithm is implemented to estimate the asymmetric damaged rope capacity curve, stress and strain distributions throughout rope cross-section and rope geometry deformation for a prescribed axial displacement of the rope. On the other hand, the potential development of a strain localization region around rope components failure site is accounted by discretizing the rope into a series of two-noded axial-torsional elements along the length over which damage propagates along the length of a rope (recovery length). The recovery length concept is related to the fact that broken rope components are capable of supporting their total share of axial load due to frictional effects that depend on the presence of contact forces between rope components (due to their helical nature and/or rope jacket confinement) and the surface characteristics (i.e., coefficient of friction) of the components in contact. The formulation of the two-noded axial-torsional elements accounts for material and geometric nonlinearities; thus, an incremental-iterative numerical procedure is implemented to compute the overall damaged rope response. The analyses are focused on homogeneous large-scale jacketed ropes with nonlinear constitutive laws and overall diameters that range from 32 mm to 166 mm. Ropes are damaged at ropes midspan location with damage levels (percentage of the broken components of the damaged cross-section with respect to the intact rope) asymmetrically distributed on ropes surfaces that vary from 5% to 15% (obtained from literature). Preliminary results indicate that numerical simulations bound the experimental capacity curves: strain localization effect provides an upper bound and asymmetric damage distribution a lower bound. Both effects stiffen damaged rope response relative to net area model (reduction in rope strength and stiffness is proportional to the loss of cross-sectional area) and reduce residual strength and deformation capacity of a damaged rope relative to its intact state. The reduction in the residual strength and deformation capacity due to strain localization effect is close to the percentage of damage level. For the case of the asymmetric damage distribution, the reduction in deformation capacity is less than for the case of strain localization effect but it induces a greater reduction in residual strength reaching a value of 25% for the case of 15% of damage level.

209: Numerical Investigation for Bridge Seismic Performance Correlation

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Yao Liu, Tongji University

Bridges in a regional transportation network are generally designed following similar design guidelines, usually those developed by the local Department of Transportation. This, in turn, makes the seismic performance of these bridges similar. Examples of such similar performance are column flexural and/or shear failures of bridges during 2008 Wenchuan earthquake and column shear failures of numerous bridges along the I-10 highway in Los Angeles that occurred during the 1994 Northridge earthquake. The Pacific Earthquake Engineering Research (PEER) Center framework for probabilistic performance-based seismic evaluation (Cornell and Krawinkler, 2000) is centered around a decision-making mean annual frequency model that involves the sub-models of hazard intensity measure (IM), engineering demand parameter (EDP), damage measure (DM) and decision variable (DV) for individual structures. Further, in 2013, a model consistent with the PEER framework is proposed by Qin et al. (2013) to capture the correlation of bridge seismic performance that simultaneously accounts for three sources of correlation: 1) seismic hazard; 2) structural configuration; and 3) structural element design and detailing. These three sources of correlation are mapped to the IM, EDP and DM sub-models. The formulation of the model from theoretical derivation seems nice. Nevertheless, the numerical investigation of the correlation model is still missing. The aim of the present paper is to present the numerical approach for the investigation of bridge seismic performance correlation following the PEER framework. And further, some case study would be illustrated to verify the correlation model by Qin et. al (2013). Reference: Cornell, C. A. & Krawinkler, H., 2000. Progress and Challenges in Seismic Performance Assessment, PEER Center News, PEER Center, University of California, Berkeley, USA Qin, J., Stojadinovic, B. & Mackie, K. R., 2013. A Model for Bridge Seismic Performance Correlation, in 11th International Conference on Structural Safety & Reliability (ICOSSAR 2013), Columbia University, New York, USA

193: Observation and Model for Acoustic Emission Aftershocks Generated Around the Surface of Tensile Cracks in Crystalline Rock

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While much attention has been given to generation of acoustic emission (AE) prior to breakage of rock, relatively little consideration has been given to the AE generated following rock breakage. In the few cases where it has been observed, the possibility that the sustained AE is associated with continued rupture of previously unbroken ligaments or interaction between closing crack surfaces could not be eliminated. Here we present experiments in which beams of a crystalline rock (an Australian gabbro) were broken in three point bending. AE was observed, as expected, during loading with the event frequency increasing until failure. After breakage, the two halves of the beams were separated and acoustically isolated, allowing for ongoing AE monitoring with no interaction between the beam halves. We observe continued AE for days after the initial breakage. The frequency of the events decays hyperbolically, consistent with the classical Omori law behavior. The location of the events is concentrated around the crack surfaces. A power-law relationship between magnitude and event frequency according to Gutenberg-Richter law is also observed, however, with the magnitude of events generally decreasing with time since the macroscopic crack growth. AE is proposed to be generated in the region of residual strain around the crack surfaces. This residual strain is related to stress via a Young’s modulus that is a function of the number of generated microcracks. As microcracks are generated, with time delay according to kinetic fracture (static fatigue) theory, the Young’s modulus decays leading to relaxation of residual stress and hence a decline in the event frequency. We show the observed behavior, including the best fit parameters obtained from Omori law, to be consistent with this newly developed model.

350: On Efficient and Robust Numerical Bifurcation Analysis of Fluid-Saturated Porous Geomaterials

Qiushi Chen, Clemson University
Zhengshou Lai, Clemson University

Efficient and robust numerical algorithms for the detection of material bifurcation are crucial for multiphysics problems involving material instability and failure, such as localization and liquefaction. The mechanical state of the geomaterial under consideration is given in terms of its fourth-order tangent moduli. The detection of material bifurcation is then posed as an optimization problem, where the determinant of the acoustic tensor is minimized with respect to directions. In this work, efficient and robust algorithms based on conventional Newton-based iterative solution method and stochastic optimization-based approaches are introduced for the numerical bifurcation analysis of fluid-saturated porous geomaterials. The bifurcation mode, bifurcation time and the corresponding bifurcation directions will be investigated. Of particular interest are the presence of pore fluid on the stability of the porous geomaterials and the computational performance of the numerical algorithm for bifurcation analysis within a finite element simulation.

230: On Macro- and Multi-Scale Approximations for Micro-Scale Material Responses

Mircea Grigoriu, Cornell University

We view macro- and multi-scales material responses as approximations of responses based on micro-scale material properties. Macro-scale responses are delivered by the continuum mechanics and are based on effective material properties, i.e., deterministic material models which exists under some conditions and capture global features of microstructure properties. Multi-scale models couple macro- and micro-scale material models to take advantage of the simplicity and efficiency of the continuum mechanics solutions and the accuracy of material responses based on micro-scale models. Let $U_{\rm CM}(x)$, $U_{\rm MS}(x)$, and $U(x)$, $x\in D$, denote the macro-, multi-, and micro-scale material responses of a specimen in a bounded domain D under deterministic boundary conditions. Then, $U_{\rm CM}(x)$ is a deterministic function while $U_{\rm MC}(x)$ and $U(x)$ are random fields. Theoretical arguments and numerical examples are used to show that (1)continuum mechanics solutions $U_{\rm CM}(x)$ may or may not be consistent, i.e., they may or may not match the expectations of micro-scale solutions $U(x)$, and (2) multi- and micro-scale solutions, generally, have similar first two moments but the extremes of the random fields $U_{\rm MS}(x)$, and $U(x)$ differ significantly, which suggests that multi-scale solutions $U_{\rm MS}(x)$ cannot be used as surrogates of micro-scale $U(x)$ for reliability studies since, e.g., the distributions of the random variables $\{\max_{x\in D}\|U_{\rm CM}(x)\|\}$ and $\{\max_{x\in D}\|U_(x)\|\}$ usually differ.

627: On Performance of Elements in the Finite Element Analysis of Strain Localization in Granular Soils using Micropolar Constitutive Model

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Majid Manzari, The George Washington University

In the finite element analysis of strain localization in granular soils using micropolar constitutive model, non-standard elements are required to describe the kinematics and constitutive relation associated to the micropolar continuum. For this purpose, mixed elements with nodal micro-rotations in addition to the nodal displacements are needed. Also micropolar enhancement introduces couple-stresses and curvatures in the element formulation along with the force-stresses and strains which are now unsymmetric. Furthermore, to consider the globally undrained and partially drained condition mixed elements with additional nodal degree of freedom for pore water pressure are needed. In this work, confining to plane strain/stress application, a total of eight elements are developed and implemented: four elements (u4-□4, u8-□4, u3-□3, u6-□3) the drained case and four elements (u4-□4-p4, u8-□4-p4, u3-□3-p3, u6-□3-p3) for the globally undrained and partially drained case. u, □ and p in the element notation correspond to nodal displacements, micro-rotations, and pore water pressure, respectively. The elements consist of linear and quadratic triangles and quadrilaterals. Employing the developed elements, finite element analyses of strain localization in granular soils using micropolar enhanced constitutive model are conducted for drained, globally undrained and partially drained conditions. Comparison of the performance of developed elements is carried out to demonstrate their suitability in analyzing strain localization problems using micropolar constitutive model in drained, globally undrained and partially drained conditions.

611: On Performance of Implicit Integration for a Micropolar Critical State Model

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Karma Yonten, The George Washington University

Failure and collapse of geo-structures containing granular materials such as sand often involve strain localization in which band(s) of intense concentrated deformation are formed. Although several advanced constitutive models are shown to well predict the pre-peak phase of the soil stress-strain behavior, majority of commonly used models often fail to capture the post-peak regime associated with the post-failure of the material. This is primarily due to the loss of well-posedness of the underlying boundary value problem during strain localization in the numerical analysis that is based on standard continuum mechanics. To alleviate this shortcoming, one suitable approach is using micropolar continuum which incorporates some microstructural features of the material response and help retain the well-posedness of the incremental boundary value problem. Implementation of these advanced constitutive models, however, is quite challenging and requires the development of a robust and accurate integration scheme. □□While it is often challenging to implement a fully implicit integration scheme for complex constitutive models it is often observed that they are more reliable than simpler techniques such as explicit and sub-stepping techniques. In the present work, a fully implicit integration scheme is formulated and implemented for a micropolar-equipped critical state model for sand. Detailed numerical analyses of strain localization in sands are conducted at both specimen and structural levels. The performance of the developed implicit integration scheme is compared with two other schemes that are commonly used: an explicit method with sub-stepping and a semi-implicit technique. Detailed comparisons of the three techniques demonstrate the superior accuracy and robustness of the implicit technique for problems in which significant strain localization develops in soil. The analyses also demonstrate the relevance of each numerical integration schemes in problems involving drained, undrained, and partially drained responses of saturated granular soils.

745: On the Nanoscale Origins of Time-Dependent Deformations in Nanoporous Materials

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Long term creep (i.e. the long-term behavior of materials under sustained stress load) is one of the most challenging "crossing scales effects" in engineering mechanics. Indeed, it plays an important role in effectively influencing the durability of structures. As long-term creep usually takes place on very long timescales (spanning decades or more), its continuing observation is practically impossible and hence its true nature is still unknown. It has been suggested by several recent studies that the slow kinetics of autogenous creep (when the system does not exchange fluid with the environment) originates from the motion of the fluid in the tiniest pores [1,2]. Creep is thus especially crucial for soils, cementitious materials as well as tight rocks and shales that have significant meso- and microporosity. In usual ground conditions this porosity might be partially or fully saturated with fluids. In nanopores (< few nanometers) the fluid is however under such a high confinement that it becomes strongly inhomogeneous due to surface effects. Indeed, the different interactions between the walls of the pores as well as between the fluid and the walls, manifesting themselves in the form of "disjoining pressure" and "solvation pressure", lead to significant ordering of fluid molecules in the vicinity of the walls. This induced inhomogeneity strongly influences the rheology of the fluid in the pore, and ultimately the response of the whole system. Models have been proposed to understand the long term creep behavior of fully or partially saturated porous media which has led to controversial interpretations. In this work, our goal is to clarify some of the controversies regarding explanations of autogenous creep. We perform molecular simulations of fluids nanoconfined in slit pores, which allows us to directly observe the molecular ordering at the surface. The considered fluids range from simple model Lennard-Jones particles to alkanes and water. In these systems we determine the coupling between compressive or tensile deformations (shrinkage and swelling) and shear [3]. In the second part of this study, we apply a microplane homogenization scheme to link the confined microscopic rheology to the macroscale time-dependent creep behavior of the porous materials by averaging over all possible pore orientations [4]. We also determine the macroscopic response as the saturation of pores is varied. [1] Vlahinic, I., Thomas, J.T., Jennings, H., Andrade, J., J. Mech. Phys. Solids, 60, 1350-1362, (2012). [2] Vandamme, M., Bažant, Z.P., Keten S., J. Nanomech. Micromech., doi: 10.1061/(ASCE)NM.2153-5477.0000102 (2015). [3] Hoang, H., Galliero, G., Phys. Rev. E, 91, 012401 (2015). [4] Bažant, Z.P., Caner F.C., J. Eng. Mech. ASCE, 131, 31-40 (2005).

99: On the Parametric Sensitivity of Cohesive Zone Models for High-Cycle Fatigue Delamination of Composites

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This article investigates the sensitivity of cohesive zone models (CZMs) for high-cycle fatigue delamination in relation to constituent static parameters, namely, the cohesive strength and stiffness, whose values are frequently calibrated by curve fitting or selected for convenience without any physical basis. After reviewing the damage mechanics formulation of mixed-mode CZMs for static (monotonic) loading in bilinear, exponential, and polynomial cohesive laws, the source of uncertainty arising from the calibration or selection of static parameters is remarked. The formulation of the CZMs for high-cycle fatigue loading using interface separation, strain, and strain energy release rate (SERR) based fatigue damage rate functions is discussed. Several numerical studies are conducted to explore the sensitivity of CZMs for fatigue delamination in relation to static cohesive parameters and to the shape of the cohesive law under mode I and mixed-mode loading. The performance of the CZMs is also investigated for additive and non-additive decomposition of total damage into its static and fatigue components, and for constrained and unconstrained damage update strategies in the vicinity of the crack tip. Numerical studies illustrate that a CZM employing the separation or strain based fatigue damage rate function is highly sensitive to phenomenological cohesive strength and stiffness parameters, whereas a CZM employing the SERR based damage rate function is minimally sensitive to the same static parameters. While the shape of the static cohesive law does not affect fatigue crack growth rate predictions, studies show that cohesive laws with higher-order smoothness can better describe linear Paris regime behavior. The main conclusion of this article is that incorporating a SERR based fatigue damage rate function into a CZM with higher-order smoothness leads to a more robust approach for simulating high-cycle fatigue delamination of laminated composite materials.

95: Online Bayesian Model Assessment for Structural Health Monitoring Using Nonlinear Filters

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Model assessment is an integral part of many engineering applications, since any analytical or numerical mathematical model used for predictive purposes is only an approximation of the real system. An issue for which model assessment methods need to account is the bias-variance tradeoff; the model should balance simplicity (low variance) against accuracy (low bias). Luckily, this is a built-in feature of Bayesian approaches to model assessment. However, Bayesian model assessment requires the calculation of the evidence of each candidate model considered given the available measured data, which is a non-trivial task and it is usually attempted offline, e.g., by using a stochastic simulation scheme or some deterministic approximation. Very few authors, especially in the field of structural dynamics, have investigated online application of model assessment. The current work explores how Bayesian model assessment and an online identification scheme for joint state and parameter estimation, in particular the unscented Kalman filter, whose computational efficiency has been widely recognized, could be integrated into a single method. This hierarchical Bayesian modeling approach involves two inference levels, namely model assessment and parameter estimation. There is the possibility of adding another level within the hierarchy for noise estimation. An illustrative example involving several hysteretic candidate models is presented to demonstrate the implementation of the proposed procedure in structural health monitoring applications.

217: Onset of Grain Size Segregation in Bi-Disperse Chute Flow

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Segregation due to the difference in grain size, density, shape and/or other properties is commonly found in industrial processes and in nature. In bi-disperse chute flow, size segregation is triggered by the percolation of small particles through the opened voids (kinetic sieving). The imbalance in contact force and the mass conservation normal to the base lead the larger grains to drift towards the top of the flow (squeeze expulsion), and large particles are accumulated in the upper layer as the flow reaches steady state. In this study, three-dimensional DEM simulations of size segregation in granular flow down chute are presented [1]. At varied slope angles, it exhibits different rates of segregation; the higher the slope angle is, the faster the segregation occurs and completes. The same degree of segregation (~0.85) can be eventually reached in the fully developed, steady state. However, it is found that when the slope angle is lower than a critical value (i.e. 22), the final degree of segregation is dropped dramatically. No segregation is observed when the slope angle is as low as 18, although steady flow is achieved in the same case. This implies that one critical value of slope angle controls the onset of segregation, while another controls the saturated degree of segregation. In order to explore the microscopic origin underlying the two critical values, the spatial force correlation is proposed to be examined in the DEM simulations. Previous studies [2] show that in the granular flow under simple shear, the characteristic length of spatial force correlation decreases with the increase of inertial number. In the static or quasi-static regime, force chains with longer length scale tend to be formed through the contact network. In contrary, it is difficult to form

force chains in the dynamic regime, while clusters within shorter length scale can be found. The same concept is applied to the size segregation in gravity flow in the present study. As the slope angle increases, the increasing inertia leads to a 'weaker' structure (i.e. shorter force chain) of contact network, which initiates the rearrangement of particles and thus the segregation. On the other hand, the clusters formed in the high inertia regime seem to be crucial to the completion of segregation.

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437: Optimal Approximation of Multi-Variate Stochastic Processes by Functional Quantization

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Many important applications in probabilistic mechanics require the simulation of multi-variate stochastic processes. For example, in the three-dimensional structural dynamic analysis of structures with large dimensions in plan, the orthogonal components of seismic ground motion time-histories at different support locations should be correlated according to a coherence function. Similarly, wind velocity fluctuations corresponding to different locations over the façade of a building should be simulated as vector processes, which have to match a prescribed target cross-spectral density matrix. When these multi-variate realizations are considered as input quantities in stochastic mechanics simulations, the output quantities can be probabilistically accurate only when the stochastic input quantities correctly represent the entire sample space. Many times, however, the deterministic analysis that needs to be run for each input sample is computationally very expensive. In such cases, the use of Monte Carlo simulation with a large number of samples is prohibitive. Because of this reason, probabilistic methodologies for optimal sampling of multi-variate random processes are sought. Functional Quantization (FQ) is a technique for the optimal approximation of random processes [1] using a finite collection ("quantizer") of representative functions and corresponding probability masses. The FQ method has a close relation to the Centroidal Voronoi Tessellation concept, which was extended to the infinite-dimensional space of square integrable functions [2]. Additionally, it has been shown [2] that the FQ technique is quite versatile, being applicable to both stationary and non-stationary processes. Recently, an iterative algorithm for the computation of quantizers has been developed for univariate 1D processes and 2D fields with any marginal distribution [2, 3]. The focus of this paper is to present a technique for the computation of quantizers for multi-variate stochastic processes. The optimality of the approximation lies in the minimization of a metric called "multi-variate distortion". This criterion yields a mean-square optimal result, which is particularly important in applications like risk analysis and loss estimation in civil engineering.

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699: Optimal Clipped Linear Strategies for Controllable Damping

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A common approach for designing strategies for controllable dampers is based upon the clipped-optimal control paradigm (Dyke et al., 1996). In this control strategy, a linear optimal control strategy is designed assuming that the damping device is a linear actuator that can exert any force; typically, an optimal control such as a linear quadratic regulator (LQR) is employed to minimize, for the active system, some mean square cost metric. Then, a secondary controller evaluates whether the force commanded by the primary linear controller would be achievable by the semiactive/controllable damper: if so, then the damper is commanded to exert that force; and if not, then the damper is commanded to exert a force as close as possible to the desired (which is usually a zero force). In many cases, this approach provides satisfactory performance. However, for some structures and some performance objectives, the linear actuator assumption in the primary control design can result in forces that are frequently non-dissipative, trying to inject energy into the system, which simply cannot be accomplished with a controllable damper; the result effectively is to deactivate the controllable damper for most of the time history. This study investigates, for some simple structural models, (brute force) optimization to find alternate linear controllers that provide superior clipped semiactive performance in these cases where clipped-optimal control does not perform satisfactorily. For simple models, the linear control gain is of low dimension, enabling a reasonably computationally tractable brute-force optimization solution. Optimal strategies for several excitations will be studied, including Gaussian white noise (which is effectively the same excitation considered by stochastic optimal control using LQR, the most commonly used optimal primary controller in clipped-optimal control), a Kanai-Tajimi-based filtered Gaussian excitation that has spectral content similar to that of a suite of historical earthquakes, as well as several historical earthquakes themselves, resulting in several different clipped linear strategies for commanding the controllable damper. These strategies will be compared with each other, with their corresponding linear system (without clipping), with the LQR active and clipped LQR semiactive strategies, and with a nonlinear hybrid model predictive control strategy previously studied by the senior authors.

539: Optimal Design for Future Uncertainty with Adaptable Infrastructure

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Engineering design is subject to significant uncertainties both in describing the present state and in predicting the future. The later type of uncertainty has not been addressed in classical static design approaches, where the system and the surrounding conditions are assumed to be stationary. In recent years, uncertainty on future conditions, associated with climate change, system deterioration or socio-economical development, has been recognized as an important factor and a variety of strategies are being investigated and pursued to deal with this type of uncertainties. Designing adaptable systems is one of them. The challenge is in quantifying the value of adaptability. Is it worth to build a (more expensive) adaptable system that can be adjusted in the future depending on the future conditions? Or is it more cost-effective to make a conservative (robust) design that is satisfactory under many future scenarios? This contribution will present a quantitative methodology based on Bayesian decision analysis for optimizing the system design taking into account its adaptability (i.e. the costs for changing the system in the future). The framework further allows comparing the adaptable systems with non-adaptable ones and thus determining the value of adaptability. The theoretical concept is demonstrated on examples.

675: Optimal Deterioration Modeling for Infrastructures

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Hadi Meidani, University of Illinois

The large volumes of measurement data currently being collected from infrastructures, such as pavement conditions data or rail track geometry data, provide a unique opportunity to generate predictive analytics about the deterioration behavior of these systems. Deterioration is a complex stochastic process whose many factors may not be captured by the measurement data. Therefore, probabilistic models that account for stochastic nature of deterioration have been our focus. In this presentation, examples of our work on predictive modeling for track and pavement degradation are presented. Specifically, survival analysis and Markov deterioration models are considered and the issue of scale in these models is investigated. We will demonstrate that the right choice of scale or resolution for these predictive models will improved prediction accuracy and lead to significant savings in maintenance costs.

248: Optimal Sequential Sensor Placement for Fatigue Damage Monitoring of Structures

Eric Hernandez, University of Vermont

Fatigue can be defined as failure due to repeated application of load cycles, which individually do not cause failure. Fatigue is the main cause of failure for structures subjected to vibration effects and time varying loading such as bridges, wind turbines, ships and aircraft. Fatigue is a multi-scale phenomenon that begins with initial defects and micro-cracks propagating and coalescing, until a visible macro-crack emerges. This is followed by macro-crack propagation and ultimately, failure. Most of the fatigue life of a component is spent in the micro-crack phase and once a macro-crack appears and is actively propagating, failure is almost imminent. Therefore it is convenient to perform fatigue monitoring and diagnosis at the early stage before cracks become apparent. Fatigue monitoring involves two main components: (i) damage modeling and (ii) usage monitoring, i.e. stress and strain estimation at locations of interest. This contribution presents a sequential Bayesian methodology to perform optimal sensor placement for fatigue usage monitoring in structures. The proposed method operates within the context of the Kalman filter and has as objective function variance minimization of the estimated stress/strain at arbitrary points of interest in the structure. It is shown that the proposed sequential sensor placement method results in the solution of “m” sequential Riccati equations, where “m” is the number of sensors. The methodology is verified in numerical simulations and validated using small scale laboratory experiments. The proposed sensor placement algorithm will enable engineers to monitor fatigue throughout a structure using the minimal number of sensors in order to achieve a predefined level of damage estimation variance.

753: Optimization of Data Collection Protocols for Efficient Microstructure Reconstruction

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Lori Graham-Brady, Johns Hopkins University
Michael Uchic, Air Force Research Laboratory
Michael Groeber, Air Force Research Laboratory

Three-dimensional digitally reconstructed microstructures obtained via EBSD-FIB serial sectioning are extremely valuable for validating computational models aiming to predict relationships between microstructure and material properties. These data sets are expensive to generate, and there is a trade-off between cost and accuracy as determined by the data collection and microstructure reconstruction parameters. This work introduces a constrained optimization formulation to minimize the cost of data collection such that the accuracy of the ensuing reconstructed microstructure is within some user-specified tolerance. Accuracy is determined by the discrepancy between the reconstructed microstructure and reference values known about the material being characterized. In this work, phantom, or virtual, microstructures are generated to serve as the reference or true microstructure, and the features determining accuracy are cumulative distribution functions of grain volume, major and minor aspect ratios, number of adjacent neighbors, and the moment invariant 3 shape factor. The EBSD-FIB collection process is artificially simulated with in-plane resolution, serial section thickness, and dwell time taken to be model parameters. This virtual data is fed into DREAM.3D software to reconstruct the microstructure. Three hypothetical, yet realistic, examples demonstrate the performance of this optimization framework. The implications of this work are that the cost of data collection can be significantly be reduced in many scenarios and that this work denotes progress towards the goal of real-time optimization of experimental data collection for materials characterization.

240: Optimization of Geometric Parameters of an Adjustable Module for Variable Depth Arch Bridges

Yao Wang, University of Notre Dame
Ashley Thrall, University of Notre Dame
Theodore Zoli, HNTB Corporation

This research optimizes the geometry of an adjustable module – comprised of a four bar linkage – which can be configured to form variable depth three-hinged arch bridges. Challenges in the development of an adjustable module are selecting geometric parameters (i.e., lengths of links) which provide significant versatility in form balanced with structural performance. This research optimizes the length of the links of an adjustable module for maximum (1) versatility, quantified as number of span lengths [ranging from 61.0 m to 183 m (200 to 600 ft)] and span to depth ratios (ranging from 4-6) for which the link length meets geometric constraints, and (2) resistance to in-plane buckling, quantified as the inverse of the longest in-plane unbraced length of the upper or lower chord squared. Constraints include feasibility requirements related to the angle between links and that the module is capable of generating the desired variable depth. This depth is determined by developing pressure lines using graphic statics for the arch under dead load and a distributed live load acting on the (1) full span, (2) half of the span, (3) 5/8 of the span, and (4) 3/8 of the middle of the span. An optimized geometry for the adjustable module is determined. The promise of this module is then compared with existing modular bridge systems (e.g., Bailey, Acrow, Mabey Johnston) - comprised of rectangular steel panels connected longitudinally to form a girder-type bridge. This material is based upon work supported by the National Science Foundation under Grant No. CMMI-1351272.

265: Optimizing Sensing Based on Value of Information Using Spatio-Temporal Probabilistic and Network Models of Infrastructure Systems

Carl Malings, Carnegie Mellon University
Matteo Pozzi, Carnegie Mellon University

Distributed infrastructure systems (e.g. a transportation system) consist of a number of components (e.g. bridges, tunnels, and roadways) which, operating together, fulfill a basic function for society (e.g. transit connectivity). These systems can be subjected to spatially and temporally varying demands (e.g. temperature, wind intensity, structural loading), which affect the performance of each component. This in turn affects the behavior of the system, depending on the topological arrangement of the components, i.e. how they act together to fulfill the system's function. In managing such a distributed system, intervention actions can be taken (e.g. repairing or replacing a component), with certain effects on the behaviors of the components and incurring certain costs.

Furthermore, data can be collected in the system, which can support the optimal selection of management actions by updating the manager's knowledge of the demands on each component, as well as their current and projected future states. Optimal collection of this information, through the design of a spatially distributed sensor network and appropriate choice of sensing schedules, is crucial to supporting the management of the system in an efficient and cost-effective way. In this paper, we integrate a Gaussian random field model with a known spatio-temporal correlation structure, describing the demand on an infrastructure system, with a network-based model of the system topology. This combined model allows us to describe the behavior and evolution of the system over space and through time. Within this combined model, the value-of-information metric, based on the difference in expected management costs with and without collected sensor information, is used to optimize the allocation and scheduling of sensors within the system. The sensing network and schedules will therefore be optimized such that the information provided to infrastructure managers will allow them to make decisions which will most reduce the expected system-level management costs. A general outline of this approach will be given, and a demonstrative example of its application to support optimal decision-making for a system of infrastructure will be presented.

738: Osteocyte Calcium Response to Mechanical Load Quantified in Live Allograft Biological Systems at Successive Differentiation Stages

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With increasing life expectancy, pathologies related to massive bone loss carry $10 billion financial burden on the U.S. healthcare system. Successful techniques to repair massive tissue regeneration can be however difficult and will require the addition of functional materials. As the result of continuous remodeling, human Haversian cortical bone is a complex hierarchical heterogeneous where microdamage are mechanical stimuli to initiate tissue resorption by osteoclasts cells before tubular lamellar structures called osteons are formed by osteoblast cells. Osteoblasts lay an extra cellular matrix composed of Type I collagen fibrils mineralized by hydroxyapatite nano platelet crystals glued together with non-collagen proteins and proteoglycans. Trapped osteoblasts further differentiate into mechano-sensitive osteocytes that are able to sense stimulation produced by microdamage. Osteocytes have the particularity to bear a large number of cytoplasmic processes extending into canaliculi to create a syncytial network with the neighboring cells with which they can exchange signals in a fashion similar to the nervous system. Osteocytes regulate healthy bone turnover and it is essential to quantify the relationship between in situ mechanical stimulation and the cell biological response. Dual experimental and numerical top-down 3D investigations to create Live Allograft Biological Systems (LABS) composed of progenitor and mature osteocytes reseeded on donor human femoral fresh cadaver bone. The systems showed in vitro osteocytes biological response to in situ mechanical loads. The live systems were subjected to micro bending tests to produce, image and model the growth of controlled nascent sub-microscopic damage near live osteocytes. The balance of the energies at the global scale identified the multiscale local constitutive fracture mechanisms scale by scale to measure the in situ stress field near live bone cells. The finite element model represented the explicit bone tissue 3D morphology and the boundary conditions were calculated by digital volume correlation. Grey scale identification in micro CT imaging in targeted nano-indented regions measured the material properties while UV and fluorescent confocal microscopy coupled contributed to the measurements of the cell morphology and released chemicals upon loading. The numerical model shows nascent diffuse damage within the 3D osteon lamellae near the live progenitor and mature osteocytes. The cells reorganize in vitro as they are in vivo at the different stage of differentiation. The fluorescent observations revealed the calcium membrane transport adaptation of the cells to the in situ mechanical cyclic loading at successive stages of differentiation.

461: Parallel Asynchronous Space-Time Method for Computational Structural Dynamics

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Karel Matous, University of Notre Dame

In practical large-scale engineering problems with localized phenomena, it is important to focus computing power where needed. Thus, a localized treatment of the mesh and time resolutions is required to efficiently capture the local spatial and temporal scales of the problem. In other words, the computational subdomains should be independently refined in the spatial and temporal directions based on the local space and time physics. The local treatment of the spatial and temporal resolutions however, often leads to non-matching meshes along the interfaces and subdomains with heterogeneous time steps. To this end, we propose a Parallel Asynchronous Space-Time Algorithm based on the Domain Decomposition Method (PASTA-DDM) for time-dependent problems disceretized with non-matching meshes along the interfaces. For accuracy and fulfilling the conservation requirements, we adopt the common-refinement-based technique to transfer data among the adjacent subdomains having non-matching meshes and different time steps. The proposed algorithm is parallel and well suited for heterogeneous computing environment. For linear dynamical problems, PASTA-DDM maintains second order spatial and temporal convergence properties, shows unconditionally stable behavior and ensures conservative of physical quantities along the interfaces. The numerical scalability and the computational complexity of the algorithm is thoroughly investigated. Furthermore, for the numerical application, we consider a sandwich plate impacted by a projectile. Based on the physical properties of the problem, the computational domain is split into a number of non-overlapping subdomains. The subdomain meshes and time steps are selected based on the local dynamical behavior of the multi-scale problem leading to large degree of asynchrony.

518: Parallelized Coupling Simulation of a Multiphysical Problem in the Many Integrated Core (MIC) Architecture

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Taehyo Park, Hanyang University

The multiphysical problems such as solid-solid and solid-fluid interaction problems are simulated using a parallel algorithm suited for the Intel many integrated core (MIC) architecture. First of all, a non-overlapping domain decomposition method (DDM) based on a modified Dirichlet boundary condition is introduced, then a computational procedure for the Intel MIC architecture is dealt with. For this, the non-overlapping DDM is applied into the Lagrangian mesh for solid and the Eulerian mesh for fluid, respectively. This makes possible to perform the finite element method dependently on each core in the MIC. In this MIC, total 60 cores are participated for calculation, and each cores are integrated on a high speed internal network bus. In order to verify a parallel effectiveness, scalability is examined for simple examples. We also handle a transient contact problem between two different physical phases. The non-smoothed contact method which does not allow overlapping contact domain is introduced, and the detail numerical approach to calculate a contact force and a contact pressure is also presented. This approach can be related to the parallel algorithms in the MIC. Namely, the contact force in solid phase and the contact pressures in fluid phase result from DDM is shared by data transfer using MPI

library.

730: Patient-Specific Fracture Risk Assessment of Vertebrae: A Multiscale Approach Coupling X-Ray Physics and Continuum Micromechanics

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Claire Morin, Ecole Nationale Superieure des Mines
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Alain Vella, University of Malta
Zdenka Sant, University of Malta
Christian Hellmich, TU Wien- Vienna University of Technology

While in clinical settings, bone mineral density (BMD) measured by Computed Tomography, remains the key indicator for bone fracture risk, there is an ongoing quest for more engineering mechanicsbased approaches for safety analyses of the skeleton. This calls for determination of suitable material properties from respective CT-data, where the traditional approach consists of regression analyses between attenuation-related grey values and mechanical properties. We here present a physics-oriented approach, considering that elasticity and strength of bone tissue originate from the material microstructure and the mechanical properties of its elementary components. Firstly, we re-construct the linear relation between the clinically accessible grey values making up a Computed Tomograph, and the X-ray attenuation coefficients quantifying the intensity losses from which the image is actually reconstructed. Therefore, we combine X-ray attenuation averaging at different length scales and over different tissues, with recently identified "universal" composition characteristics of the latter. This gives access to both the normally non-disclosed X-ray energy employed in the CT-device, and to in vivo, patient- and location-specific bone composition variables, such as voxel-specific mass density, as well as collagen and mineral contents. The latter feed an experimentally validated multiscale elastoplastic model, based on the hierarchical organization of bone. Corresponding elasticity maps across the organ enter a Finite Element simulation of a typical load case, and the resulting stress states are increased in a proportional fashion, so as to check the safety against ultimate material failure. In the young patient investigated, even normal physiological loading is probable to already imply plastic events associated with the hydrated mineral crystals in the bone ultrastructure, while the safety factor against failure is still as high as five.

105: Performance Based Design of Diagrid Tall Buildings

Mohammad Bhuiyan, West Virginia State University
Roberto Leon, Virginia Tech

A triangulated exoskeleton, or diagird, structural system has emerging as a structurally efficient and architecturally valid solution for tall buildings. The diagrid creates a highly efficient and redundant tube structure by providing a structural network allowing multiple load paths. The diagrid system has higher inherent torsional rigidity than most other structural systems. Although engineers recently started using this structural system for tall buildings, almost all its applications have been in areas of low seismicity. The main goal for this study is to examine the potentional utilization of this highly efficient and economic structural system to tall buildings in high-seismic regions. Three buildings with different height (82-, 64-, and 38-story) and footprint are selected. Detailed performance-based assessments are carried out for earthquake action at various hazard levels for serviceability, survivability, and collapse prevention. The results from the analyses showed a superior performance for the diagrid structures under seismic loading.

80: Performance-Based Design of Inundated Coastal Structures

Trung Do, Colorado State University
John van de Lindt, Colorado State University
Daniel Cox, Oregon State University

Finite element models for modeling the structural response of structures to earthquakes and wind loading are well developed. However, the applicability of these numerical models to other hazards such as wave loading due to extreme wind storms is less well understood, particularly due to complex nature of waves interacting with real geometries. This paper presents a unique application to performance-based design development using a numerical model of a wave flume. The model is shown to be able represent the physical 2-D wave flume at Oregon State University including the wave maker, flume and test specimens with sufficient accuracy for design code development applications. Wave spectra at the location of the test specimens were compared to wave spectra in shallow water to ensure they matched the design hurricane waves. Two existing laboratory tests, namely a full-scale transverse wood wall subjected to wave loading and a large scale I-10 bridge subjected to wave loading, were used to confirm the accuracy of the modeling approach. The same approach is used for a full-scale numerical model of a bridge section to illustrate the use of fragility curves for performance-based design of inundated coastal infrastructures.

