18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Variational Coupling of DG and CG Methods for Local Damage in Multi-Constituent Materials

Author(s): *Arif Masud, *University of Illinois at Urbana-Champaign*; Pinlei Chen, *University of Illinois at Urbana-Champaign*;

This talk presents 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. Introducing an interfacial gap function that evolves subject to constraints imposed by opening and/or sliding interfaces, the proposed Variational Multiscale DG (VMDG) method seamlessly tracks interface debonding by treating damage and friction in a unified way. An internal variable formalism together with the notion of irreversibility of damage results in a set of evolution equations for the gap function. Evolution of the debonding surfaces requires interfacial stabilization that is developed based on residual-based stabilization concepts. Tension debonding, compression damage, and frictional sliding are accommodated, and return mapping algorithms in the presence of evolving strong discontinuities are developed. A significant contribution of the paper is the consistently derived method to model the Lagrange multiplier field via interfacial flux and jump terms and variational embedding of various nonlinear interfacial debonding models at the interfacial boundaries. This derivation variationally embeds the interfacial kinematic models that are crucial to capturing the physical and mathematical properties involving large stains and damage. A set of representative test cases highlight the salient features of the proposed VMDG method and confirm its robustness and range of applicability.

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Creep Damage Detection in 410 Stainless Steel using Acoustic Micro Imaging

Author(s): *Didem Ozevin, *University of Illinois at Chicago*; Niloofar Nabili Tehrani, *University of Illinois at Chicago*; Zeynab Abbasi, *University of Illinois at Chicago*; Ernesto Indacochia, *University of Illinois at Chicago*;

The early detection of stage III creep damage is a critical issue since at this stage creep damage becomes localized that can result in sudden failure. If the component is under almost uniform mechanical and thermal stresses, the creep mode will be a volumetric creep, which indicates a widespread damage and the generation of multiple cracks within a relatively large area. There may be some critical locations such as the stress risers or pre-existing defects regions, which require close monitoring to prevent the failure. In-situ assessment of the structures can play a significant role in predicting the remaining life and evaluating the damage progression. While it has been shown that the ultrasonic velocity is more sensitive than the attenuation, the limitation of these conventional ultrasonic methods is that the generated defect during the creep should be apparent sufficiently to be detected. The problem becomes even more pronounced when the creep damage is in the early stage and reveals in the form of subtle microstructural changes. In this paper, the acoustic microscope is used with the focused transducers of up to 400 MHz and the resolution of 3 µm and 100 gates for multi-dimensional analyses. The system is based on immersion ultrasonics, which utilizes de-ionizing water as a coupling medium. It is shown that the creep damage leading to thickness change and the presence of porosity at the secondary stage of creep life can be detected by acoustic imaging without any destructive testing. The thickness change is measured through the profilometer image using 15 MHz transducer. The presence of porosity is quantified with multi-gate imaging focused on different layers with the resolution of 250 ?m.

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Fatigue and Fracture Mechanical Behavior for Chinese A5083 Steel at Room Temperature

Author(s): *Kaikai SHI, *Science an Technology on Reactor System Design Technology Laboratory*; Jun Tian, *Science an Technology on Reactor System Design Technology Laboratory*;

The basic material experimental data is important input parameters for the structural integrity assessment of engineering components. The reactor pressure vessel (RPV) is a key component of the existing and next generation nuclear power plants containing the reactor coolant, core shroud and the reactor core. RPVs are usually made of low alloy ferritic steel having better weldability and radiation resistant properties. The A508-3 steel is low carbon ferritic steel developed in American for pressure vessel application in nuclear reactors of nuclear power plants. In the present study, fatigue and fracture mechanical behavior of Chinese A508-3 steel at room temperature are studied by mechanical material testing machine (MTS). Test data of material's mechanical behavior including uniaxial tension, low cycle fatigue, threshold stress intensity factor range, fatigue crack growth, and fracture toughness is generated and given for further study. It is worth noting that the model in predicting fatigue crack growth based on low cycle fatigue is verified and discussed.

