Abstracts

Lightning talks on promising current and future directions

Zdenek P. Bazant (*Northwestern University*)

Scaling Law of HRR Theory of Plastic-Hardening Metals Based on the Gap Test

In 1968, Jim Rice (with Rosengren) and John Hutchinson published two epoch-making papers on fracture of plastic-hardening metals. Their work, with the T-stress effect, is now extended by formulating the scaling law. Gap tests of aluminum provide limited verification. More generally, scaling is a powerful check on all fracture theories. Can the recently popular phase-field model pass such a check?

With his impactful original contributions, Jim, at 80, is my most admired scientist in our field.

Martine D. Ben Amar (*Sorbonne Universite & Ecole Normale Superieure)*

Cusps in Growing Soft Materials: Prediction of J And M Integrals

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Gregory C. Beroza (*Stanford University*)

Machine Learning and Seismicity - What’s Next?

Machine-learning-based earthquake monitoring has been developed in research mode to analyze seismicity after earthquakes have occurred and is poised to be implemented for real-time monitoring. The next generation catalogs that result will feature at least a factor of ten more earthquakes than present catalogs. These catalogs will illuminate active faulting more clearly than ever before and their high dimensionality will motivate new approaches to understanding earthquake occurrence.

Jay Fineberg (*The Hebrew University of Jerusalem)*

How Earthquakes (or Frictional Motion) Start: Earthquake Nucleation

In the laboratory, rapid rupture fronts, akin to earthquakes, mediate the transition to frictional motion. Once formed, their singular form, dynamics and arrest are well-described by fracture mechanics. Ruptures, however, first need to be created within initially rough frictional interfaces. Hence, ``static friction coefficients” are not well-defined; frictional ruptures nucleate over a wide range of applied forces. A critical open question is, therefore, how the nucleation of rupture fronts actually takes place. New experiments show that rupture fronts are prefaced by slow nucleation fronts that bring the system to the Griffith length. These fronts are self-similar entities not described by fracture mechanics. We will briefly describe them and continue to a discussion.

Chen Gu (*Massachusetts Institute of Technology*)

Deciphering Time Series Signal from Labquakes to Building Shakings

We combine data-driven and physics-based methods to decipher time series data from labquakes to building shakings, which advances the characterization of various dynamical systems from fracture stimulation to building resonance.

Kyung-Suk Kim (*Brown University*)

Deformation and Failure Mechanisms of Multiphase Random Nanostructures

Low-density multiphase materials of multiple molecular-binding energy levels are often designed and used for high-strength and high-toughness structures under extreme loading conditions. Here, we present the discovery of self-organizing deformation and failure mechanisms stem from phase transitions comprised of nanoscale fragmentation and self-healing processes. Examples include the high dynamic toughness of polyurea and the failure waves in soda-lime glasses.

(The first course I took at Brown was “Advanced dynamics and random vibrations”, taught by Jim Rice and Paul Paris in 1976, where I learned how to handle randomness and disorder.)

Jeffrey W. Kysar (*Columbia University*)

Mechanics and Inner Ear Therapeutics

The inner ear, or cochlea, is a fluid-filled chamber surrounded by bone that transduces acoustic and inertial signals to electrical signals for processing by the brain. Given its inaccessibility, clinicians are not able to aspirate perilymph from the cochlea for diagnostic purposes nor are they able to inject drugs into the cochlea for treatment of inner ear disfunctions. The Round Window Membrane (RMW) is the only non-osseous barrier between the air-filled middle ear space and the cochlea, and thus is a potential portal into the cochlea. However, given its small size (about 2 mm in diameter and 70 µm thick) and its state of residual tension, the RWM tears uncontrollably when perforated with standard surgical tools with potential severe consequences for hearing. Herein, we discuss the design, manufacture and deployment of micrometer scale surgical tools that provide routine and safe access to the cochlea by creating temporary perforations across the RWM with no long-term structural or functional consequence.

Nadia Lapusta (*California Institute of Technology*)

Are Mature Faults Dynamically or Chronically Weak?