589: Performance-Based Multi-Hazard Topology Optimization of Structural Systems

Arthriya Suksuwan, University of Michigan
Seymour M.J. Spence, University of Michigan

Recently there has been growing interest in developing probabilistic topology optimization techniques for the reliability-/performance-based conceptual design of structural systems. Research efforts have focused on developing frameworks for the topology optimization of building systems subject to a variety of natural hazards, e.g. wind or seismic actions [1,2]. In general, these approaches have been applied to single hazard design scenarios. This is, however, in contrast to the often multiple natural hazards, such as earthquakes, tsunamis, windstorms, and floods, which may be experienced by a structure over its lifespan. Therefore, if truly optimal systems are to be found, a new generation of multi-hazard design and optimization frameworks must be developed. This paper focuses on the initial development of such a framework for the topology optimization of structural systems of buildings subject to significant wind and seismic hazards. In particular, the goal is to describe the performance of the system in terms of metrics, e.g. damage ratios, consistent with the next generation of probabilistic performance-based design (PBD) [3]. The multi-hazard annual exceedance probabilities of these metrics are then estimated through a simulation-based framework that allows a probabilistic auxiliary variable vector (AVV) to be defined for each realization of the simulation. This AVV can then be used to define an optimization sub-problem that not only approximately decouples the optimization problem from the multi-hazard simulation framework, but also allows the optimization problem to take on a classic static and deterministic form. This permits the use of extremely efficient and well established optimization algorithms to be used for finding solutions. By sequentially solving a series of sub-problems, a sequence of steadily improving designs are found. Because each sub-problem is exact in the point in which it is formulated, the final designs rigorously meet the performance constraints of the original optimization problem. The potential of the proposed performance-based multi-hazard topology optimization framework is illustrated through the topology design of a lateral load resisting system of a 2D building subject to significant wind and seismic hazard risks. A parametric study is also carried out in order to investigate the sensitivity of the lateral load resisting system to different natural hazards.
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533: Plasticity Modeling of Liquefaction Effects under Sloping Ground Conditions: Investigation of Underlying Mechanisms and Recent Advancements

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Ross Boulanger, University of California, Davis

Numerical simulations for performance-based evaluation of liquefaction effects under sloping ground conditions greatly rely on the constitutive model's ability to accurately predict the cyclic mobility behavior associated with the undrained cyclic loading of sand under a nonzero static shear stress ratio. Exercising constitutive models under such boundary conditions reveals that most are challenged in replicating experimentally observed trends of such behaviors. Evidence from a centrifuge test on sloping ground consisting of liquefiable sand subjected to an irregular seismic input motion, suggests that loading history plays a significant role in the slope's response and in particular in the cyclic resistance and subsequent amount of accumulated deformations. The relative extent of this contribution however remains unknown. The body of experimental data presented by various researchers describing the elemental behavior of sands under sloping ground conditions does not provide any evidence related to this particular issue. This is because all the experimental results on a range of sands under sloping ground conditions correspond to uniform cyclic loading and thus provide limited insights on how irregular cyclic loading affects the cyclic resistance of liquefiable soils. Herein, the pertinent body of data that serves as the validation domain for constitutive models is reviewed, and new experimental data from undrained cyclic Direct Simple Shear (DSS) lab tests of liquefiable sand under sloping ground conditions subjected to irregular cyclic loading are introduced. Evidence from the laboratory tests will show that it is the effect of loading history on the dilatancy and stiffness characteristics of the response that guide the targeted behavior. Modifications to the formulation of a plasticity model are introduced by revising the dependency of dilatancy and plastic modulus on the fabric tensor and its history. Finally, two examples of calibration are presented: one against a specific lab test result for a single sand and one against an engineering correlation describing trends observed for many sands across a broader range of relative densities, confining stresses, and loading conditions. The results are shown to be instrumental in advancing our fundamental understanding of such mechanisms at the soil grain level, and facilitating their reasonably successful numerical simulation.

630: Polygonal Finite Elements for Finite Elasticty

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Cameron Talischi, University of Illinois
Oscar Lopez-Pamies, University of Illinois
Glaucio Paulino, Georgia Institue of Technology

Recent studies have demonstrated that polygonal elements possess great potential in the study of nonlinear elastic materials under finite deformations. Yet, those elements generally suffer from persistent consistency errors under mesh refinement with the commonly used numerical integration schemes. As a result, non-convergent finite element results typically occur, which severely limit their applications. In this work, a general gradient correction scheme is adopted that restores the polynomial consistency by adding a minimal perturbation to the gradient of the displacement field. With the correction scheme, the recovery of the optimal convergence for solutions of

displacement-based and mixed formulations with both linear and quadratic displacement interpolants is confirmed by numerical studies of several boundary value problems in finite elasticity. In addition, for mixed polygonal elements, the various choices of the pressure field approximations are discussed, and their performance on stability and accuracy are numerically investigated. We present applications of those elements in physically-based examples including a study of filled elastomers with interphasial effect and a qualitative comparison with cavitation experiments for fiber reinforced elastomers.

231: Poromechanical Cohesive Surface Element with Elastoplasticity for Modeling Cracks and Interfaces in Fluid-Saturated Geomaterials

Richard Regueiro, University of Colorado
John Sweetser, Lockheed Martin Space Systems Company
Wei Wang, Lawrence Livermore National Laboratory
Erik Jensen, University of Colorado

The talk will present the formulation and implementation of a fluid-saturated poromechanical cohesive surface element (CSE) based upon biphasic (solid-fluid) mixture theory at small strain, with strong discontinuity kinematics. The Strong form (coupled partial differential equations) is presented, upon which Weak and Galerkin forms are formulated using different representations of the fields outside and inside the discontinuity domain. A mixed Q6P4 six-noded CSE is implemented within the coupled nonlinear Finite Element (FE) equations, along with a mixed Q9P4 biquadratic/bilinear quadrilateral for the surrounding bulk porous continuum. Numerical examples demonstrate the features of the CSE for fluid-saturated geomaterials.

498: Power Spectral Density Response Through Modal Analysis Framed Into Analytical Dynamics

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Ioannis Kougioumtzoglou, Columbia University
Athanasios Pantelous, University of Liverpool
Antonina Pirrotta, University of Liverpool and Dipartimento di Ingegneria Civile, Ambientale, Aerospaziale e dei Materiali (DICAM)

In classical structural dynamics, equilibrium equations are referred to the minimum set of coordinates: Then equations in differential form are number strictly necessary, have a complex algebraic structure and are strongly coupled. However, for complex systems, such as the multi-body ones, it is a very challenging task to write the equation of motion using the minimum set of coordinates. As regards, choosing redundant set of coordinates, the way of writing equilibrium equations can become much easier. In this context, the set of equations appears to be, however, in an algebraic-differential form and it composes a lot of equations, but with a simple algebraic structure. Thus, the solution which uses analytical dynamics tool provides not only information about the motion, but also on the forces of the constraints. Hence, the classical modal analysis is not applicable as the coefficient matrices are singular. Consequently, it is easier to write the equations of motion by using the recently developed methods in structural dynamics, see [1, 2], but on the other hand, the most important physical characteristics are not highlighted. In this direction, this paper aims to introduce a proper modal transformation for such systems returning the physical meaning which is important in structural dynamics. Moreover, such proposed modal analysis solves out the differential system of equations referred to redundant variables, decoupling the system itself and returning the main dynamics characteristics as frequency and mode shape. In this context, once the natural frequencies of the system are determined, the Power Spectral Density function response can be easily and

conveniently formulated through modal analysis in frequency domain.

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299: Predicting Characteristics of Polymer Blends Through a Rigorous Thermodynamical Modeling of Structural Length Scales

Andreas Krischok, Stanford University
Lihua Jin, Stanford University
Christian Linder, Stanford University

The aim to enhance the properties of high-performance polymers such as the stretchability and the electrical conductivity has caused researchers to blend two or more polymers to a mixture analogous to metal alloys. In order to predict and improve the performance of polymer blends it is desirable to better understand how the material behavior is affected by the mixing ratio of the different components and their morphology. As fundamental theoretical studies are lacking at the moment, numerical studies can give material scientist a valuable insight into the relation between structural length scales and important characteristics such as the fracture toughness. Existing continuum-based models are usually restricted to single characterizing phenomena such as crystallization or evaporation and neglect the mechanical coupling during the solidification. It is however desirable to model the formation of Marangoni-like surface instabilities during the spin-coating process as they govern the phase separation considerably. We adapt the notion of time discrete mixed incremental energy potentials for Cahn-Hilliard-type phase-field models and extend the formulation to a multi-physics problem that is capable to capture all the phenomena that lead to a typical morphology in a solidified polymer system with multiple blended constituents. A rigorous thermodynamical approach allows the consistent incorporation of effects such as crystallization, evaporation and interfacial tensions that govern the phase separation during the spin-coating process. The variational expression maintains the symmetry of the algebraic system in the nonlinear range and includes recent time-integration methods for Cahn-Hilliard-type phase field models to reduce the computational cost of the procedure. Studying the formation of morphologies allows the subsequent investigation of important characteristics, in particular the fracture toughness and the conductivity.

520: Prediction of Material Consolidation in In718 Produced Using Selective Laser Melting in the Higher Throughput Parameter Regime

Tracie Prater, NASA

Selective Laser Melting (SLM) is a powder bed fusion additive manufacturing process used increasingly in the aerospace industry to reduce the cost, weight, and fabrication time for complex propulsion components. SLM stands poised to revolutionize propulsion manufacturing, but there are a number of technical questions that must be addressed in order to achieve rapid, efficient fabrication and ensure adequate performance of parts manufactured using this process in safety-critical flight applications. The objective of this investigation is to characterize the impact of higher throughput parameters (increased laser powers and faster scan speeds) on material consolidation. In phase I of this work, density blocks were analyzed to explore the relationship between build parameters (laser power, scan speed, hatch spacing, and layer thickness) and material consolidation

(assessed in terms of as-built density and porosity). Phase II additionally considers the impact of post-processing, specifically hot isostatic pressing and heat treatment, as well as deposition pattern on material consolidation in the same higher energy parameter regime considered in the phase I work. Density and microstructure represent the “first-gate” metrics for determining the adequacy of the SLM process in this parameter range and, as a critical initial indicator of material quality, will factor into a follow-on DOE that assesses the impact of these parameters on mechanical properties. Key outcomes are predictive models of material consolidation based on process parameters. This work will contribute to creating a knowledge base (understanding material behavior in all ranges of the AM equipment operating envelope and process/property relationship at higher throughput parameters in particular) that is critical to transitioning AM from the custom low rate production sphere it currently occupies to the world of mass high rate production, where parts are fabricated at a rapid rate with confidence that they will meet or exceed all stringent functional requirements for spaceflight hardware. These studies will also provide important data on the sensitivity of material consolidation to process parameters that will inform the design and development of future flight articles using SLM.

205: Primal Method for GND-Based Kinematic Hardening Model

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This paper presents a framework for modeling the kinematic hardening of plastic materials. The need to predict size-dependent response of a material -which are not captured by conventional crystal plasticity models- has motivated the inclusion of Geometrically-Necessary Dislocations (GNDs) in the constitutive modeling. GNDs which cause a non-zero Burgers vector within the material induce long range stresses that results in a back stress. This back stress in turn influences the effective resolved shear stress required to produce crystallographic slip. This paper adopts a formulation of the back stress expressed through the spatial gradient of the GND density, which has traditionally been treated as an additional solution field to be interpolated at the nodes of the finite element mesh. To avoid the computational cost of using a mixed approach having extra degrees of freedom represented by the GNDs of each crystallographic slip system, this paper utilizes the concept of the Nye tensor and its relation to the elastic deformation gradient to develop a measure of GND density. The density field on each slip system is apportioned using a least-squares approach, and field gradients are generated using nodal projections, leading to a primal approach. Simulations of material response with scale-dependent effects are investigated, such as the bending of single crystals. Comparison of the method’s effectiveness using linear and quadratic finite elements is established.

351: Probabilistic Assessment of Regional Liquefaction-Induced Settlement through Multiscale Random Field Models

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The probabilistic assessment of regional seismic hazards such as liquefaction-induced settlement requires the consideration of both the spatially correlated geotechnical and hydrological parameters and the uncertainties in ground motion intensity. In this work, we propose a framework to evaluate the probability of exceeding a specified liquefaction-induced settlement over a region in a given exposure time. This framework firstly characterizes all possible ground motions at the given site using a novel simplified procedure for the joint distributions of amax and Mw. Then, the spatial structure of geotechnical parameters of interest is characterized and simulated through multiscale random field models. Empirical and mechanics-based models to evaluate liquefaction-induced settlement will be incorporated into the proposed framework. Monte Carlo simulations will be performed for probabilistic assessment. The applicability of the proposed framework will be demonstrated through a case study in a liquefaction-prone region.

45: Probabilistic Detection of Delamination in Composite Laminates Using Bayesian inference of Lamb Wave Signals

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In this paper, a general probabilistic method for delamination detection is proposed using Bayesian inference technique with Lamb wave signals measured from piezoelectric sensor network. The damage possibility at each point is computed from the posterior distribution of Bayesian inference. The locations with the highest damage possibilities are interpreted as delaminated areas. First, a general algorithm for probabilistic delamination size and location detection is developed using Bayesian theorem. Next, demonstration using experimental testing data on composite dog bone coupons under fatigue testing is presented. The Lamb wave signal features are incorporated in the probabilistic framework for delamination size and location detection. Damage profiling images are constructed using the samples from the Bayesian posterior distribution. These images are validated using the ground truth experimental X-ray images. Finally, some conclusions and future work are generated on the basis of current investigation.

11: Probabilistic Fatigue Life Assessment of Reinforced Concrete Structures Subjected to Corrosion

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Aging reinforced concrete bridge corrosion-fatigue issue has been identified as one of the most important failure patterns. The paper proposes a probabilistic fatigue life prediction method of reinforced concrete structures using an equivalent initial crack model. The corrosion fatigue process consists of two major stages: stable corrosion fatigue damage accumulation, and unstable crack growth and strength rupture. The first stage includes general corrosion and pitting corrosion. General corrosion decreases the net section area and increases the nominal stress of rebars. Pitting corrosion increases the local stress and accelerates the fatigue damage accumulation. In this study, the relationship between corrosion pit depth and corrosion loss is investigated based on the experimental results from artificially corrosion test. A phenomenological model based on a calibration process is developed to investigate the stress concentration factor under different corrosion levels. Then the developed model is integrated to calculate the stress intensity factor for the cracks at corrosion pit roots. Following this, a probabilistic time-dependent limit state-function is proposed to perform the reliability/life prediction analysis. Six random variables, corrosion loss, pitting factor, fatigue limit, and fatigue crack growth parameters, are considered for the uncertainty modeling. An efficient probabilistic approach using the inverse first-order reliability method is performed to include the above uncertainties for the life prediction. The prediction life and the experimental results are compared for model validation.

144: Probabilistic Framework to Assess Maximum Nonlinear Structural Response Based on Sensor Measurements

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Assessing the maximum of the response of a structure under stochastic loadings, including earthquakes, is important in structural heath monitoring and reliability analyses. Inclusion of nonlinear material behavior in design and analysis is necessary to extend analysis beyond serviceability-level seismic events. We propose a probabilistic framework to infer the maximum nonlinear response of a structure under seismic excitation based on sensor measurements using a Dynamic Bayesian Network (DBN) framework with a time-evolving system state. This evolution is modeled using an exact discretization solution of the equation of motion. The measurements are recorded by accelerometers placed on the structure, which serve as Bayesian priors in the estimation of the structural response. A simulation approach is used to obtain the stochastic distribution of the maximum structural response exceeding different thresholds. The proposed method also enables investigation of the role of the number, mounting locations, and measurement errors of the accelerometers to infer the system state and support decision making in structural health monitoring applications. The framework is applied to an example shear-type ten-story structure to assess the performance. The ability of methodology to accurately estimate nonlinear structural response is demonstrated.

18: Probabilistic Geotechnical Site Characterization through Stochastic Inverse Analysis of Geophysical Test Measurements

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Geophysical tests are increasingly being used in the field of geotechnical engineering to estimate soil parameters at any geotechnical sites. A typical geophysical test involves excitation of the ground (usually at the surface) and measurement of the resulting waves at several receiver locations on and inside the ground. Inverse analysis is then performed using the receiver measurements to estimate the soil parameters for the site. This research study develops a stochastic inverse analysis methodology to also quantify the uncertainties associated with the estimated soil parameters by accounting for the uncertain spatial variability of the soil deposit as well as any measurement uncertainty. Assuming the soil parameters to be a multivariate, three-dimensional, anisotropic random field, the methodology first formulates the forward, uncertain wave propagation problem using a stochastic collocation approach to characterize the effect of spatially variable, uncertain soil parameters on the model response variable, e.g., strains and accelerations. The stochastic collocation approach utilizes recently developed non-product quadrature method Conjugate Unscented Transformation to accurately propagate statistical moments corresponding to the model response variables in a computationally efficient manner. The methodology then employs the concept of Bayesian belief to merge the information obtained from the model prediction and the sparse geophysical test measurements to update the statistical information pertaining to soil parameters.The methodology is verified using synthetic data from a fictitious downhole seismic survey.A number of numerical experiments have been conducted to illustrate the formulation and to highlight the applicability of the methodology in estimating the non-Gaussian statistics of the soil parameters.

263: Probabilistic Mesoscale Simulation of High Cycle Fatigue by Mixed Trans-Intergranular Crack Growth Method

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Wei Zhang, University of Connecticut
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For most metal, the microstructurally small fatigue cracks (MSC) are usually transgranular ones. However, for metal with heat treatment or in the early stage of corrosion, strong misorientation or weakened strength of the grain boundaries could lead to arbitrary path of early cracks including both transgranular and intergranular track. To explore the mean and scattering high cycle fatigue (HCF) responses, a mixed trans-intergranular crack growth framework is proposed for the 2D probabilistic mesoscale finite element simulation. The state-of-art microstructure-sensitive fatigue model and fatigue indicator parameter (FIP) concept are used for better description of microstructurally fatigue damage.The mixed trans-intergranular crack growth method consists of the crack initiation part by crystal plasticity and corresponding FIP, transgranular crack part by persistent slip band (PSB) model, intergranular crack part by inherent cohesive zone and the manipulation scheme at the grain boundaries. In the initial modeling stage, the grain boundaries are built using cohesive elements. During the loading process, cracks initiate at one of predefined PSBs of which the FIP reaches the limit values and the initiation life is obtained. The cracked PSB is inserted across the whole grain by cohesive elements with reduced strength. At the grain boundary, the nodes of transgranular cohesive element will be tied to the closest nodes of intergranular cohesive elements. The path of the crack extension (transgranular or intergranular) is determined by minimum number needed to crack the neighbor grain or grain boundary calculated by corresponding FIP-based crack growth rate equation. If the crack goes transgranular, a new cracked PSB will be generated. Otherwise, the part of the intergranular cohesive elements with minimum cycle number to fracture is set to have reduced strength. Meanwhile, the randomness of the material properties and model parameters will be included in the simulation framework, which is based on ABAQUS. User defined subroutine UMAT is used to including crystal plasticity and a Python code is scripted to carry out the whole procedure including the interaction with ABAQUS. The numerical calibration and prediction test which rely on the comparison with S-N and crack length a vs. N data of flat specimen fatigue tests with mixed trans-intergranular crack behavior will be presented as the results.

153: Probabilistic Modeling of Failure of Polycrystalline Silicon MEMS Structures

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MEMS devices typically need to be designed against a very low failure probability, which is beyond the capacity of histogram testing. Therefore, it is critical to understand the probabilistic failure of MEMS devices. Currently available probabilistic models for predicting the strength statistics of MEMS structures are based on classical Weibull statistics. Significant advances in experimental techniques for measuring the strength of MEMS devices have produced data that have unambiguously demonstrated the inadequacy of the Weibull distribution. This paper presents a robust probabilistic model for strength distribution of polycrystalline silicon (poly-Si) MEMS structures that could be extended to other brittle materials at the microscale. The overall failure probability of the structure is related to the failure probability of each material element along its sidewalls through a weakest-link statistical model. The failure statistics of the material element is determined by both the intrinsic random material strength as well as the random stress field induced by the sidewall geometry. Different from the classical Weibull statistics, the present model accounts for structures consisting of a finite number of material elements, and it predicts a scale effect on their failure statistics. It is shown that the model agrees well with the measured strength distributions of poly-Si MEMS specimens of different sizes. The present model also explicitly relates the strength distribution to the size effect on the mean structural strength, and therefore provides an efficient means of determining the failure statistics of MEMS structures.

159: Probabilistic Modeling of Interdependencies between Critical Infrastructure Systems for Resilience

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Cascading failures of interdependent infrastructure networks have become increasingly critical as revealed by recent hazard events, including natural disasters and human disruptions. By determining how different types of interdependencies affect the fragility of infrastructure systems, we propose to improve the resilience of infrastructure systems by developing a methodology to identify the most critical components in a system, determine which infrastructure components to reinforce, and decrease the time to regain operational status. To do this, we model the interdependent systems using a Bayesian network (BN) framework. A BN is a probabilistic graph that captures the dependencies between components and systems and allows for the addition of prior and updating information that propagates through each node in the graph. We define and consider three types of interdependencies: service provision, geographic, and access. For service interdependencies, the functioning of one infrastructure is dependent on the service outputs of another. Geographical interdependency refers to infrastructure components in the same geographical area. Access interdependency refers to the inability to repair failed components because of decreased access, e.g., damaged roads or bridges. The network being modeled consists of the power, water, and gas distribution systems in Shelby County, Tennessee. The entire network contains 125 components – 60 power, 49 water, and 16 gas – and 164 links – 74 power, 72 water, and 18 gas. Each component represents a supply station, substation, or bus station where two or more distribution lines meet. Each link represents a distribution line, i.e., gas or water pipe or power lines. The large number of components and links raises a challenge in the BN modeling of this interdependent network. This is due to the exponentially increasing size of the conditional probability tables (CPTs) for the BN, which are used to calculate failure probabilities of components and systems. The Shelby County network, for example, assuming binary (working or failed) components, would require CPTs with over 20 million elements. To address this complexity, the systems can be formulated in several ways. First, a compression algorithm can be used that accounts for patterns in the CPTs to simplify the network and make computation manageable. Second, "supercomponents" can be developed that represent several nodes that exhibit similar behavior. Finally, the system can be formulated as a chain-like network where nodes represent survival or failure paths rather than individual system components. A comparison of these methods is conducted to enable the probabilistic modeling of interdependent infrastructure systems for analysis.

58: Probabilistic Modeling of Thermal Properties of Hot Structures and Its Propagation to the Nonlinear Geometric Structural Response

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Over the last three decades, significant efforts has been devoted to the modeling of uncertain physical properties and their propagation to the solution of particular disciplinary problems, e.g., the modeling of uncertain elastic properties and their effects on the structural response. The consideration of uncertainty in multidisciplinary problems has also been considered, in connection with aeroelastic problems in particular, but less often. The focus of this investigation is to complement these multidisciplinary efforts by studying the effects of uncertainty on the thermal properties of heated structures on both their temperature distributions and structural responses. The specific thermal properties considered here uncertain are the thermal conduction and capacitance, as well as the thermo-elastic coupling property, i.e., the thermal expansion coefficients. Of particular interest for heated thin walled structures are thermal buckling and post-buckling behavior which are best treated within a geometrically nonlinear structural framework. The heat conduction equation on the other hand may be considered linear unless the radiation effects become significant. While finite element techniques are appropriate to carry out the coupled thermal and structural analyses, such computations are very intensive especially when proceeding with the Monte Carlo simulations associated with the propagation of uncertainty. To ease these computations, the present effort relies on a coupled structural-thermal nonlinear reduced order modeling technique recently developed in which both temperature distribution and structural displacement field are represented in modal-like expansions with physically derived basis functions. Then, the coefficients of the expansions, i.e., the structural and thermal generalized coordinates satisfy a coupled set of ordinary differential equations. Those associated with the structural response are nonlinear, of a generalized Duffing-type, and explicitly involve the thermal generalized coordinates in the stiffness terms as well as through an excitation term. When considering uncertainty, the thermal and structural bases are considered fixed so that the uncertainty is reflected solely on the coefficients of the reduced order model differential equations. The probabilistic modeling of the uncertain properties is then accomplished in two separate ways: first by simulating these properties at the finite element level and mapping them to the reduced order level and second by proceeding directly at that level relying on maximum entropy concepts. For the thermal conductance and capacitance matrices, it is shown that a modification of the standard algorithm may be necessary to account for the potential localized character of the temperature distribution. The above methodology is demonstrated on a structural model representative of a hypersonic vehicle panel subjected to aero heating.

186: Probabilistic Seismic Performance of Dry Cask Structures under Strong Ground Motions

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Dry cask structures are used for the intermediate storage of spent nuclear fuel, typically located at independent spent fuel storage installations of nuclear facilities. Given the potentially significant consequences of damage to such free standing structures, performance assessment of dry casks under extreme events, such as earthquakes, is critical to inform risk assessment and mitigation activities. Sliding and rocking limit states are of particular interest given the prospect of impacting adjacent casks or tip over of the dry cask. This paper investigates the probabilistic seismic performance of reinforced concrete dry cask storage systems with an emphasis on cask sliding. Variation in geometrical and material parameters such as the typical dimensions of the cask and its foundation as well as the concrete material properties are considered with Latin Hypercube Sampling utilized to generate 160 cask samples. The 3-dimensional finite element models developed in LS-DYNA are subjected to an equivalent number of three-component earthquake records to evaluate the maximum sliding of each cask relative to its supporting foundation. Probabilistic seismic response models of cask sliding are developed to depict the maximum sliding of the cask relative to its foundation as a function of geometric, material, and ground motion parameters. The results provide insight into parameters which have a significant influence on the probabilistic seismic response of dry cask structures. Furthermore, the resulting parameterized models can support risk assessment of a broad range of reinforced concrete dry casks storage systems located in seismic zones.

688: Process Parameter Uncertainty in Additive Manufacturing of Metals

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Additive Manufacturing (AM), the fabrication of 3-D parts from CAD models, is a disruptive technology that is transforming the manufacturing industry. AM is attractive due to the potential for energy savings, reduced design cycle times, cost savings, and especially design freedom. One common AM process for metals such as Ti, stainless steel, and Inconel alloys uses electron beams to melt powder layer by layer to progressively build structures of almost arbitrary complexity. We have been able to demonstrate the relationship between process parameters and microstructure - specifically columnar and equiaxed grain structure. These process parameters, such as pre-heat, beam diameter, power, and velocity, together with the build pattern, determine the shape of the melt pool and solidification of the material, which in turn determine grain structure. Our goal is to be able to specify grain structure throughout a complex part, which requires optimization of both the process parameters and build pattern, all of which include uncertainties. Since the ultimate goal is to be able to design and build a desired part with confidence in its ability to meet specifications without testing, an understanding of both the process and its parameters is required. We describe the relative sensitivity of these parameters, as well as their uncertainty, and their relationship to the grain structure of additively manufactured objects.

166: Propagation of Uncertain Probability Distributions Using Bayesian Inference and Importance Sampling

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Simulation-based uncertainty analyses are known to be computationally expensive owing to the combined computational expense of large and complex numerical analyses with the large number of simulations required to propagate uncertainty. Making matters worse, uncertainty commonly arises in the assignment of distributions for a probability study. Lack of data creates uncertainties that are difficult to quantify and even more difficult to propagate. Existing approaches require a suite of probabilistic analyses that spans the range of distributional uncertainties but, given the large computational cost of conducting even a single probability study, these methods quickly become computationally intractable. In this study, we develop a simulation-based uncertainty quantification and reliability method that is capable of propagating uncertain probability distributions. First, Bayesian inference is used to quantify the uncertainty associated with a distribution derived from data. In the almost universal case of lack of complete data, the derived distribution from this inference cannot be precisely specified. In general, its parameters (e.g. mean and variance) are random variables and the distributional form itself may not be known. We propose a novel approach, based on Importance Sampling, for propagating uncertain probability distributions. The method identifies an optimal sampling distribution that is representative of the possible range of distributions and adaptively reweights the samples to simultaneously propagate the full range of possible distributions. The result is a suite of response probability distributions obtained by conducting only a single Monte Carlo simulation study. These uncertainty analyses can be updated to incorporate new information without requiring additional simulations. The approach can also be used to assess the sensitivities of the response to the input uncertainties such that future data collection efforts can be targeted to reducing the uncertainties that are more important.

331: Property Analysis of Exfoliated Graphite Nanoplatelets Modified Asphalt Model Using Molecular Dynamics (MD) Method

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The molecular model of the multi-layer graphite xGNP nanoplatelets was created for the modification of the asphalt model, and the control asphalt model consists of three components: asphaltenes, aromatics, and saturates based on the previous study of our group. The multi-layer graphite model was randomly added to the control asphalt model, and the xGNP modified asphalt model was generated. This modified asphalt model was verified through the density calculations and comparisons. After the model verification, the properties of the control and xGNP modified asphalt were computed and analyzed using Molecular Dynamics (MD) method, and the material properties include the glass transition temperature, viscosity and thermal conductivity. Meanwhile, the laboratory tests were conducted to evaluate the viscosity and thermal conductivity of the control and xGNP modified asphalt. The test and MD simulation results show that: (1) the density of the xGNP modified asphalt model is higher than that of the control asphalt model; (2) the glass transition temperature (250 K) of the xGNP modified asphalt model is closer to the laboratory data of Strategic Highway Research Program (SHRP) asphalt binders than that of the control asphalt model; (3) the viscosities of the xGNP modified asphalt model at different temperatures are higher than those of the control asphalt, and it coincides with the trend of laboratory data. The viscosities of the xGNP modified asphalt model are also closer to the laboratory data of the xGNP modified asphalt compared to those of the control asphalt; (4) the thermal conductivities of the xGNP modified asphalt model are higher than those of the control asphalt model at different temperatures, and it is consistent with the trend of laboratory results.

765: Quantifying Resilience-Based Importance Measures Using Bayesian Kernel Methods

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Problem Critical infrastructure systems have become increasingly vulnerable to disruptive events resulting from natural hazards, extreme weather, accidents, and manmade attacks, among others. Such disruptions lead to cascading failures within the physically disrupted system as well as to other interdependent systems causing large scale impacts. The ability of an infrastructure to withstand these disruptive events and recover rapidly with the minimum amount of damages and losses is vital to a society's welfare and safety in the event of disasters. As a result, modeling the resilience of critical infrastructure systems became of interest to risk managers and decision makers, and evidently researchers. Questions The most recent advances in resilience modeling are approaches that utilize qualitative tools or simulation that rely heavily on assumptions of prior knowledge, probability distributions, and potential risk scenarios. How would resilience modeling change if we use data-driven methods? Would these methods improve decision making? Is the data currently available enough to make accurate predictions of future infrastructure resilience? Are these methods compromising for the experts' knowledge expressed in traditional risk management strategies? Proposed solution This research is a first step in the investigation of data-driven tools in resilience modeling of critical infrastructure systems. The work deploys a Beta Bayesian kernel model to assess resilience-based importance measures identifying critical components in an infrastructure network that contribute to the recovery process. Integrating Bayesian methods with kernel methods has recently garnered attention, as this tool (i) consists of a classification algorithm which provides probabilistic outcomes as opposed to deterministic outcomes, and (ii) allows decision makers to gather information from multiple sources such as experts in the field, historical events, and characteristics of the system to make informed decisions. The model is deployed in an application to an inland waterway transportation network, the Mississippi River Navigation system, for which the recovery of disrupted nodes represented by locks and dams is analyzed by estimating their resilience importance using the Bayesian kernel model. The goal of this work is to identify the opportunities and challenges of using data-driven Bayesian methods to analyze the resilience. A sensitivity analysis and a comparison with other classical tools shed light on the benefits of the approach and its applicability in decision making.

309: Quantitative Analysis of the Micro-Mechanisms of Piping Erosion with Coupled CFD-DEM Method

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Piping, as one of the critical pattern of internal erosion, has been reported as a major threat to embankment dams and levee. The fundamental mechanism of piping was traditionally investigated with experimental and simplified theoretical methods in a macroscale. However, the initiation and progressive evolution of piping is a microscale phenomenon in its essence. Currently, the knowledge on the micro-mechanism of piping erosion is limited due to lack of quantitative analysis. In general, seepage flows can affect the soil fabrics and contact forces between particles. But how these fabrics and contact forces evolves under critical hydraulic gradient is still a mystery. This paper presents a coupled Computational Fluid Dynamics and Discrete Element Method (CFD-DEM) approach to investigate the piping erosion process in sand samples. The soil-flow interactions are accounted for by exchanging the momentum exchange between the two phases. In the simulation, piping erosion process is initiated by incrementally ascending differential water head across the soil samples. The three main stages of piping erosion including initial movement, progressive heave and total heave are described. Specifically, the evolution of contact force, drag force, coordination number and porosity is inspected to provide insightful understanding into the micro-mechanism of piping erosion.

482: Quantitative Assessment of Pavement Use Phase Impacts on Vehicle Fuel Consumption

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The sustainable development of our nation’s roadway system requires quantitative means to link infrastructure performance to lifecycle energy use and greenhouse gas (GHG) emissions. In addition to surface texture and roughness induced Pavement-Vehicle Interactions (PVI), we recognize that the dissipation of mechanical work provided by the vehicle due to viscous deformation within the pavement structure contributes to fuel consumption. Herein, we identify the key drivers of deflection-induced PVI through a combination of dimensional analysis, experiments and model-based simulations of energy dissipation in pavement structures. Specifically, development of a novel experimental setup is described to study the mechanism of deflection-induced PVI on small-scale silicone elastomer representations of two layered pavement systems, through visual observations of the pavement response and measurements of the dissipated energy. These experimental findings form the basis for model development in which the pavement is represented as a viscoelastic beam on elastic foundation in a moving coordinate system. Using the experimentally identified dimensionless form of the model, the dimensionless energy dissipation is calibrated against actual pavement materials (concrete and asphalt) considering the specific temperature dependence of the viscoelastic deformation rate of these materials. We demonstrate that the derived model, implemented for the roadway network of the state of California, provides a powerful basis for big data analytics of excess-energy consumption and GHG emission by integrating spatially and temporally varying road conditions, pavement structures, traffic loads and climatic conditions. Moreover, we recognize that a ranking based on the inferred GHG-emissions exhibits a power-law data distribution, akin to Zipf’s Law, which provides a means to map an optimum path for GHG savings per retrofit at network scale.

85: Quantitative inference of failure conditions for individual grain boundaries

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Current understanding of fracture at individual microstructural features—such as grain boundaries (GBs)—is incomplete and often not predictive. We present a statistical method for inferring the conditions for failure at individual GBs based on data collected from high-throughput experiments. This method minimizes the Kullback-Leibler divergence of fracture probabilities constructed based on hypothesized fracture mechanisms from the experimentally determined fracture probability. We apply this approach to hydrogen-assisted crack initiation at coherent twin boundaries in Ni-base alloy 725 and find that the conditions for fracture along these GBs are well described by a modified Mohr-Coulomb criterion. Our findings enable improved lifetime predictions for Ni-base alloys that have been embrittled by H as well as for other materials that undergo intergranular fracture.

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285: Random Vibration Integrals for Systems Endowed with Fractional Derivative Elements

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Abstract. In general, the most efficient technique for determining the response statistics of multi-degree-of-freedom linear systems subject to stationary random excitation relates to a frequency domain analysis, and the evaluation of classical random vibration integrals that represent the spectral moments of the system stationary response. In this regard, several techniques have been developed in the literature for deriving closed-form expressions for the above integrals (e.g. [1]). In this paper, several concepts and tools utilized in [1] are generalized to account for dynamic systems endowed with fractional derivative elements. The aforementioned generalization is especially important considering the recent utilization of fractional derivative modeling in a plethora of applications in engineering and materials science such as viscoelastic materials modeling and analysis.