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Granular Media Entropy Revisited

Author(s): *Yuri Schreiber, *Schreiber Consulting*; Alexander Chudnovsky, *University of Illinois at Chicago*;

Statistical Mechanics of granular media has been proposed by Sir S.F. Edwards more than a quarter-century ago. It was constructed in the same way as classical Statistical Mechanics with the energy replaced by volume. Edwards work has triggered a large number of theoretical and experimental studies by Edwards with co-workers and many of his followers. However, some of the basic hypotheses of Edwards's statistical mechanics such as ergodicity and equiprobability of microstates have not been confirmed in experiments; some other fundamental assumption such as additivity of entropy still needs verification. Parallel to that developments and for about the same time numerous works concern with generalization of the classical Boltzmann-Gibbs-Shannon entropy have been published in physics community. A re-consideration of entropy and application of generalized entropy for granular media appears to be important since some laws of the random variables distribution for granular media are evaluated experimentally. Following “Occam’s razor” approach it is desirable to minimize additional assumptions compatible with known data for a complex system. In this communication we propose a generalized entropy for a complex system, if the probability distribution is known. It is constructed as the solution of the inverse problem for Jaynes’ principle of maximum of entropy with mean value as the only constraint. In such case the functional form of the generalized entropy is not universal as in classical statistical mechanics, but varies for different distribution laws. The approach is illustrated by the examples of the generalized entropy for the truncated normal and the gamma distributions. The gamma distribution is the best fit for the volume fluctuations of the granular media.

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Probabilistic Fatigue Assessment of High-Speed Railway Axles Due to Foreign Object Damage

Author(s): *S.C. Wu, *Southwest Jiaotong University/Xi’an Jiaotong University*; Z.W. Xu, *Southwest Jiaotong University*; C.H. Li, *Southwest Jiatong University*; G.Z. Kang, *Southwest Jiatong University*;

Surface defect data of high-speed railway axles were collected. In combination with the compressed-gas gun facility, simulation experiments of foreign object damage (FOD) were conducted. The surface defects were divided into corner, edge, and surface defects corresponding to different axle surface impact defect types. Furthermore, based on a rotating bending fatigue experiment and the approximate Owen one-side tolerance limit method, the fatigue P–S–N curves and fatigue limits, with 95% confidence and 95% reliability level, of smooth and FOD-affected specimens were obtained. Considering the obvious differences in size and roughness between the full-scale axle and specimens, the full-scale axle fatigue limits with different defect types were modified and calculated. Finally, the Kitagawa–Takahashi diagram widely used in aero-engine FOD was further improved. For the first time, the fatigue limits of an FOD-affected axle with a 95% confidence and 95% reliability level were proposed to replace that of a smooth specimen, which can further prevent microdefects and microcracks caused by FOD from initiating and expanding under service loading, and ensure operation safety of high-speed railway axles. KEYWORDS: High-speed railway axles; Foreign object damage; Kitagawa–Takahashi diagram; Probabilistic fatigue assessment; High-cycle fatigue; EA4T steel Acknowledgements The authors wish to extend their very sincere thanks to the National Natural Science Foundation of China (11572267), the Science and Technology Research & Development Application Project of Sichuan Province (2017JY0216), and the Basis Research Project of the State Key Laboratory for Strength and Vibration of Mechanical Structures (2018TPL_T03).

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Time-Dependent Delamination of Thin Film and Its Computer-Vision-Based Blister Profile Analyzer

Author(s): *Haiying Zhang, *University of Illinois at Chicago*; Yang Chen, *TUM*; Alexander Chudnovsky, *University of Illinois at Chicago*; Hoang Pham, *Avery Dennison*;

The paper discusses thin film buckling-delamination from a substrate and its progression in time. The following issues are addressed: 1) leading physical and geometrical parameters of the film-adhesive-substrate system play the major role in initiation and progression of delamination; 2) the root cause of slow delamination growth in time; and 3) formulation of a quantitative model of the process. A brief review of existing approaches, design of experimental apparatus, observations and the modeling results are reported. Post-experimental processing requires unavoidable yet extremely laborious manual measurement of blister parameters (i.e., length and height). To accelerate the workflow of blister profile characterization, a full-automatic image analysis system has been developed. The underlying computer vision algorithm combines global clustering-based segmentation method with local adaptive thresholding approach to mitigate various limitations of the imaging system. Furthermore, a contour-based object recognition algorithm has been devised to decipher the reference scale without user intervention. The whole image processing pipeline is implemented on a state-of-the-art, energy-efficient embedded computing platform, whose architecture is specifically conceptualized and optimized for the given system framework, so that this newly designed computer-vision-based device can be seamlessly integrated into the existing delamination measuring device without compromising its extensibility in future upgrades.