Observations suggest that mature faults host large earthquakes at much lower levels of stress than their expected static strength. Potential explanations are that faults are indeed quasi-statically strong but experience dramatic weakening during earthquakes [e.g., Rice, *J. Geophys. Res.,* 2006], or that faults are persistently weak, e.g., due to fluid overpressure [e.g., Rice, *Fault Mechanics and Transport Properties in Rocks,* 1992]. Recent numerical simulations [Lambert and Lapusta, *Nature*, 2021] show that the two models can be potentially distinguished by seismic radiation, with potential differences between tectonic settings and important implications for seismic hazard.

Jean-Baptiste Leblond (*Sorbonne Université, Faculté des Sciences et Ingénierie*)

Recent Advances and Open Problems In Mixed-Mode (I+III) Propagation of Cracks in Brittle Materials

The theoretical understanding and prediction of the well-documented instability of coplanar propagation of cracks loaded in mode I+III raises a considerable theoretical challenge. In spite of recent interesting advances in the field, many questions remain unsolved at present. A short presentation will be made of such advances and questions.

Xanthippi Markenscoff (*University of California, San Diego*)

Deep-Focus Earthquakes: The Strange Mechanics of Dynamic Phase Transformations Under High Pressures

The "mystery" of the deep-focus earthquake---of why no volumetric radiation is produced, and only shear, if they are due to a phase transformation with change in density---is resolved [Markenscoff, *J. Mech. Phys. Sol*., 2021] as due to instabilities under high pressure, even in the absence of any deviatoric pre-stress and full isotropy. The deep earthquake is the manifestation of instabilities under high pressures, with the instabilities manifested in the shape (planar) and and in growth (at constant potential energy) as allowed by the *M* integral [Budiansky and Rice, *J. Appl. Mech*., 1973]. Conservation laws and energy release rates. *J. Appl. Mech*.]. The deformation fields are those of the dynamic Eshelby problem that exhibit the "lacuna" phenomenon, of zero particle velocity inside the expanding region of phase transformation [Atiyah et al., *Acta Math*., 1970]. At present, new facilities, such as the National Ignition Facility (NIF), make possible experiments under ultra-high pressures (up to terra!), so that phenomena of phase transformations, as those occurring in planetary impacts, water to ice phase transitions (with recent publications in *Nature*), and processes deep in the Earth, amorphization in alloys, etc. can be probed. The discovered instabilities provide insight into these phenomena that are now opening to our understanding.

Robert C. Viesca (*Tufts University*)

Coupling Friction and Fracture During Geologic Fault Rupture

How does a fault's evolving interfacial friction couple with bulk deformation to lead to the spectrum of quasi-static slip episodes, earthquake nucleation, and dynamic rupture propagation? Alternatively, what can we infer about that coupling from remote seismological observations of earthquakes, laboratory rupture experiments, or intermediate-scale field experiments?

Comparison of Mode I Fatigue Delamination Propagation in Two Laminate Composites

Leslie Banks-Sills, Ido Simon and, Tomer Chocron

Tel Aviv University

Double cantilever beam (DCB) specimens composed of carbon fiber reinforced polymer laminate composites were tested. Two material systems were investigated. In the first, the specimens were fabricated from 15 plies of a plain woven prepreg (G0814/913) arranged in a multi-directional (MD) layup. The plies alternated with yarn in the $0^0/90^0$- directions and $+45^0/-45^0$- directions with the delamination between these two ply types. For the second material type, the specimens were fabricated from 19 plies with the delamination between a unidirectional fabric and a woven ply with yarn in the $+45^0/-45^0$- directions. The remainder of the plies were woven, with yarn alternating between the $0^0/90^0$ and $+45^0/-45^0$- directions. This laminate was produced by means of a wet-layup.