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718: Rebar Concrete Bond Degradation Under Combined Effects of Alkali-Silica Reaction and Corrosion

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Alkali Silica Reaction (ASR) is one of the major long-term deterioration mechanisms for many concrete structures especially in high humidity environments. ASR is a reaction between alkali ions present in the cement paste an slilica inside aggregate that results in the formation of an amorphous gel. In the presence of high humidity conditions (typically +80%), this gel imbibes additional water creating high expansive pressure inside concrete meso-structure which leads to extensive distributed cracking. In reinforced concrete structures, the structural integrity even worsen as cracking from ASR allows for more possible diffusion of external corrosive agent like chlorides in case of close to shore structures or chlorides from de-icing salts used in cold regions. Corrosion of rebars in concrete is one of the main life time limit states for many infrastructures. Together with ASR, the loss of bond between rebars and concrete enables larger deformations that are not easily understood nor expected. To understand the effects of both mechanisms and their interplay, a series of accelerated ASR and corrosion experiments were conducted. Concrete cylinders prepared with high alkali contents (5 kg/m3 of NaOH) are used with rebars imbedded during casting. To accelerate curing, the specimens are cured in water for 1 day at 55°C. After curing, specimens are sealed and kept for different durations at 55°C. Reference Specimens are also prepared and cured in the same conditions using non-reactive aggregate. At each testing duration, reference and reactive specimens are retrieved for testing. Sealing is removed then all specimens are immersed in 2% NaCl solution. Half of the reference and reactive specimens are corroded by passing constant current through the rebars. Rebars are coated and only exposed over the contact area to guarantee a uniform corrosion profile along the concrete-rebar interface. Different corrosion levels were achieved by imposing electric current over different intervals. Following the accelerated corrosion tests, rebar pull out tests were conducted in order to quantify the change in bond strength due to ASR, rebar corrosion, and combined ASR/Rebar corrosion. The free end displacement was measured against pull out force and bond-slip curves were developed. The contact area was at the end of the rebar, thus, the measured force represented only bond-slip behavior of the corroded part. Finally, the whole bond-slip behavior is modeled using the Lattice Discrete Particle Model and a corrosion/ASR dependent Bond-Slip model is formulated. Results show excellent agreement between experimental and numerical simulations.

78: Reconstruction of Acoustic Sources in a Heterogeneous Elastic Solid

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This paper discusses a novel, robust, computational framework for reconstructing spatial and temporal profiles of acoustic sources by using sparsely measured wave responses. This method can be scalable to a broad range of acoustic-source inversion (ASI) problems for heterogeneous, complex-shaped coupled dynamic systems. Sources could be either moving vibrational tractions and/or impacts on surfaces or vibrational forces in hosting media. We use the finite element method (FEM) to obtain wave solutions because of its flexibility and robustness for heterogeneous coupled media. To reconstruct acoustic source profiles without a-priori knowledge of sources, we will employ high-resolution discretization of source functions in space and time. Because of such dense discretization, the order of magnitude of number of inversion parameters could range from millions to billions. To resolve such large-scale inverse problems, a novel adjoint-gradient-based source-inversion approach is used in high-performance computing (HPC) platforms. Numerical experiments prove the robustness of this method by reconstructing spatial and temporal profiles of multiple dynamic moving body forces in a one-dimensional heterogeneous solid bar. The sources create stress waves propagating through the bar. The guessed source functions are spatially discretized by using linear shape functions with an element size of 1m at discrete times

with a time step of 0.001s. Thus, the total number of control parameters is half a million in this example (i.e., 1000 (in space) by 500 (in time)). The convergence toward the target in the numerical example is excellent, reconstructing the spatial and temporal footprints of the sources.

325: Reduced Order Modeling for Progressive Collapse Simulation of RC Structures

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Disproportionate collapse of building structures continues to be a subject of considerable interest to structural engineers and researchers. In this study, a reduced order model of a multistory reinforced concrete (RC) frame building comprised of beam-column elements with cross-section integration and layered shells to represent the floor slabs within the LS-DYNA computational framework is developed. The reduced-order model is first validated with pushdown simulations of a high fidelity model of a beam-slab-column subassembly under a column-loss scenario. The high fidelity simulations are carried out on the Greenfield cluster at the Pittsburgh supercomputing facility which consists of 60 CPU cores with 3TB memory. Following validation of the model, collapse simulations are carried out on a 6-story 5x5 bay RC building in accordance with the Alternate Path Method (APM). An energy-based approach for evaluating the potential for progressive collapse of RC frame buildings under sudden column removal scenarios is proposed. The procedure attempts to identify the critical sequence of column removals that results in partial or complete collapse of the structure. The methodology is applied to the 6-story RC building designed to current code requirements in a non-seismic zone. Findings from the study indicate that the proposed energy based robustness index serves as a measure of structure resilience to progressive collapse.

74: Reduced Order Variational Multiscale Enrichment Method for Thermo-mechanical Problems

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We present the formulation and implementation of the reduced order variational multiscale enrichment (ROVME) method for the analysis of coupled thermo-mechanical problems. Based on the variational multiscale enrichment (VME) method [1], ROVME provides a model order reduction technique for elsto-viscoplastic problems [2]. It eliminates the requirement of fine scale discretization at subdomains of interests and significantly enhances the computational efficiency of the direct VME method. We extend the ROVME method for coupled thermo-mechanical problems, since the properties of temperature sensitive materials vary at different temperatures. In such case, the coefficient tenors of the ROVME method vary along with temperature changing. A numerical approach is incorporated to evaluate the temperature sensitive coefficient tensors in an efficient manner. The novel contribution of this presentation are: 1) extending the eigen-deformation based model order reduction technique to strongly coupled thermo-mechanical problems, under the context of scale-inseparable multiscale computational framework; 2) the temperature dependent coefficient tensors are accurately approximated through temperature finite element method, rather than evaluating at every temperature. Numerical verifications are performed to assess the capabilities of the computational framework, against the direct finite element analysis method and direct VME method. To ensure the accuracy of the proposed method, the coupled thermo-mechanical effect is tested from different perspectives, such as structures with uniform temperature field, structures with temperature gradient and temperature induced plastic deformation. The results of the numerical verifications reveal high accuracy of the ROVME computational methodology, comparing with the direct finite element

analysis and direct VME results.

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723: Redundancy Measures for Deteriorating Structures under Uncertainty

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For deteriorating structures the identification of local failure modes and their occurrence in time can represent an important information to maintain the system performance and avoid collapse over the structural lifetime. In fact, repairable local failures can be considered as a warning of damage propagation and possible occurrence of more severe and not repairable failures. Structural redundancy defined in terms of failure loads is a key performance indicator to this purpose, since it measures the ability of the system to redistribute among its active members the load which can no longer be sustained by other damaged members after the occurrence of a local failure. However, this indicator refers to a prescribed point in time and does not provide a direct measure of the failure rate, which depends on the damage scenario and damage propagation mechanism. Failure times and time intervals between subsequent failures, or elapsed time between failures, should be computed to provide complete information about the available structural resources after occurrence of local failures. The elapsed time between failures can be considered as a measure of system redundancy in terms of rapidity of evacuation and/or ability of the system to be repaired right after a critical damage state is reached. The knowledge of the local failure modes up to collapse and their occurrence in time could be helpful to plan emergency procedures, repair interventions and maintenance actions to ensure suitable levels of life-cycle system performance and functionality. To this purpose, life-cycle-oriented criteria and methods for the definition of redundancy measures in terms of both failure loads and failure times are presented. The uncertainties in the material and geometrical properties, in the physical model of the deterioration process, and in the mechanical and environmental stressors, are taken into account in probabilistic terms. The proposed approach is illustrated through the application to reinforced concrete frame buildings and arch bridges under corrosion. The results show that redundancy measures related to failure loads and failure times provide important information to protect, maintain, restore and improve the life-cycle structural resources of deteriorating systems.

582: Reinforcing Cementitious Structures by In-Situ Shrinking Microfibers

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Eric Kim, University of Vermont
Louis Kiefer, University of Vermont
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This study describes the development of an active fiber-tension reinforcement strengthening technology for concrete, asphalt, and composite structures. A new and noble technology includes the design and fabrication of in-situ shrinking microfibers for active reinforcement. Unlike incumbent passive reinforcing technology, these microfibers can induce pre-stressing or post-tensioning by responding to external stimuli such as heat and mixture conditions during curing. The typical reinforced concrete assembly places the steel and the polymer fibers in the concrete, while it is wet and uncured with no pre-stress. Tension loads of sufficient magnitude cracks the

concrete and the load transfers to the steel and the fibers. Pre-stressing or post-tensioning creates a higher performance composite that tends to not crack in tension, compression, and distortion loads, thereby increasing the versatility of applications. The concept is that post-tensioned fibers dispersed in a concrete matrix have the potential to provide 3-D confining stresses and possibly jamming of aggregates in a manner that produces a composite high-performance structural material system. However, there are no practical means of pre-stressing or post-tensioning the fibers. With this new technology, it is possible to create a whole new class of high-performance concrete composites with a similar overall cost. The technique initially disperses the fibers into fresh uncured concrete mixes, and then the fibers shrink as the concrete cures. Results from laboratory experiments that compare active-shrinking fibers, passive fibers, and neat concrete will be presented, as well as methods for creating shrinking fibers. Our preliminary data demonstrates that the concrete samples with in-situ heat shrinking fibers are more resilient to various loads than the samples with incumbent static fibers.

172: Reliability Analysis of Steel Frames Under Earthquake Loading Using Meta-Models

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Realistic seismic performance of buildings should be evaluated in the probabilistic frameworks since earthquake motions, loads, structural geometries and material properties are normally random or known with imprecision. Structural reliability is the mainstream method that approximates the failure probability and probabilistic performance of structure in realistic manner. Many of the presented methods for reliability are computationally expensive, especially when the number of degrees of freedom increases. Therefore, there should be an alternative method to overcome this problem. Various reliability methods are presented in which among these methods, simulations are the powerful approaches that approximate the failure probability with high accuracy and few limitations. For this purpose, this study investigates the reliability of a five-story steel frame under earthquake load by using the simulation methods. For this purpose, the random variables of the problems recognized. Then, considering material non-linearity, the performance function evaluated through the pushover analysis and assessment the initial stiffness of the pushover curve. However, employing simulation methods for these cases could be the complex and time consuming. To handle this problem, integrating the simulation method with a performance predictor could be effective. In the present work, feasibility of employing Meta-Models as the predictor in reliability process to attain the proposed aim is evaluated.

300: Reliability analysis of structures subject to spatio-temporal loading

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Zhen Hu, Vanderbilt University
Sankaran Mahadevan, Vanderbilt University

A framework is developed in this presentation for the reliability analysis of structures in the presence of quantities that vary randomly over both space and time. Two limit states are considered, namely deflection and buckling. The current work addresses three challenges: (1) Modeling spatio-temporally varying random data; (2) quantifying epistemic uncertainty in the representation of quantities varying spatially and temporally; and (3) reliability analysis of the buckling limit state subject to spatio-temporal variability. The first challenge is addressed by employing a singular value decomposition (SVD) approach for modeling the spatially and temporally varying random quantities. Using this, the spatial and temporal variations are effectively separated. While the spatial component is thereafter treated as basis, the temporal component is modeled using an auto-regressive moving average (ARMA) model. However, due to insufficient data, the ARMA model parameters

can't be estimated with absolute certainty. This epistemic uncertainty is quantified in the current work, using a Bayesian approach. In addition to quantifying the epistemic uncertainty in the spatio-temporal representation, it may also be required to calibrate several unknown model parameters, such as the Young's modulus or the moment of inertia of the structure. Again, due to limited data on the model input versus the output, epistemic uncertainty arises during the calibration these parameters. The well-known Kennedy and O'Hagan (KOH) framework is employed for quantifying this uncertainty in the model parameters. Suitable surrogate models are used in the place of expensive computational physics-based models. Further, current snap-through buckling reliability analysis methods mainly rely on the computation of the critical buckling load. During the flight missions of supersonic/hypersonic vehicles, the vehicle structures are subjected to loads with both spatial and temporal variability, which makes current buckling reliability analysis methods inapplicable. This work proposes a new buckling reliability analysis method for structures subject to spatiotemporal variability using the support vector machines (SVM). The concept of auxiliary variable is exploited to replace a double-loop Monte Carlo simulation (MCS), arising due to the presence of both epistemic and aleatory uncertainty, with a single-loop implementation for reliability analysis.A curved beam with uncertain boundary condition and spatio-temporally varying loading is used to demonstrate the effectiveness of the proposed reliability analysis method.

307: Reliability Analysis with Linguistic Data: An Evidential Network Approach

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Sankaran Mahadevan, Vanderbilt University

In practical applications of reliability assessment of a system in service, records about the condition of a system and its components are often in text form, e.g., inspection reports. Estimation of the system reliability from such text-based records becomes a challenging problem. In this paper, we propose a four-step framework to deal with this problem. In the first step, we construct an evidential network with the consideration of available knowledge and data. Secondly, we train a Naive Bayes text classification algorithm based on the past records. By using the trained Naive Bayes algorithm to classify the new records, we build interval basic probability assignments (BPA) for the records available in the form of texts. Third, we combine the interval BPAs using an evidence combination approach based on evidence theory. Finally, we propagate the interval BPA through the evidential network constructed above to obtain the system reliability. Two numerical examples are used to demonstrate the efficiency of the proposed method. The first example is the classical Wheatstone bridge system with five components. Each component has four states: Bad, Medium, Good, and Unknown. In this example, we are given 100 text records as the training set, and another 20 records as test set. Based on the Naive Bayes Classifier, we construct interval BPA for each component. By propagating it through the network, the system reliability can be calculated. Another example is a safety instrumentation system with a pressurized vessel containing a volatile flammable liquid. Similarly, 134 text records are used to train the system while another 36 text records act as test set. Ultimately, we obtain the system reliability. Different from the existing methods, the proposed approach is able to handle both linguistic and numerical data, and quantify the uncertainty on each state of each component. This capability extends its application to systems where data in the text format is available.

690: Reliability Assessment of Power Distribution Lines against Wind Loadings Using an Adaptive Kriging Method

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Wood utility poles supporting a significant portion of overhead distribution lines in the U.S. are vulnerable against wind loadings during hurricanes and other strong wind events. Estimation of failure probabilities of poles against these hazards is a complex task considering that the performance of the poles depends on a set of design parameters such as span length, basic wind speed, class, age and height of poles, and type and number of conductors, and probabilistic parameters such as shape factor, velocity pressure exposure coefficient, gust factor, and directionality factor. This task becomes even more challenging, if time-consuming dynamic analyses are required to evaluate wind performance of distribution lines for each realization of involved random variables and design parameters. Conventional Monte Carlo-based methods such as Latin Hypercube sampling technique can be used to determine the reliability of utility poles for a specific set of design parameters. However, such methods are not efficient for high dimensional problems where a large number of random variables and design parameters are involved. The goal of this paper is to evaluate the reliability of utility poles in distribution lines as a function of design parameters. This goal is achieved here by decomposing the problem into first evaluating the failure probability for a given realization of design parameters considering uncertainties in random variables, and second developing a meta-model to estimate failure probabilities across the design space. The first stage is accomplished through an adaptive Kriging method which considers the distance and level of variation for the known data points to perform optimal and unbiased estimates for other regions. The initial training samples in adaptive Kriging are generated using Centroidal Voronoi Tessellations (CVT) design. Additional training samples are created based on a probabilistic classification function defined using results of initial Kriging. The stopping criteria for sampling is based on the mean squared error of the limit state function. For the second stage, an adaptive Kriging method similar to the first stage is used to properly select points in the design space and fit a function to the calculated failure probabilities. The proposed procedure significantly reduces the computational cost of reliability assessment of wood utility poles in distribution lines given that a large number of design and probabilistic variables are involved.

244: Reliability Assessment with Efficient Sequential Importance Sampling

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We present an efficient sequential importance sampling (SIS) method for estimation of the probability of failure in structural reliability. SIS is an adaptive Monte Carlo method that was originally developed in the statistical community for exploring posterior distributions (Chopin 2002) and estimating normalizing constants (Del Moral et al. 2006) in the context of Bayesian analysis. The basic idea of SIS for reliability assessment is to gradually translate samples from the distribution of the random variables to samples from an approximately optimal importance sampling density. The transition of the samples is defined through the construction of a sequence of intermediate distributions. To obtain samples from each of the distributions in the sequence, weighted samples from the previous distribution are resampled and the resulting samples are moved applying a Markov chain Monte Carlo (MCMC) algorithm. We present an efficient MCMC algorithm that performs independent Metropolis-Hastings moves with proposal distribution specified through fitting a Gaussian mixture model with the weighted samples from each target distribution (Papaioannou et al.). We demonstrate the efficiency and accuracy of the derived SIS algorithm with numerical examples involving component and system reliability problems.
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184: Reliability Evaluation of Large Nonlinear Structures Excited by Dynamic Loadings Applied in Time Domain

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Abstract: Reliability estimation of large nonlinear structural systems excited by dynamic loadings applied in time domain is expected to be very challenging. Extensive damages caused by recent earthquakes indicate that in spite of our best effort it is not possible to design completely safe seismic load-tolerant structures. It is known to the profession that absolute safety of a structure cannot be assured for both static and dynamic applications of loading. Various codes and design guidelines are available to manage the risk. They were developed under the concept of Load and Resistance Factor Design (LRFD). Unfortunately, no similar guidelines are available for dynamic including seismic excitation applied in time domain. The authors and their research team members are working on developing a realistic reliability evaluation method to fill the gap. Basic challenges in developing such an advanced reliability evaluation methods are numerous. To estimate responses in time domain just before failure satisfying underlying physics, nonlinear finite element-based formulation is generally used by the deterministic community. An acceptable reliability estimation method to all concerned parties should use similar techniques. Dynamic loading applied in time domain is required for most advanced deterministic evaluation. Reliability evaluation needs to be conducted in time domain. It will provide an alternative to the classical random vibration concept. Available reliability evaluation methods are relatively simple particularly when limit state functions are explicit. For nonlinear dynamic problems, the limit state functions are expected to be implicit and the tasks required to extract reliability information can be very demanding. Under a research grant from NSF, the authors are now trying to develop a new reliability evaluation method. They are using the response surface based methodology to explicitly represent a limit state function. They are considering the advanced factorial concept, Kriging method, and moving least squares method to generate a response surface. Since these techniques require deterministic responses obtained at numerous sampling points, the algorithm gets very time consuming if a nonlinear finite element-based formulation takes a considerable amount of computing time. The authors will propose several intelligent strategies to extract reliability information using only tens of deterministic evaluations.
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316: Reliability-Based Topology Optimization of Truss Structures Using a Discrete Filtering System

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Junho Song, Seoul National University

Consideration of uncertainties in loads and material properties is an important aspect of structural engineering because they help to prevent unexpected structural failures that may result in destructive performance or reliability. Therefore, optimization processes associated with the treatment of uncertainties should be utilized to obtain engineering solutions so that the satisfactory level of reliability can be achieved. This paper proposes the incorporation of the discrete filtering technique into reliability-based topology optimization (RBTO) of truss structures using the elastic formulation of the ground structure method. At the end of the ground structure method, the conventional filter selects bars of areas greater than an arbitrarily selected area, which is generally very small. The selected bar subsequently becomes the optimized topology. However, the selection criteria of small preselected are ambiguous. Thus, the filtering method may result in ill-conditioned solutions, such as a singular stiffness matrix or many thin bars, which may be undesirable from an engineering and architectural perspective. In addition, the conventional filtering scheme in RBTO is highly likely to violate the probabilistic constraints. To

address aforementioned issues, a discrete filtering method proposed by Ramos Jr. and Paulino is utilized to obtain a binary truss design such as "zero or non-zero area" while satisfying the target failure probability. In this method, the potential energy approach with Tikhonov regularization is used to solve a singular matrix of a system. Therefore, the reliability-based truss size optimization problem can be transformed into a topology optimization problem accounting for uncertainties. A single-loop approach is adopted in order to increase the computational efficiency in RBTO. The single loop algorithm decouples an inner-loop for the structural analysis in the optimization problem and converts a probabilistic constraint into an equivalent constraint. Numerical examples of 2D and 3D engineering designs are given as features of the proposed method and to illustrate the influence of the discrete filter and parameter uncertainties on the optimization results. In order to verify the target failure probabilities of optimal solutions achieved by the proposed approach, the First-Order Reliability Method and Monte Carlo Simulations are performed.

772: Reliability-Based Topology Optimization Using a New Method for Sensitivity Approximation

Ke Liu, Georgia Institute of Technology
Glaucio Paulino, Georgia Institute of Technology
Paolo Gardoni, University of Illinois

Reliability-based topology optimization can help engineers design structures that are both economical and safe. This work proposes an efficient gradient-based approach for reliability-based topology optimization (RBTO). In particular, we investigate the optimal topologies for discrete structures under uncertain design conditions. Our objective is to find the optimized topology of structures with minimum weight which also satisfy certain reliability requirements. In the literature, RBTO problems are primarily performed with approaches that use a first-order reliability method (FORM) to estimate the gradient of the probability of failure. However, these approaches may lead to deficient or even invalid results for RBTO problems because the gradient of probabilistic constraints, calculated by first order approximation, might not be sufficiently accurate. To overcome this issue, a newly developed segmental multi-point linearization (SML) method is employed in the optimization approach for a more accurate estimation of the gradient of failure probability. Meanwhile, this implementation also improves the approximation of the probability evaluation at no extra cost. Ultimately, the adoption of the SML method makes a more accurate and robust approach to the solutions of RBTO problems. Numerical examples show that the new approach based on the SML method usually provides optimized structures that have more of the desired features than conventional FORM-based approaches, and the approach also becomes more numerically stable. Furthermore, the new RBTO approach typically does not lead to a fully stressed design, and this feature will be verified by numerical examples.

725: Remaining Potentials of Alkali-Silica Reaction of Existing Concrete Structures

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Extensive researches have been done on the chemical mechanisms of alkali-silica reaction (ASR) of concrete. However, there has been no systematic research conducted for evaluating the remaining potentials of ASR of old concrete, which is very important for long-term performance evaluation of existing concrete structures. Also, there has been no research on the effect of alkali content on ASR. The objectives of this study were to develop new testing methods that can be used to determine the ASR potentials in existing concrete structures and the critical alkali content corresponding to the maximum ASR. Systematic experimental study was done and results

were reported.

580: Representing Model Error in Reduced Combustion Mechanisms: A Stochastic Operator Approach

Rebecca Morrison, The University of Texas at Austin
Robert Moser, The University of Texas at Austin
Todd Oliver, The University of Texas at Austin

An accurate description of the chemical processes involved in the oxidation of hydrocarbons may include hundreds of reactions and fifty or more chemical species. Kinetics models of these chemical mechanisms are often embedded in a fluid dynamics solver to represent combustion. Because the computational cost of such detailed mechanisms is so high, it is common practice to use drastically reduced mechanisms. But, this introduces modeling errors which may render the model inadequate. In this talk, we present a formulation of the model inadequacy in reduced models of combustion mechanisms. Our goal is to account for the discrepancy between the detailed model and its reduced version by incorporating an inadequacy operator that is both stochastic and physically meaningful. The operator displays interesting properties due to conservation constraints. The parameters of the operator are characterized by probability distributions, which are calibrated using high-dimensional hierarchical Bayesian modeling. In particular, we investigate how the inclusion of the inadequacy operator affects the prediction of a quantity of interest at a higher time-scale, namely, the flame speed in a one-dimensional hydrogen laminar flame.

606: Reproducing Kernel Collocation Method for the Phase-Field Fracture Model

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Phase-field model for brittle fracture has recently gained attention widely for predicting the crack propagation. It is shown to be able of predicting multiple cracks merging and branching process to an accurate level. In this model, propagation, bifurcation and merging of cracks are based on finding the global minimizer of the total potential energy (including the elastic energy and the fracture energy portion) [1]. Since, solving this vibrational problem numerically for discrete cracks is difficult, because of the evolution of the crack path with time, an approximation based on a continuous scalar-valued phase-field is used to represent the crack [2]. The variational approach reduces the difficulties of numerical tracking of the discontinuities in the displacement field as it removes the need of remeshing the domain or using enriched functions for describing the crack. However, this method adds an extra diffusion-type equation to the momentum (equilibrium) equation which makes the computational process considerably expensive when using the Galerkin weak form in the framework of the Finite Element Method (FEM) or Mesh-free methods. In this research, phase-field model for brittle fracture in elastic materials is solved in the framework of the Reproducing Kernel Collocation Method (RKCM). RKCM is based on strong formulation and reduces the computational expenses by avoiding the domain integration [3]. The stress Intensity Factor (SIF) is used to compare the stress field near the crack tip in this model and results are also compared with other methods such as the eXtended Finite Element Method (XFEM) and the Adaptive Finite Element Method. Since, the phase-field does not explicitly locate the crack-tip position, the SIF comparison is used to discuss the best approximation for the crack-tip location in this model. Finally, crack path and displacement and stress fields for the first and mixed mode fracture are presented and compared to other methods.
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451: Research on Frequency-Temperature Correlation of Runyang Suspension Bridge during Typhoon Matsa Using Structural Health Monitoring and Finite Element Analysis

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A good understanding of structural dynamic characteristics of long span bridges is essential for operational condition assessment under wind disasters. In this paper, the modal parameters of Runyang Suspension Bridge (RSB) during typhoon Matsa are investigated. Based on the recorded acceleration responses and environmental factors by the structural health monitoring system (SHMS), modal frequencies and vibration shapes of RSB are identified using Subspace Stochastic Identification method. Then, the correlation coefficients between identified frequencies and environmental factors are calculated. Results indicate that the effect of temperature on frequencies is more obvious than that of wind speed and wind direction. Therefore, the frequency-temperature model of RSB is established using combined nonlinear principal component analysis and relative vector machine. Aimed at validating the established model, another frequency-temperature model of RSB is built based on finite element analysis. Results show that the aforementioned two models fit well with each other. Consequently, an environmental elimination method is used to update the identified frequencies of RSB. The fluctuation amplitude of the updated frequencies decreases obviously, which means the updated values are ergodic. And these can improve the accuracy of measured modal frequencies and provide the research basis for finite element updating and damage diagnosis of similar large span suspension bridges.

779: Residual Strength of Preloaded Quasibrittle Structures and Size Effect on Its Statistical Distribution Based on Nanomechanics

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Kedar Kirane, Northwestern University

In preceding studies, the type of cumulative probability distribution functions (cdf) of strength and of static lifetime of quasibrittle structures, including their tails, was mathematically derived from atomistic scale arguments based on nano-scale cracks propagating by many small, activation energy-controlled, random breaks of atomic bonds in the nanostructure. It was shown that a quasibrittle structure (of positive geometry) must be modeled by a finite (rather than infinite) weakest-link model, and that the cdf of structural strength as well as lifetime varies from nearly Gaussian to Weibullian as a function of structure size and shape. Excellent agreement with the observed distributions of structural strength and static lifetime was demonstrated. Based on the same theoretical framework, the present paper formulates the statistics of the residual structural strength, which is the strength after the structure has been subjected to sustained loading. A strength degradation equation is derived based on Evans law for static crack growth during sustained loading. It is shown that the rate of strength degradation is not constant but continuously increasing. The cdf of residual strength of one RVE is shown to be closely approximated by a graft of Weibull and Gaussian (normal) distributions. In the left tail, the cdf is a three-

parameter Weibull distribution consisting of the (n+1)-th power of the residual strength, where n is the exponent of the Evans law and the threshold is a function of the applied load and load duration. The finiteness of the threshold, which is typically very small, is a new feature of quasibrittle strength statistics, contrasting with the previously established absence of a threshold for strength and lifetime. Its cause is that there is a non-zero probability that some specimens fail during the static preloading, and thus are excluded from the statistics of the overload. The predictions of the theory are validated by available test data on glass-epoxy composites and on borosilicate and soda-lime silicate glasses. The size effect on the cdf of residual strength is also determined. The size effect on the mean residual strength is found to be as strong as the size effect on the mean initial strength.

312: Resilience and Dependency Modeling of Critical Civil Infrastructures Using Graph Theory and Dynamic Inoperability Input-Output Model

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Eun Jeong Cha, University of Illinois

Societal and economic functionality of a modern society highly depends on continuous functionality of civil infrastructure systems, such as electric power, telecommunication, water, and transportation. These critical civil infrastructures are highly connected and mutually dependent in complex ways, physically and/or indirectly through the information technology system. Thus, understanding how the critical civil infrastructures are dependent upon each other is essential for modeling the impact of a disaster on a community and its recovery from the disaster, which are primary components of the community resilience modeling. This study employs the dynamic inoperability input-output model (DIIM) and graph theory to model the interconnected and mutually dependent critical infrastructures and their recovery after damage caused by natural hazards. The critical civil infrastructure systems are modeled as a network where different critical infrastructure facilities are represented by different nodes and the nodes are connected by the links through which the products, information or services flow. When a disruptive event occurs, a set of civil infrastructures are physically damaged, which decreases the operability of those affected infrastructures. The operability of a civil infrastructure facility can be determined by utilizing the concepts of minimum required input and output. The propagation of the initial operability or inoperability throughout the entire interdependent civil infrastructure systems over time can be simulated utilizing DIIM. The input and output matrices will be defined, which will be used to determine resilience coefficient of each individual infrastructure facility. Some characteristic parameters of the network, such as efficiency, clustering coefficient, will be used to describe the operability of the entire infrastructure system and to model its resilience. This method will be illustrated using a brief example including electric power system, telecommunication system and water system under hurricane hazard.

399: Resilience of Lifeline Infrastructures

Jianjun Qin, Tongji University
Jie Li, Tongji University

Lifeline infrastructures, generally defined as the infrastructure systems to sustain proper operation and economic function of modern cities, are essential to people's daily life in our modern society. Such systems are gaining increasing importance in society and at the same time also becoming increasingly complex. Constituents of such networked systems, which might be different to each other, are geographically distributed but interconnected. Failure of one or more constituents may cause the failure of other constituents due to changes in internal flow demands, the event of which is referred to as cascading failure. However, surviving constituents may also lose their functionality due to loss of connection within the system. The present paper considers the resilience analysis

of lifeline infrastructures subject to hazards, specially concerning the ability to withstand the shocks and to recover the performance (the desired functionality) afterwards. The core of the resilience research lies in the performance analysis, which mainly depends on the reliability assessment, including the reliability of individual elements and the connective reliability, as the first step. Here, three key problems relevant to the reliability analysis of lifeline infrastructures would be identified and discussed. One problem is the consideration of time and spatial variation in the assessment. Another is the optimization of the infrastructure based on the reliability analysis. Last but also the most important problem is lifeline infrastructures have generally complex and large-scale topologies and it is necessary to investigate the efficient algorithm for the reliability assessment of such large-scale systems. Recursive decomposition algorithm was developed by the author and it will be mainly introduced for large-scale network connective reliability analysis. Further, based on the proposed efficient reliability analysis approach, the performance assessment of lifeline infrastructures in the context of resilience analysis would be investigated combining with engineering practice in China. Finally, the framework of the resilience analysis of lifeline infrastructures would be formulated.

340: Resilience of Small Bridges in Case of Extreme Rainstorms

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Linda Giresini, University of Sassari
Mauro Sassu, University of Pisa

The contribution is related to some flooding occurred in an Italian district after heavy rain events (November 2012, October 2013, October 2014) that caused the overlap of some hydraulic crossings roads of reduced span, causing them to collapse or dragging downstream of vehicles, with loss of lives. The hydraulic event was characterized by values of exceptionality, intensity and concentration of rain in small areas. The flood waves had rapid evolution over time and an effect of accumulation that produced water flows with centenarian return periods. The collapse events under study regard the category small masonry-r.c. bridges, frequently used on secondary suburban roads. The modeling of the collapse scenarios are performed considering three possible occurrences: a) The sweeping effect, due to the overlapping of the small bridge, causing excessive transverse pressure on the lateral side of the cars; b) The erosion effect, due to the overlapping of the crossing road, that induces collapse of the side opposite to the water flow through the washout of the bridge supports; c) The floating effect, due to the Archimede's principle caused by the raising of the water level during the flood wave: in case of coupled extrados longitudinal beams it occurs an upward thrust, that reduces the vertical load on the masonry supports; it implies a reduction of the shear strength of the walls. The examined case studies are representative of scenarios in suburban areas, whose probability of occurrence is not negligible. The events have been structurally analyzed, providing some suggestions on possible defense strategies.

132: Resilience Quantification through Various Detection Indices of SHE^TM

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Several damage detection algorithms are present in literature; however, little comparison among them exists. Each has been verified for a specific case, often numerical in nature. One current need is to apply these formulations to a variety of structures, preferably massive low frequency infrastructure, so that sensitivity analysis can be performed. The use of captured experimental data will help identify the best indicator(s) for specific structural types as well as contribute to potentially "safe" threshold development. The overarching hypothesis is that specific indicators work best for certain structural classes. For example, a combinatorial metric of a few select indicators could provide reasonable inspection results for all steel building configurations. Note that significant uncertainties can be introduced by physical damage type, structure geometry, data quality, etc., so metric performance must be judiciously evaluated. The Multi-Function Dynamics Laboratory at the University of Mississippi has produced a software package SHE^TM (Structural Health Evaluation^TM), which is nearing delivery as an inspection tool. The program employs any sensor's time history data to deliver visual representations of structural condition by indicating weak and strong locations. Output is provided for fourteen damage detection methods as comparatively applied to any two data sets. Proof-of-concept work has been completed for a 1:12 scale reinforced concrete bridge and the AISC-ASCE Benchmark scaled steel structure. In this study the resilience of a two-story steel frame has been evaluated for both damage and reinforcement. While this is a laboratory-scale construction six feet tall, the fairly flexible structure mimics low frequency infrastructure signal content with high interference levels. Regarding damage, the as-built structure is considered a baseline, and then structural damage is induced by consecutively inserting rubber washers to represent progressive joint softening by story. Regarding reinforcement, the same baseline configuration is augmented with sequential addition of wood shear walls. Using the SHE^TM program, accelerometer time histories processed to obtain modal information for the baseline and damaged/reinforced cases, and output plots visualize location and percentage of structural difference. Analytical comparison reveals the effects of softening and shoring for this specific structure. The purposes of presenting this work are to demonstrate program capabilities and to develop new collaborations. Access to inspection data is required for this tool and its metrics to be practical for infrastructure management.

199: Resilience-Based Risk Mitigation and Recovery for Highway Transportation Networks

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The resilience of robust, large-scale, interdependent civil infrastructure networks, including transportation systems, utilities, telecommunication facilities, and social networks, individually and collectively, plays a major role in determining the resilience of a community as a whole. The performance of transportation networks, in particular, is critical because post-disaster emergency response, recovery and restoration of virtually all other facilities and lifeline systems are dependent on people and equipment being able to move to the sites where damage has occurred. Highway bridges are points of vulnerability in transportation networks exposed to extreme natural hazards. Existing retrofit and hazard mitigation programs for highway bridge systems usually have been developed by optimizing the life-cycle cost of individual bridges without considering the interdependencies that exist among individual bridges or the consequences of their failure on the integrity of a transportation network if an extreme natural hazard were to occur. To enhance community resilience, risk mitigation strategies and decision frameworks for transportation networks should take a system perspective at the community or regional scale and should be aimed at maximizing the resilience of the network as a whole.

In this study, we firstly utilize modern network theory to introduce a comprehensive indicator, weighted independent pathways (WIPW), to measure resilience of a transportation network, which permits risk mitigation alternatives for improving transportation network resilience to be compared on a common basis. This WIPW integrates the network topology, redundancy level, traffic patterns, and functionality as well as structural reliability (failure probability) of individual bridges in the network resilience quantification. Next, a project ranking mechanism is proposed, based on the newly developed WIPW, for identifying and prioritizing bridge retrofit projects that are critical for effective pre-disaster risk mitigation for bridge networks. Finally, we further propose a restoration scheduling method for optimal post-disaster recovery planning using a two-dimensional network recovery metric, i.e. total recovery time (TRT) and the skew of the recovery trajectory (SRT) defined for the first time in this study to capture the characteristics of the recovery trajectory that relate to the efficacy of the restoration strategies. An illustration of this resilience-based risk mitigation and recovery framework is given using a hypothetical bridge network susceptible to seismic hazards. A sensitivity study using this network

illustrates the impact of the resourcefulness of a community and its time-dependent commitment of resources on the network recovery characteristics.

96: Revisiting Moment-based Hermite Model for Estimation of Extreme Value Distributions of non-Gaussian Response Processes

Min Liu, Beijing Jiaotong University
Xinzhong Chen, Texas Tech University
Qingshan Yang, Beijing Jiaotong University

The moment-based Hermite polynomial function model approach is often used to estimate the extreme value distribution and peak factor of a non-Gaussian process through those of the underlying Gaussian process. This paper presents a comprehensive study on the performance of moment-based model approach as applied to various non-Gaussian wind pressures on a large span saddle type roof, by comparing the estimated peak factors with those directly derived from the long-term wind tunnel data. The results showed that the moment-based model approach can be less accurate for a large number of non-Gaussian pressure data. One of the reasons is that the skewness and kurtosis are statistical moments affected by both positive and negative probability distribution tails, thus are less specific in defining only one of the distribution tails which determines the statistics of maximum or minimum. To improve the accuracy of the moment-based model approach, new statistical moments are defined using the distribution greater or lower than the median for the estimation of distribution of maximum or minimum, respectively. The distributions of maximum and minimum are addressed separately using newly defined two sets of statistical moments with zero skewness. The effectiveness of the newly proposed approach is examined for various non-Gaussian wind pressures.