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Structural and Material Failure Prediction Based On Multiscale Space-time Approach

Author(s): *Rui Zhang, *University of Texas at Dallas*; Shogo Wada, *Bridgestone Corporation, Japan*; Clint Nicely, *University of Texas at Dallas/ 2Raytheon Space and Airborne Systems*; Dong Qian, *University of Texas at Dallas*;

Many engineering applications are featured by a multitude of spatial and temporal scales that poses a great challenge for design and analysis. While a few hierarchical and concurrent multiscale approaches have been proposed to address the multiple spatial scales, the subject of multiple temporal scales has received relatively less attention and remains a critical bottleneck for establishing a robust simulation-based design platform. In this talk, a multiscale space-time method will be presented with a focus on modeling mechanical failures in structure and materials. This approach is established by integrating the time discontinuous Galerkin (TDG) formulation with an enrichment approach. The integrated space-time framework allows for a flexible choice of the time step sizes in different regions of interest thereby circumventing the limitation associated with the critical time step size in the traditional finite difference based time integration scheme. Furthermore, physics-based enrichment ensures that the relevant time scales are fully captured and thus enhances the convergence and accuracy. Following a presentation of the computational theory, applications of the approaches will be demonstrated in two separate cases: The first deals with concurrent models of peridynamic solids. While the subject of high-cycle fatigue in metals is investigated in the second case, in which it is shown that fatigue failures up to millions of cycles can be effectively simulated. This talk concludes with perspectives on how proposed computational framework can be extended to other complex structural and material systems.

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Stress Corrosion Cracking of Copper Tubing, Examination of Copper Tubing and Closed Cell Insulation

Author(s): *Zhenwen Zhou, *The University of Illinois at Chicago*; Alexander Chudnovsky, *The University of Illinois at Chicago*;

We have conducted a detail visual inspection and Optical microscope and SEM, EDX examination of failed tubes; tube wall thickness measurements and estimation of the approximate residual circumferential stress. High residual stress (compared with tensile strength) has been determined. (In some tubes, the residual stress reaches 50 ~ 60 % of the minimum tensile strength required by the standards). Multiple dark and green corrosion patches have been observed under Armacel isolation. Multiple axial cracks, typical for stress corrosion cracking, constitute the fracture site. Optical & SEM fracture surface as well as circumferential cross sections observations reveal extremely brittle mode of fracture. No trace of characteristic for copper ductility has been observed. It appears severally cold worked copper has existed the ductility in circumferential direction. The corrosion deposits are also observed on fracture surface. The Stress Corrosion Cracking appears to be the failure mechanism.

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Predicting Fracture and Lifetime Without Curve Fitting: Unification of Newtonian Mechanics & Thermodynamics

Author(s): *Cemal Basaran, *University at Buffalo*;

Abstract The field of classical mechanics is based on Sir Isaac Newton's work in "The Principia," published in 1687. In this work, Newton introduced the world to three universal laws of motion, which describe the relationships of any object, the forces acting upon it and the object's resulting motion. It is these three laws that make up the foundation for classical mechanics, and all subsequent theories of mechanics are derived from them. But Newtonian mechanics still cannot account for the past, present or future of any aspect of a physical body or its governing equations. Around 1850, Rudolf Clausius and William Thomson (Kelvin) formulated both the First and Second Laws of Thermodynamics. Because the field of thermodynamics governs the past, present and future of all physical bodies, the aging process and life span of any physical body can be modeled in accordance with the thermodynamics laws. Still, thermodynamics alone cannot convey the response of a physical body under an external force at any given moment – something classical mechanics equations are able to achieve. Being able to accurately predict the life span of physical bodies, both living and non-living, has been one of humankind's eternal endeavors. Over the last 150 years, many unsuccessful attempts were made to unify the fields of classical mechanics and thermodynamics, in order to create a generalized and consistent theory of evolution of life-span of inorganic and organic systems. The objective has been to map out the aging process of a physical body using classical mechanics equilibrium equations while also predicting its life span. Most past attempts were based solely on the use of physical experiments, which would reveal the aging rate and life span of any physical body first. The experimental data is later be used to create a life-span expectancy model by curve fitting, like in the damage mechanics theory proposed by L. M. Kachanov. Author, will report a new unified mechanics theory that can now predict the fracture and life span of any physical body based purely on mathematical calculations and without the need for any prior life-span degradation testing or curve fitting phenomenological damage mechanics models.