Fatigue delamination propagation tests were carried out with different displacement cyclic ratios R_d where

$$R_d = \frac{d_{min}}{d_{max}} \tag{1}$$

with d_{min} and d_{max} the minimum and maximum displacements in a fatigue cycle. For the prepreg laminate, R_d = 0.1, 0.33, 0.5 and 0.75; for the wet-layup, $R_d = 0.1$ and 0.48. The tests were carried out with frequencies between 4 and 6 Hz, many of them running continuously up to 3,000,000 cycles.

The delamination propagation rate $\mathrm{d}a/\mathrm{d}N$ was calculated from the experimental data and plotted using a modified Paris law with different functions of the mode I energy release rate $\mathcal{G}_I$, as well as its normalized value $\hat{\mathcal{G}}_I$; the energy release rate was normalized with respect to its fracture toughness. As expected, the $\mathrm{d}a/\mathrm{d}N$ curves depend on R_d. Using a different parameter, it is possible to obtain a master-curve for all R_d-ratios. Define

$$\Delta\overline{\mathcal{K}}_I \equiv \frac{\sqrt{\hat{\mathcal{G}}_{Imax}} - \sqrt{\hat{\mathcal{G}}_{Ith}}}{\sqrt{1-\sqrt{\hat{\mathcal{G}}_{Imax}}}} \tag{2}$$

where $\hat{\mathcal{G}}_{Imax}$ is the maximum value of the normalized energy release rate in a cycle and $\hat{\mathcal{G}}_{Ith}$ is the normalized value of the threshold energy release rate. Using the parameter in eq. (2) in a Paris type law, it may be observed in Fig. 1 that for each material system a unified master-curve is found. There is no dependence on R_d. The data is shown as dots. The slope of 5.2 for the prepreg is higher than that of 4.0 for the wet-layup. But the rate of propagation is higher for the wet-layup.

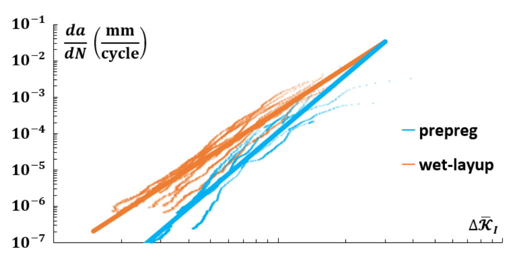


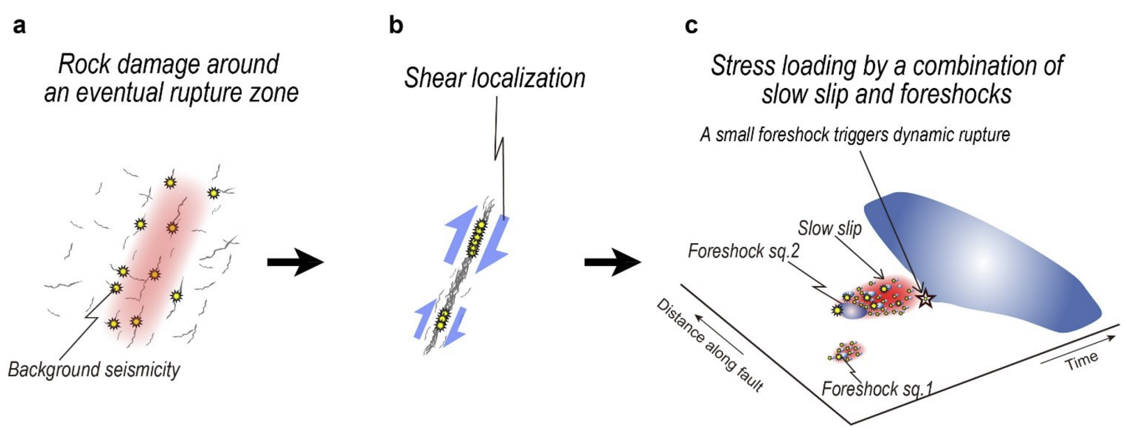
Figure 1. Delamination propagation rate as a function of $\Delta\overline{\mathcal{K}}_I$.