456: Risk of Fracture at Early Ages: A Criterion for Cutting Pavement Joints

Arghavan Louhghalam, Massachusetts Institute of Technology
Franz-Josef Ulm, Massachusetts Institute of Technology

Propagation of tensile cracks affects durability of concrete pavements by providing sites for penetration of water and aggressive chemicals, accelerating pavement deterioration, leading to an increase in pavement maintenance costs. Designing durable pavements therefore, requires a framework for minimizing the risk of fracture. Autogenous shrinkage can result in tensile cracks in concrete pavements via the accumulation of chemo-mechanical eigenstresses at early ages. To prevent random and uncontrolled cracking due to this distress mechanism, joints are cut in Portland cement concrete pavements some time after concrete placement. Here we propose a method for evaluating the critical time before which pavement joints must be cut to prevent pavement early-age cracking. A fracture-based model is developed that relates thermal, chemical and hygral eigenstress evolutions to the risk of fracture at the structural scale. The model is based on the application of linear elastic fracture mechanics (LEFM) to an infinite- and a finite-length elastic beam on an elastic foundation. The energy release rate and stress intensity factor are expressed in terms of the shrinkage-induced eigenstresses, for a worst-case scenario of crack propagating through the entire pavement section. Using elastic thermo-chemo-mechanical couplings of concrete at early ages, the corresponding parameters are expressed in function of the degree of hydration, thus providing the scaling relationship between the hydration degree and material and structural properties. Finally by adapting to the external temperature, the degree of hydration and its experimental counterpart, concrete maturity, are related to the characteristic time of chemical reaction.

657: Risk-based Life-cycle Management of Fatigue-sensitive Structures

Mohamed Soliman, Oklahoma State University

Reliable prediction of damage initiation and propagation is an essential task in the life-cycle management of fatigue-critical structures. This task is generally challenging due to the presence of uncertainties which affect the performance prediction parameters (e.g., stress levels, initial defects, and material properties, among others). Therefore, model updating based on field measurements is an essential task to achieve better damage diagnosis and prognosis. The resulting updated performance profiles can be subsequently used to establish the optimum life-cycle management plan. This paper presents a risk-based approach to obtain optimum management schedules for fatigue sensitive structures by integrating available information from inspection actions. The proposed approach utilizes a probabilistic time-dependent damage criterion, inspection cost, and failure cost to find the optimum inspection and maintenance times and types which minimizes the risk of failure. New information resulting from inspection actions performed during the lifetime of the structure is used to update the damage propagation parameters as well as the optimization procedure. Surrogate modeling is implemented to reduce computational cost and enable informed real-time decision making regarding future management actions at the inspected location.

241: Robust Bayesian Fatigue Monitoring of Structures Using Minimal Instrumentation

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Eric Hernandez, University of Vermont

Fatigue can be defined as failure due to repeated application of load cycles, which individually do not cause failure. Fatigue is the main cause of failure for structures subjected to vibration effects and time varying loading such as bridges, wind turbines, ships and aircraft. Fatigue is a multi-scale phenomenon that begins with initial defects and micro-cracks propagating and coalescing, until a visible macro-crack emerges. This is followed by macro-crack propagation and ultimately, failure. Most of the fatigue life of a component is spent in the micro-crack phase and once a macro-crack appears and is actively propagating, failure is almost imminent. It is widely documented that given a stress time history in a member, total fatigue life is a random variable and thus there is significant uncertainty regarding the time-to-failure of a component due to fatigue. Moreover, the actual stress/strain time history at critical points of the structures, unless it is measured directly, is unknown; this is because operational loads in structures are very difficult to measure. Therefore fatigue monitoring involves two main components: (i) damage modeling and (ii) usage monitoring, i.e. stress and strain estimation at locations of interest. This contribution presents a Robust Bayesian methodology to perform probabilistic fatigue usage monitoring of structural systems subjected to unmeasured excitations using minimal instrumentation. The proposed method is a variation of the Kalman filter with modifications to improve the robustness to various sources of modeling errors, including excitation characterization, measurement noise model and structural model. The methodology is verified in numerical simulations and validated using small scale laboratory experiments. The proposed methodology can be used within the context of structural health monitoring in order to safely extend the operational life of fatigue-prone structures.

591: Robust Design of Ultra-Dissipative Metamaterials via Stochastic Topology Optimization

Alireza Asadpoure, University of Massachusetts Dartmouth
Mazdak Tootkaboni, University of Massachusetts Dartmouth

Topology optimization has allowed for efficient exploration of multiphase materials design space facilitating the search for micro-architectures with unprecedented mechanical properties. Although stiffness optimization of lightweight cellular materials and structures made of a single phase has been extensively investigated, the application of topology optimization to more complex objective functions and multiphase material systems is still in its infancy. In addition efforts geared towards optimal design of material micro-architecture has so far mainly focused on deterministic conditions where potential uncertainties associated with excitation and the built geometry is ignored. In this presentation, we will discuss a systematic optimal design approach for hybrid periodic materials with ideal combinations of high stiffness, low density, and high loss coefficient. Classic homogenization theory and Bloch-Floquet approach are used to model the effective stiffness of the unit cell and to obtain the damping capacity of the microstructure. Moreover, the inclusion of uncertainties in the optimization framework to arrive at robust designs is carried out through computational stochastic techniques such as Monte Carlo simulation and spectral stochastic approach to uncertainty quantification.

577: Robust Lattice Architectures with Improved Stability Performance

Mazdak Tootkaboni, University of Massachusetts Dartmouth
Alireza Asadpoure, University of Massachusetts Dartmouth
Lorenzo Valdevit, University of California, Irvine

We investigate the optimal architecture of micro lattice materials for minimum weight under axial and shear stiffness constraints. A well-established discrete structural topology optimization approach, the ground structure approach, is used in conjunction with stochastic perturbation to achieve optimality and robustness at the same time. Potential dislocation of the lattice nodal coordinates is considered as the source of uncertainty. To improve the stability performance an indirect approach is adopted where the inclusion of higher order terms in perturbation expansions results in altering the covariance structure of random vector representing uncertainty in the system. Hollow circular cross-sections are assumed for all elements, although the shape of the cross-section has minimal effect on most optimal topologies. We identify hierarchical lattices that are not only significantly more efficient than well-known isotropic lattices but also exhibit improved stability behavior. We illustrate this by performing geometrically nonlinear analysis on a few optimized lattices undergoing elastic large deformations.

161: Role of Organic-inorganic Interface Properties in Brick and Mortar Composites

Sina Askarinejad, Worcester Polytechnic Institute
Nima Rahbar, Worcester Polytechnic Institute

Naturally growing composites give us a fantastic vision to design and fabricate tough, stiff while strong composites. Bone and nacre are prime examples of natural ceramic-based composites with high strength and toughness. Previous studies on mechanical performance of these structural materials show that their outstanding properties are direct results of the nano-scale features and the optimized arrangement of the elements. Moreover, to provide the outstanding mechanical functions, nature has evolved complex and effective functionally graded interfaces. Particularly in nacre, organic-inorganic interface in which the proteins behave stiffer and stronger in proximity of calcium carbonate minerals provide an impressive role in structural integrity and mechanical deformation of the natural composite. However, further research on the toughening mechanisms and the role of the interface properties as a guide on design and synthesize new materials is essential. In this study, a micromechanical analysis of the mechanical response of “Brick-Mortar” and “Brick-Bridge-Mortar” composites is presented considering interface properties. The closed-form solutions for the displacements in the elastic components as a function of constituent properties can be used to calculate the effective mechanical properties of composite such as elastic modulus, strength and work-to-failure. Detailed relationships are presented to identify

future directions for material development.

532: Run-Out Distance and Depositional Configuration for Flow-Like Landslides Using the SPH Method

Alomir Favero, Stanford University
Ronaldo Borja, Stanford University

This paper presents a theoretical model for two-dimensional simulation of flow-like landslides using the SPH method. The model is based on an open-source SPH code called (Dual)SPHysics that utilizes a rheological theory appropriate for soils, and accommodates complex topographic information for high-fidelity simulation of real slope cases. The work focuses on two-dimensional analysis of slope movement; however, extension to three-dimensional analysis is also discussed. Two well-documented slopes that failed as a debris flow are analyzed, namely, the Coos Bay experimental catchment in Oregon, USA, and the Ruedlingen test slope in Switzerland. The analyses focus on predicting the final depositional configuration of the debris flow, and on parametric studies to understand the sensitivity of the solution to variation in material parameters. The paper also discusses the impact of the constitutive model on the simulation results, as well as the potential of the SPH approach in general for routine simulation of flow-like landslides.

98: Rutting Performance Prediction And Analysis Of Airfield Pavements Subjected To Next Generation Aircraft

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The combined effect of climatic conditions, progressive increase in the traffic volume, and appearance of next generation commercial aircraft (e.g., B 787 and A350), jet fighters (e.g., F15-E), and cargo aircraft (e.g., C17) with high tire pressure have caused pavements to experience severe distresses. To address these issues the FAA and Army Corps of Engineers have conducted several full scale tests including newly planned tests using the world's largest Heavy Vehicle Simulator (HVS). This study presents the rutting performance results of full-scale pavement test sections subjected to next generation aircraft. Pavement structures for the sections subjected to F-15E and C17 were constructed under shelter in U.S. Army Engineer Research and Development Center's (ERDC) pavement test facility. Pavement structures subjected to commercial aircraft tire pressure were constructed at FAA's National Airport Pavement and Materials Research Center (NAPMRC). The full-scale test results are used to validate viscoelastic, viscoplastic, and hardening-relaxation constitutive relationships implemented in the Pavement Analysis Using Nonlinear Damage Approach (PANDA) model. PANDA is a mechanistic-based model and incorporates nonlinear viscoelastic, viscoplastic, hardening-relaxation, viscodamage, moisture-induced damage, and aging constitutive relationships. Once calibrated against laboratory experiments, PANDA is used to predict the rutting performance observed in full-scale pavement test sections. The simulation results illustrate that PANDA is capable of predicting the rutting of airfield pavements subjected to heavy aircraft wheel loads at intermediate and high temperatures. It is shown that PANDA successfully predicts the effect of shear flow and upheaval at the edges of the wheel.

107: Safety Factor Calibration for Residual Hull Girder Ultimate Strength Analysis

Eric VanDerHorn, Vanderbilt University
Sankaran Mahadevan, Vanderbilt University

Cold expansion is a mechanical process in which a compressive residual stress field is created in the region around a hole which serves to enhance the fatigue performance of the hole. The remaining fatigue life of a cold expanded hole is strongly affected by the form and magnitude of this residual stress field, with variations of ±10% in the residual stress field leading to three to four times variation in the remaining fatigue life. This requires that the uncertainties in the residual stress field be well characterized to ensure propagation of these uncertainties to the fatigue life calculations. In this study, a finite element model was developed to characterize the residual stress field as a function of the stochastic input variables and the radial distance from the hole surface. The resulting finite element results were used to train a Gaussian process surrogate model using several different correlation models. The surrogate model error was then evaluated using cross-validation and final form of correlation model was determined based on consideration of both the error residuals and in-process variance.

376: Scaling of Fracturing Behavior of Graphene Reinforced Polymers: Experimental Characterization and Modeling

Cory Hage, University of Washington
Marco Salviato, University of Washington

The recent progresses in nanotechnology have enabled the development of novel materials with unprecedented properties which are revolutionizing the current structural design paradigm. Among the various nanofillers in the market today, graphene nanoplatelets seem the most promising for the enhancement of specific functional and mechanical properties of aeronautical and mechanical structures. Graphene has been recently used to improve strength, fracture toughness, fatigue behavior as well as to provide enhanced thermal and electric conductivity for lightening protection of composite structures. However, in order to take advantage fully of the potential of these materials, experimental characterization and multiscale modeling are quintessential. Some studies have been conducted but an important issue escaped attention: scaling. Understanding structural scaling means being able to predict how the characteristics of the structure change with size, from lab scale specimens to large aeronautical components. This work aims at filling this knowledge gap with respect to quasi-static fracture properties by providing a comprehensive study on the scaling of graphene reinforced polymer structures. Three point bending specimens made of a binary system of epoxy matrix and graphene nanoplatelet were manufactured. A low viscosity epoxy resin suitable for vacuum infusion of large aeronautical or naval components was adopted whereas the graphene/surfactant system was chosen to best adapt to the matrix under investigation. In order to investigate the way structural properties scale, geometrically scaled specimens of four sizes scaling as 1:2:4:8 were studied. Then, the effects of different graphene platelet contents on the scaling were investigated by studying various weight fractions, namely 0%, 1%, 3%, 6% and 8% wt. The results provided key indications for the development of lighter, safer and more reliable aeronautical structures.

390: Seismic fragility Analysis and Resilience Assessment of Highway Bridges Incorporating the Effects of Cumulative Damage Due to Main Shock – Aftershock Earthquake Sequences

Ioannis Gidaris, Rice University
Jamie Padgett, Rice University

Main shock and aftershock seismic sequences can lead to severe damage accumulation and structural degradation to bridge components resulting in extensive required repairs or even collapse. Therefore, the seismic vulnerability and ultimately the recovery of highway bridges can be significantly underestimated if the hazard characterization considers only main shock earthquake events and the occurrence probability of one or more following aftershocks is neglected. This study presents a comprehensive methodology for risk and resilience assessment of highway bridges that incorporates effects of cumulative seismic damage due to main shock and aftershock sequences. Within this methodology the structural response is evaluated through nonlinear time history analysis, uncertainty is included in various structural and hazard model parameters, whereas a seismic hazard characterization is adopted that is able to simulate main shock and aftershock events modeled as homogeneous and non-homogeneous Poisson processes, respectively. Sophisticated finite element models are employed to capture the deterioration effects of seismic damage accumulation on the behavior of bridge components. Appropriate engineering demand parameters (EDPs), such as damage indices or relevant response quantities, are utilized to link the bridge's seismic response with damage states and ultimately estimate fragility quantifying the conditional probability of exceeding a specified damage state given one or more intensity measures of the earthquake excitation. Then the estimated fragilities can be mapped to restoration models describing the percentage of the bridge's functionality as a function of the damage state attained and the time elapsed after the seismic event. Knowledge of the functionality allows calculation of resilience that can facilitate risk-informed decision making related to mitigation strategies. Because of the complexity of the adopted numerical and probability models all required risk and resilience metrics are estimated through stochastic simulation, which can facilitate high-accuracy estimates, though frequently at a large computational burden. Therefore, in this study efficient surrogate modeling techniques are adopted to alleviate this burden by approximating the EDPs of interest with respect to the uncertain hazard and structural model parameters. Once the surrogate model is developed, the risk and resilience metrics are efficiently calculated by performing Monte Carlo analysis. Also global sensitivity analysis is integrated within this methodology to investigate the importance of the different uncertain model parameters (risk factors) towards the risk and resilience metrics. The proposed methodology is implemented to assess the impact of main shock-aftershock induced cumulative seismic damage on the fragility and resilience of an example highway bridge in California.

647: Seismic Fragility Assessment of Restrained Nonstructural Components Considering Multiple Modes of Failure and Existing Damage from Prior Events

Jieun Hur, The Ohio State University
Abdollah Shafieezadeh, The Ohio State University

Nonstructural components (NCs) such as mechanical and electrical equipment in lifeline systems e.g. hospitals, power plants, and communication stations are critical to function following seismic events. To enhance the performance of these devices in seismic areas, a common practice is to restrain them to the supporting floor. However, deterioration in the anchorage system or loosened restrainers due to residual damage from prior events may significantly impact the seismic behavior of these components; a factor that is not accounted for in the initial design of NCs. This issue may considerably increase likelihoods of operational and physical failure of these equipment during future events. Because of the diversity and complexity of nonstructural components, a systematic approach is required for fragility assessment of damaged nonstructural equipment to improve their initial design, retrofit and repair. The objective of this study is to develop seismic fragility functions of restrained nonstructural components considering their variety, existing damage conditions from prior events, and various operational and physical failure modes. This goal is achieved through subjecting nonlinear models of NCs to a set of main-shock (primary shakings) and aftershock (following shakings) events and performing time-history analyses to evaluate their seismic performance for different types of nonlinear restraints. This approach enables

evaluating the impact of existing damage in restraints from prior hazards on their seismic performance during next events. The fragility of NCs is analyzed in terms of engineering demand parameters such as displacement for physical damage assessment and acceleration for operational failure characterization of the equipment. Sample sets for various probabilistic parameters involved in nonlinear simulations are generated using Latin Hypercube Sampling (LHS) method. Using this framework, uncertainties in material properties of the restraints, the mass distribution of the equipment, and the characteristics of main-shock and aftershock time-histories are considered. Simulation results are analyzed to develop a new correlated multi-dimensional probabilistic seismic demand model for NCs. System-level fragility functions of nonstructural components are then generated as a function of seismic intensity measure and existing damage conditions of restraints. The present study will enhance the understanding of the seismic performance and fragility of NCs with existing damage from prior events. The produced models will help to develop systematic and reliable decision making approaches for seismic risk management of critical facilities.

709: Seismic Resilience Assessment of RC Highway Continuous Bridges in China

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Due to the great losses and paralysis caused by the Wenchuan earthquake in 2008 as well as the sequent main earthquakes occurred in China, governments, academic organizations and engineering fields have realized the importance of paradigm shift from infrastructure protection to infrastructure resilience. In this paper, RC continuous girder bridges, one of usual types of highway bridges, also as the vulnerable parts in transportation systems, are taken as research objects. The Liangzi river bridge in Qingzhou-Linshu highway line, in Shandong Province, is taken as a case study. The finite element model of the bridge is built in the platform OpenSees. One hundred real ground motion records are selected to perform nonlinear time history analyses to consider the influence of record-to-record uncertainty on structural seismic demands. The maximum displacement ductility of the piers and the maximum displacement of the bearings are selected as demand parameters; while the peak ground acceleration and pseudo spectral acceleration are selected as seismic intensity parameters. Taking into account the uncertainties of both ground motions and structures, 100 samples of ground motion - structure are generated by using Latin hypercube sampling approach. The probabilistic seismic demand models of bridge components are obtained by regression analysis of seismic demands and seismic intensity measures. Based on the developed PSDMs and seismic damage criteria, seismic vulnerability analysis of the bridge is performed. The seismic fragility curves of bridge components under different damage states are derived. The direct economic losses, the indirect economic losses caused by traffic disruptions, and the casualty losses by use of Life Quality Index (LQI) criteria and Life-Saving Costs (LSC) of Society, are evaluated. Based on the results of seismic vulnerability assessment and earthquake losses evaluation as well as the results of probabilistic seismic hazard assessment of the bridge site, the seismic resilience index of the bridge is calculated according to the definition of MCEER. Furthermore, two quantitative measures, one measuring the ability of resilience, while the other quantifying the economic benefits of resilience, are selected as decision variables to help selection of optimal strategy of resilience enhancing.

455: Seismic Response Analysis of Slender, Free-Standing Columns and the Competing Effects of Size and Slenderness

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Georgios Kampas, University of Central Florida

This paper investigates how the two competing parameters of size and slenderness affect the stability of tall, free-standing columns when subjected to horizontal and vertical ground shaking. The paper shows that the outcome of this competition is sensitive to local details of the ground shaking and the dominant frequency of a possible coherent pulse. The paper concludes that there is no clear outcome from this competition and that the level of ground shaking that is needed to overturn a tall, free-standing column of any size and any slenderness is a decreasing function of the length scale of the dominant coherent acceleration pulse normalized to the base-width of the column.

633: Seismic Soil-Structure Interaction Analysis of Nuclear Power Plants: Time Domain versus Frequency Domain

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Benjamin Kosbab, SC Solutions, Inc.

The seismic Soil-Structure Interaction (SSI) analysis of nuclear facilities is usually performed in frequency domain where the response of the soil-structure system's components is modeled as linear. The linear response assumption may be appropriate for small- to medium-intensity seismic events; however, the Seismic Probabilistic Risk Assessment (SPRA) of nuclear facilities requires the study of the system's response under large seismic events with very small annual exceedance probabilities as well. It is known that under such large events the soil response may be highly nonlinear, gapping and sliding may occur at the soil-structure interface, and structural components may experience damage; consequently, the equivalent-linear treatment of soil, ignoring the interface nonlinearities, and linear modeling of structural components in frequency domain may not capture the physical response of the system. These nonlinearities however can be modeled in time domain. In this study the seismic response of a typical Pressurized Water Reactor (PWR) containment building under a relatively large seismic event is analyzed using three different approaches: linear frequency domain, linear time domain, and nonlinear time domain. The time domain response history analyses are performed in LS-DYNA while the frequency domain analysis is performed in SC-SASSI using the direct method. SC-SASSI is an in-house version of SASSI program developed at SC Solutions. It is shown that the obtained seismic responses, presented as in-structure response spectra at different locations within the containment building, are similar for both linear time domain and frequency domain analyses. The soil material and interface nonlinearities are then introduced into the time domain model to perform the third analysis. It is shown that the seismic response of the nonlinear system deviates from what is obtained via linear analyses. Linear analyses may either under-predict or over-predict the response depending on the frequency range of interest. The observed discrepancies are also dependent on the site soil and structural properties of the SSI system as well as the characteristics of the ground motion under study.

388: Self-Heating of a Polymeric Particulate Composite Under Mechanical Excitations

Zhenyu Shou, Columbia University
Fangliang Chen, Columbia University
Huiming Yin, Columbia University

The thermal and mechanical responses of a polymeric particulate composite under different mechanical excitations have been studied. The particulate composite consists of polymeric matrix and aluminum particles. An electrodynamic shaker was used to provide mechanical excitations to the composite, which allows for band limited white noise or single–frequency harmonic inertial excitation, and the mechanical and thermal responses were collected by the accelerometer mounted on the shaker and thermocouples attached to the sample surface/embedded in the sample, respectively. Both the inner and surface temperatures of composites with different sizes and volume fractions of aluminum particles with respect to PDMS are measured by sweeping the excitation frequency from low frequency (~10 Hz) to high frequency (~1 MHz), through which the active heating mechanisms are found to be highly dependent on the frequency of excitation, and the effects of the metallic particle size and volume fractions on the thermal response are disclosed. A thermomechanical model has also been developed to predict the thermal and mechanical responses of the polymeric particulate composite under mechanical excitations, and was validated by comparing with the experimental results.

121: Semi-Analytical Modeling of Post-Critical Delamination Growth in Buckled Composite Plates

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A method capable of modelling damage propagation/growth within the framework of a general structural stability analysis (e.g. see [1]) is presented. Therefore, the conventional total potential energy approach is extended into an extended total potential energy-like function capable of describing certain inelastic processes such as stable delamination growth in layered composite structures. The work deals with systems which are fully described by n generalized coordinates and m damage parameters. Considering stable damage processes the force available for a change in structure (thermodynamic force) is equal to the force required for such a change (which may be a material parameter) [2]. The thermodynamic force is a function of the generalized coordinates, the load parameters and the damage parameters. The force required is assumed to be a function of the damage parameters only. Hence, assuming a stable damage process the damage parameters may be derived as functions of generalized coordinates and the load parameters [3]. Such functions are inserted in the underlying variational principle for inelastic solids [4]. The solution of the variational principle describes the deformation paths of the systems while accounting for damage to occur. The evolution of the damage parameters may be calculated by inserting the solutions for loads and generalized coordinates. The method proposed is applied to a multi-layered composite plate of differently stacked transversally isotropic unidirectional layers. A pre-existing delamination is assigned in between two layers. First, by evaluating the energy release rate it is determined whether a stable damage process is given. Subsequently, the variational principles for conservative and inelastic processes are applied. The problem may be solved using the Rayleigh-Ritz formulation leading to a non-linear set of algebraic equations comprising post-critical equilibrium paths and damage propagation, i.e. delamination growth. The work provides a semi-analytical method using only a few generalized coordinates which contrary to pre-existing models comprises deformation paths and damage growth.
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566: Semicircular Bend Fracture Test Integrated with Numerical Simulation to Characterize Mixed-mode Fracture Properties of Asphaltic Materials

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Yong-Rak Kim, University of Nebraska-Lincoln

Cracking in asphalt pavements causes primary failure in structure, with long-term durability issues often related to moisture damage. Fracture resistance and characteristics of asphalt materials significantly affect asphalt pavement service life. Studies have typically considered only mode-I (opening) fracture, but many observations demonstrate the significance of mode-II (sliding) fracture for better design of pavement structures and damage characterization of asphaltic materials. This paper presents integrated experimental-computational efforts to characterize the mixed-mode fracture of a fine aggregate matrix mixture which is the primary phase of cracks around stiffer coarse aggregates when typical asphalt concrete mixtures are subjected to intermediate service temperatures. Experimentally, semicircular bend fracture tests were conducted by varying the geometric-loading configurations with different initial notch inclination angles and supporting spans to achieve different fracture modes (opening mode-I, in-plane shear mode-II, and mixed). The semicircular bend fracture test results were then integrated with the extended finite element model which is also incorporated with mode-dependent cohesive zone fracture to properly identify the mode-dependent fracture properties. The test and model simulation results indicated that the cohesive zone fracture toughness of in-plane shear mode-II is quite different (approximately three times greater) from opening mode-I fracture toughness. The critical fracture energy was related to the mixed-mode ratio, which presented a power relationship between the total fracture toughness and involvement of in-plane shear mode-II fracture in the total. Findings and observations from this study, although they are limited at this stage, imply that the mixed-mode fracture characteristics are significant and need to be considered in the structural design of asphalt pavements with which multi-axial cracking is usually associated.

130: Sensitivity Assessment of Interatomic Potentials On-the-fly in Molecular Dynamics Simulation

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In molecular dynamics simulation, the accuracy of the interatomic potential contributes a vital role toward the reliability of the predictions. These interatomic potentials, which are the main sources of uncertainty, are inherently imprecise due to errors in experimental measurements or ab initio calculation. Existing studies of uncertainty effects in MD mostly use non-intrusive uncertainty quantification (UQ) techniques. In this work, a reliable MD (R-MD) mechanism as an intrusive UQ technique is developed. In R-MD, the velocities and locations of particles are not assumed to be precisely known, as a result of imprecise interatomic potentials. Instead, they are represented as generalized intervals, and are propagated by Kaucher arithmetic. The new simulation mechanism is demonstrated for isothermal-isobaric ensemble. The advantage of this approach is that uncertainty effect can be assessed on-the-fly in one run of simulation.

727: Sensitivity of Thermal Conductivity to Force Estimates in Molecular Dynamics Simulations

Greg Walker, Vanderbilt University
CN Brock,
MD Gerboth,

The quality of a molecular dynamics (MD) simulations is determined by the accuracy of interatomic forces. Ideally interatomic forces would be determined using quantum mechanical methods such as density functional theory (DFT), particularly for situations like defects and interfaces where empirical potentials tend to fail. However, we don't know how improvements in the potential will affect transport properties derived from

molecular dynamics simulations. We are interested in quantifying the uncertainty in the calculation of thermal conductivity (k) from molecular dynamics simulations using empirical forces and those derived from DFT. We calculate the sensitivity of the property to the interatomic forces (dk/dF). Unfortunately, direct exploration of changes in k by varying parameters for the DFT calculations would be very expensive, but we can extract the relationship indirectly. Typically empirical potentials instead of DFT are used to calculate interatomic forces because of drastic speed advantages. These potentials are designed to realistically model interactions between atoms, but this is only achieved to a certain extent because the potentials are empirical models. We can use empirical potentials as a tool to calculate the change in forces with respect to changes in the interatomic potential, dF/dU. By varying parameters in the interatomic potential and then calculating k, we can also get the change in k with respect to interatomic potential, dk/dU. Given dU/dF and dk/dU, we can quantitatively evaluate the effects of changes in interatomic forces on thermal conductivity calculations.

90: Sensor Placement for Structural Health Monitoring: An Optimal Bayesian Experimental Design Approach

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Stefano Mariani, Politecnico di Milano

Structural health monitoring (SHM) is widely employed to estimate the remaining lifetime or the residual mechanical properties of existing structures, given a set of measurements collected by a network of sensors. To optimize the deployment of such sensors and promptly identify damage as soon as it is incepted, several approaches have been proposed in the literature including the effective independence method, the effective independence driving-point residue, and the maximum kinetic energy method. In this work, we frame the optimal design of the network topology, relying on the error between the prediction model and the measurements. To this end, a Bayesian experimental design approach, based on [1], is adopted. The rationale of the proposed approach is to determine an optimal instrumentation configuration, i.e. the optimal deployment of the sensors on the structure, so as to infer maximal information relating to structural condition. The optimal configuration is obtained by maximizing the expected utility gain, that is by ensuring the largest Kullbach-Leibler divergence from posterior to prior probability distributions and, therefore, the largest decrease in entropy. This is then linked to the most informative configuration with respect to the state-dependent model parameters to be inferred. Since it is not possible to analytically compute the aforementioned expected utility gain, a numerical approximation based on Monte Carlo sampling is exploited. In reducing the computational toll of a forward simulation, a surrogate model based on polynomial chaos expansion is adopted: each sample is jointly defined from both the parameters and design variables spaces, and the polynomial bases and coefficients are next obtained from the relevant responses through a least angle regression. Finally, a stochastic optimization method, the covariance matrix adaptation evolution strategy, is used for determining the optimal solution without computing the expected utility gain for each possible design point. The method is implemented on a simply supported thin plate, and the results are compared to those of a deterministic optimal placement method described in [2]. It is further demonstrated how the choice of the prior and likelihood distributions can drive the optimal sensor deployment process. [1] X. Huan, Y. M. Marzouk, Simulation-based optimal Bayesian experimental design for nonlinear systems, J. of Computational Physics, 2013. [2] M. Bruggi, S. Mariani, Optimization of sensor placement to detect damage in flexible plates, Engineering Otimization, 2013.

327: Sequential Damage Localization: A Data-driven Approach

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Anne Kiremidjian, Stanford University

Ram Rajagopal, Stanford University
Chin-Hsiung Loh, National Taiwan University

Damage diagnosis is an important component of Structural Health Monitoring. During the past few decades, there have been many successful efforts on the development of model-based damage detection algorithms. With the recent development of sensing technology, wireless sensors have been widely deployed to monitor the structural status. These sensors provide a large amount of data and can be designed to have algorithms embedded on their microprocessors to direct damage interrogation. In addition to onboard computational capabilities, multiple types of sensors can be deployed simultaneously within the same sensing unit providing independent measurements for greater reliability of damage diagnosis. In this paper, we build on previous work by the authors to propose a sequential damage localization algorithm using data from different types of sensors. In particular, acceleration and angular velocity measurements obtained from sensors are modeled as autoregressive (AR) time series. The damage sensitive features (DSFs) are defined as a function of the AR coefficients. It has been found that the mean values of the DSF for the damaged and undamaged signals are different. Therefore, we employ a Bayesian detector to declare the existence of damages in a sequential manner. Since each detector can perform damage detection on the sensor, we utilize the sensor topology information to localize the damage. Furthermore, we propose an algorithm to localize damages collaboratively by using the information from multiple sensors. Many Bayesian damage detection algorithms need to know the statistics of DSFs after damage. However, this information is not always available. Thus, we will extend our Bayesian approach to have unknown post-damage feature distribution. This extension will help us to understand the damage level severity. In the proposed approach, we will firstly validate the damage localization algorithm on the ASCE benchmark structure by numerically simulating damage at various locations. This will enable us to test the accuracy of the proposed algorithm. In addition, we will show the performance of our algorithm on the experimental data collected from a shake table test conducted at National Taiwan University. In this experiment, two three-story structures were placed on the same shake table side by side. For one of the specimens, one of the first floor columns was replaced with a weakened column. Accelerometers and gyroscopes were installed at various locations of both specimens to collect measurements. We will utilize these data to detect and localize damages.

418: Shear Induced Glass Transition in a Granular System

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Yinqiao Wang, Shanghai Jiaotong University
Yi Luo, Shanghai Jiaotong University

In this study, we investigate the granular materials in a 2D Couette cell under shear using photo-elastic disks. We find there is a novel shear induced glass transition at the packing fraction around 82%: the relaxation time of the system diverges as the packing fraction approaches 82%. We will present results to analyze the connection between the structure and the dynamics. We will also discuss the relevance of this discovery to the discrete shear thickening in the granular suspensions.

341: Simulation of 3-D Hydraulic Fracture Propagation and Interactions Near a Wellbore

Armando Duarte, University of Illinois
Piyush Gupta, University of Illinois

There are two key technologies behind the recent boom in gas and oil production in the U.S. The first one is horizontal drilling and the second one is multistage fracturing in which between three and eight fractures are simultaneously propagated. Each fracture starts from a cluster of perforations connecting the well to the reservoir. The near wellbore merging of initial fractures and their reorientation towards the preferred fracture plane leads to complex fracture geometries which in turn induce a strong nonlinear pressure drop near the wellbore. The fracture shape, and consequently pressure drop, varies significantly between clusters. As a result, the majority of the gas and oil production, comes from only 20 to 30% of the clusters. While this near wellbore fracture tortuosity plays a key role on the performance of multistage fracturing, all computational methods adopted in the oil and gas industry for the simulation of hydraulic fractures assume planar crack geometries.This presentation reports on recent advances of the Generalized Finite Element Method (GFEM) for three-dimensional hydraulic factures. The proposed GFEM is able to handle (i) Simulations of 3-D non-planar fractures with complex geometries; (ii) Interaction and coalescence of 3-D non-planar crack surfaces and (iii) Simulations involving highly non-convex crack fronts. Discretization errors and computational cost are controlled through adaptive mesh refinement and enrichment. Strongly graded 3-D discretizations are automatically updated as the fracture evolves. Examples illustrating these capabilities and the robustness of the method are presented.

141: Simulation of Wind and Wave Field for Coastal Infrastructures

Jin Zhu, University of Connecticut
Wei Zhang, University of Connecticut

Effective simulations of wind and wave and their possible correlations, as well as their effects on structures, are critical for coastal infrastructure resiliency, which require sufficient structural reliability either during normal operations or under extreme weather conditions. This paper presents an efficient simulation methodology to generate non-stationary wind and wave field for coastal infrastructures, such as long-span bridges, based on the evolutionary power spectral density (EPSD) matrix method, spectral component method, and long term monitoring data (e.g. data from NOAA). In the present study, the wind is simulated as a deterministic mean and a non-stationary fluctuation. The mean wind data are retrieved from either local long term monitoring data or the wind profile record available in literature, such as those from historical hurricanes and downbursts. The nonstationary wind fluctuation is regarded as a zero-mean Gaussian evolutionary vector process, which is characterized by an evolutionary power spectral density (EPSD) matrix. To improve the simulation efficiency of the vector-valued nonstationary process, a hybrid efficient simulation method is applied for the decomposition of time-dependent EPSD matrix, using wavelets and spectral representation method (SRM). The numerical modelling of multi-directional random wave propagation over shallow water with varying topography is based on the elliptic formulation of the mild-slope equation. With the implementation of numerical formulations of the breaking phenomenon into the equation, the model is able to simulate the processes of random wave transformation due to the phenomena of shoaling, refraction, diffraction and breaking. The randomness of the wave field is simulated based on a spectral component method, in which the directional wave spectrum is discretized into components of equal energy. At last, a numerical example is presented to demonstrate the proposed methodologies. Based on the long term monitoring data from NOAA, a typical stochastic wind and wave field near a double-pylon cable-stayed bridge is simulated. Different correlation scenarios are investigated for typical hurricane events.

404: Simulation on Ethanol Based Foaming Process in Asphalt Using Smooth Particle Hydrodynamics

Siyu Zhu, Columbia University
Huiming Yin, Columbia University

Foaming asphalt is a widely used technology to produce Warm mix asphalt (WMA) in current practice to reduce

energy consumption and environmental impacts. The foaming technology produces asphalt materials with better workability at lower temperatures, reducing energy consumption and gas emissions. However, the foaming process and its associated influencing factors are currently not well understood. In this study, both experiments and simulations are investigated to understand the foaming process using ethanol forming agents. A smooth particle hydrodynamics (SPH) model is applied to simulate the foaming process of ethanol mixed asphalt. Multiphase models are used to represent asphalt and liquid agents, while liquid agents get evaporated among the asphalt and cause the total volume change. The volume expansion rate is carried out as a major property to evaluate the foaming property. The effects of temperature and material proportion on the foaming performance are investigated. Corresponding laboratory tests are conducted to validate the simulation results.