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Beyond Classical Thermodynamics: Crystal Plasticity

Author(s): *Victor Berdichevsky, *Wayne State University*;

Thermodynamics is a macroscopic theory of material bodies. The laws of thermodynamics can be derived from equations governing the motion of atoms. The key point of this derivation is the existence of two characteristic times, the characteristic time of atomic motion and that of macroscopic evolution. Thermodynamic equations are obtained from equations of atomic motion by an elimination of fast variables. For fluids, elimination of fast variables yields equations of continuum mechanics. For solids, however, the situation is principally different: elimination of fast variables does not result in macro-equations as it brings the dynamic equations of defects thus remaining on the mesoscopic level. Dynamic equations for defects do obey the laws of classical thermodynamics. However, one more elimination of fast variables is needed to get to the macroscopic level. Such a step is quite different from that made by classical thermodynamics because fast variables must be eliminated not from ergodic Hamiltonian equations with a very simple structure of phase space, but from dissipative equations the space phase of which can be extremely complicated. It has become clear only recently that in case of dislocation dynamics phase space admits a relatively simple description which results in a special structure of plasticity equations involving entropy and temperature of dislocation microstructures. In this talk, a recent progress in this field will be presented.

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Challenges in Defining the Structure of Nanocomposites of Discrete Carbon Nanotubes in Various Materials during Deformation

Author(s): *Clive Bosnyak, *Molecular Rebar Design, LLC*; Kurt Swogger, *Molecular Rebar Design, LLC*;

In this paper we will present new work related to understanding the structural aspects during the deformation of several materials with discrete multiwall carbon nanotubes. These carbon nanotubes have dimensions of diameter about 13nm and contour length about 900 nm, so this scale bridges from just above molecular dimensions towards the macroscopic world. In particular, we will contrast the deformation behavior of composites materials with low strain to failure, i.e., less than 0.1, versus those with high strains to failure greater than 3. We will show that discrete carbon nanotubes investigated here can considered as more like stiff, yet flexible molecules in concerted flow processes and their properties of stiffness and strength realized only when the tubes are well bonded to the matrix. Effects of a range of carbon nanotube concentrations will also be presented to highlight the complexity of structural interactions between the tubes.

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: The Effects of Ply Thickness and Orientation in Fracture of Thin-ply Composites

Author(s): *John Botsis, *École Polytechnique Fédérale de Lausanne (EPFL), STI-LMAF, Lausanne, CH-1015, Switzerland*; Thomas Gmür, *École Polytechnique Fédérale de Lausanne (EPFL), STI-LMAF, Lausanne, CH-1015, Switzerland*; Guillaume Frossard, *École Polytechnique Fédérale de Lausanne (EPFL), STI-LMAF, Lausanne, CH-1015, Switzerland*; Joel Cugnoni, *École Polytechnique Fédérale de Lausanne (EPFL), STI-LMAF, Lausanne, CH-1015, Switzerland*;

Thin-ply composites (ply thickness down to 0.020mm) have gained considerable interest in the recent past due to certain advantages as compared to standard composites: thinner and lighter structures can be designed with thin-ply laminates and for a certain composite plate, more ply orientations can be selected accordingly increasing the design space. Another advantage of thin-ply composites is the higher strength property as compared with the standard composites. It has been reported that the onset of damage and ultimate strength increase significantly with reducing ply thickness. However, the increased strength is associated with a decrease in the resistance to fracture. Thus, a thorough understanding of fracture and failure characteristics of these composites is required before they can be used in design of advanced structures. In this study, experimental and modeling works are aimed at characterizing the inter- and intralaminar fracture of unidirectional layouts, in terms of three ply thicknesses t=0.030, 0.075 and 0.150 mm in DCB specimens, as well as translaminar fracture of CT specimens with cross-ply and a quasi-isotropic layouts using four ply thicknesses t=0.030, 0.075, 0.100 and 0.150 mm in monotonic loads. The experimental results show that in unidirectional layouts the resistance to crack initiation is the same but the consequent fracture progression is accompanied by long bridging zones leading to significant increase in energy release rate (ERR) at the steady state. In both cases the steady ERR increases with ply thickness and is attributed to fiber bridging in the wake of the crack. The results also show that the corresponding ERR in intralaminar fracture is well higher that the ERR in interlaminar fracture. Mechanistic investigations show that the microstructure's heterogeneity increases with ply thickness giving rise to bigger fiber bundles and longer bridging zone. The fracture experiments of the CT specimens resulted in a linear decrease of toughness with decreasing ply thickness at crack initiation as well as the steady-state propagation. The translaminar fracture toughness is approximately 70% lower than for a standard ply thickness (t=0.150 mm). Such a decrease of toughness is a major limitation for the use of thin-ply composites in structural applications. This strong reduction in toughness is attributed to a reduction of pull-out fibers height. Mechanistic investigations also highlight the interaction between adjacent plies in the quasi-isotropic laminates. In all cases, pertinent simplified traction-separation relations are proposed to simulate fracture of these materials.