Localization of seismicity prior to large crustal earthquakes

Yehuda Ben-Zion[1] and Ilya Zaliapin[2]

[1]Department of Earth Sciences and Southern California Earthquake Center, University of Southern California, [2]Department of Mathematics and Statistics, University of Nevada, Reno

Localization of deformation signifies macroscopic instability (*Rudnicki & Rice*, *J. of Mech. and Phys. of Solids*, 1975). This fundamental insight suggests the possibility of tracking preparation processes leading to large earthquakes by monitoring localization of deformation. We present results on progressive localization of seismic activity before several $M > 7$ earthquakes in Southern and Baja California (*Ben-Zion & Zaliapin, Geophys. J. Int.*, 2020). The results are based on three complementary analyses: (i) estimated production of rock damage by background seismicity, (ii) spatial localization of background events within damaged areas, and (iii) progressive coalescence of individual earthquakes into clusters. Techniques (i) and (ii) employ declustered catalogs to avoid the occasional strong fluctuations associated with aftershock sequences, while technique (iii) examines developing clusters in entire catalog data. The different techniques provide information on different time scales and on the spatial extent of weakened damaged regions. The analyses reveal generation of earthquake-induced rock damage on a decadal timescale around eventual rupture zones, and progressive localization of background seismicity 2-3 yrs before the largest ($M > 7$) earthquake in the southern California catalog. This localization phase is followed by coalescence of earthquakes into growing clusters that precede the mainshocks. Corresponding analyses around the 2004 M6 Parkfield earthquake in the creeping section of the San Andreas fault, which is essentially always localized, show opposite tendencies to those associated with the faults that are locked in interseismic periods. Continuing studies with these techniques, combined with analysis of geodetic data and insights from laboratory experiments and model simulations, may allow developing a multi-signal procedure to estimate the approaching time and size of large earthquakes.