164: Simultaneous Topology and Material Design Optimization of Functionally Graded Structures

Kai A. James, University of Illinois
Anurag Bhattacharyya, University of Illinois
Cian Conlan-Smith, University of Illinois

The advent of 3D printing has had a major impact on structural and mechanical design, making plausible entire classes of structures and materials that could not previously be manufactured using earlier technologies. One such class of materials, is functionally graded materials (FGMs), whose mechanical properties vary spatially in a smooth, graded fashion within a single part. This functionality allows designers to optimally address local mechanical needs across different sections of the material domain. The current study introduces a novel SIMP-type method for simultaneous optimization of the topology of the material domain, while also optimizing the local material properties throughout the structure. The design is optimized using a gradient-based approach, with sensitivities evaluated using the adjoint method. A series of numerical examples are used to demonstrate the effectiveness of the new algorithm, and the response of the functionally graded structures is compared with that of conventional designs comprised of uniform homogeneous material.

781: Six Sigma-based Robust Design Optimization of Prestressed Girder Bridges

Yassin Al-Delaimi, University of Ottawa
Elena Dragomirescu, University of Ottawa

The prestressed concrete girder bridges are popular structures due to their simplicity of fabrication, speed of construction, ease of inspection, maintenance and replacement. Many design factors play an essential role in deciding the members' dimensions, geometry, weights, and cost. This reflects the importance of developing optimization tools that provide cost-effective design by determining certain design variables to achieve the best measurable objective function under given constraints. However, in order to maintain appropriate safety levels in the optimized structural configuration, it becomes necessary to adopt a probabilistic approach that considers the uncertainties associated with the basic design variables that affect the bridge performance. For a successful probabilistic optimization approach, it is important to focus on ensuring not only that a bridge performs as designed but also that the bridge consistently performs as designed. In this paper, the six sigma quality concept is integrated with a probabilistic design optimization applied to prestressed girder bridges in order to achieve an economical design solution that: (1) maintains performance within acceptable limits (consistent reliability), and (2) reduces performance variation (high robustness). From a pre-defined loads and resistance models, all the uncertainties associated with the basic design variables were probabilistically modelled with a suitable statistical distribution type and statistical parameters. The unit cost of the bridge superstructure represents the objective

function. The optimization process aims to assign the best values to the design variables in order to minimize the objective function within the optimization constraints. Two types of constraints exists: deterministic and probabilistic. Deterministic constraints represent the limitations of the AASHTO LRFD (sixth edition 2012) requirements. The probabilistic constraints require that neither the individual reliability indices with respect to limit state functions nor the overall system reliability to be less than specified target reliabilities. The number of standard deviations that control the dispersion the mean of every random variable is decided on based on six sigma concept. For that purpose, a computer-aided model (BREL), for Bridge RELiability analysis and design, was developed using Visual Basic Application VBA code. The proposed methodology proposes a simulation based optimization technique. The simulation engine utilizes Monte Carlo analysis while the optimization engine performs metaheuristic scatter search optimization with neural network accelerator. A case study conducted to examine the applicability of the proposed model. The results showed around 20% cost saving with consistent safety levels reserved in the optimized structural configuration.

273: Smart Monitoring System Based on Electromechanical Impedance and Guided Ultrasonic Waves

Amir Nasrollahi, University of Pittsburgh
Vincenzo Gulizzi, University of Palermo
Piervincenzo Rizzo, University of Pittsburgh

In this paper we present a structural health monitoring (SHM) paradigm based on the simultaneous use of ultrasounds and electromechanical impedance (EMI) to monitor waveguides. The paradigm uses guided ultrasonic waves (GUWs) in pulse-echo and pitch-catch mode, and EMI simultaneously. The three methodologies are driven by the same sensing/hardware/software unit. To assess the feasibility of this unified system an aluminum plate was monitored and its repeatability under varying environmental conditions was evaluated. Damage was simulated by adding small masses to the plate. The results associated with pulse-echo and pitch-catch GUW testing and with EMI monitoring show that the proposed system is robust and can be developed further to address the challenges associated with the SHM of complex structures.

317: Sparse Bayesian Learning for Failure Prognostics and Uncertainty Management

Pingfeng Wang, Wichita State University
Parse Kianpour, Wichita State University

Failure prognostics can be broadly applied to various engineered artifacts, despite the fact that techniques and methodologies for health prognostics are largely application-specific. Difficulties in developing an application generic methodology mostly result from heterogeneity of sensory data, a wide range of data acquisition frequency and size, and different characteristics in uncertain manufacturing and operation conditions. This study thus aims at formulating a generic framework of failure prognostics and uncertainty management employing sparse Bayesian learning (SBL) technique. The developed framework is composed of four core elements: (a) a generic virtual health index system that enables the use of heterogeneous sensory signals, (b) a generic offline training scheme using the SBL technique, (c) a generic online prognostics scheme using the similarity-based interpolation, that predicts the remaining useful lives with background health knowledge obtained under uncertain manufacturing and operation conditions, and (d) an uncertainty propagation map that enables the predicted remaining useful lives to be loaded with their statistical characteristics. Because of the SBL scheme, the sparseness feature employing only a few neighboring kernel functions enables the real-time prediction of remaining useful lives regardless of data size. The proposed generic framework of prognostics is applicable to

different engineered systems and its effectiveness is demonstrated with case studies.

355: Stability Analysis of the Phase-Field Method for Fracture in Linear Elastic, Rate-Independent Plastic, and Visco-Plastic Materials

Miguel Arriaga, Columbia University
Colin McAuliffe, Columbia University
Haim Waisman, Columbia University

The phase-field method is a popular technique for modeling crack initiation, bifurcation and coalescence without the need to explicitly track the crack surfaces. In this framework, the governing equations are derived from thermodynamic principles and cracks are modeled as continuous entities, whose width is defined by a small process zone parameter. Propagation of cracks is governed by the partition of strain energy that contributes to fracture and may be stable, in which case additional elastic energy is required to form cracks, or unstable, where cracks advance with no additional input energy. In this work we propose a stability framework, based on a linear perturbation analysis, to determine the onset of unstable crack growth. The derivations lead to an analytical, energy based criterion for the phase field method in linear elastic, rate-independent plastic, and visco-plastic materials. Numerical results on linear elastic materials show that the proposed criterion not only recovers the critical stress value reported in the literature but also provides additional information on the growth rate of unstable cracks. Furthermore, for visco-plastic materials the onset of unstable crack propagation and post-critical behavior are reported and shown to be dependent on the loading rate. The criterion is tested on one dimensional problems and a two dimensions homogeneous example, successfully predicting the instability point.

226: Stabilized Interface Formulation for Frictional Dynamics

Timothy Truster, University of Tennessee
Arif Masud, University of Illinois

Frictional contact is a significant feature of many natural and engineered systems, such as the stick and sliding of rock formations during seismic activity and the vibration of bolted structural connections under dynamic excitation. Accurate finite element simulation of these problems requires proper treatment of the interface conditions. We present a formulation well suited to these problems that incorporates Discontinuous Galerkin treatment locally at the interface. The weak imposition of continuity constraints allows the stick-slip behavior at the jointed surface to proceed more smoothly, reducing the numerical instability compared to node-to-node contact techniques. Nonconforming element interfaces, commonly encountered in complex three-dimensional meshes and in finite deformation contact problems, are naturally treated by this method. The interface flux terms that are consistently derived through a Variational Multiscale approach provide a variationally consistent mechanism to embed friction models. Several numerical examples are provided for structural domains under impact loading, including the response of a bolted lap joint. Specific attention is paid to the stable and accurate response for nonconforming meshes as well as contribution of the frictional interface to the overall response of the system.

394: Stabilized Methods for Coupled Thermomechanical effects in Multi-Constituent Materials

Harishanker Gajendran, University of Illinois

Arif Masud, University of Illinois

The major life limiting factors in composites are the residual stresses that often arise due to the differential expansion and cooling of the constituents during the curing cycle. These differential stresses weaken the strength of fiber-matrix interface, thereby reducing the load carrying capacity and thus lead to premature failure of the composite. The single continuum theories modeling the effective composite behavior provide a smeared response at the continuum level, while providing no information about the constituents and interface. Though the microscopic modeling of constituents provides accurate response, it can become computationally intractable for real word applications. A mixture theory based constitutive model is employed for modeling of multi-constituent materials, wherein the constitutive relations for the constituents and their interactive force fields are derived through the maximization of rate of dissipation constraint. A new stabilized method is presented for this thermodynamically consistent theory. The new framework provides enhanced numerical stabilization, which allows the modeling of the displacement and temperature fields of both the constituents with arbitrary combinations of interpolation functions. Specifically, easy to implement equal-order interpolations are shown to give stable and convergent solutions. Several representative benchmark problems are presented to show the performance of the model and the method.

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668: Staggered Schemes for Multiscale Arlequin Poromechanics Problems

WaiChing Sun, Columbia University
Zhijun Cai, Columbia University

The mechanical behavior of a fluid-infiltrating porous solid is significantly influenced by the presence and diffusion of the pore fluid in the voids. This hydro-mechanical coupling effect can be observed in a wide range of materials, including rocks, soils, concretes, bones and soft tissues. Nevertheless, due to the high computational demand, explicitly simulating the pore scale solid-fluid interactions of every single grain in the solid skeleton remains impractical for engineering problems commonly encountered in the field and basin scales. The objective of this research is to extend the Arlequin formulation such that hydro-mechanical coupling effects at different spatial scales can be captured in a concurrent computational framework. In particular, we recast the deformation-diffusion problems as the saddle point that optimizes the constrained partitioned incremental work of a multi-field energy functional. By introducing appropriate Lagrange multiplier fields and compatibility energy functional, we enforce the weak compatibility of the hydro-mechanical responses in the multiscale overlapped domain. Modified inf-sup tests are established to examine the spatial stability issues of the multiphysics Arlequin formulation. Staggered schemes are introduced both in space and between the solid and fluid solvers such that the computational resources may allocate efficiently.

671: Statistical Modelling of Hurricane Trajectories in the North Atlantic Ocean for Structural Integrity and Damage Cost Estimation

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Luca Caracoglia, Northeastern University

Hurricane is the one of most destructive weather phenomena, which can cause severe structural damage to properties and loss of life due to combined strong wind and surge effects. Therefore, accurate modelling of hurricane trajectory as it approaches the built environments and it lands ashore is important to ensure public safety. Traditionally, two approaches have been usually employed to predict hurricane trajectories: the Markov Chain method proposed by K. Emanuel and the regression method proposed by P. Vickery. In this study, a new statistical modelling approach for the simulation of hurricane trajectories in the North Atlantic is presented. The historical hurricane data are derived from the HurDat database, maintained by NOAA (National Oceanic and Atmospheric Administration) in the United States. In this model, the means and variances of the latitude and longitude position of the hurricane eye, as it travels from one location to another one, are determined by dividing the Atlantic Ocean in 5 x 5 degree grids. The correlation of the variances between the latitude and longitude instantaneous positions is considered in this model. All historical hurricanes that passed through each grid are recorded; the model coefficients are estimated by assigning the mean and standard deviation of the instantaneous positions to the center of each grid; finally, spatial interpolation is used to calculate the values of the model coefficients at other points inside each grid. After all the model coefficients are determined, this model is used to predict the hurricane risk along the US East coastline by combining the hurricane intensity model; the model can also be used to the predict future hurricane landing probability and location, based on current and historical information. At last, the hurricane tracks are simulated and compared against Atlantic historical records, and the simulated hurricane arrival (and landing) rate along the US East coastline is examined to demonstrate the validity of the proposed model.

380: Stochastic Analysis of Polymer Composites Failure in Large Deformations Modeled by a Phase Field Method

Jie Wu, Columbia University
Colin McAuliffe, Columbia University
Haim Waisman, Columbia University
George Deodatis, Columbia University

Carbon black reinforced natural rubber is a composite material that is increasingly being used in engineering applications. Carbon black is orders of magnitude stiffer than natural rubber, resulting in a composite material with increased stiffness, but decreased fracture strain. Detailed knowledge of the relationship between the composition of reinforced rubber and its fracture toughness is important for analysis and design of various engineering systems. To this end, the Arruda-Boyce model is adopted for modeling the hyperelastic rubber matrix and a Neo-Hookean model is used for the reinforcing particles. A phase field method is then employed to simulate damage nucleation and propagation under quasi-static loading. The phase field method is well suited for such problems, since it can capture complex patterns of damage nucleation, coalescence, and propagation. The phase field hyperelastic model is validated on a set of experimental data available in the literature. To quantify the uncertainty in the failure of these materials, a Monte Carlo simulation is carried out with random ellipsoidal particles distribution. Each realization undergoes large stretching up to failure, where force displacement curves and fracture surface energies are recorded. Failure of a sample is defined as the point for which the load drops to 75% of the peak force. Numerical examples of stiff inclusions and voids are considered and the composite response is examined on an intact and pre notched unit cells. A rigorous stochastic analysis reveals the statistical distributions corresponding to the rupture of polymer composites and provides insight into better design of these materials.

94: Stochastic Design Optimization Involving Mixed Design Variables by Augmented Polynomial Dimensional Decomposition

Xuchun Ren, Georgia Southern University
Sharif Rahman, The University of Iowa

Abstract This paper presents a new method, named as augmented polynomial dimensional decomposition (PDD) method, for robust design optimization (RDO) and reliability-based design optimization (RBDO) subject to mixed design variables comprising both distributional and structural design variables. The method involves a new augmented PDD of a high-dimensional stochastic response for statistical moment and reliability analyses; an integration of the augmented PDD, score functions, and finite-difference approximation for calculating the sensitivities of the first two moments and the failure probability with respect to distributional and structural design variables; and standard gradient-based optimization algorithms. New closed-form formulae are presented for the design sensitivities of moments that are simultaneously determined along with the moments. A finite-difference approximation integrated with the embedded Monte Carlo simulation of the augmented PDD is put forward for design sensitivities of the failure probability. In conjunction with the multi-point, single-step design process, the new method provides an efficient means to solve a general stochastic design problem entailing mixed design variables with a large design space. Numerical results, including a three-hole bracket design, indicate that the proposed methods provide accurate and computationally efficient sensitivity estimates and optimal solutions for RDO and RBDO problems.

21: Stochastic Modeling of Hyperelastic Materials

Brian Staber, Universite Paris-Est
Johann Guilleminot, Universite Paris-Est

In this work, we address the construction of parametric probabilistic models for isotropic hyperelastic media. Emphasis is specifically put on the stochastic modeling of Ogden's hyperelastic materials, which were extensively studied from both experimental and theoretical deterministic standpoints. The construction is completed within the framework of Information Theory, and is essentially governed by existence theorems in nonlinear elasticity. The probabilistic models for the stochastic stored energy functions are constructed by introducing a conditioning with respect to the elastic moduli, taking hence into account polyconvexity and coerciveness constraints. Two formulations are subsequently provided and illustrated on classical Neo-Hookean and Mooney-Rivlin models. Finally, an inverse calibration procedure involving experimental data (for the incompressible case) is proposed and used to demonstrate some salient features of the stochastic models.

701: Stochastic Simulation of Random Material Microstructures Using Ellipsoidal Growth Structures

Nicolas Venkovic, Johns Hopkins University
Lori Graham-Brady, Johns Hopkins University

Ellipsoidal growth structures (EGS) are introduced as a generalization of tessellation growth models as formulated by Teferra and Graham-Brady (2015). In an EGS, an adjustable set of rules allows to draw a specific morphological structure from a given set of positive definite second order tensors and nucleation points. We show that EGS can be used as parametric representations of material structures that can be defined as a collection of common surfaces, points and curves such as polycrystals, foams, trabecular bones and some porous media. Although EGS can be numerically resolved through spatial discretization, we introduce a semi-analytical

approach for the resolution of closed form equations of the common surfaces and curves of a microstructure. These equations allow us to compute Minkowski tensors of arbitrary orders for EGS cells (e.g. grains in polycrystals, pores in foams and so on). The importance of distinct types and orders of Minkowski tensors to clearly distinguish EGS cells is investigated numerically. Other morphological metrics such as interception length distributions and Minkowski correlators are computed as a mean to characterize random structures. A methodology is proposed to simulate random microstructures as realizations of stochastic EGS processes with prescribed marginal cell morphology distributions and correlations. Some simple mechanical boundary value problems are identified and solved using finite elements for some microstructure realizations. The sensitivity of some performance indexes of these mechanical systems is studied with respect to the prescribed morphological features of the random microstructures. K. Teferra and L. Graham-Brady, Tessellation growth models for polycrystalline microstructures, Computational Materials Science, 102 (2015) 57-67.

483: Strain and Damage Identification in Piezoresistive Nanocomposites Using Electrical Impedance Tomography with Constrained Sine-Wave Solutions

Tyler Tallman, Purdue University

Recent work has demonstrated that electrical impedance tomography (EIT) has considerable potential for structural health monitoring (SHM), damage identification, strain sensing, and environmental sensing by tracking changes in the electrical conductivity of a structure. EIT also, however, has important limitations such as requiring non-negligible computational resources that may not be available to on-board SHM systems. Furthermore, EIT requires a suitable initial estimate of the conductivity distribution which may not be easy to discern. To overcome these limitations, a novel reconstruction algorithm is herein presented that makes use of constrained sine wave solutions. By constraining the solution to be the summation of a series of two-dimensional sine waves, considerable computational burden is alleviated from EIT. Additionally, this method is completely independent of initial conductivity estimates. This method is first explored analytically and then demonstrated experimentally on several different materials.

524: Strain Rate Dependent Failure Of Interfaces In Glass/Epoxy And Energetic Materials At Nano-Microscale Via Dynamic Indentation

Devendra Verma, Purdue University West Lafayette
Vikas Tomar, Purdue University West Lafayette

The main factors contributing to the modes of failure in composites are initiated at the interface of glass phase in glass fiber composites and at interface between Sylgard-Ammonia in energetic materials. The interface mechanical strength is characterized using dynamic indentation experiments at strain rates up to 400 s-1. The experiments were conducted with indenters of radius 1, 10 and 100 μm on the interfaces with thicknesses of 1, 10 and 100 μms within the spatial error tolerance of less than 3 μms to capture the size effect. The interface thickness was also verified using the Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) analysis. The stress maps using Nano Mechanical Raman Spectroscopy (NRS) were also captured before and after the impact experiments to analyze the change in the stress distribution around interfaces. The measurements of dynamic hardness, strain rates, and plastic-residual depths were correlated to show the relation of interface mechanical strength with the bulk phase mechanical strength. The Johnson-Cook constitutive model was fitted to the obtained interface normal-stress and normal-strain data based on the nano-impact experiments. Results show that interfacial properties are affected by the rate of loading and are largely dependent upon the interface structural inhomogeneity.

31: Strain Rate Dependent Microplane Constitutive Model for Comminution of Concrete under Projectile Impact

Kedar Kirane, Northwestern University
Yewang Su, Northwestern University
Zdenek Bazant, Northwestern University

The pulverization, fracturing and crushing of materials, briefly called comminution, creates numerous cracks which dissipate a large amount of kinetic energy during projectile impact. At high shear strain rates (10/s—1000000/s), this causes an apparent large increase of strength, called `dynamic overstress'. This long debated phenomenon has recently been explained by the theory of release of local kinetic energy of shear strain rate in finite size particles that are about to form. The theory yields the particle size and the additional kinetic energy density that must be dissipated in finite element codes. In previous research, it was dissipated by additional viscosity, in a model partly analogous to turbulence theory. Here it is dissipated by scaling up the material strength. Microplane model M7 is used and its stress-strain boundaries are scaled up by factors proportional to the - 4/3rd power of the effective deviatoric strain rate and to its time derivative. The crack band model with a random tetrahedral mesh is used and all the artificial damping is eliminated from the finite element program. The scaled model M7 is seen to predict the crater shapes and exit velocities of projectiles penetrating concrete walls as closely as the previous models. The choice of the finite strain threshold for element deletion, which can have a big effect, is also studied. It is proposed to use the highest threshold above which a further increase has a negligible effect.

328: Strategies to Tackle the Dimensionality Issue for Nonlinear Bayesian Filtering and Parameter Identification

Audrey Olivier, Columbia University
Andrew Smyth, Columbia University

In structural health monitoring, one wants to detect damage if present, its location and extent, and if possible evaluate the remaining life of a structure. Performing nonlinear system identification enables one to tackle those tasks for nonlinear structural systems, also accounting for process and measurement noise inherently present in real-life systems. However, performing Bayesian inference can become very computationally expensive, or even infeasible, for medium to large dimensional systems. Overcoming this dimensionality issue is key to rendering this type of approach feasible for real-life nonlinear systems, which will often include many degrees of freedom. In this talk we will first provide a review of nonlinear filtering algorithms, especially nonlinear Kalman filtering and particle filtering, focusing on their advantages and drawbacks in regard with structural health monitoring purposes and possible issues regarding large scale systems. We will also present novel refinements of these algorithms, based on partitioning/substructuring principles such as the Rao-Blackwellisation concept, which we have adapted/developed to handle more specifically structural systems of interest for SHM. We will then present examples of medium to large dimensional systems to study the performance of these algorithms.

228: Stress-Based Topology Optimization of Continua with Material Uncertainty

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Navid Changizi, Cleveland State University

Mehdi Jalalpour, Cleveland State University

In design of structures and components, stress constraints are usually of paramount of importance. Therefore, topology optimization research is recently moving towards proposing methodologies capable of stress-based design (in place of traditional compliance-based design). Most of these applications are, however, limited to deterministic conditions. Real-world applications are accompanied by uncertainties, and if overlooked during the design process, may result in designs that are sub-optimal. We proposed an efficient stress-based topology optimization for continua under material uncertainty. This uncertainty is propagated to response level by stochastic perturbation method. We provide numerical examples demonstrating the changes in topology when material uncertainty is considered, and verify the stochastic perturbation method predictions with Monte Carlo simulation.

476: Structural Health Monitoring Using a Network of Smartphones

Kyle Wyatt, University of New Hampshire
Tat Fu, University of New Hampshire
Rui Zhang, University of New Hampshire

Structural health monitoring (SHM) assesses a structure's integrity through analyzing structural response data such as accelerations and strains to detect changes (caused by damage, deterioration, etc.) in structural characteristics. A key component in SHM is a sensing system that measure structural response data. SHM sensing systems are often complex and costly. In this study, the authors investigate the use of smartphones as an alternative sensing network that is capable of recording accelerations (using built-in accelerometers) and time synchronization(using built-in processors and wireless communication channels). Recent studies have verified that smartphone accelerometers are valid options in measuring structural vibrations. This project builds on prior efforts and creates a network of time-synchronized smartphones that can measure vibrations in multiple locations of a structure. This is a crucial development because SHM systems require a network of sensors with accurate time synchronization. In this project, an application is developed on the Android platform. This "app" allows users to obtain accelerations from multiple locations of a structure and send data to a computer for post-processing and estimating the structure's characteristics. Experiments were conducted to validate smartphone capability for SHM purposes. A six-foot, six-story shear structure (made of steel columns and aluminum floors) was mounted on a shake table at the University of New Hampshire. Cross braced springs were installed on each story level in order to simulate "healthy" and "damaged" cases; a healthy structure was fully braced with springs and damage was introduced by removing bracing springs at certain story level(s). Five damage cases were studied: three cases had damage in one level (2nd, 4th or 6th story) and two cases had damage in multi-levels (damage at the 1st and 3rd story and damage at the 4th and 6th story). The structure was subjected to impulse excitations by the stake table. Acceleration data of each story were recorded by a smartphone (a 2013 Motorola G) using the developed app and a Microstrain® G-Link® -LXRS® wireless accelerometer. Modal parameters and stiffness values of the structure was estimated. The results from smartphones and Microstrain accelerometers were compared. Given that the smartphones' sampling rate was not as consistent as the one of Microstrain sensors, smartphone results were not as accurate compared to the Microstrain data. Nonetheless, both data sets could successfully detect the five damage cases.

77: Structural Identification and Modeling of a Three-Story School Building Damaged During the 2015 Gorkha Earthquake

Wen Yu Chang, University at Buffalo

Amin Nozari, Tufts University
Mohammad Shafiqual Alam, Oregon State University
Andreas Stavridis, University at Buffalo
Babak Moaveni, Tufts University
Andre Barbosa, Oregon State Un iversity
Richard Wood, University of Nebraska

This presentation will discuss the structural identification and model calibration of a three-story school building in Tarun, an area at the southeast of Kathmandu, Nepal. The building had a masonry-infilled reinforced concrete frame which was severely damaged during the 7.8 magnitude 2015 Gorkha Earthquake and the aftershocks that followed. The concentration of damage in the east end of the third story indicates that the structure exhibited torsional response in the upper stories. This is a rather unusual response damage pattern for this structural system and it can be attributed to the asymmetric plan and the strength and stiffness discontinuities along the height. The authors visited the structure two months after the earthquake and recorded the ambient acceleration response of the damaged structure, as they instrumented the structure with four unidirectional accelerometers on every floor; two at opposite corners, to capture the translational and torsional modes of vibration. These modes are identified using an operational modal analysis method namely, the stochastic subspace identification method. The identified modal properties are compared with the modal frequencies identified using recordings obtained before the earthquake to estimate the change of frequencies due to the earthquake damage. Moreover, the modal properties are used to validate a finite element model of the structure. The model uses diagonal struts to represent the effect of the masonry infill walls and frame elements to simulate the reinforced concrete beams and columns. The paper will discuss the accuracy of the numerical model which is used to shed light into the load transfer and failure mechanisms that developed during the earthquake.

310: Structural Response Analysis using a Novel Predictive Stochastic Ground Motion Model

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Konstantinos G. Papakonstantinou, Pennsylvania State University
George Deodatis, Dept. of Civil Engineering and Engineering Mechanics, Columbia University

The problem of predicting appropriate ground motions for future seismic events is currently receiving a great deal of attention in the engineering community. Concerning seismic analysis and design of structures, modern building codes suggest use of seismic response time-history procedures under certain conditions. The constantly rising interest in the performance-based earthquake engineering (PBEE) has further enhanced the need for realistic and diverse earthquake acceleration time-histories, pertaining to a variety of earthquake design scenarios. This work presents a rigorous scientific, as well as practical, predictive fully non-stationary stochastic simulation framework, capable of producing synthetic acceleration time-histories associated with commonly used earthquake ground motion predictors at a site of interest. A parametric bimodal evolutionary Kanai-Tajimi (K-T) model forms the core of the developed stochastic simulation method. The K-T model parameters are linked though advanced linear random-effect regression models to typical earthquake scenario defining parameters, such as the moment magnitude Mw, closest distance Rrup and shear-wave velocity VS30 at a specified site. An extensive Californian subset of the recently available NGA-West2 database is used to calibrate the regression models. Sample acceleration time-histories of the stochastic K-T model for a user-specified earthquake scenario are obtained through the powerful Spectral Representation Method (SRM). The developed predictive stochastic model is compared and verified against state-of-the-art GMPEs for a number of different earthquake scenarios. Finally, the presented model goes through a detailed validation process to confirm that seismic structural responses are consistent with the ones obtained from recorded ground motions and accessible for engineering applications.

356: Structural Response Sensitivity to Boundary Layer Transition in High Speed Flow

Zachary Riley, The Ohio State University
Jack McNamara, The Ohio State University

Load bearing thermal protection systems, in the form of thin-gauge metallic airframes, provide a means to minimize the weight and improve the serviceability of reusable, long duration cruise hypersonic aircraft. However, the compliant nature of these structures, in combination with the severe aerothermodynamic loading, results in a propensity for nonlinear fluid-structural interactions. Due to this interaction, the boundary layer state (laminar, transitional, or turbulent) is dependent on the structural response. Accurate determination of the aerodynamic heat load, which varies significantly with the state of the boundary layer, is detrimental to structural life prediction and optimal weight design. Therefore, the future design of hypersonic aircraft may necessitate aerothermoelastic analysis which accounts for the state of the boundary layer. To study this interaction, a boundary layer transition prediction capability is incorporated into an aerothermoelastic model to compute the response of representative hypersonic vehicle surface panels. The transition onset location is obtained using STABL, which assesses boundary layer stability using the linear Parabolized Stability Equations (PSE) and predicts transition using the semi-empirical eN correlation method. To reduce the computational expense associated with applying the PSE to a temporally evolving structure, a Kriging surrogate is developed which predicts transition onset as a function of the surface temperature and deformation. The objective of this work is to characterize the sensitivity of the structural response of a panel to a spatiotemporally evolving transition front, which accounts for the state of the structure. Additionally, the sensitivity of the predicted transition onset location to the eN method input and modeling assumptions will also be assessed. Completion of this study will help to identify key uncertain parameters and quantify the degree of coupling fidelity required to accurately predict the response of a structure subject to hypersonic aerothermodynamic loading. Further, this study will assess the robustness of PSE/eN based transition prediction for aerothermally compliant structures.

416: Structure-Invariant Occupant Detection Using Footstep-Induced Structural Vibration

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Mike Lam, Carnegie Mellon University
Pei Zhang, Carnegie Mellon University
Hae Young Noh, Carnegie Mellon University

We present a structure-invariant algorithm that robustly detects human occupants across different structures through step-induced structural vibrations. Many smart building applications, such as space/energy management, use occupant information to save resources while maintaining occupant comfort and productivity. To this end, researchers have developed various sensing platforms, including infrastructure- and device-based systems. In general, they use various sensing approaches, such as cameras, infrared (IR) sensors, radio frequency (RF) sensors, and acoustic sensors. However, they often require dense deployment or user inputs, which is not desirable for large scale monitoring. In this project, we use vibration sensors to detect occupants by analyzing their step-induced structural vibration. This approach allows sparse sensor configuration using wave propagation characteristics and provides a non-obtrusive alternative by directly using human structure interaction. The main challenge is that the shape of footstep induced vibration waves is highly dependant on wave propagation characteristics of underlying structure. This makes developing a common algorithm which robustly detects footstep across different structures a difficult task. We overcome this challenge by using the properties of the underlying structure (as the propagation medium) and its effect on the received signal. Our structure-invariant occupant detection algorithm consists of two modules: 1) detect possible step-induced signals from noisy data, and 2) classify them into step or non-steps. To achieve high detection accuracy in different structures without re-training the algorithm, the key is to introduce features which are robust to changes in step-induced signals resulted by structural characteristics. Our features are based on wavelet analysis of the footstep-induced signals to decompose the signal into different scales and calibrate for the structural effects, such as dominant frequencies and damping patterns. Wavelet analysis is selected due to the nonstationary nature of the step-induced signals. The method is validated experimentally in two buildings with different structural properties and usage patterns: CMU campus building and Vincentian Nursing Home deployments. The algorithm is trained using the data from one building and then tested for the other one to evaluate its robustness. The preliminary results show that the calibrated features can significantly improve the stability of the detection algorithm.

626: Study of a Long Span Railroad Truss Bridge using the Finite Element Model and Experimental Testing

Ramesh Malla, University of Connecticut
Surendra Baniya, University of Connecticut
Suvash Dhakal, University of Connecticut
David Jacobs, University of Connecticut

This paper presents results obtained from the finite element model and experimental field test of an old long span, open deck through truss railroad bridge under moving passenger trains at various speeds. The motivation for the study comes from the fact that there are numerous old truss bridges in the U.S. and their performance and safety are not known under higher speed trains of the future. The open deck through truss railroad bridges have certain uniquely different features, including they being of longer span than their counter part girder bridges and they Several analytical and experimental studies have been conducted to determine the static and dynamic behavior of railroad bridges. But most of the studies have been on the girder type bridges and are based on the simplified assumptions such as modelling the whole intricate bridge as a simply supported beam. This method of calculating response is not suitable for a truss bridge, because it has many structural components, which makes it difficult to reduce the whole bridge into a simplified model.For this study, one of the 7 spans of a 108-year old through truss open-deck railroad bridge over Housatonic River in Devon, Connecticut was modeled using the finite element (FE) method. The bridge is on the Northeast Corridor, which is the busiest passenger rail-line in the U.S. and is traversed by both passenger (Metro-North, Amtrak Acela, and Amtrak Regional trains) and freight trains. The loading chosen for the analysis was based on axle load and axle configuration of these 3 types of passenger trains. A comprehensive analysis using the FE model of the bridge, including live load static, frequency, and dynamic time history, was performed. The modal characteristics of the bridge, such as natural frequencies and mode shapes, were obtained. Also obtained from the FE model was the displacement response of the bridge in vertical and lateral directions under the above mentioned 3 types of passenger trains at various speeds. A detail field study of the bridge had been also conducted using accelerometers, strain gages, and linear variable displacement transducers. The results from the finite element analysis and field testing were compared to validate/verify the FE model of the bridge. An attempt has been made to identify the resonant condition (identified as a critical train speed) for the displacement of bridge under each type of trains.

169: Subcritical Crack Growth Induced by Coupled Chemo-mechanical Attack in Hardened Cement Paste

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Teng Tong, University of Pittsburgh

Qiang Yu, University of Pittsburgh

One of the main mechanisms that accelerate the deterioration of concrete structures is the damage accumulation caused by the subcritical crack growth in concrete under the coupled chemo-mechanical attack. Usually, the subcritical crack growth (SCG) in concrete members under sustained service load is intertwined with the concurrent process of chemical corrosion. In this proposed study, the kinetics of subcritical crack growth (SCG) in cement paste specimen under simultaneous chemical and mechanical attacks will be investigated both experimentally and numerically. A novel test is designed to track the subcritical crack growth (SCG) through experimental characterization and the complete crack velocity-stress intensity factor (K-v) curves will be obtained based on this experiment. In this test, specimens subject to sustained loading will be immersed in a high-concentration corrosive solution to mimic the coupled chemo-mechanical attack during service. A high-resolution microscopy system together with a non-contact 3D digital image correlation system will be used in the test to scan the specimen surface for probing the sub-critical crack propagation as well as the strain/stress distribution around the crack tip. According to the experimental results, numerical simulations based on lattice model will be developed. In order to capture the heterogeneity of cement paste at meso-scale, the specimen will be dicretized into a lattice system and different material properties will be assigned to the lattice elements representing different constituents. With the aid of the proposed discretization technique, corresponding transport properties can also be assigned to the lattice elements to approximate the corrosion process in the specimens. Based on the numerical simulations, a thorough parametric exploration is undertaken aiming to investigate the correlation between SCG kinetics and the coupled chemo-mechanical attack.

590: Subsurface Damage and Scour Detection Using Deck Level Vibrations to Enhance Highway Bridge Maintenance and Resilience

Amir Irhayyim, University of Mississippi
Chris Mullen, University of Mississippi

Recent highway bridge infrastructure failures have highlighted the importance of understanding the condition of the subsurface and other damage conditions not visible from a visual inspection. Vibration testing at the deck level offers one means to gain information on these conditions. This study uses advanced 3D FE tools available in ABAQUS CAE to capture detailed representation of the superstructure, substructure and foundation soil and rock as well as damage conditions including loss of local soil capacity in subsurface layers and scour. Static, eigenfrequency, and dynamic analysis offer the ability to visualize and quantify the fundamentally 3D effects of changes in the localized subsurface conditions on mode shape and frequency relative to the design or undamaged condition. Focus here is given on the observations possible at the deck level. A 3-span, 1940s era reinforced concrete bridge founded on a chalk subsurface layer with sedimentary and fill overburden soil layers is used to characterize the problem. The bridge is located in north Mississippi in an economically import corridor and is typical of many such bridges operating throughout the US on state and federal highway systems. The soil-foundation-structure model is first built in the original geometry based on design drawings. 3D continua and infinite elements are used throughout to capture detailed response behaviors and subsystem interactions. The base case model is then modified to enable representation of several cases of subsurface damage including severe scour projected 50 years past observed patterns which are already severe. The study is part of a larger scope effort involving other bridge types including those with different superstructure, substructure, and soil conditions. Results are discussed in light of the ability of advanced FE tools and vibration measurement techniques to enhance current maintenance practices based on visual inspection and deck level measurements focused only on the superstructure. The intent is to provide more reliable predictions of these complex soil-structure response behavior in the presence of deterioration and damage will in so doing provide both objective and cost-effective means of improving the multihazard resilience of our highway infrastructure systems.