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Reproducing Kernel Collocation Method for the Phase-Field Fracture Model

Author(s): *Sheng-Wei Chi, *University of Illinois at Chicago*; Ashkan Mahdavi, *University of Illinois at Chicago*;

Phase-field model has recently been introduced for brittle fracture simulation. Since crack surfaces are implicitly represented by a function in the higher dimension, it is versatile for predicting crack branching and nucleation processes. In this model, propagation, bifurcation, and nucleation of cracks are based on finding the global minimizer of the total potential energy [1]. An additional approximation based on a continuous scalar-valued phase-field is used to represent the crack topology [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 equilibrium equation which makes the computational process considerably expensive when using the Galerkin-based methods. Moreover, dependent on the phase field model, the method may lead to a 4th-order partial differential equation, which requires smoother approximation functions. In this paper, 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-form formulation and reduces the computational expenses by avoiding the domain integration [3]. The effectiveness of the proposed numerical method is demonstrated using linear fracture mechanics problems. 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 is presented and compared to other methods.
[1] G.A. Francfort, J.-J. Marigo, “Revisiting Brittle Fracture as an Energy Minimization Problem," Journal of the Mechanics and Physics of Solids, Vol. 46, Issue 8, 1 August 1998, P. 1319-1342 [2] M.J. Borden, T. J.R. Hughes, C. M. Landis, C. V. Verhoosel, “A Higher-Order Phase-Field Model for Brittle Fracture: Formulation and Analysis within the Isogeometric Analysis framework,” Computer Methods in Applied Mechanics and Engineering, Vol. 273, 1 May 2014, P. 100-118 [3] S.W. Chi, J.S. Chen, H.Y. Hu, J.P. Yang, “A gradient reproducing kernel collocation method for boundary value problems,” International Journal for Numerical Methods in Engineering 93 (13), 1381-1402.

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Stochastic Analysis of the Lifetime Evaluation of Polyethylene Pipes Based on the Crack Layer Theory

Author(s): *Byoung-Ho Choi, *Korea University*; Jung-Wook Wee, *Korea University*;

Polyethylene piping has recently been used in a variety of industrial applications and has replaced existing metal piping. However, polyethylene has various fracture mechanisms depending on the internal pressure conditions of the pipe, environmental conditions as well as materials structures, i.e. ductile, brittle and chemical-assisted fractures. When polyethylene pipes are tested based on well-known standard hydrostatic tests such as ISO 9080 and ASTM D2837 is carried out, a large scatter in the lifetime data is commonly observed around the knee point which is point of the transition of fracture mechanisms from ductile to brittle fractures, and this large scatter does not improve much even after the brittle fracture is observed. Especially, when the brittle fracture occurs, the life span of the polyethylene is very large depending on the size and distribution of inclusions and defects in the pipe wall. Moreover, once a crack initiated from one of inclusions and defects, the crack grows in very complicated manners either discontinuous or continuous modes, or a combination of these two modes. This complex crack growth characteristics are not easily analyzed by traditional and empirical fracture mechanics approaches, but the crack layer theory can be used to model such complicated crack growth behaviors to understand the lifetime variation. Crack layer theory has been used to theoretically explain the interaction effect between the crack and the process zone, and the mechanism of crack growth has been explained by two different driving forces for the crack and the process zone that are based on crack layer theory. In this paper, the scatter of lifetime data of polyethylene pipe is investigated using stochastic approaches, and the quasi-brittle and discontinuous crack growth behaviors of polyethylene are simulated based on the crack layer theory. Key parameters in the crack layer theory as well as probability functions are considered to understand root causes of a large scatter of the lifetime data of polyethylene pipe.