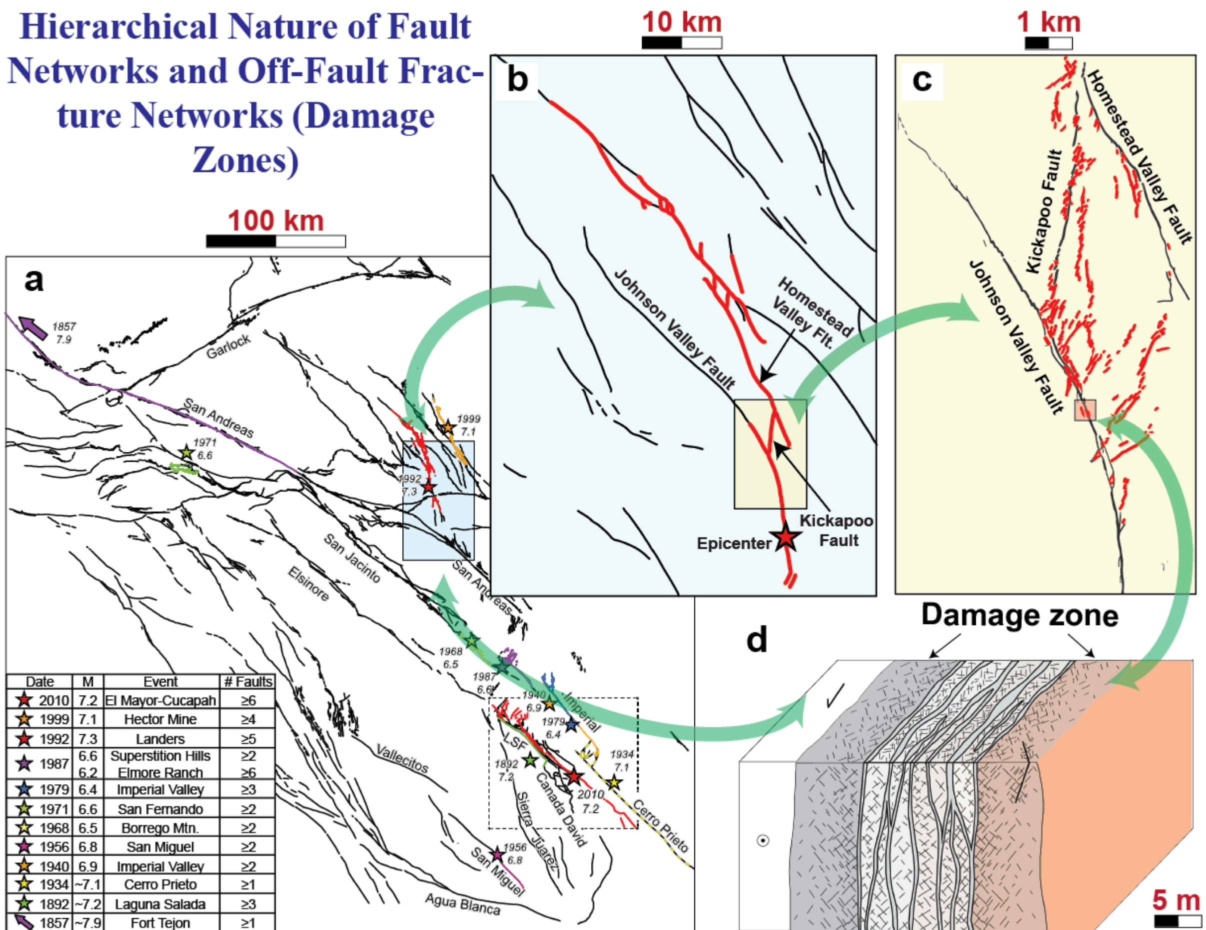


Schematic illustration of processes leading to large earthquakes. Generation of earthquake-induced rock damage (**a**) is followed by progressive localization of shear deformation and background seismicity (**b**) and final triggering of large rupture by slow slip and/or foreshock sequences (**c**). The space–time diagram in (**c**) includes, as example, 2 foreshock sequences. (After *Kato & Ben-Zion*, *Nature Reviews Earth & Environment*, 2021.)

Slip Instabilities Across Spatiotemporal Scales

Harsha S. Bhat[1]

[1]*Ecole Normale Supérieure, Paris*



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The past few decades have seen a veritable explosion of observations of dynamics of fault systems. All these observations show that the fault networks constantly release energy over a large range of spatiotemporal scales. In this very brief talk, I will provide insights into their mechanics from my group’s perspective. It is also an apt occasion to highlight how Jim and Renata have contributed to, inspired and encouraged our work across these scales.

Testing Griffith's theory of fracture in 2D materials

Huajian Gao[1,2]

[1]Nanyang Technological University, Singapore, [2]Institute of High Performance Computing, Singapore

Recent advances in nanoscale experimental mechanics have enabled researchers to test the fracture behavior of 2D materials consisting of a single layer of atoms, prominent examples including graphene and hexagonal boron nitride (hBN). Interestingly, it was found that graphene follows the classical theory of Griffith but hBN does not (Y.C. Yang, Z.G. Song, G.Y. Lu, Q.H. Zhang, B.Y. Zhang, B. Ni, C. Wang, X.Y. Li, L. Gu, X.M. Xie, H. Gao, J. Lou, "Intrinsic Toughening and Stable Crack Propagation in Hexagonal Boron Nitride," Nature, to appear). Specifically, hBN exhibits an energy release rate which is up to one order of magnitude higher than that predicted by Griffith's theory. Here, we show that the unexpected fracture behavior of hBN is due to an intrinsic toughening mechanism induced by its lattice asymmetry (Fig. 1). The asymmetric edge elastic properties of hBN causes a phenomenon called edge swapping during crack propagation, leading to repeated crack deflection and branching, which toughens h-BN tremendously and enables stable crack propagation not seen in graphene. This study sheds light on the toughening of 2D materials via atomic scale design.