708: Supervised Learning of Constitutive Laws

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Zeliang Liu, Northwestern University
Wei Chen, Northwestern University
Wing Kam Liu, Northwestern University

In this work, we apply the state-of-the-art computational methods to the analysis and design of heterogeneous hyperelastic composites. Specifically, we investigate how the effective behavior of a hyperelastic composite can be predicted through the knowledge of its morphology and constituent properties. Hyperelastic materials such as reinforced rubbers and biological tissues cannot be analyzed in the same manner as linear elastic materials as they possess material and topological nonlinearities and oftentimes undergo large deformations. This means that the general form of the constitutive law is not known a priori and the superposition principles developed for linear materials break down. Several methods have been introduced in the past to address these issues: extended analytical homogenization techniques, concurrent numerical multiscale, and decoupled multiscale analysis. In this work, we build on the latest developments on the decoupled analyses. In particular, we first characterize the effective behavior of a representative volume element (RVE). The characterization in our case essentially consists of (1) building a training dataset by calculating the potential energy density (i.e. via finite elements) associated with an RVE under various boundary conditions, constituent properties (i.e. Young's modulus of the inclusions), and morphological features (i.e. the volume fraction of the inclusions in the matrix), and (2) fitting a concise and efficient model to the aforementioned dataset via various supervised learning approaches such as multi-response Gaussian processes. Once an RVE is characterized, we use the supervised learner as the effective constitutive law of the RVE at the microscale to obtain the stress-strain relation at the macroscale. This procedure not only allows one to investigate the effect of each parameter of the constitutive law of the RVE (i.e. morphological ones) on the macroscale response of the composite material, but also significantly reduces the computational costs associated with multiscale analysis and design.

319: Sustainability Score for Urban Systems

Ruda Zhang, University of Southern California
Roger Ghanem, University of Southern California

Commoditization of sensor and communication technologies has made extensive instrumentation at the urban scale possible. Together with recent advancement in open data, researchers in urban science are presented with troves of data in unprecedented volume. Here we propose an aggregate score function to quantify the sustainability of an urban area, in an effort to integrate the various metrics and indicators relevant to urban sustainability that can be derived from available datasets. Our model captures three aspects affecting the sustainable development of an urban area, which we refer to as access, exposure and equity. Access indicators correspond to access to resources (e.g. top public K-12 schools) at the society level; exposure indicators correspond to exposure to hazard at the society level, e.g. citizen exposure to transportation-induced contamination. Borrowing methodology from multiple-criteria decision-making, our model is able to integrate arbitrary numbers of indicators given certain independence conditions. Equity refers to the distribution of access and exposure indicators over communities within a society, and is specified consistent with preferential orderings of indicator distributions. Later we apply our sustainability score function to scenarios of infrastructure investment. Improvements in sustainability score are compared to identify the optimal resource allocation portfolio. Our study examined urban areas like Portand and New York City. In this presentation, I'll also cover advanced analysis tools and computing techniques we deployed to handle the challenges of massive datasets.

162: Sustainability under Multiple Hazard Exposure: Life-cycle analysis for Bridges

Navya Vishnu, Rice University
Jamie Padgett, Rice University

Performance of bridges is critical in a transportation network, especially in the recovery phase after the occurrence of an earthquake or hurricane. Inadequate structural performance of a bridge can have an adverse social, economic and environmental impact on the network. Life-cycle sustainability analysis (LCS-A) of a bridge can help us understand the environmental effect of a bridge's performance in terms of indicators/metrics like energy embodied and carbon dioxide emissions. Apart from loads like earthquakes, hurricanes, service truck loads, bridges also undergo deterioration due to aging or corrosion. Multi-hazard risk analysis of bridges has gained momentum recently and the LCS-A framework should be extended to incorporate effect of multiple threats throughout the life-time of a bridge. This paper formulates an LCS framework to incorporate effect of multiple hazards and aims to illustrate how sustainability metrics vary for life-time exposure to different hazards. Regular maintenance and repair activities post-hazard events can lead to closure of bridges and in turn incur additional life-cycle costs due to re-routing. The LCS-A illustrated in the paper includes these maintenance as well as repair activities to quantify sustainability metrics. The application of the outlined LCS framework to case-study bridges will demonstrate the benefits of regular maintenance on corroded bridges in mitigating damage under multi-hazard exposure, in terms of life-cycle sustainability costs.

212: System Identification and Bayesian Model Updating of a Cable-Stayed Bridge Through Long-Term Structural Health Monitoring Using Wireless Smart Sensor Networks

Parisa Asadollahi, University of Kansas
Jian Li, University of Kansas

Recently, a long-term deployment of wireless smart sensor networks was carried out on a cable-stayed bridge in South Korea. With a dense array of 113 smart sensors, the deployment features the world's largest wireless sensor network for civil infrastructure monitoring. The long-term deployment collected a large amount of vibration data, which presents an excellent opportunity to understand the statistical feature of the modal properties of the bridge, which in turn enables quantification of uncertainties of the structural model itself. This presentation will first introduce a statistical analysis of the identified modal properties (natural frequency, mode shape, and damping ratio) of the bridge based on long-term ambient vibration data monitored during a 12-month period of the deployment. Bayesian statistical finite element model updating was then performed utilizing the large set of identified modal frequencies and mode shapes. Hybrid Monte Carlo Simulation was used to draw samples from the joint poster distribution to estimate the mean and variance of each updating structural parameter. Practical issues such as computational cost related to Monte Carlo simulation based on the large finite element model of the bridge will be discussed. The results demonstrated the benefit of long-term monitoring using dense wireless smart networks for quantifying uncertainties of dynamic behavior as well as structural parameters of large-scale civil engineering structures.

573: System Reliability Analysis of Wood-Sheathed Cold-Formed Steel Diaphragm Subsystems

Aritra Chatterjee, Virginia Tech
Cristopher D. Moen, Virginia Tech
Sanjay R. Arwade, University of Massachusetts Amherst
Benjamin W. Schafer, Johns Hopkins University

Simulation based system reliability estimates are obtained for a wood sheathed cold-formed steel floor diaphragm subsystem. The diaphragm represents the second floor of a two-story cold formed steel framed building recently tested in shake table experiments by researchers at the Johns Hopkins University. The goal is to calculate system reliability sensitivities for the floor diaphragm– defined as derivatives of system reliability with respect to component reliabilities. The sensitivities can inform modifications in target component reliability indices used in design codes to account for system effects. High fidelity finite element models are developed for the as-designed floor system using the commercial software ABAQUS. Cold-formed steel framing, clip angles, blocking, strap bracing and wood sheathing are modelled as shell finite elements. Steel-to-steel and wood-to-steel connections are modelled as ABAQUS multi-linear spring elements that are experimentally characterized by applying shear loads to single fastener assemblages. Deterministic geometrically and materially nonlinear simulations indicate that the connections govern system response to in-plane lateral loads which is consistent with the literature and design assumptions. A set of system models with randomly sampled fasteners are simulated to failure to stochastically characterize the system capacity, which is then numerically convolved with the random system load to obtain failure probability estimates. The simulations also provide estimates for component demand to capacity ratios and reliabilities, and correlation coefficients between system and component strengths which characterizes their relative importance to the system.

470: System Reliability of Cold-Formed Steel Framed Shear Walls

Guanbo Bian, Johns Hopkins University
Aritra Chatterjee, Virginia Tech
Stephen Buonopane, Bucknell University
Sanjay Arwade, University of Massachusetts Amherst
Cristopher Moen, Virginia Tech
Benjamin Schafer, Johns Hopkins University

The objective of this paper is to examine the reliability of cold-formed steel framed shear walls with a particular emphasis on walls sheathed with wood structural panels. A sheathed cold-formed steel framed shear wall is a system consisting of studs, tracks, and sheathing often with bridging and/or blocking, connected with steel-to-steel and sheathing-to-steel fasteners. The shear walls may be integrally connected to foundations, floors, or other shear walls through a variety of means including hold downs, straps, diaphragm chords and collectors, etc. Shear wall lateral resistance in cold-formed steel framed buildings varies because of the randomness in the components and connections that comprise the wall. For example, chord stud buckling and sheathing-to-stud fastener damage are two possible failure modes in cold-formed steel framed shear walls. In wind and seismic design, the reliability approach in current code differs with respect to the chord stud stability design and this treatment of chord stud buckling can have an impact on the shear wall system reliability. Although the nominal strengths for different shear wall configurations are stated in the current design codes, variability of shear wall lateral capacity is not explicitly considered. The existing reliability factors are extrapolations from steel diaphragm testing. To explore shear wall reliability Monte Carlo simulation of a shear wall under monotonic loading with random fastener property is conducted based on a fastener-based OpenSees model. Variability in fastener Pinching04 material model is considered based on separate fastener tests. Statistical properties of shear wall strength, demand capacity ratio of key fasteners, as well as correlation between fastener strength and shear wall strength are all explored. The results from this work are useful for shear wall stability design with analysis-based models and uncertainty quantification. The long-term goal of this research is to incorporate shear wall reliability analysis into system reliability models of cold-formed steel framed buildings.

111: Temperature and Moisture Effects on the Hurricane Wind Field based on A Simplified Model

Reda Snaiki, University at Buffalo--SUNY
Teng Wu, University at Buffalo--SUNY

Temperature and moisture demonstrate quite rapid changes with time and space as depicted by a number of field measurements and could have significant effects on the hurricane hazard modeling. As the theory predicted, the global climate-change causes extra heat and moisture in the troposphere. Hence it would be interesting to investigate the roles of these two factors and assess their contributions to the wind field inside the boundary layer of a hurricane. This paper discusses the thermodynamic constraints and the sensitivity of a new proposed wind field model to several major parameters of the equations. The pressure expression used in this paper depends not only on the temperature and the moisture but takes also into account the variation of the central pressure with respect to the height. Both temperature and moisture were incorporated in the simplified model by using the virtual temperature which may be the easiest way to proceed. The model was compared with the one proposed by W.F. Huang et al. (2011) which is basically based on Meng et al. (1995) model and includes the temperature effects. The results obtained indicate that the current model gives more accurate representation of the wind speed and profile.

551: Temperature Effects on Modal Properties of an Updated Full Scale FE Model

Jinwoo Jang, Columbia University
Andrew Smyth, Columbia University

When identifying model properties of structures, an ambient dynamic testing is generally the most feasible and therefore popular since there is no need for a specific excitation device which might induce damage and would lead to added cost. However, modal properties of structures in operational conditions are affected by various environmental factors such as the changes of temperature and the amount of traffic. It has been observed that identified natural frequencies vary over a 24 hour period as well as over a year period. A better understanding of the environmental effects on natural frequencies can help increase the accuracy of the system identification techniques. In addition, it is also critical for damage detection because the changes in model properties due to the environmental effects should be separated from possible damage. In this presentation, the temperature effects on natural frequencies and mode shapes are studied using an updated full-scaled FE model. Pre-stresses in the structural components due to thermal expansions are used to model the temperature effects on the natural frequencies and mode shapes. Uniform and non-uniform distributions of temperature are used to study the fluctuation of the natural frequencies. Moreover, the multiple combinations of temperature fields are applied to the deck of the model. Based on the various temperature fields and the corresponding natural frequencies, a regression analysis is conducted to study their relationship.

507: Temporal Coherence in Turbulent Wind Fields: Modeling and Simulation

Jennifer Rinker, Duke University
Henri Gavin, Duke University

In the simulation of stochastic fields through spectral representation, complex spectra with uniformly distributed and uncorrelated phases are equivalent to stationary and Gaussean processes. Many natural phenomena, including wind velocity fields, however, are neither stationary nor Gaussean. This presentation describes a generalization of the spectral representation method that permits the simulation of nonstationary processes and fields. In this generalized spectral representations method, the difference between the phases at adjacent Fourier frequencies are drawn from a circular distribution, and cumulatively summed to form the phases of the complex spectrum. The parameters of this circular distribution describe the central tendency of the distribution and the location of the mode of the distribution in the domain (-pi to pi]. Processes with high concentration in the phase-difference distribution are said to be 'temporally coherent.' This approach is illustrated in the analysis and simulation of nonstationary wind fields. The complete model is parameterized by the joint distribution of these two parameters along with the mean wind speed, the turbulence, and the Kaimal length scale. This joint distribution is calibrated to a very large set of wind data collected at the National Renewable Energy Lab, (Boulder CO). The spatial correlation of independent process with similar concentration and location parameter values can lower the temporal coherence of the correlated field. Three sample cases are presented to examine the effects of different parameters on this reduction in temporal coherence, and a two-sample Kolmogorov-Smirnov test is used to demonstrate that this reduction is negligible in practical scenarios. Finally, implications of the effects of temporal coherence on wind turbine design loads are summarized.

610: Temporal Probabilistic Capacity Models of Prestressed Concrete Piles in Corrosive Marine Environments using Metamodeling Techniques

Jieun Hur, The Ohio State University
Abdollah Shafieezadeh, Ohio State University

Seaports are one of the critical infrastructures for national and international trade in the U.S. In addition, these systems play strategic roles in the aftermath of potential natural disasters in delivering immediate aid following hazard incidents and the recovery of affected areas. Damage to pile-supported wharves and cranes in Port-au-Prince during Haiti Earthquake in 2010 is one of the examples that highlight the vulnerability of these structures and the potential dire consequences. However, seismic risk evaluation of seaports is challenging as structural components in these systems and the soil-structure interactions exhibit complex nonlinear behavior during seismic events. In addition, due to exposure to the marine environment, the chloride-induced corrosion of steel reinforcement in piles degrade the structural performance of wharves over long periods; a phenomenon that is temporally and spatially stochastic. The deterioration of the capacity of wharves may have a significant impact on the seismic fragility of seaports; therefore, this factor must be accounted for in the initial design and retrofit of wharves. Addressing this objective requires development of predictive models for the capacity of concrete piles considering the large number of variables that impact the long-term performance of the piles and the uncertainties in these parameters. This study focuses on prestressed concrete piles and presents a framework for developing temporal probabilistic capacity models for these components when subjected to lateral forces. Detailed finite element models for piles are used to account for the nonlinear behavior of concrete, steel tendons, concrete-steel bonding, and pile-soil interactions. A time-dependent probabilistic chloride-induced deterioration model predicts pitting corrosion of steel tendons. The framework considers uncertainties in various environmental, structural, and material parameters that affect the capacity of the piles. Latin Hypercube Sampling (LHS) technique is employed to efficiently generate random realizations of involved parameters considering their spatial correlations. Each sample set is used to generate a finite element model of the pile with nonlinear soil springs; the structural performance of these models against lateral loadings is evaluated in the object oriented platform OpenSEES. A meta-model based on Kriging approach is generated using structural simulation results of deteriorating piles to reliably predict the capacity of these components as a function of age, environmental factors, and a set of design parameters. Results of this work provide a valuable tool for sustainable design, maintenance, and retrofit of prestressed piles in marine environments.

777: Tensegrity Topology Optimization on Ground Structures

Ke Liu, Georgia Institute of Technology
Glaucio Paulino, Georgia Institute of Technology

We propose an optimization formulation for the form finding problem of tensegrity. Tensegrity, originally as an art form, has now attracts tremendous interests in the field of engineering, due to its simplicity in components, reconfigurability/deployability, as well as the intrinsic aesthetic pleasantness. However, to design a tensegrity form that is suitable for specific applications is still a big challenge. Various numerical methods have been proposed in the literature but most of them require a "clever" choice of topology a priori for finding a self-equilibrating configuration, so there is no precise control over the geometry of the final design. However, sometimes it is important that the tensegrity structure has to adapt to a predefined domain or boundaries, and the topology of the tensegrity can be freely chosen. The proposed method is a topology design method that finds a tensegrity given certain geometry. A mixed integer linear programming (MILP) is performed based on the ground structure approach. The method provides a different perceptive of tensegrity design that emphasizes more on the geometry of the final design rather than the topology. In other words, the proposed method adapts topology to prescribed geometry, unlike the common way of tensegrity form-finding that adapts geometry to given topology. The method are further equipped with the capability of avoiding physical contacting of members and constraining of member lengths and member connectivity. We show that the obtained designs are prone to be stable structures. We also constructed the real models designed by the proposed method to exhibit the potential to be applied to design for real applications.

91: The Adaptive Wavelet Enhancement of the Crystal Plasticity Finite Element Method

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Computational simulations of crystal plasticity based on realistic microstructure are computationally costly. This arises from the high number of degree of freedoms required to accurately encompass the geometry and the local phenomenology. Efficient discretization is then critical for problems that introduce localization, such as shear banding, twinning or fracture. We have developed an adaptive enrichment scheme that would selectively allocate degrees of freedom when and where necessary in the simulation. Crystal plasticity simulation have recently been developed with Fast Fourier Transform (FFT) based methods in order to accelerate the solving part of the simulation. However, such methods rely on a basis of global periodical functions that cannot capture local discontinuities with a high convergence rate. Hence, we propose a local enrichment scheme to extend the current conventional FEA framework. In our method, a wavelet decomposition scheme is used to analyze error indicators in order to provide a basis of enrichment functions. The wavelet family is chosen such that the enrichment functions constitute a hierarchical finite element basis. These functions are introduced adaptively in the FEM scheme to locally enrich the solution. The novelty of this method is that the enhanced discretization basis is conform to the error profile. A comparative study between FFT and FEM strategies is presented to justify our approach. The implementation of the Adaptive Wavelet Enhancement method is discussed. The efficiency of the method is demonstrated on a polycrystalline crystal plasticity example.

286: The Critical Role of Interdependency in Infrastructure Resilience to Natural Hazards

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The civil infrastructure of a modern community is highly interdependent. Accurately capturing the influence of this interdependency is critical to understanding the performance of the infrastructure in the event of a hazard. In this paper, the characterization of interdependency is explored as a relationship among the lifelines that comprise the civil infrastructure whether they are modeled as networks or systems. The role of interdependencies in maintaining infrastructure performance changes for pre-, trans- and post-hazard event conditions. Interdependencies that emerge post-event have received the most attention from engineers and emergency managers because response and recovery efforts are critical to community resilience, and are often hampered by such relationships. The nature and complexity of the interdependency evaluation depends in large part upon the spatial and temporal scale at which the lifelines are modeled: Some researchers implement a "network of networks" approach, while others examine resilience though interdependent "system of systems" approaches. In this paper, the two different modeling approaches and their relative benefits are examined using case studies. Interdependency metrics will be derived from community resilience models incorporating the functions of hazards, vulnerability and consequences. Interdependency influences each of these constituent elements in different ways. The interdependent nature of lifelines can influence the degree to which one hazard such as flooding will affect the lifelines in a community versus that of another hazard. Vulnerability can be modeled through structural fragility functions, which are defined here as the "conditional probability of failure given levels of hazard intensity". Interdependency may make some lifelines more robust, i.e., less vulnerable, while in other cases, the opposite may be true. The consequences of the hazard will be modeled here through the response and recovery of the lifelines. That is, the capability of each lifeline to provide necessary services for the proper functioning of society is modeled to assess, in part, community resilience. In this regard, interdependency may play another role. For example, some aspects of communication lifeline recovery depend upon electric power delivery recovery because both systems use the same underlying support systems comprised of poles, towers and lines. The availability of water supply often depends on electrical power. In addition, because society depends upon these lifeline services, an investigation into acceptable thresholds for them at the community level is underway.

174: The Effect of Water Molecules on Mechanical Properties of Bamboo Microfibrils

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Bamboo fibers have higher strength-to-weight ratios than steel and concrete. The unique properties of bamboo fibers come from their natural composite structures that comprise mainly cellulose nanofibrils in a matrix of intertwined hemicellulose and lignin called lignin-carbohydrate complex (LCC). Here, we have utilized atomistic simulations to investigate the mechanical properties and mechanisms of interactions between these materials, in the presence of water molecules. Our results suggest that hemicellulose exhibits better mechanical properties and lignin shows greater tendency to adhere to cellulose nanofibrils. Consequently, the role of hemicellulose found to be enhancing the mechanical properties and lignin found to be providing the strength of bamboo fibers. The abundance of Hbonds in hemicellulose chains is responsible for improving the mechanical behavior of LCC. The

strong van der Waals forces between lignin molecules and cellulose nanofibrils is responsible for higher adhesion energy between LCC/cellulose nanofibrils. We also found out that the amorphous regions of cellulose nanofibrils is the weakest interface in bamboo Microfibrils. In presence of water, the elastic modulus of lignin increases at low water content (less than 10%) and decreases in higher water content, whereas the hemicellulose elastic modulus constantly decreases. The variations of Radial Distribution Function and Free Fractional Volume of these materials with water suggest that water molecules enhance the mechanical properties of lignin by filling voids in the system and creating Hbond bridges between polymer chains. For hemicellulose, however, the effect is always regressive due to the destructive effect of water molecules on the Hbond of its dense structure.

434: The Establish of Particle Fracture Model in 3-Dimensional Discrete Element Method and its Application in Compression Simulation at High Strain Rate

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The fracture of sand grains is very important to the mechanical properties of soils, such as strength, permeability and so on. We proposed a numerical model to study the fracture behaviors of sand grains in Discrete Element Method (DEM) with poly-ellipsoidal particles. In this model, the DEM particle can be fractured by its average stress state and/or the maximum tensile stresses in contacts area. The Weibull function has been introduced to show the statistics and size effects of the strength of sand grains. Then the force-displacement curve in experiment of single particle fracture is fitted to calibrate our model. The effects of the packing of soil samples and the effects of the different break planes on the fracture behaviors have been studied. Finally the simulation of uniaxial compression at high strain rate (~1000/s) has been conducted to study the comminution process of soils under dynamic loading.

656: The f-Sensitivity Index

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This article presents a general multivariate f-sensitivity index, rooted in the f-divergence between the unconditional and conditional probability measures of a stochastic response, for global sensitivity analysis [1]. Unlike the variance-based Sobol index, the f-sensitivity index is applicable to random input following dependent as well as independent probability distributions. Since the class of f-divergences supports a wide variety of divergence or distance measures, a plethora of f-sensitivity indices are possible, affording diverse choices to sensitivity analysis. Commonly used sensitivity indices or measures, such as mutual information, squared-loss mutual information, and Borgonovo's importance measure, are shown to be special cases of the proposed sensitivity index. New theoretical results, revealing fundamental properties of the f-sensitivity index and establishing important inequalities, are presented. Three new approximate methods, depending on how the probability densities of a stochastic response are determined, are proposed to estimate the sensitivity index. Numerical examples, including a computationally intensive stochastic boundary-value problem, illustrate these methods and explain when one method is more relevant than the others.

References: 1. Rahman, S., "The f-Sensitivity Index," accepted in SIAM/ASA Journal on Uncertainty Quantification, 2015 (In Press).

484: The Impact of Recovery Time on the Lifecycle Performance of Infrastructures Exposed to Multiple Occurrences of Multiple Types of Hazards

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Infrastructure systems may experience multiple hazard incidents of various types during their lifetime. These events can affect the structural integrity of systems and degrade their functionality. The repair time after each incident depends on many uncertain factors such as the extent of damage, the type of retrofit and repair strategy, and socio-economic factors. While the repair of damage from prior incidents is underway, there is a non-negligible chance that new hazard events may occur. In such cases, the existing condition of the system impacts its performance during next events. Given the stochastic nature of hazard incidents of various types and the uncertainty in the repair times, it is imperative to develop a comprehensive probabilistic framework for optimal retrofit and repair decision-making of infrastructures subject to multiple-occurrences of multiple types of hazards. Lifecycle cost has been used in the past as a common performance measure to compare various retrofit options. However in many of these studies, the performance of the system was assessed for the occurrence of a single hazard incident. In others where multiple hazards were considered, either effects of repair time were disregarded or not properly addressed, or the framework required intensive scenario-based nonlinear structural simulations. To address these limitations, this study proposes a risk-informed retrofit decision-making approach using lifecycle cost as the performance measure. For a predefined time-horizon, the initial cost of retrofit action, lifecycle maintenance cost, potential lifecycle restoration cost, and the salvage value of the system at the end of its lifetime are considered. The restoration cost accounts for all possibilities of multiple occurrences of multiple types of hazard incidents through a novel recursive algorithm that utilizes damage state-dependent fragility curves for the evaluation of the expected condition-state of the system at each occurrence of any type of hazard incident. The proposed method also incorporates the two possibilities of system repair status i.e. complete or incomplete repair based on probability distribution functions of repair times. The proposed method is demonstrated for a bridge system that is subject to flood-induced scour and earthquake hazards. Lifecycle costs of several retrofit options are compared and effects of recovery time variation on the optimal retrofit decision-making are investigated and discussed. The suggested method provides a capable yet practical framework for risk-informed lifecycle cost management of infrastructures to further enhance their resilience against adverse effects of multi-hazards.

425: The Influence of Random Microstructure on Wave Propagation through Heterogeneous Media

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In this presentation the influence of mechanical and geometrical properties of a heterogeneous periodic composite material, both deterministic and stochastic in nature, on wave propagation will be discussed from the position of stop band phenomenon. We will discuss numerical analyses used to identify parameters that have the most significant effect on the wave filtering properties of the medium. The discussion will start with a one dimensional solid periodic laminate material. Further, randomness will be added to the material properties (mechanical and geometrical) to investigate its effect on the stop band properties. We will look into different types of randomness: starting from small perturbations on the periodic structures, we will then look into quasi-random (Fibonacci based) properties and finish with fully random properties. The stop band phenomenon will also be studied for two dimensional samples with deterministic and random material microstructure. Special attention will be given to the prediction of the first stop band frequency with numerical analysis of an explicitly defined heterogeneous structure compared and confirmed by results obtained using gradient theory (specific type of multi-scale approach, based on analytical homogenisation) and analytical derivations.

526: The Mechanics of Biomimetic Polymer Artificial Muscles

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Matthew Fisher, Northern Arizona University

Polymer monofilaments such as fishing lines and some sewing threads are actually composed of many polymer chains aligned along the length of the filament. When a monofilament is twisted, these polymer chains become wrapped into a helical shape. The helical monofilament can then be twisted further until it wraps around itself into a coiled shape. These drawn polymer monofilaments have anisotropic thermal expansion, such that the filament radius increases with heat while the length of the filament remains relatively constant or shrinks. When twisted, this anisotropic thermal expansion results in an “untwisting” of the filament upon heating. This untwist manifests itself as a contraction when the twisted monofilament is coiled and heated. The result is an extremely powerful, lightweight, and inexpensive thermally-activated actuator whose specific load capacity is higher than human muscle [Haines et al. 2014]. Due to their extreme force to weight ratio, coiled polymer actuators have the potential to propel a number of applications that require low mass actuation. Devices such as prosthetic limbs strive to be lightweight for user comfort. Robotic applications requiring actuation currently employ standard electromagnetic motors or pneumatically/hydraulic McKibben actuators, both of which have drawbacks including design complexity for linear actuation and the routing of high pressure fluids lines. The promise of a low mass, high force solution could decrease mass allocation and design complexity of a number of robotic devices. Research efforts on this coiled nylon have focused on experimentally exploring the actuation phenomenon and characterizing actuator performance [Cherubini et al. 2015, Haines et al. 2014, Moretti et al. 2015]. Due in part to the novelty of these devices, the complex geometry of the coiling, and the experimental challenges in model validation, there has yet to be any significant efforts in the analytic modeling of these synthetic actuators. In this work, we develop a preliminary model for the 1D mechanical behavior of the twisted monofilament. In this preliminary model, we consider a twisted (not coiled) single polymer chain, i.e. a single fiber. Using classical methods in mechanics, we develop an elastic relationship between applied torque and temperature changes and the resulting rotation of the fiber. The 1D model is compared to experimental results.

584: The Mesoscale Texture of Cement Hydrates

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Strength and other mechanical properties of cement paste and concrete rely upon the formation of calcium-silicate-hydrates (C-S-H) during cement hydration. Despite the potential for technological transformation, controlling the structure and properties of C-S-H phase is still a challenge, due to the complexity of this hydration product and of the mechanisms that drive its precipitation from ionic solution upon dissolution of cement grains in water. Departing from traditional models that are mostly focused on length-scales above the micrometer, molecular models have recently addressed the nanometer-scale structure and properties of C-S-H. However, small angle neutron scattering, electron-microscopy imaging, and mechanical nano-indentation experiments, all suggest that an even more important role is played by the mesoscale organization of the C-S-H structure that extends over hundreds of nanometers. New quantitative models are needed to address this unexplored mesoscale, elucidate the experimental observations, and complete the understanding of the multi-scale structure of cement paste. Here we present a novel description of the C-S-H meso-structure that offers an opportunity to translate results from the fundamental scales to the macro-scale of engineering properties. We use simulations that combine information of the nano-scale building units of C-S-H and on their effective interactions, obtained from atomistic simulations and experiments, into a statistical physics framework for aggregating nanoparticles. We compute small angle scattering intensities, pore size distributions and nano-indentation modulus and hardness, providing a new quantitative understanding of the relevant features observed experimentally. Our results suggest that speci fic heterogeneities developed during the early stages of hydration persist in the structure of C-S-H, impacting the rheological and mechanical performance of the hardened cement paste. Understanding and controlling this pro-cess in C-S-H can be the key to smarter mix designs of cementitious materials.

578: The Role of Interior Gravity Columns on Blast-Induced Progressive Collapse Potential of Tall Buildings

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Simos Gerasimidis, University of Massachusetts Amherst
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Progressive collapse of buildings may be triggered by extreme loading conditions such as vehicle impact, fire, blast events, structural design or construction defects etc. Recent terrorist attacks have initiated extensive research on the quantification of structural robustness by employing threat-independent methods that introduce damage through loss of key load-bearing elements (Alternate Load Path Method). However, such simplified threat-independent methods fail to incorporate the role of distributed damage caused by real-threat blast scenarios on the collapse mechanisms of structures. The scope of the current work is to investigate the behavior of 3D steel buildings subjected to external blast loading and establish a methodology to assess the progressive collapse vulnerability. The methodology proposed includes four consecutive steps that simulate the sequence of loading events, accounting for spatially distributed damage and response of structural members. Through 3D non-linear dynamic finite element analysis of a tall steel building under an external blast scenario, the role of interior gravity columns as the most critical components of the structural system is identified, since their response governs the overall stability of the building.

499: The Three-Dimensional Response of Magnetic Shape Memory Alloys

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Magnetic shape memory alloys can exhibit either magnetic field or stress induced martensite reorientation. Because the martensitic phase consists of tetragonal unit cells, when a compressive stress is applied to the material, the short axis of the unit cell tends to align with the direction of the compressive stress. The magnetic easy axis for the internal magnetization vector is approximately aligned with the short side of the unit cell. When the material is placed in a magnetic field, the magnetization vectors tend to align with the external field in order to minimize the magnetic potential energy of the material. This is achieved by rotating the internal magnetization vector away from the magnetic easy axis and towards the external field and/or by reorienting from one variant to another. Researchers have attempted to predict the magneto-mechanical behavior of magnetic shape memory alloys (MSMAs) for over a decade, but all of the models developed to date have only been validated against experimental data generated under two-dimensional loading conditions. As efforts have been underway to develop models able to predict the most general (i.e. 3D) loading conditions for the material, there is a need for experimental data to support the calibration and validation of these models. This paper presents magneto-mechanical data from experiments where a MSMA specimen whose microstructure accommodates three martensite variants is subjected to three-dimensional magneto-mechanical loading. To the best of our knowledge, all prior experimental investigations on MSMA have been performed on samples accommodating two martensite variants and exposed to two-dimensional magneto-mechanical loads. The experimental results from the 3D loading of the three variant MSMA specimen are used to calibrate and validate a 3D model developed by this group [LaMaster et al. (2014)]. This model assumes that three martensite variants coexist in the material. Based on the experimental findings, this model has been modified, and specifically the hardening function in this model is revised in this work. Results show that the LaMaster et al. model captures the general trends seen in the experimental data, but does not predict the data with a high degree of accuracy. Possible reasons for the mismatch between experimental data and model predictions include mechanisms missing in the model and the fact that the model is at a material point, and therefore cannot capture the boundary conditions of the experiment. Future work will include additional model improvements and implementation of the model into finite element software.

276: The Use of Shape Memory Alloys in Near-Surface Mounted Strengthening Applications

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Over their lifetime, reinforced concrete elements experience degradation due to various aging factors under structural and environmental effects. Moreover, many of the existing structures were designed according to old standards that do not meet the current design requirements. Therefore, there are a large number of reinforced concrete structures that need to be either rehabilitated or strengthened. Fiber reinforced polymer (FRP) composites have been favored over conventional strengthening materials due to their lightweight, high strength-to-weight ratio, and their high corrosion resistance. FRPs have been utilized in strengthening applications as either externally bonded (EB) systems, where FRP plates or sheets are bonded to the external face of the concrete, or as near-surface-mounted (NSM) reinforcement, where FRP bars or strips are inserted in longitudinal grooves cut into the concrete cover and bonded with an epoxy paste or cementitious material. Compared to the EB systems, the NSM technique has several advantages such as limited surface preparation or treatment, improved bond, protection of the reinforcement against mechanical and environmental damage, better aesthetics, and possibility to strengthen members in their negative moment regions. Although the NSM reinforcement can preclude delamination-type failure, one of the main factors that affect the efficiency of the NSM method is still the bond between the NSM reinforcement and the concrete. In addition, the FRP rods and laminates could not achieve full material strength due to bond and anchorage problems. An active strengthening technique where the NSM reinforcement is prestressed can lead to better utilization of the NSM material and enhance the serviceability by reducing the crack size/extent and service load deflections. Yet, the studies on the prestressed NSM applications have been limited due to the difficulty in prestressing the NSM reinforcement. This study explores passive and active NSM strengthening techniques with shape memory alloys (SMAs) to eliminate the problems associated with using FRPs as NSM reinforcement. Three-point bending tests are conducted on scaled concrete beams that are strengthened in flexure with NSM superelastic and heat-activated SMAs. The results of experimental tests are assessed through considering various factors such as cracking load, yield load, ultimate load, failure modes, and tensile strain in NSM reinforcement.

3: Theoretical Background of Steel Storage Tanks Buckling Design Equations: Assumptions and Limitations

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Empty steel storage tanks with thin walls are vulnerable to buckling under wind and other external pressure loading. Buckling of cylinders due to uniform external pressure has been extensively studied both experimentally and analytically. To stiffen thin-walled cylindrical shells, stiffening rings are frequently used. Von Mises' buckling equations may be used as a starting point to find an expression for the maximum allowed distance between the stiffening rings. Buckling design of step-wise cylindrical storage tanks is very similar to the buckling design of cylinders of uniform thickness. The current design provisions in API Standard 650 "Welded Tanks for Oil Storage" rely on the theoretical background used for uniform thickness cylinders; which may produce conservative designs. The assumptions and derivation steps used to arrive from the analytical expression of von Mises to the simplified API 650 design equations are discussed in this talk. The sizing of the stiffener rings does not follow a purely analytical approach like the distance between the rings but rather an intuitive approach coming from experience. This work explores the API 650 approach for designing stiffener rings for storage tanks. We investigate the different assumptions on the derivation of the buckling design equations in the API 650 standard. The current design methodology is overly conservative because of these assumptions. The original expressions with the underlying assumptions are presented as well.

705: Thermally Activated Building Envelope for Integrated Hazard Mitigation and Thermal Load Management: An Inspiration from Homoeothermic Animal Skin

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Currently, the dominant modes of building heating and cooling are air-based HVAC; however, air is, in fact, a poor medium for distributing thermal energy. Further complications arise as infiltration, buoyancy, and convection of airflow makes the heat flow in the building inefficient and unpredictable. Lessons are taken from nature for efficient energy management and distribution using fluids; specifically, homoeothermic animals regulate deep and surface body temperature through hydronic exchanges with the circulatory and integumentary systems that use the skin as thermal source and sink. Owing to the capillary mat blood vessels and regulated blood flow, living skin develops an extraordinarily high thermal emissivity and absorptivity. Analogous to animal skin, the two primary functions of building envelope systems are managing the thermal load of its enclosed spaces and protecting the occupants from hazardous external environments. However, to date, the designs of building envelope components against structural and thermal loads are carried out separately using isolated approaches. Achieving seamless integration of building envelope's structural and thermal load management functionalities will lead to a substantial improvement in the system-level energy efficiency. This research seeks to utilize hydronic circuits, embedded in the load-bearing structural backbone, to create next-generation envelope systems that are capable of performing the full range of structural functions, while in the meantime, possess the ability to convey and distribute thermal energy for building thermal load management. The initial work was inspired by the thermoregulation mechanism of homoeothermic animal skins and the recognition of the impacts of fluidic properties on both the mechanical and heat conductive properties of hydronically activated systems. For the purpose of concept demonstration, light-frame envelope components were prototyped via a unique "monolithic"

approach, where hydronic circuits are internally built-in an agricultural waste, plant fiber-based sheathing for active temperature conditioning. The performance of the hyronically activated light-frame envelope were investigated experimentally at both material and component levels; and the effects of the embedded pipelines and their topology on the component's structural and energetic efficiencies were studied in conjunction with temperature and the cooling/heating conditions. The results indicated that the internally built-in hydronic channels within building envelope can tremendously improve building energy efficiency by effectively store and deliver thermal energy when and where it is needed. Meanwhile, by utilizing the high energy dissipation ability and high specific of fluids, the hydronically activated system has exhibited superior structural performance under hazardous load conditions (i.e., earthquake, wind-storm and fire).