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Reflections on the Role of Microdefects in Brittle Fracture

Author(s): *Alexander Chudnovsky, *The University of Illinois at Chicago*;

Brittle fracture is typically manifested by development of macro crack(s) splitting a solid. It is commonly accompanied by relatively small overall deformation in contrast with ductile fracture associated with large irreversible strain. The microdefects play various roles in brittle fracture depending on material chemical makeup and morphology, material and component manufacturing process as well as the service loading conditions. It results in a multitude of fracture scenarios. However, for simple classification one can identify two main patterns. One is labeled “cooperative fracture” and another is “true brittle fracture”. Cooperative fracture is manifested by appearance of an array of newly formed microdefects within a small domain in a vicinity of main crack front (process zone). Microcracks, crazing, shear bands (plastic deformation), micro cavitation etc. constitute the process zone (PZ). Development of PZ is a material response to the stress concentration at the crack tip. In turn the newly formed microdefects overwhelm the field of preexisting defect and strongly affect the main crack growth. The crack and PZ evolve together as one deterministic system (Crack Layer) with multiple degrees of freedom. A true brittle fracture in contrast with the cooperative fracture the macroscopic crack propagates trough the random field of preexisting defects. It is manifested in stochastic crack paths, large scatter of strength and toughness and significant scale effect (specimen shape and size dependency). Such behavior results from material inability to form new defects either due to material makeup, loading conditions or both. In real life fracture of engineering materials both identified above extremes patterns are present in different proportions. Lifetime and reliability of structural elements are directly link with specific scenarios of crack-microdefects interaction. Proposed classification of brittle fracture is illustrated by various examples of field failures.

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Fracture and Failure in Earthen Structural Materials

Author(s): *Craig Foster, *University of Illinois at Chicago*; Mohammad Hosein Motamedi, *Rowan University*; Adam Tennant, *University of Southern Indian*; David Weed, *ANSYS, Inc.*;

While often overlooked by many in modern structural engineering applications, roughly one in three people still live in a structure made primarily of earth. Modern earthen structural materials have been developed that are sustainable, local, and economical in areas with relatively low labor costs. Modern materials often include a small amount of cement, lime, or other stabilizer to improve structural performance. Materials are also compressed either into bricks, as in compressed earth block, or in forms, like rammed earth. While these materials show great promise in certain applications, they are still not completely understood mechanically. In this presentation, we examine bulk constitutive behavior and the fracture behavior of the materials. The bulk behavior is fit by a cap plasticity model that features a nonlinear shear/tension surface, difference in triaxial extension and compression strength, and isotropic and kinematic hardening. The cap surface exhibits hardening related to inelastic pore collapse and grain crushing. The fracture inception in the bulk material is governed by a bifurcation condition, with a separate traction-based condition on weak interfaces. A traction-separation law governs the opening behavior in tension and sliding behavior in shear, with an elliptical surface coupling them. A friction law is employed on the fracture surface under mixed compression and shear, and a linear cohesion softening law is used. These material models are implemented in a custom enhanced strain finite element code. The models are compared to experiments of compression and bending on small wall samples, and agree well with the observed behavior. Further simulations are run to show the behavior of the material in more complex situations.

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Configurational Forces in Mechanochemistry of Chemical Reaction Fronts and in Biomechanics of Growth

Author(s): *Alexander Freidin, *Institute for Problems in Mechanical Engineering of Russian Academy of Sciences, St. Petersburg, Russia*;

A reaction between diffusive (movable) constituent and a solid similar to the reactions of silicon oxidation or lithiation is modelled basing on the expression of the chemical affinity tensor equal to the combination of Eshelby stress tensors of solid constituents and chemical potential of the diffusive constituent. The expression was derived from fundamental laws and entropy inequality written for an open system with chemical reactions (see Appendix in [1]). The normal component of the affinity tensor acts as a configurational force driving the reaction front, and the invariants of the chemical affinity determine the bulk reaction rate. We present a solutions of a number of boundary value problems for solids undergoing chemical transformations and demonstrate how external stresses and stresses induced by the transformation strain and stress concentrators can accelerate or retard the reaction. Then we focus on reaction locking effects – blocking the reaction by stresses, and construct forbidden regions in strain or stress spaces formed by strains or stresses at which the chemical reaction cannot go. We study the stability of the reaction front in the vicinity of the reaction blocking state and note that the loss of the front stability may be the source of damage. Then the concept of the chemical affinity tensor is developed for modeling biological growth. The expressions of configurational forces driving the growth are discussed. The model is examined for bone remodeling processes. References [1] Freidin, A.B., Vilchevskaya, E.N., and Korolev, I.K., Stress-assist chemical reactions front propagation in deformable solids, Int. J. Eng. Sci., 83, 57-75 (2014).

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Scaling Law Describing the Failure and Its Application in Predicting the Failure Time

Author(s): *Shengwang Hao, *School of Civil Engineering and Mechanics, Yanshan University, Qinhuangdao, China*; Lei Yang, *School of Civil Engineering and Mechanics, Yanshan University, Qinhuangdao, China*; Guojun Du, *School of Civil Engineering and Mechanics, Yanshan University, Qinhuangdao, China*;

Real-time prediction by monitoring of the evolution of response variables is a central goal in predicting failure. This paper focuses on the scaling law during the process of damage evolution inducing the failure. We perform three types of quasi-static experiments: monotonic loading (type 1), brittle creep (type 2), and brittle creep relaxation (type 3), that are designed to simulate the three typical types of fault loading occurring in the upper crust. We illustrate the scaling law of average failure rate and steady-state rate.The evolution properties in the steady stage of a rock specimen are reflective of the damage or weakening growth within and thus are used to determine whether an unstable transition occurs. The average failure rate presents a common power–law relationship with the evolution rate in the steady stage, although the exponent is different for different loading modes. The results indicate that a lower ratio of the slope of the secondary stage with respect to the average rate of the entire lifetime implies a more brittle failure. This provides a potential method for estimating time-to-failure through the information of the steady stage. On the other hand, our results show the critical power law ecceleration precursor of the response function with the time-to-failure. In the quasi-static monotonic loading, the response function is defined as the relative change of strain with respect to the controlling variable, and the strain rate in the brittle creep and creep-relaxation experiments.It is shown that the critical exponent varies between -1 and -1/2. Our results show that the tertiary stage may be divided into two parts, only the final part follows the power law relation. We suggest a new relation combining the power law and exponential functions to describe the acceleration of the strain rate. Techniques are developed to perform predictions and to illustrate the effects of data selection on the results. Laboratory creep failure experiments on granites show that the linear relation works well during the final approach to failure. The data nearby the failure time following the power law behavior present stable and indentical estimations of the failure time.

18th U.S. National Congress on Theoretical and Applied Mechanics
June 5-9, 2018, Chicago, Illinois

Title: Size Effect in Concrete Fracture: Statistical Analysis and Numerical Simulation

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Cementitious materials, such as mortar and concrete, are highly heterogeneous in nature. These composites generally exhibit high compressive strength, low tensile strength, and brittle failure under tensile loading. This heterogeneity, voids and micro cracks, result in highly nonlinear behavior of cement base composite in spite of highly brittle nature. The non-linear behavior shows that concrete is damaged with slow crack growth before catastrophic failure. Fracture mechanics in cementitious materials depends on intrinsic factors such as aggregate size and extrinsic factors such as specimen size, influence of micro cracking, type and geometry of test specimen, and rate of loading. The well-recognized scale effect significantly alters the fracture behavior from the laboratory sized specimens to the actual applications, which obstructs a simple extrapolation. These factors have a great effect on the conventional fracture parameters that may contribute to the large scatter and sometimes controversial results reported in the literatures. This study is based on an extensive experimental program aimed at assessing the influence of maximum aggregate size and specimen size on the fracture properties of the concrete (Issa et. al). Concrete specimens were prepared with varying aggregate size of 4.75, 9.5, 19, 38, and 76 mm. The main purpose is to quantify the size dependent of G_1c (critical energy release rate) of various specimen size and aggregate size. Step by step analysis for each model will be performed using finite element modeling of fracture processes in order to find the fracture properties of the specimens. The data pertaining to the crack tip location and maximum load at each cycle will be used as the input data for the finite element analysis. In addition, the energy release rate, as a plot of crack length for a typical specimen, will be derived and compared with experimental data. The apparent randomness of brittle fracture is closely associated with the distribution of defects within the solid. In this paper, the Monte Carlo method will be proposed for solving the problem. Following the spirit of the Monte Carlo technique, we will substitute the averaging over all the path by a computer simulation of N number of virtual paths when a crack extends from point x to X along these trajectories. The material defects and heterogeneities will be accounted for by considering the specific fracture energy as a random field and the crack arrest and initiation will be determined by Griffith criterion applied along each crack trajectories.