147: Thermo-Mechanical Description of C45 Steel Over a Range of Temperatures and Loading Rates

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Understanding the behavior of any material is the most important phase prior to its use in order to assess its response against different exposures. This helps to identify the limitations of the material and design it to accommodate the factors that affect its physical characteristics. This research aims to describe the behavior of certain type of structural steel that is excessively used in environment where high temperatures and strain rates are applied. The primary goal is to understand the damage effect on the structural steel response under complex loading conditions and to be implemented in previously developed constitutive models. A series of experimental tests are conducted on C45 structural steel at different levels of temperatures and strain rates to extract the true stress – true strain behavior of the material. Dynamic tests are also conducted using drop hammer for strain rates up to 10^2 s^(-1). Scanning electron microscopy are utilized to measure the material damage at each test condition. The test results are used to develop a constitutive equation which describes the damage response in C45 structural steel plates to be integrated into a previous suggested constitutive model (VA Model). The results of the updated model are compared to the results of another suggested constitutive model (JC Model) for the purpose of validation and comparison.

207: Thermo-Mechanical Modeling of Reinforced Concrete Masonry Infill Panels Exposed to Fire

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Masonry infill-panels are widely utilized as structural and non-structural elements in construction industry due to their good thermal, moisture and acoustic insulation properties. Although these infill-panels significantly enhance the in-plane stiffness of the structural reinforced concrete (RC) frame, still they are relatively weaker under out-of-plane loading and are susceptible to partial or complete collapse under eccentric loading. This makes characterization of their behavior under fire very important as fire has strong potential for inducing such eccentric loadings as a result of degradation in structural material properties at elevated temperatures. This study details the development of a full-scale generic 3D finite element (FE) model, capable of characterizing both in-plane and out-of-plane behavior of RC masonry infill-panels under thermal exposure, using commercial FE software ANSYS. Concrete and masonry units have been modeled using solid elements while steel rebars have been modeled using the smeared reinforcement approach. The cracking of concrete and masonry is addressed using the Willam Warnke failure envelop (suitable for brittle materials), and the complex contact interactions in terms

of shear or tension de-bonding and sliding at the interfaces are modeled using the cohesive zone model of ANSYS. The transient thermal analysis is performed using the multiphysics capability of ANSYS which allows modeling of the real-time thermal response of the infill-panel under the desired fire exposure conditions considering the effects of conduction, convection, and radiation. In addition to modeling appropriate thermal boundary conditions during fire, the transient heat transfer at interfaces is also addressed using multiphysics interface elements to enhance the accuracy of the thermal model. The experimental data available in the literature has been utilized to validate the developed FE model that has been subsequently utilized to perform parametric studies. These parametric studies aim to quantify the effects of both standard and design fires on the key parameters such as load carrying capacity, initial stiffness, and stability of the infill panel for both in-plane and out-of-plane cases. It was observed that one-sided fire exposure can induce about 50 mm out-of-plane displacements in the infill-panels and can reduce the initial stiffness of these panels by about 30%. These insights in the behavior of such systems under thermal exposure can be further incorporated in the design process to improve their fire safety.

330: Three Dimensional Poroelastic Solution of an Inclined Borehole Subjected to Finite Length Fluid Injection

Shengli Chen, Louisiana State University

Hydraulic fracturing is the primary method of stimulation in unconventional reservoirs playing a significant role in oil and gas production enhancement. A key issue for the analysis of the hydraulic fracture initiation and propagation is to accurately determine the stress distributions, usually the tangential stress component, in the vicinity of the borehole caused by the fluid pumping as well as the drilling of wellbore. Due to the complexities of the mathematical formulations involved for two-phase porous media and the coupled nature between the pumping induced pore pressure and radial stress at the borehole surface, analytical formulas on the stress perturbation related to the hydraulic fracturing are not well established, even in an approximate matter. This paper presents an exact analytical solution for the poromechanical responses of a borehole inclined with respect to the three dimensional in-situ stresses and subjected to a finite length fluid discharge over its surface. The solution procedure proposed starts with solving directly the general poroelasticity governing equations by using the Fourier expansion theorem as well as the combine Laplace-Fourier integral transform technique. The hydraulic fracturing problem addressed is then decomposed into five fundamental, easier to handle modes based on the superposition principle. The mixed and coupled boundary value problem, for each of the individual modes, is found to be equivalent to solving a set of dual integral equations with the transformed total stress at the borehole surfaced being the only unknown, which can be further reduced to a single Fredholm integral equation of the second kind and readily solved numerically. Extensive numerical analyses are finally carried out to examine the influences of the geometrical and mechanical parameters on the calculated effective tangential stress and pore water pressure distributions. The solution can be a powerful design tool for the petroleum production industry.

32: Three-dimensional DEM-CFD Coupled Modeling of Gas-particles Interaction in Supersonic Compressible Flows and Buried Landmine Blast Wave

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Richard Regueiro, University of Colorado

A two-way mechanical coupling code is developed to model the transient interaction between overlapped supersonic/subsonic compressible gas and solid particles or particles assemblage. The Gas domain (CFD) is resolved using Roe/HLLC/HLLE/Exact solvers of Riemann Problem of 3D Euler equations with high Mach number; and the particles domain is resolved using Discrete Element Method (DEM) tackling particle size, shape,

translation, rotation and inter-particle contact. An “internal porous drag” model is proposed though modifying classic Euler equations by incorporating a fictive particle porosity to approximate the gas-obstacle surface flow and satisfy a two-way goal: the particles acquire correct translational and rotational drag from the gas and the gas pressure around a particle is recovered in shock wave impact and agrees with classic results from aero-dynamics equations. Simulation of centrifuge explosion in sand (1 gram C4, 1 g-level, 5.1 cm DOB) has been successfully conducted using the two-way mechanical model: firstly particles are gravitationally deposited in terms of sand gradation curve; secondly a cavity inside the sand assembly is excavated to hold corresponding amount of explosive charges; lastly a spherical shock wave is blown from the explosive charge location beneath the sand assembly. The initial states of the explosion products are carefully examined against CJ/ZND explosion models and calibrated using laboratory scale explosion data. The sand particle motions predicted by the model agree so well with the centrifuge experiment captured using high-speed camera: velocities of top sand particle at early stage of 0.3 ms after detonation are 29.2 m/s and 28.9 m/s respectively. It is observed clearly that shock wave of detonation products is impeded by surrounding particles assemblage if compared to the situation without particles, and high pressure and velocity of the detonation products decay very quickly inside particles assemblage. The numerical simulation can be practically divided into two stages: 1. In-shock stage: blast wave/particles interaction in the time scale of milliseconds, which must be modeled by DEM-CFD coupling technique; 2. Post-shock stage: particles continue to move in the air (subjected to air drag) in the time scale of seconds, which can be modeled by DEM with simple air drag.

69: Three-dimensional Displacement Field of Isotropic Elastic Spheres

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In this paper, we consider a new framework of analyzing the three-dimensional solutions of elastic isotropic spheres. In particular, the general solution for the equilibrium equations in spherical coordinates can be obtained a superposition of three independent sub-problems. Each of these sub-problems are solved analytically. They reflect deformations corresponding to nonzero circumferential component of rotation vector (or curl of displacement vector), to nonzero radial component of rotation vector, and to nonzero longitudinal component of rotation vector separately. The Navier’s equations of equilibrium in displacement is first expressed in terms of a scalar function (or volumetric strain) and a vector function (or curl of displacement vector). Each sub-problem is formulated and is found governed by a system of two coupled partial differential equations, and a single displacement potential is proposed in each case to uncouple the partial differential equations. Separation of variables is used to convert the partial differential equation of the proposed displacement potential to two independent ordinary differential equations. After the displacement potential is solved, back substitution to the volumetric strain and rotation vector component leads to two nonhomogeneous partial differential equations for the two unknown displacements for each sub-problems. The final solution in displacement is expressed as sum of the homogeneous solution and the particular solution. The displacements for sub-problem I (corresponding to zonal harmonics) are expressed in terms of power of radial coordinate and Legendre polynomials in equatorial direction, sub-problem II in terms of powers some trigonometric functions, and sub-problem III in terms of powers of radial coordinate with its index being function of mode number and circumferential angle and circular function. The present framework of analysis should be more appealing than Lord Kelvin's approach expressing in terms of harmonic polynomials and than Lure's approach expressing in terms of harmonic Papkovitch-Neuber vectors in view of the physical meanings of the solutions.

439: Tightly Coupled Multiphysics Simulation of Alkali-Silica Reaction

Benjamin Spencer, Idaho National Laboratory

Hai Huang, Idaho National Laboratory

The U.S. Department of Energy's Light Water Reactor Sustainability (LWRS) program is performing research and development in support of long term operation of commercial nuclear power plants. As a part of this effort, a simulation code called Grizzly is being developed to model aging mechanisms and their effects on a variety of nuclear power plant systems, structures, and components. Nuclear power plants contain a number of large reinforced and prestressed concrete structures that are subject to many of the same aging mechanisms that can affect other civil concrete structures. Alkali-silica reactions (ASR) have been identified as a degradation mechanism in nuclear power plant concrete structures that warrants high priority research. The Grizzly code is based on an open-source multiphysics, parallel simulation framework developed at Idaho National Laboratory known as MOOSE. This environment permits the solution of partial differential equations using the finite element method, and has a modular architecture that permits the straightforward addition of new physics models. MOOSE employs a Jacobian-free Newton Krylov solver, which naturally supports the tightly coupled solution of systems of equations arising from multiple physics. This multiphysics environment has been employed to model the processes leading to expansive ASR. The extent of the expansive swelling due to ASR at a given location in a concrete structure is a strong function of the temperature and moisture conditions, as well as of the stress state. A set of code modules has been developed in Grizzly to solve a tightly coupled system of equations for the temperature, relative humidity, and displacement fields. A set of appropriate constitutive models has been developed to represent the constitutive behavior of heat and moisture transfer. These have been coupled with a model for the extent of ASR reaction, and the anisotropic strains induced by this reaction are computed as a function of the local stress state. This code has been applied to simulate a number of benchmark problems, and as will be shown, produces results that compare well with those experimental results. This initial work provides a foundation for a general tool that can be applied to a variety of related aging mechanisms in concrete, and which will be applied to better address aging issues in nuclear power plants.

536: Time-Dependent Seismic Fragility Models of RC Buildings for Aging Considerations

Zengping Wen, Institute of Geophysics, China Earthquake Administration
Fei Geng, Institute of Geophysics, China Earthquake Administration

The structural properties of reinforced concrete buildings change over time due to the onset of corrosion of steel reinforcement due to carbonation of concrete in general atmospheric environment. Therefore seismic fragility functions of reinforced concrete buildings change during a buildings life time. But the potential effects of aging and deterioration on seismic vulnerability traditionally neglected in fragility modeling. This paper aims at the assessment of time-dependent vulnerability of reinforced concrete buildings considering aging and deterioration due to the carbonation induced reinforcement corrosion. A method is proposed to estimate the time dependant seismic fragility functions of corroding and deteriorating reinforced concrete buildings. The loss of reinforcement cross-sectional area, the reduction of yield strength of reinforcement and the deterioration of core concrete due to carbonation induced corrosion were calculated as a function of corrosion rate and the potential effects of aging and deterioration on seismic fragility function are investigated. Five models of the structure at different time periods were established. Pushover analysis was used to determine the limit states of the models in terms of drift ratio. The results of pushover analysis show that the drift capacity of the structure decreases significantly due to aging and deteriorating overtime. The time-dependent fragility functions were derived from incremental dynamic analysis with predefined limit states. The results indicate that the seismic fragility functions of RC buildings increases significantly over time. Furthermore, the change of limit states has a critical impact on the fragility functions. Therefore, more attention should be paid to the change of limit states of structures over time.

333: Time-Scale Blind Source Separation Using Independent Component Analysis for Identification of Highly-damped Structures

Arash Kamali-Asl, University of Vermont
Alireza Farzampour, Virginia Polytechnic Institute and State University
Babak Kamali Asl,

Output-only algorithms are used to identify modal characteristics of the systems with implementation of available structural response. The fast development of Blind Source Separation (BSS) as an efficient signal processing method results in recovering the sources using only the measured mixtures. Independent Component Analysis (ICA), as the well-established tool to overcome the BSS problem, is capable of time-domain modal responses' direct extraction; however, it has been shown that ICA loses precision for highly-damped systems. In this study, the modal identification issue is transformed into a time-frequency framework. The time-frequency representations of the monotone modal responses are proposed as the targeted independent sources hidden in those of the system responses which have been Wavelet-Transformed (WT); they can then be efficiently extracted by ICA, whereby the time-domain modal responses are recovered such that the modal parameters are readily obtained. The simulation results of a Multi-Degree-of-Freedom (MDoF) system illustrate that the proposed output-only WT-ICA method is capable of accurately identifying modal information of lightly- and highly-damped structures.

44: Time-space Probabilistic Model for Wind Speeds and Structural Responses

Haoran Zhao, Cornell university
Mircea Grigoriu, Cornell University

A probabilistic model is constructed for assessing the performances of linear structural systems subjected to extreme wind environment. The construction of this model is based on 1) stochastic reduced order model (SROM), 2) database-assisted design, and 3) models for time-space random functions. First, SROM is constructed for the largest annual wind speed V, i.e., a simple random variable matches the probability law of V in some sense. Second, like database-assisted design, numerical simulation of Navier-Stokes equation with boundary conditions corresponding to the selected largest annual wind speed and terrain condition are used to generate samples of pressure fields, then samples of wind effects are obtained from samples of wind pressure fields. Third, models for time-space random functions are calibrated to the stationary parts of the samples of the wind effects. Examples are provided to illustrate the construction of this model, its use for assessing structural performance, and accuracy.

724: Time-variant Seismic Resilience of Aging Bridge Networks

Fabio Biondini, Politecnico di Milano
Luca Capacci, Politecnico di Milano
Andrea Titi, Politecnico di Milano

The consequences of natural and man-made catastrophes show how communities are heavily affected by outages and disruptions of critical facilities. Resilience has recently gained a prominent importance in design and assessment of structure and infrastructure systems exposed to extreme events, such as earthquakes. In particular, the resilience of bridges and road infrastructure networks plays a key role in the emergency response to seismic

events, to ensure both a quick deployment of aids and resources to distressed communities and a prompt repair of the surrounding lifelines and buildings. However, resilience can be reduced over time by aging and deterioration processes of materials and structures. In fact, the effects of environmental aggressiveness can modify the seismic performance and functionality and, consequently, make the system resilience depending on the time of occurrence of the seismic event. This paper presents a probabilistic approach to lifetime seismic assessment of deteriorating bridges and resilience analysis of road infrastructure networks considering the interaction of seismic and environmental hazards. The time-variant seismic capacity associated to prescribed limit states is assumed as functionality indicator for single bridges, and traffic analysis is carried out at both component and network levels to compute the time-variant system functionality and seismic resilience of the road network. The proposed approach is applied to reinforced concrete bridges under corrosion and highway networks with detours and re-entry links. The results show that the network functionality can be substantially reduced due to seismic damage, particularly when important traffic restrictions are applied and traffic flow cannot be detoured to secondary roads. The impact of the functionality drop on the time-variant resilience is emphasized when the combined effects of seismic damage and structural deterioration are taken into account. This indicates the importance of a multi-hazard life-cycle-oriented approach to seismic design of resilient structure and infrastructure systems.

511: Topology Optimization for Additive Manufacturing

Mikhail Osanov, Johns Hopkins University
Christopher B. Williams, Virginia Tech
James K. Guest, Johns Hopkins University

Topology optimization provides tremendous opportunities for re-thinking design to create highly efficient components and systems tailored for a specific application. Additive manufacturing provides a new means of realizing topology-optimized designs, particularly those with complex topologies or distributions of material. These new design and manufacturing technologies, however, must be integrated into a design-manufacture framework to fully leverage their capabilities. This talk will discuss the latest advancements in design for additive manufacturing including multi material design, geometric constraints, and inherent anisotropies. Several examples related to optimization of mechanical properties will be presented.

429: Topology Optimization of Geometrically Nonlinear Trusses with Critical Load Constraint

Lei Li, University of Notre Dame
Kapil Khandelwal, University of Notre Dame

Geometrically nonlinear truss topology optimization with and without stability constraints is investigated in this study. It is shown that if a minimum compliance formulation is used without any stability considerations, the optimal topology designs are usually unstable and convergence issues may be encountered during the optimization process. The convergence issues include converging to an unstable equilibrium or failing of the Newton-Raphson solution process. These issues lead to erroneous sensitivity information and even interruption of optimization process. To address these issues in a ground structure based geometrically nonlinear truss topology optimization, a minimum compliance formulation with critical load factor constraint is presented. For the enforcement of correct constraint, a strategy based on spurious modal energy ratio is proposed to determine the true critical eigenmodes and the corresponding critical load factor. Several numerical examples are shown to demonstrate the effectiveness of the proposed approaches. The topology results obtained using the critical load factor constraint show that the optimized topologies are stable and no convergence issues are encountered during

the load control Newton-Raphson solution process.

133: Topology Optimization of Structures Considering Constructability Costs

Saranthip Koh, Johns Hopkins University
James K. Guest, Johns Hopkins University

As topology optimization is a free-form approach to optimizing structural layout, it has a tendency to produce light-weight but complex structural solutions that may be difficult to manufacture and construct. In large-scale structures, such as building systems, construction labor cost typically governs, potentially making topology-optimized solutions impractical. This work examines constructability in the topology optimization of structures, and proposes several new algorithms for influencing fabrication and construction costs. These include cost metrics associated with repeatability, complexity, and cost premiums for non-standard members. Each of these algorithms is formulated in a continuous form such that sensitivities are readily available for use with gradient-based optimizers. The algorithms are demonstrated on static design problems and solutions. The tradeoffs between constructability and material usage are also explored.

774: Topology Optimization with Manufacturing Constraints: A Unified Projection-Based Approach

Cicero de Lima,
Sandro Vatanabe,
Tiago Lippi,
Emilio Silva,
Glaucio Paulino, Georgia Institute of Technology

Despite being an effective and general method to obtain optimal solutions, topology optimization generates solutions with complex geometries that are neither cost-effective nor practical from manufacturing (industrial) perspective. In this paper, manufacturing constraint techniques based on a unified projection-based approach are presented to properly restrict the range of solutions of the optimization problem. The traditional stiffness maximization problem is considered in conjunction with a novel projection scheme for implementing constraints. Essentially the present technique considers a domain of design variables which is projected in a pseudo-density domain to find the solution. The relation between both domains is defined by the projection function and variable mappings according to each constraint of interest. The following constraints have been implemented: minimum member size, minimum hole size, symmetry, pattern repetition, extrusion, turning, casting, forging and rolling. These constraints illustrate the capability of the projection scheme to control the optimization solution efficiently (i.e. without adding a large computational cost). Illustrative examples are provided in order to explore the manufacturing constraints in conjunction with the unified projection-based approach.

586: Towards Incorporating Soil Substrate Properties into a Marsh Edge Erosion Model

Cody Johnson, Louisiana State University
Qin Chen, Louisiana State University
Arash Karimpour, Louisiana State University
Navid Jafari, Louisiana State Univeristy
Thomas Everett, Louisiana State University

Louisiana is experiencing some of the highest land loss rates in the world. The majority of this occurs in its coastal wetlands. This is partly attributed to an increase in the factors which influence erosive mechanisms, e.g. increased fetch, reduced sediment delivery, relative sea level rise. The working hypothesis has been made that locally generated wind waves are responsible for a large proportion of the observed land loss. This is due to a positive feedback between increasing fetch in a shallow coastal water body, their depth, and the retreat of their coastline. This scenario can quickly lead to devastating rates of marsh edge erosion as has been observed in Terrebonne Bay, Barataria Bay, and Breton Sound, LA. A model which is able to confidently predict the response of a stretch of coastal marsh to a given wave climate is a valuable tool for the management of coastal resources to mitigate erosion hazards. Recently, attempts have been made to relate marsh edge retreat rate (m yr-1) to wave power (kW m-1). They have meet with varying levels of success. The shortcomings are attributed to the exclusion of the marsh's resistivity to erosion or generally speaking the marsh's strength. Marsh edge strength is a complex function of abiotic, biotic, and geochemical factors. It can however be plausibly assumed that geotechnical soil properties form a governing set of parameters. The inclusion of spatially varying, site-specific soil properties in addition to the hydrodynamic driving force is then a logical step towards improving any predictive model for marsh edge erosion. To this end, a multi-disciplinary field campaign was designed and undertaken in order to capture essential soil properties and geological data over a wide expanse of coastal wetlands in coastal Louisiana. The sites were subjected to vibracore sampling and in-situ tests to determine bulk density, organic content, grain size, undrained shear strength, and erosive critical shear stress at discrete subsurface intervals. Further, waves were measured in Terrebonne Bay, LA over the course of a year. To calculate the marsh edge retreat rate at the study sites, GIS techniques were used along with yearly aerial photography. Numerical and parametric wave generation models were calibrated with the measured wave record and used to calculate wave power at the study sites. The soil properties are then used to incorporate site-specific differences in the relationship between observed marsh edge retreat rate and modeled wave power. Funding for this research has come from the National Science Foundation (NSF) and the Louisiana Coastal Restoration and Protection Authority (CPRA).

622: Tracking Longterm Ambient Responses of Bridges Using Multivariate Correlational Data Analysis Based Upon Measurement Data

Mehdi Norouzi, University of Cincinnati
Ehsan Haji Agha, University of Cincinnati
Victor Hunt, University of Cincinnati
Arthur Helmicki, University of Cincinnati

Using historical measurement data and observing multivariate correlations, statistical data models can be created for structures. Statistical classification of structure responses and detection of extreme variations and/or abnormal behaviors are beneficiary especially in cases where calibration of a precise finite element model is costly or not applicable. This paper presents the results of statistical data analysis of the daily measurement data for major bridges in Ohio aimed at classifying structure responses over the years. First, the seasonal nature of the measurement data will be presented. Second, employing major principle components, variation in long term data will be compared with controlled structure responses such as truck load tests and hence, variation of the measurement data will be clustered. Finally, the consistency of structure behavior over the years within each cluster will be investigated and having ambient data such as temperature, structure response will be forecasted statistically.

435: Transient Effects of Drying Creep in Nanoporous Solids: Understanding the Effects of Nanoscale Energy Barriers

Robert Sinko, Northwestern University
Matthieu Vandamme, Laboratoire Navier
Zdeněk Bažant, Northwestern University
Sinan Keten, Northwestern University

The Pickett effect is a phenomenon that has been observed for many nanoporous solids, including concrete, wood, and Kevlar. It represents the strain due to creep during drying of a material that is in excess of the sum of strains from pure creep and drying shrinkage. Understanding this effect and being able to accurately predict drying creep strains for these materials is of great importance as they are often used in structural engineering applications. Incorrect estimations of these strains can lead to excessive deflections and major loss of prestress in structures including bridges, roof shells, etc. Existing micromechanical models can partially explain this effect by considering microstress relaxation and microcracks. It is believed that nanoscale effects emerging from the dynamics of water in nanopores are of paramount importance, but have yet to be explicitly considered in these models. Here, we examine how creep deformations in a slit pore are accelerated by the motion of water due to drying forces using coarse-grained molecular dynamics simulations. We find that the drying that drives water flow in the nanopores lowers both the activation energy of pore walls sliding past one another and the apparent viscosity of confined water molecules. This lowering can be captured with an analytical Arrhenius relationship accounting for the role of water flow in overcoming the energy barriers. Notably, we directly compare this model and simulation results to demonstrate that the drying creep strain is not linearly dependent on the applied creep stress at the nanopore level. Nevertheless, a linear approximation serves adequately over small ranges of creep stress. Our findings establish scaling relationships that explain how the creep force, drying force, and fluid properties are related, thereby explaining the nanoscale origins of the Pickett effect, and providing strategies for minimizing the emergent displacements arising from this effect.

54: Transient Solid Dynamics on Linear Tetrahedral Finite Elements Using a Variational Multi-Scale Approach

Guglielmo Scovazzi, Duke University
Xianyi Zeng, Duke University
Simone Rossi, Duke University

A new tetrahedral finite element for transient dynamic computations in solids is presented [G. Scovazzi, B. Carnes, X. Zeng, and S. Rossi, "A simple, stable, and accurate tetrahedral finite element for transient, nearly and fully incompressible solid dynamics: A dynamic variational multiscale approach," IJNME; DOI: 10.1002/nme.5138]. It utilizes the simplest possible finite element interpolations: Piece-wise linear continuous functions are used for displacements and pressures (P1/P1), while the deviatoric part of the stress tensor is evaluated with simple single-point quadrature formulas. This approach takes inspiration from previous work of the first author in the case of compressible fluid dynamics in Lagrangian coordinates. The variational multiscale stabilization eliminates the pressure checkerboard instabilities affecting the numerical solution in the Stokes-type operator that arises in solid dynamics computations. The formulation is extended to visco-elastic solids. Extensive numerical tests are presented. Because of its simplicity, the proposed element could favorably impact complex geometry, fluid/structure interaction, and embedded discontinuity computations.

741: Transition from Ductile Shear to Brittle Tensile Failure Mode in Scratch Testing of Rocks

Emmanuel Detournay, University of Minnesota

Jia-Liang Le, University of Minnesota

Scratch testing has long been recognized as an e_cient engineering tool for material characterization, with recent e_orts aimed at evaluating its capability to assess the strength of materials such as of rocks, cement, polymers and ceramics that are highly relevant to many engineering applications. Although scratch testing is appealing for a number of reasons that include low cost and assessment of the spatial variation of strength at a scale of less than 1 cm, a comprehensive theoretical foundation for establishing the link between scratch measurements and properties assessed in conventional material testing does not exist yet. Recent experiments have shown that two distinct failure mechanisms can be induced in scratch testing of granular materials, depending on the depth of cut: 1) at a shallow cutting depth, the material experiences a continuous ductile failure process, which is governed by the de-cohesion of the matrix and grains; and 2) at a deep cutting depth, the failure is brittle and is characterized by a repeated process of initiation and propagation of macroscopic tensile cracks. These two failure mechanisms are governed by di_erent material properties. Indeed, there is considerable empirical evidence that the speci c energy " | the energy expended per unit volume of rock cut| determined from shallow scratch tests on sedimentary rocks is about equal to the uniaxial compressive strength _c, while there is evidence that for deeper cuts (brittle mode) " = _KIcd

713: Transportation Network Disruptions and Vulnerability Assessment for Retro fitting and Recovery Planning: An Agent-based Modeling Approach

Alireza Mostafizi, Oregon State University
Haizhong Wang, Oregon State University
Dan Cox, Oregon State University
Lori Cramer, Oregon State University

This paper presents an agent-based modeling approach to assess the vulnerability of a transportation network under network disruptions (i.e., bridge failures) for retrofitting and recovery planning on the coast of State of Oregon. This paper focuses on unplanned transportation network disruptions, including local link disruptions by earthquakes and post-disaster bridge failure under near-field tsunami evacuation scenarios. It integrates the transportation network disruption uncertainties into a multimodal agent-based tsunami evacuation model to assess the impacts of disruptions on evacuee's choice of modes (i.e. car, walking on foot) and their life safety from a network-wide perspective. The criticality of each link in the transportation network is evaluated subject to link failures and the resultant mortality rate. Thus, critical linkages can be identified through these mortality rate changes. The results show that neither all the most used links nor all the initially expected important links throughout the networks are critical. The criticality of a link is calculated by the impact of the particular link's failure on the mortality rate of the scenario. After assessing all the links in a network, this paper used an agent-based Monte Carlo simulation method to identify the most critical links within the network, and the method is applied to the city of Seaside, Oregon which is one of the most vulnerable cities on the Oregon coast. Further assessment is conducted on the identified critical links to formulate an optimal bridge retrofitting plan to minimize the mortality rates. Results show that the criticality of transportation network is sensitive to the overall mortality; the critical links are not necessarily the bridges in the network. Therefore, the identification of the critical links requires a systematic assessment of the entire transportation network. Moreover, Monte-Carlo simulations demonstrate how mortality rates fluctuate with varying failure probabilities of the identified critical links. This research can enlighten policy-makers as to how local link disruptions or bridge failures can affect the evacuees' rerouting decision-making behavior since their planned evacuation route is no longer available. An optimal retrofitting and recovery plan can be designed to minimize the fatalities considering the limited resources for the case study, Seaside, OR.

431: Treating System Reliability, Redundancy, Risk, and Sustainability as Performance-Based Design and Assessment Requirements in a Life-Cycle Context

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Dan Frangopol, Lehigh University

ABSTRACT Performance-based design provides a vehicle for implementing system reliability- , redundancy- , risk- , and sustainability-informed concepts into life-cycle structural design and assessment of infrastructure systems. In this context, this paper presents a framework for implementing these concepts in structural design and assessment in a life-cycle perspective. The main aspects related to probabilistic performance assessment and prediction of deteriorating structural systems are discussed. System reliability is a problem involving multiple correlated and/or independent failure modes. Most design and assessment specifications are based on component reliability analysis. However, most structural systems are composed of a combination of series, parallel, or series-parallel connected components. For this reason, the reliability of a system may be lower or higher than the reliability of its weakest component. Redundancy, as a performance indicator, represents the capability of a structural system to carry loads after damage or failure of one or more of its components. Approaches for the life-cycle management of infrastructure involving reliability and redundancy performance indicators consider uncertainties associated with loads and resistance, but do not account for the consequences incurred from structural failure. Risk-based performance metrics provide the means to combine the probability of structural failure with the consequences corresponding to this event. Methodologies which incorporate risk within the generalized life-cycle management framework are presented herein. In addition, approaches considering sustainability as a performance indicator are discussed. ACKNOWLEDGEMENTS The support from (a) the National Science Foundation through Awards CMS-0639428 and CMMI-1537926, (b) the Commonwealth of Pennsylvania, Department of Community and Eco-nomic Development, through the Pennsylvania Infrastructure Technology Alliance (PITA), (c) the U.S. Federal Highway Administration Cooperative Agreement Awards DTFH61-07-H-00040 and DTFH61-11-H-00027, and (d) the U.S. Office of Naval Research (ONR) Awards N00014-08-1-0188 and N00014-12-1-0023 is gratefully acknowledged. The opinions and con-clusions presented in this paper are those of the authors and do not necessarily reflect the views of the sponsoring organizations.

83: Triaxial Material Model for Concrete under Cyclic Loading

Mohammadreza Moharrami Gargari, Virginia Tech
Ioannis Koutromanos, Virginia Tech

This presentation will describe a new material model that has been developed for the analysis of concrete under multiaxial, cyclic loading conditions. An elastoplastic formulation, having a non-associative flow rule to capture compression-dominated response, is combined with a rotating smeared-crack model to capture the damage associated with tensile strains and cracking. The proposed formulation resolves the issues which exist in many available concrete material models, related to properly capturing the crack opening and closing behavior and accounting for the effect of confinement on the strength and ductility under compressive stress states. The accuracy and the numerical efficiency of the model are evaluated by conducting nonlinear static analyses at both material and component levels. Parametric analyses have been performed to demonstrate the need to regularize the softening laws to address the mesh size effect and the importance of accounting the increased ductility of confined concrete. A discussion is presented to explain the impact of using different yield surfaces for the elastoplastic model on the simulation results. The validated material model is combined with constitutive laws for reinforcing steel to capture the hysteretic behavior and damage evolution of reinforced concrete structural components up to the occurrence of severe strength degradation.

181: Tsunami-Induced Forces on Bridge Components

Andrew Winter, University of Washington
Michael Motley, University of Washington
Marc Eberhard, University of Washington

Natural disasters such as tsunamis have caused significant damage to transportation infrastructures in many parts of the world. The loss of bridges and roadways delayed recovery efforts and emergency services immediately following these events, and in some cases, has had long-term impacts on local economies. Despite the critical post-event role of lifelines, most of the recent research has focused on tsunami modeling, evacuation strategies, and to a lesser extent building design. Far less research has been done on the effects of tsunamis on bridges, and there are no formal design guidelines. Research is necessary to both improve the understanding of tsunami-impact on bridges and to begin the process of developing design codes that consider the effects of tsunamis. It is challenging to develop models to accurately predict tsunami-induced loads on structures. Bridge superstructures have complex geometries, including multiple girders or barriers, whose details affect the induced loads. Most past studies of tsunami loading on bridge structures have focused on estimating the resultant horizontal and vertical forces and corresponding overturning moments. These analyses provide important information for estimating preliminary design loads, but they do not allow engineers to understand how individual girders or barriers affect the force histories. Fortunately, recent advances in numerical modeling and increased computational capabilities now make it possible to perform the needed complex analyses. This work uses the open-source computational fluid dynamics (CFD) solver OpenFOAM to develop numerical models of a suite of concrete and steel girder bridges, box-girder bridges, and flat slab bridges to assess the effects of bridge geometry on tsunami forces. The bridges are discretized into a series of surfaces such that the force contribution from each individual surface (e.g., top and bottom of the deck; front, bottom, and back sides of each girder) is considered separately to determine its contribution to the total force time history. Phenomena such as initial wave impact, splashing, and subsequent steady state flow will be presented. The effects of superelevation will also be investigated systematically. The goal of this work is to provide information that can be used to design individual support components, such as bearings, or to make design recommendations for components that aid in preventing the loss of bridge superstructures, such as tie downs or breakaway barriers such that, ultimately, the safety and resilience of the transportation infrastructure is improved.

113: Uncertain Seismic Wave Propagation through Uncertain Elastic-Plastic Soils

Fangbo Wang, University at Buffalo
Kallol Sett, University at Buffalo

This research study develops an efficient computational methodology to simulate uncertain seismic wave propagation through uncertain, elastic-plastic soils. The methodology is based on the spectral approach of the stochastic finite element method. It utilizes multidimensional, Hermite polynomial chaos in conjunction with the Kosambi-Karhunen-Loeve expansion to efficiently represent the input seismic wave (a non stationary random process) and the soil strength and stiffness parameters (heterogeneous random fields). The response variables (displacement, velocity and acceleration), which are spatio-temporal random processes, are also represented using multidimensional polynomial chaos expansions whose coefficients at each time step are then computed using a stochastic Galerkin approach. A Fokker-Planck-Kolmogorov equation approach is used to probabilistically solve the uncertain elastic-plastic constitutive equation at each material integration point and to update the

tangent stiffness matrix after each time step, while the time integration is performed via the Newmark's method. The formulation is general enough to encompass any arbitrary probability distribution and correlation structure for the input seismic wave and the soil parameters. The salient features of the formulation are highlighted through three example simulations of one-dimensional propagation of seismic shear wave through a fictitious soil deposit. The first example assumes the only uncertainty to be in the soil parameters, the second example assumes the only uncertainty to be in the input seismic wave, while the third example considers uncertainties in both the soil parameters and input seismic wave.

88: Uncertainty Quantification and Model Verification and Validation in Multiscale Simulation

Paul Braden, U.S. Air Force

Shape Memory Alloys (SMA's) are certain classes of metal alloys that undergo phase transformation from an austenite crystal structure to de-twinned martensite and vice versa under certain temperature and stress conditions. Considering the possibility of over 8% recoverable strain for SMA's, there are several applications that wish to utilize this unique material property of phase transformation such as morphing wing structures, passive damping, actuators and sensors. As this transformation occurs, several important material properties change which can lead to complex modelling. Understanding the proper characterization of the SMA during transformation is critical in a multitude of applications which require a delicate level of control. Several models by Lagoudas et al have addressed this concern for both stress and temperature induced transformation. The question of uncertainty is still very chaotic for these models and so verification and validation can only be done for one behavior at a time. Part of the reason is the polycrystalline structure of SMA's that results in variations in the phase transformation temperatures and stress levels. In this case of 55.5% wt Ni 45.5 % wt Ti (Nitinol) SMA, several test cases are run to generate a better assessment of the uncertainty in modelling the transformation behavior. Stress is maintained as a constant to analyze the uncertainties in the transformation temperature and associated strain. Then, strain is held constant and stress is allowed to vary during thermal contraction. Different scales of the length of the SMA used in the experiments are presented to reveal the dependence on extrinsic properties that affect the polycrystalline structure. Both tests are then compared with the Lagoudas et al model to show how the material properties are stochastically uncertain throughout phase transformation.

143: Uncertainty Quantification and Model Verification for Nanoindentation Simulations: a combined MD and hybrid MD/FEM study

Francesca Tavazza, National Institute of Standards and Technology
Li Ma, National Institute of Standards and Technology
Dilip Banerjee, National Institute of Standards and Technology
Lyle Levine, National Institute of Standards and Technology

Nanoindentation experiments give important insights into mechanical properties of materials at the nanoscale. Molecular Dynamics (MD) simulations are the most common approach for modeling this experimental technique. However, literature results are typically presented without any discussion of uncertainties and, usually, not even a qualitative estimate of the effects of the various approximations is provided. Using a combination of MD and hybrid MD/FEM (Finite Element method) simulations, we quantified the effect of some commonly used approximations, such as rigid and/or spherical indenters or repulsive-only interactions between the indenter and specimen, as well as simulation parameters such as system size, indentation speed and temperature. We also estimated the uncertainty of determined quantities such as the depth at which the first dislocation is nucleated, for several choices of the above-mentioned parameters.

438: Uncertainty Quantification for Multi-scale Mortar Discretizations

Tim Wildey, Sandia National Labs
Bart van Bloemen Waanders, Sandia National Labs

A number of critical science applications require predictive simulation of multi-scale systems. One of the emerging approaches for multi-scale modeling is the multi-scale mortar approach, which enables micro-scale information to be incorporated into a macro-scale numerical approximation without resorting to computational homogenization. Mortar methods also provide a convenient and mathematically elegant approach for coupling different physical models and numerical methods through physically meaningful interface conditions. This approach does not require the discretizations to match along the interface and has been successfully used to model multiphase flow in porous media, multi-physics couplings, computational mechanics and geomechanics. Moreover, recent work has shown that adjoint models, which are critical to optimization and UQ, can be developed in a straightforward manner. In this presentation, we review the multi-scale mortar approach and demonstrate the methodology on a computational mechanics model with a heterogeneous fine scale micro-structure. We also discuss the propagation of uncertainty between the micro- and macro- scales and the quantification of this uncertainty on macro-scale quantities of interest.

367: Uncertainty Quantification in Manufacturing Process Evaluation

Saideep Nannapaneni, Vanderbilt University
Sankaran Mahadevan, Vanderbilt University
Sudarsan Rachuri, National Institute of Standards and Technology

Manufacturing processes and production networks have been rapidly pushing the envelope in building complex, optimized products through new materials, advanced manufacturing techniques and digital information technology. With the increasing complexity, the quantification of performance metrics (such as energy consumption) becomes quite complicated due to the presence of variability and uncertainty in various parameters and models used to model the manufacturing processes. Understanding the sources of uncertainty and quantifying them can improve the decision-making process, making the manufacturing processes more efficient. Manufacturing processes, in general, can be considered as hierarchical or multi-level processes; the hierarchy in this paper is divided into three levels – (1) unit process level, (2) line level, and (3) factory level. The entire manufacturing process is considered at the factory level and this factory can be divided into several lines, where each line undertakes a fraction of the overall manufacturing process. Each line may consist of several unit processes, where each unit process accomplishes a specific task. To estimate the uncertainty in the performance prediction, this work proposes a hierarchical Bayesian network (HBN) approach to aggregate the uncertainty arising from multiple models at multiple levels in the manufacturing process hierarchy. Hierarchical Bayesian networks are an extension of Bayesian networks for modeling hierarchical stochastic systems. In simple cases, each unit process can be replaced by its associated BN to obtain a HBN for representing a manufacturing process. The BNs corresponding to the unit processes can be constructed separately and can be composed to form a HBN. In general, the BNs for unit processes can be constructed using physics-based models or learnt from available data using BN learning algorithms or by a hybrid approach through a combination of physics-based models and data. In some cases, along with the numerical data, semantic data might also be available from the semantic models of manufacturing processes. A semantic model here is defined here as a high-level representation of the system and associated parameters. Such semantic data also needs be included in the BN construction. Towards this objective, an automated procedure is developed to construct the BN for a unit process using available numerical and semantic data. The injection molding process, which is composed of three sub-processes (heating of polymer, injection into the mold and cooling), is used to demonstrate the proposed methodology for uncertainty quantification in the energy consumption of the process.

191: Uncertainty Quantification of Manufacturing Process Effects on Macro-scale Material Properties

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This paper presents a methodology to propagate the uncertainties in the manufacturing process parameters to bulk material properties through multi-scale modeling. Randomness of material initial condition and uncertainties in the manufacturing process lead to variability in the microstructure, which in turn leads to variability in the macro-level properties of the material. In this paper, 2-D dual phase polycrystalline microstructure is simulated based on the initial condition of the grain cores and the manufacturing environment, instead of Voronoi tessellation which assumes equal grain growth velocities for different phases and therefore is unable to link variability in grain growth velocity to the manufacturing process variability. Then the prediction of macro-level properties is realized via a homogenization method. Mori-Tanaka and Self-consistent homogenization methods are applied, and the results are compared for different grain growth initial conditions. To illustrate the methodology, cooling schedule of a dual phase alloy is simulated, and Young's modulus is the prediction quantity of interest. Even with a given cooling schedule, spatial variation of temperature affects the microstructure and properties; this variability is also incorporated in this work through a random field representation. For this demonstration, the temperature random field is represented by a Karhunen–Loève expansion with a squared exponential kernel. The realization of the whole process presents significant computational challenge for uncertainty quantification, so Gaussian Process surrogate modeling is used for the sake of computational efficiency. The relative contributions of both aleatory and epistemic sources to the overall bulk property uncertainty are quantified using an innovative global sensitivity analysis approach; this provides guidance for manufacturing process control in order to meet the desired uncertainty bounds in the bulk property estimates. It shows that by reducing the variability of the manufacturing process, the prediction uncertainty decreases correspondingly.

712: Understanding Interdependencies Between Systems towards Resilient Critical Lifeline Infrastructures

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Problem Definition Critical lifeline infrastructure refers to the electric power, gas and liquid fuels, water, wastewater, transportation network, and telecommunications systems-sometimes called lifeline systems-without which buildings, emergency response systems, dams, and other infrastructure cannot operate as intended (1, 2). Lifelines are highly interdependent and interdependent systems, showing a great degree of coupling between sub-components of the same system and with other infrastructure (3). Interdependent lifeline infrastructure systems are spatially embedded (4) and tied together metropolitan areas, communities, and neighborhoods, and facilitate the growth of local, regional, and national economies (2). Lifeline infrastructure systems do not work in isolation, but typically interdependent and interact with other systems (2, 5, 4). Electric power networks, for example, provide energy for pumping stations, storage facilities, and equipment control for transmission and distribution

systems for oil and natural gas. Oil provides fuel and lubricants for generators, and natural gas provides energy for generating stations, compressors, and storage, all of which are necessary for the operation of electric power networks. This reciprocity can be found among all lifeline systems. These interdependent systems work together to provide the essential services of a modern society (2) (1). The dependencies within an individual infrastructure network are well investigated, but the scope of interest in interdependencies modeling is the influence or impact that one infrastructure can impart upon another. The chain of the influence is the key to understand this problem. The current and pressing issue is the notion that our infrastructure is highly interconnected and mutually dependent in complex ways, both physically and through a host of information and communications technologies (9). Identifying, understanding, and analyzing such interdependencies are significant challenges (2, 10). These challenges are greatly magnified by the breadth and complexity of our critical infrastructure (9). Previous research in network theory primarily focused analyzing single networks, despite the fact that many real world lifeline networks interact and depend on each other. Node failures in one network will inevitably lead to the failure of its corresponding nodes in the dependent network, and vice versa. Further, this recursive process can cause cascading failures throughout the networks. In order to explicitly model the real world system, it is crucial to understand the interdependency of networks and its impact on the structural and functional behavior of the coupled systems. Objective The objective of this research is to pursue a fundamental understanding of the interdependencies between systems towards resilient critical lifeline infrastructures. To be specific, the research questions of this paper are to 1. Assess lifeline infrastructure interdependencies by identifying key links between each system and the other lifeline networks that interact with it. 2. Formulate the stochastic interdependency in various interdependent infrastructure network disruptions 3. Recommend measures to secure and recover interoperability and avoid damage related to collocation and loss of resources from other interdependent lifelines. Approach The research approach on interdependent lifeline infrastructure systems include the following identified methods from literature (13): inoperability input-put Leontief methods (14), agent-based modeling (15, 16), probabilistic model to characterize the interdependencies (17) , stochastic modeling of interdependencies (18), and complex network and percolation theory approaches (19, 4, 20). The approach is a combination of stochastic process and percolation theory. The goal is to bridge the gap between empirical understanding of critical infrastructure interdependencies and the theoretical developments of interdependent networks in the physics community.

664: Understanding Memristors and Memcapacitors in Engineering Mechanics Applications

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A significant event happened for electrical engineering in 2008, when researchers at HP Labs announced that they had found “the missing memristor”, a fourth basic circuit element that was postulated nearly forty years earlier by Dr. Leon Chua who also developed the theory of memristive systems. One consequence of this announcement has been revitalized research in all areas of brain-imitating computer technologies, primarily because memristors mimic synapses. Moreover, extended memristor theory to include memcapacitors and meminductors, thereby introducing an entire class of “mem-models”. This model class is the foundation of the present work. By applying well-known mechanical-electrical system analogies, the mathematics of memristor theory (and its extensions) may be transferred to the setting of engineering mechanics, resulting in mechanical counterparts of the mem-models. In the context of engineering mechanics, we identify some recent examples of “mem-dashpots” and

"mem-springs". In addition to the "zero-crossing" condition, we highlight the role played by discontinuities in the model and/or the excitation, the combination of which enables mem-models to produce countless hysteresis patterns. We also consider some new properties and modeling techniques that call for further improvement so that these new types of mechanical models can become more usable for analyzing real-world data.

38: Understanding the Effect of Modeling Fidelity of Particle Shapes on Simulation Fidelity of Soil Behavior through 3D Printing

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Seung Jae Lee, Florida International University
Beena Sukumaran, Rowan University

Particle morphology is one of most important grain scale property that significantly affects the macroscopic behavior of granular soils, which has been evidenced by many studies so far. Therefore, great efforts have been made in (a) the characterization of the particle shapes through imaging techniques (such as X-ray Computed Tomography), and (b) modeling of the characterized particle shapes for numerical simulation (such as Discrete Element Method) to enhance the prediction of soil behavior. While researchers have been successful in (a) characterizing the 3D particle shapes, they have struggled with (b) numerical modeling of high fidelity shapes as-is due to high computational cost typically incurred. The high fidelity shapes require significant computational cost in modeling due to high geometric complexity, thus making it practically impossible to perform any large scale DEM simulation, e.g., of several million particles, at an engineering scale. Therefore, considerably simplified particle shapes are adopted for shape modeling to keep the computational cost manageable, but it is still not clear how much modeling error is incorporated and influences the outcomes of the simulation in predicting realistic soil behavior. In this research, 3D printing is utilized to systematically investigate the morphological modeling effect while avoiding the high computational cost of DEM. Recent advances in 3D printing enable massive printing of any object with controlled input properties, e.g., particles of different shapes printed in the same material. Some engineering properties such as compressive strength can be maintained in a comparable range to that of actual mineral grains, depending on the printing material. Therefore, 3D printing provides an accessible and affordable way to systematically investigate the effect of the modeling fidelity of particle shapes on the simulation fidelity of soil behavior through physical laboratory testing on 3D printed synthetic particles, while bypassing the high computational cost generally required in DEM simulations. This presentation will further discuss the idea and the results of the study.

687: Urban Heat Island: City Texture Matters

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Thorsten Emig, Massachusetts Institute of Technology
Roland Pellenq, Massachusetts Institute of Technology
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The heat phenomenon that defines the intensification of air and surface temperatures in urban dwellings when compared to their rural surroundings poses one of the major societal climate issues imposed by a human being nowadays. By aggravating air pollution, impairing water quality, deteriorating health and comfort levels, this effect, also known as Urban Heat Island (UHI) forms externalities that peril the life of urban residents, communities that are projected to double and reach 6.4 billion people by 2050.The majority of current UHI modeling practices focus on vertical heat flow, or the idea that some heat bounces back while other heat is

absorbed by surfaces and structures, within a given Urban Boundary Layer or Canopy Layer. While the existing approaches can provide accurate results, they are generally only applicable to individual cities and, since they cannot be used universally, their practical application is limited. Further, these approaches fail to take into account the horizontal movement of heat. Here we show that looks at the horizontal movement of heat through a method that groups and characterizes cities by their urban surface geometry using a novel approach typically seen in the field of statistical physics provide an expedient to appraise the physical response of cities in the form of UHI. A Geographic Information System analysis of the UCL of 24 cities from the US and Europe revealed a striking resemblance between the cities and the molecular structure of materials. Based on their distinct geometries, as captured by the radial distribution function, we were able to categorize cities as: Crystals (i.e. Chicago, New York), Liquids (i.e. Los Angeles, Houston) and Gases (i.e. London, Paris). Since there was not much variation in building heights in a given city sample, a defined characteristic length scale became a crucial component for analyzing the heat flow simulation used to compute a View Factor (VF)—a portion of emitted heat-–in the horizontal direction. We find that lower VF cities retain a greater fraction of heat, resulting in higher UHI. Such parameter is critical for enhancing the previously established between UHI and city parameters, such as population or building density. In a broader context, our simplified UHI model may allow developers to plan more energy efficient cities and, for existing urban landscapes, prioritize the neighborhoods where taking steps to mitigate UHI can have the biggest impact, while eliminating the need for detailed surface or air temperature data.

597: Using Sobol' Decomposition in Sensitivity Analysis of Nonlinear Dynamic Behavior of RC Buildings with Viscous Damper

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Alireza Moradi, Tehran Azad University

The efficiency of viscous dampers in the structures depends on the characteristics of the applied earthquake and the properties of dampers. Therefore the behavior of viscous damper during earthquake is uncertain. In this study, the uncertainly in nonlinear dynamic response of the Reinforced Concrete building with viscous damper, are apportioned to the source of uncertainties in earthquake characteristics and damper properties. Length of the damper, damping coefficients and PGA of earthquake are considered as the inputs and maximum drift, maximum base shear and total energy dissipated during the earthquake are considered as the outputs in the sensitivity analysis. In this study, PERFORM-3D, which has capabilities to perform nonlinear time history dynamic analysis of the buildings, is used for modeling and Sobol' decomposition technique is used to perform variance based global sensitivity analysis. The results show how viscous dampers properties and PGA of the earthquake can affect the nonlinear dynamic behavior of the RC building. Results of this sensitive analysis can be used to improve the efficiency and behavior of viscous dampers in the buildings.

504: Utility Mapping and Subsurface Structural Assessment with Tri-Band Ground Penetrating Radar

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Tian Xia, University of Vermont
Yu Zhang, University of Vermont
Taian Fan, University of Vermont

Determining, remembering and analyzing the location and condition of infrastructure features, such as utility pipes, roadway material layers and concrete reinforcing can provide useful information for infrastructure maintenance and planning. This paper will describe the combined use of a novel tri-band ground penetrating radar

(GPR) with Building Information Modeling (BIM) and Geographical Information Systems (GIS) to identify and locate surface features and then form a minable graphical database for managing, storing and distributing the information. The GPR system has a custom design using three impulse-receive circuits, each with a different center frequency bands (400 MHz, 1.6 GHz and 2.3 GHz) so as to enable more agile sensing of structural conditions and utility mapping. This configuration provides a workaround for the difficulties associated with using a single center band which fixes the depth of penetration and spatial resolution to possibly non-optimal values that limit sensing capability. This system can sense at three different depths and resolutions so as to provide a wider coverage of subsurface conditions. Results from tests aimed at sensing subsurface conditions in concrete structures, roadways and buried utility location will be presented. In each of these three cases the system performs differently and better or worse for different frequency bands. Preliminary results from an effort that maps the location of the buried utilities within BIM and GIS databases will be presented. A technical challenge is precise navigation inside cities with degraded GPS signals. Also discussed will be results from the development of a frequency-agile multi-static system that can adjust the pulse shape and frequency content of different waves, along with tracking phase-shifted time-domain methods for more rapid 3-D reconstructions of subsurface conditions.

384: Variability Response Functions for Apparent Material Properties in Two-Dimensional Elasticity Problems

Jenny Sideri, Columbia University
Athina Spyridaki, Columbia University
George Deodatis, Columbia University
Sanjay R. Arwade, University of Massachusetts Amherst

The material properties of a wide range of structural mechanics problems are often characterized by random spatial fluctuations. Calculation of apparent properties of such randomly heterogeneous materials is an important procedure, yet no general method besides Monte Carlo simulation exists for evaluating the stochastic variability of these apparent properties for structures smaller than the representative volume element (RVE). In this direction, the concept of Variability Response Function (VRF) has been proposed as a means to capture the effect of stochastic spectral characteristics of uncertain system parameters modeled by homogeneous stochastic fields on the uncertain response of structural systems, without the need for computationally expensive Monte Carlo simulations. Recent studies have formally proved the existence of VRF for apparent properties for statically determinate linear beams through elastic strain energy equivalence of the heterogeneous and equivalent homogeneous bodies, while a Monte-Carlo based methodology for the generalization of the VRF concept to statically indeterminate beams has been recently developed. In this paper, the VRF methodology of apparent properties is extended to two-dimensional elasticity stochastic problems discretized on a finite element domain, in order to analytically formulate a VRF that is independent of the marginal distribution and spectral density function of the underlying random heterogeneous material property field (it depends only on the boundary conditions and deterministic structural configuration). Representative examples that illustrate the approach include two-dimensional plane stress/strain problems.

385: Variability Response Functions for Statically Determinate Beams with Arbitrary Nonlinear Constitutive Laws

Athina Spyridaki, Columbia University
Jenny Sideri, Columbia University
George Deodatis, Columbia University

Sanjay Raja Arwade, University of Massachusetts Amherst

The inadequacy of information on the probabilistic characteristics of uncertain system parameters limits the ability to determine probabilistic response quantities (e.g. displacements) in structural mechanics. Accurate estimation of the response variability of uncertain structural systems where properties are modeled by homogeneous stochastic fields is achieved with the concept of variability response function (VRF). VRF in its classical sense is only dependent on the deterministic structural configuration and boundary conditions of the system and it is independent from the marginal probability distribution function (PDF) and the spectral density function (SDF) describing the uncertain system parameters. So far the existence, uniqueness, and SDF- and PDF independence of a variability response function has been analytically proven for statically determinate beam structures following either a linear or a specific class of nonlinear constitutive laws (power laws). For a stochastic structural system governed by an arbitrary non-linear material law, only Monte-Carlo simulation exists as an approximate approach for evaluating its response variability. In the present paper, based on closed-form analytic expressions, the VRF of statically determinate beams governed by piecewise-linear nonlinear constitutive laws is derived for the variance of the response displacement. A conjecture has to be made in order to establish these analytical expressions. Considering that every arbitrary non-linear material law can be closely approximated by a piecewise-linear law, there is no limitation in the proposed VRF methodology. Numerical examples are provided involving statically determinate beams that follow different constitutive laws. Comparisons of the VRF are made for the case of power constitutive laws between the proposed methodology and the respective existing closed-form solutions.

157: Variable Input Space Controller for Multi-Hazard Mitigation

Liang Cao, Iowa State University
Simon LaFlamme, Iowa State University

We present the concept of a variable input-space controller (VISC), for mitigation of multiple types of hazards. The VISC is a multi-delays feedback controller. The dimension and time delay of the feedback follow the construction of a delay vector based on the embedding theorem. These parameters are allowed to vary in time, which enables the controller to adapt to different types of excitations, or dynamic inputs. In this presentation, we investigate the applicability of such controller by analyzing the selection procedures for the time delay, for a single-degree-of-freedom system subjected to a harmonic loading. This case leads to fixed parameters (i.e., dimension and time delay), and yields a specialized form of VISC: a multi-delay controller (MDC). The selection of the optimal time delay for a fixed-dimension MDC is analyzed based on mutual information theory, and also based on the minimization of a transfer function. The comparison of both analyzes validates that a controller based on a delay vector is effective at mitigating vibrations, and conditions a given to ensure stability of such VISC. An algorithm for real-time selection of the time delay is presented, and simulations are conducted on a SDOF subjected to a multi-frequency input. Results show that the controller can automatically adapt to different types of excitations, and can be based on limited measurements.

42: Variance Reduction Approaches for Random Materials Homogenization

Frederic Legoll, Ecole des Ponts

Computing the homogenized properties of random materials is often very expensive. A standard approach is to consider a large RVE, and solve the equilibrium problem on that RVE, submitted to e.g. periodic boundary conditions. Because the RVE is finite, the obtained apparent effective properties are random. The exact, deterministic homogenized properties are only recovered in the limit of infinitely large RVEs. Since the apparent effective coefficients are random, and therefore fluctuate from one realization to the other, it is interesting to introduce variance reduction techniques. They allow to compute the expectation of the effective coefficients (for a given RVE size) in a more efficient manner than brute force Monte Carlo methods. In this talk, we will describe recent progress on the design of efficient variance reduction approaches (e.g. based on using surrogate models) in that context. Joint works with M. Bertin, S. Brisard, C. Le Bris and W. Minvielle.

468: Variational Coupling of DG and CG Methods for Local Damage in Multi-Constituent Materials Modeled via Mixture Theory

Arif Masud, University of Illlinois
Harishanker Gajendran, University of Illlinois
Pinlei Chen, University of Illinois

We present a variational framework for local damage in multi-constituent materials by embedding Discontinuous Galerkin (DG) ideas in the Continuous Galerkin (CG) method within the context of Stabilized Methods. A mixture theory based model for multi-constituent solids is employed that assumes concurrent and overlapping existence of the constituent materials. Each material is however represented via its own balance laws and constitutive model. In the new framework, Continuous Galerkin method is used inside each of the multi-constituent laminates and it helps in cost effective solution with the mixture model. The DG strategy is used to provide a mechanism to seamlessly treat the various conditions along laminate interfaces, i.e., adhesion and or friction, and without the necessity of introducing additional Lagrange multiplier fields. Since discontinuous functions are employed across the lamina interfaces, it allows the physical fields to be either continuous or discontinuous across the interfaces, thus providing a built-in mechanism for the modeling of sharp discontinuities, a feature that naturally facilitates the formation and evolution of local debonding and delamination. A significantly novel feature of this approach is that the interface flux terms that arise naturally because of the DG relaxation of the continuity requirement on the fields across the laminate interfaces provide a natural mechanism to embed cohesive models in a variationally consistent manner. Several representative benchmark problems are presented to show the performance of the model and the method.

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715: Verification of the Spectral Period Range for Ground Motion Scaling in Structural Nonlinear Dynamic Analysis

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It is well-established that the spectral period range is one of the critical considerations in ground motion scaling. However, there are no consensus and quantitative basis in current codes for seismic design of buildings. Here, first of all, correlation analyses are carried out between acceleration spectrum corresponding to different period point and structural non-linear seismic response. The preliminary spectral period range is discussed, which makes a significant contribution to the structural non-linear seismic response. Then, based-on extensive statistic analysis

and normalization processing, the parameter proxy of pectral shape RT1,T2 is introduced to decouple the control action of Sa(T1). Finally, some suggestions are presented to determine the range for scaling ground motions. The results show that the fundamental period could meet basically the requirement of low-rise buildings, in addition, 0.2T1~2T1 is adequate for medium- and high-rise buildings.

254: Vertical Inertial Response of an Elastic Pile Embedded within Gibson's and Weathered Soils

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Euclides Mesquita, University of Campinas
Nimal Rajapakse, Carleton University

This paper presents a semi-analytical formulation of the problem of time-harmonic vertical vibrations of an elastic bar embedded in a layered transversely isotropic half-space. The formulation is presented within the framework of linear theory of elastic wave propagation that is applicable for most cases of inertial response of embedded elastic buries under external excitations. The embedding medium is described by a classical Green's functions corresponding to buried distributed vertical loading in a layered half-space. The layered half-space is described by the exact stiffness method, in which the stiffness of the layered half-space is obtained by the linear combination of the stiffness of its constituent layers. The motion of the bar is represented by a time-harmonic polynomial function containing a set of generalized coordinates. The body force field in the layered medium corresponding to each polynomial shape function of the bar is obtained numerically by solving a flexibility equation system based on the Green's functions corresponding to buried distributed vertical body forces in the layered soil. The generalized coordinates of the bar's displacement function are thereafter computed by formulating the Lagrange's equations of motion for the bar. Numerical solution of the equation motion results in the solutions for generalized coordinates. The bar displacements and axial load profiles are determined from the solutions for generalized coordinates. The section of numerical results in this paper considers two cases of practical interest: Gibson's and weathered soils, in which the soil properties vary linearly with depth. In this paper, these cases are represented with the implementation of layered half-spaces by stacking a large number of thin homogeneous layers. Vertical impedance of a bar is presented for different frequency of excitations, length-radius ratios, soil layer configurations and bar elastic moduli ratios to understand the influence of soil layering, bar flexibility and frequency of excitation. The present formulation can be used to study pile-soil interaction problems, which are of fundamental interest for geotechnical applications.

79: Vibration Analysis of Delaminated Composite Plates with Perturbation Method

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Hangbin Zhang, Shanghai Jiao Tong University

The present work focuses on vibration characteristics in delaminated composite plates using perturbation method. Damage is considered as a local anisotropic plate stiffness reduction and three damage factors are defined to describe damage status of laminated composite plates. The analytical solutions for the plates with different boundary conditions and the cases of multiple local damages in the plates are obtained by the perturbation method. A numerical analysis is conducted on the vibration of delaminated composited plates, and the effect of damage factors on the vibration characteristics is discussed. Results indicate that three damage factors have different influence on the vibration characteristics. Also, modal curvatures and strain energy show higher damage sensitivity than natural frequencies and mode shapes.

260: Vibration Based Benchmark Problem for Human Activity Recognition

Ramin Madarshahian, University of South Carolina
Juan M. Caicedo, University of South Carolina

Human Activity Recognition using floor vibration can be used intensively in field of security and health care. For example, structural vibration can be used in tele-nursing systems for health monitoring of an elderly person to determine if he or she falls or if a room is occupied or empty. This method of monitoring does not have privacy concern like video surveillance systems or compliance challenges of wearable sensors. The main challenge of using the floor vibration is classifying the signals to correctly identify the type of human activity. In this work a benchmark problem is proposed to encourage researchers to develop new algorithms for vibration based Human Activity Recognition. Seven different human activities were repeated 115 times in five excitation locations in a room located in the second floor of a two-floor steel structure. Each excitation was recorded by four sensors and a total of 16,100 records were collected. The benchmark consists of seven different cases of increasing difficulty, and is designed to evaluate and compare proposed algorithms on a set of standard metrics. The capabilities of proposed algorithm can be measured in identifying the type of activity, combination of the type and magnitude, and the location of event occurrence. To better illustrate the benchmark problem, an example solution of signal classification is included, and its performance is evaluated using the proposed evaluation criteria.

73: Vibration Testing of an In-Service Pre-Stressed Concrete Highway Bridge Using Martlet Wireless Sensing System

Xi Liu, Georgia Institute of Technology
Xinjun Dong, Georgia Institute of Technology
Yang Wang, Georgia Institute of Technology

In structural health monitoring (SHM) applications, wireless sensing systems have drawn great interest owing to faster installation process and lower system cost compared to traditional cabled sensing systems. As a new-generation wireless sensing device, Martlet features high-speed data acquisition and extensible layout, which allows easy interfacing with various types of sensors. Vibration testing of an in-service pre-stressed concrete highway bridge in Bartow County, Georgia, is carried out using the Martlet wireless sensing system, and the acceleration, strain and displacement response of the bridge are measured and analyzed. Besides impact hammer tests during periods with no traffic, dynamic bridge response data is recorded when various types of vehicles pass over the bridge. In addition, bridge vibration under ambient excitation is measured and analyzed by using the natural excitation technique (NExT) to obtain modal properties of the bridge. The modal analysis results from ambient excitation are compared with these from impact hammer tests. The reliability of the Martlet wireless sensing system and its ability to distinguish different vehicle sizes are also demonstrated.

363: Vibration-based Health Monitoring of Wind Turbine blades Under Operational Uncertainties

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Eleni Chatzi, ETH Zürich
Vasilis Dertimanis, ETH Zürich
Minas Spiridonakos, ETH Zürich

The present study focuses on damage detection of wind turbine blades. Due to the uncertainties relating to operational loads, as for instance, the centrifugal effect tied to the root boundary conditions, and environmental factors, such as the variation of temperature and humidity, damage detection within the context of Structural Healthy Monitoring (SHM) becomes a challenging task. In order to propose a robust identification scheme, a vibration-based strategy is proposed herein.The present study focuses on the damage detection problem applied to the case of a blade of a small-scale wind turbine (Sonkyo Energy Windspot 3.5 kW). To this end, the blade is dynamically tested under its nominal (healthy) state as well as various damage scenarios of ranging severity. The experiments are further carried out for varying support conditions, as well as varying environments. The collected vibration responses are then used for the estimation of appropriate nonparametric and parametric models of the structure, serving for extraction of a characteristic statistical quantity tied to structural performance. The Vector AutoregRessive with eXogenous (VARX) Inputs method is employed for extraction of the modal characteristics of the blade under various conditions. Damage detection is carried out by tracking of the curvature mode shapes, and hypothesis testing for the frequency and damping quantities. A data regularization procedure is enforced for tackling the varying operational conditions. The outcomes of the proposed approach reveal significant promise not only for damage detection but additionally for quantification and localization.

291: Virtual Crack Extension Method for Elasto Plastic Fracture Analysis using the Complex Finite Element Method

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Harry Millwater, The University of Texas at San Antonio

The computation of the strain energy release rate for elastic-plastic materials through the virtual crack extension method is known to bring additional complications. For nonlinear problems, it is essential that the original and extended crack tip positions are processed simultaneously during the incremental solution procedure. Due to the nature of the complex finite element method, ZFEM, this requirement is automatically satisfied. The real domain handles calculations related to the original crack position, while the imaginary domain operations are based on an extended position for the crack tip. The perturbation of the crack front along the imaginary directions of the complex nodal coordinates can be interpreted as a Virtual Crack Extension technique. The energy release rate is computed within the incremental-iterative finite element procedure as a numerical derivative of the strain energy with respect to a crack extension using the complex Taylor series expansion method. A compact tension specimen with a crack was modeled using bilinear isotropic and Ramberg Osgood material models. The energy release rate results obtained by (a) the American Society for Testing and Materials Standards and (b) ABAQUS finite strain analysis were compared to (c) ZFEM results. The numerical examples indicate that the energy release rates computed using ZFEM are of the same accuracy as the domain-based J integral formulation and in excellent agreement with semi-analytical solutions.

409: Virtual Experiments of the Chain-Structure Process of Magnetic Composites by the Inclusion Based Boundary Element Method (iBEM)

Gan Song, Columbia University
Huiming Yin, Columbia University

When magnetic particles are mixed in a fluid under a magnetic field, magnetic particles will be aligned into a chain structure. By coupling the Eshelby's equivalent inclusion method (EIM) with boundary element method (BEM), a novel inclusion based boundary element method (iBEM) is formulated to simulate a large many-particle system for potential problems, elastic solid problems, and Stokes fluid problems. Since the particles are presented with less degree of freedoms and only boundary is meshed, this method is much more computational efficient than the finite element method (FEM) or BEM. The chain structure process is simulated by iBEM with the coupled simulation of the Stokes flow and magnetostatics, where both particle interaction and boundary effect are taken into considerations. Higher order expansion of eigenstrain rate and magnetization is introduced into each particle to simulate the mismatch of the material property. At each step, given the particle distribution, magnetostatical simulation will be conducted to obtain the magnetic field distribution, from which the magnetic force on each particle can be calculated. Then a Stokes' flow simulation will be conducted to update the particle distribution for the next step. The iBEM model will be validated with experiment results and then be used for virtual experiments to investigate the boundary effect on the alignment process and mechanical property of the chain-structured magnetic composites with respect to different volume fractions.

550: Viscoelastic Characterization of Bituminous Materials through Multiscale Testing-Analysis

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This study explores a linkage in the viscoelastic characteristics of bituminous materials between two scales: fine aggregate matrix (FAM) scale and its corresponding asphalt binder phase. FAM is a phase consisting of asphalt binder, air voids, fine aggregates, and fillers. It acts as a primary phase in evaluating the damage and deformation of entire asphalt concrete mixtures. The simplicity, repeatability, and efficiency of the FAM testing make it a very attractive specification-type approach for evaluating the performance characteristics of the entire asphalt concrete mixtures. Asphalt binder is a primary phase in FAM causing inelastic deformation. If a linkage between characteristics of FAM and its corresponding asphalt binder phase can be obtained, it implies that the characteristics of asphalt concrete mixtures can be evaluated by performing only asphalt binder testing. To investigate the linkage between the properties of FAM and its corresponding asphalt binder phase, viscoelastic characteristics of FAM and asphalt binder are determined by performing frequency sweep tests and multiple-stress creep-recovery tests. Test results are then incorporated with the Schapery's single integral theory of viscoelasticity to find a linkage between the two length scales of linear and nonlinear viscoelastic deformation characteristics. Test and analysis results imply that the time-, rate-, and stress-dependent viscoelastic deformation characteristics of FAM (or typical asphalt concrete mixtures) could be estimated or predicted from the simple binder testing to some extent, while a simple upscaling of stiffness characteristics from binder (or mastic) to FAM is limited to provide sufficient level of accurate prediction of material properties.

48: Vulnerability Estimation of Low-Rise Buildings against Wind Hazard Considering Uncertainty in Building Components

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Natural hazards such as hurricanes could cause severe property damage. An important and challenging task of hurricane loss modeling is to predict the possibility of housing damage ratio. The probability ratio depends on both wind speed and structure of the building. In this research an investigation of the low-rise wood structures, which are the majority of the residential buildings in Florida, has been performed. The present research incorporated an uncertainty in vulnerability estimation. This research is based on five main structural building

parts: roof to wall connections, roof cover, roof sheathing, openings and walls. For the interior damage an empirical model, which was used in HAZUS, has been utilized. An innovative feature of this study is the application of the Bayesian approach, which allowed to use of both experimental data and analytical estimation to produce an updated fragility function of the house components. Specifically, it was possible to predict the standard deviation and mean at different speed points of the fragility functions of house components. Another source of uncertainty taken into account in this research is the speed of wind. In the current research, probability functions from the literature were adopted to estimate the uncertainty of wind speed. The results shed light on the role of uncertainty in vulnerability estimation. The final outcome of this investigation is a vulnerability function with boundaries, which demonstrated the ultimate uncertainty of our prediction.

117: Wave Propagation in Irregular Honeycombs

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Honeycombs have gained considerable attention in recent years as an advanced material due to its capability of meeting high performance requirements in various critically desirable application-specific parameters [1]. These structural assemblies not only make an efficient use of material, but are also characterized by interesting dynamic and wave propagation properties. An analytical formulation has been developed in this article for wave propagation in irregular honeycombs. Spatial structural irregularity of hexagonal lattices has been considered. There are few scientific literatures available concerning analysis of wave propagation in regular honeycombs [2]. However, due to inevitable uncertainties associated with manufacturing and service conditions, honeycomb lattices are not perfectly regular in practical situation. In the present article we have studied the effect of spatially random structural irregularity in wave velocities of such irregular honeycombs. To the best of authors' knowledge, this is the first attempt to develop an analytical approach for analysing wave propagation in irregular honeycombs. Results are shown considering different degree of irregularity to present a comprehensive analysis. The analytical approach developed in this study provides a computationally efficient framework to study wave propagation in irregular hexagonal honeycombs.
References:1. Gibson L., Ashby M. F. (1999) Cellular Solids Structure and Properties. Cambridge University Press, Cambridge, UK.2. Gonella S., Ruzzene M. (2008) Analysis of in-plane wave propagation in hexagonal and re-entrant lattices, Journal of Sound and Vibration 312 125–139

762: Wind-wave Induced Vibration Control of Offshore Floating Wind Turbines

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Offshore floating wind turbines (OFWTs) have enormous potential for energy production, yet one of the major concerns is the vibration induced by the coupled effects of aero-hydro-servo-dynamics in the severe marine environment. The excessive vibration compromises the power output and causes fatigue damage, instability and even collapse of OFWTs. This research proposes a new three dimensional adaptive pendulum tuned mass damper (3D APTMD) to control the excessive space vibration (six degrees of freedom) of the OFWTs. The analytical model of a Spar-buoy type offshore floating wind turbine with an APTMD is established using Finite Element method. Real-time tuning of the frequency and damping property of the APTMD is performed to maximize the kinetic energy dissipation rate. Wind and wave time histories are generated from established spectrum and applied to the model. Performance of the proposed technique is evaluated under collinear and misaligned wind wave conditions. Results indicate that the proposed control technique can effectively attenuate the excessive response of the OFWTs under severe marine environmental conditions.