Intrinsic Toughening and Stable Crack Propagation in hBN

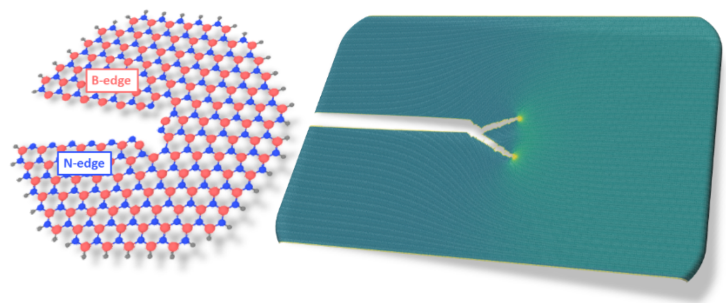

Fig. 1. An intrinsic toughening mechanism in hBN induced by lattice asymmetry.

Intersonic Bursts of Dynamic Mode I Planar Cracks

Philippe H. Geubelle[1], René Carpaij[2], Fabian Barras[2], and Jean-François Molinari[2]

[1]*University of Illinois at Urbana-Champaign,* [2]*École Polytechnique Fédérale de Lausanne*

The issue of the maximum speed of rapidly propagating cracks has long been the focus of the dynamic fracture mechanics community. A key result in this line of work is that tensile cracks with straight fronts cannot exceed the Rayleigh wave speed, as mode I cracks propagating in the intersonic (super-shear) regime do not absorb energy but emit it, which is physically impossible. In this work (Barras *et al.*, 2018), we show how a mode I crack, whose front is deformed by its interaction with an asperity, can experience bursts of super-shear motion.

The analysis is performed using a 3D spectral elastodynamic solver (Geubelle and Rice, 1995; Breitenfeld and Geubelle, 1998), which allows for very detailed simulations of the initiation and propagation of planar cracks under a wide variety of loading conditions. The spontaneous motion of the crack is modeled using a rate-independent linear cohesive traction-separation law.

By modeling the interaction between an initially straight mode I crack front and a circular asperity, we show how the highly curved front can experience short-lived super-shear propagation speeds, leading to the temporary formation of a cusp in the crack front. These local bursts create shock waves that can drive energy far from the site of the discontinuity in the crack front.

Barras, F., Carpaij, R., Geubelle, P. H., and Molinari, J.-F. (2018) “Supershear bursts in the propagation of tensile crack in linear elastic material.” *Physics Review E*, **98:6**, 063002-1-8.

Breitenfeld, M. S. and Geubelle, P. H. (1998) “Numerical analysis of dynamic debonding under 2D in-plane and 3D loading”. *Int. J. Fracture*, **93**, 13-38.

Geubelle, P. H. and Rice, J. R. (1995) “A spectral method for 3D elastodynamic fracture problems”. *J. Mech. Phys. Solids,* **43:11**, 1791-1824.

Modeling programmable drug delivery in bioelectronics with electrochemical actuation

Yonggang Huang[1], Raudel Avila[1], and John A. Rogers[1]

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Drug delivery systems featuring electrochemical actuation represent an emerging class of biomedical technology with programmable volume/flowrate capabilities for localized delivery. Recent work establishes applications in neuroscience experiments involving small animals in the context of pharmacological response. However, for programmable delivery, the available flowrate control and delivery time models fail to consider key variables of the drug delivery system—microfluidic resistance and membrane stiffness. Here we establish an analytical model that accounts for the missing variables and provides a scalable understanding of each variable influence in the physics of delivery process (i.e., maximum flowrate, delivery time). This analytical model accounts for the key parameters—initial environmental pressure, initial volume, microfluidic resistance, flexible membrane, current, and temperature—to control the delivery and bypasses numerical simulations allowing faster system optimization for different in vivo experiments. We show that the delivery process is controlled by three nondimensional parameters, and the volume/flowrate results from the proposed analytical model agree with the numerical results and experiments. These results have relevance to the many emerging applications of programmable delivery in clinical studies within the neuroscience and broader biomedical communities.

From J-integral to Infrastructure and Climate Change

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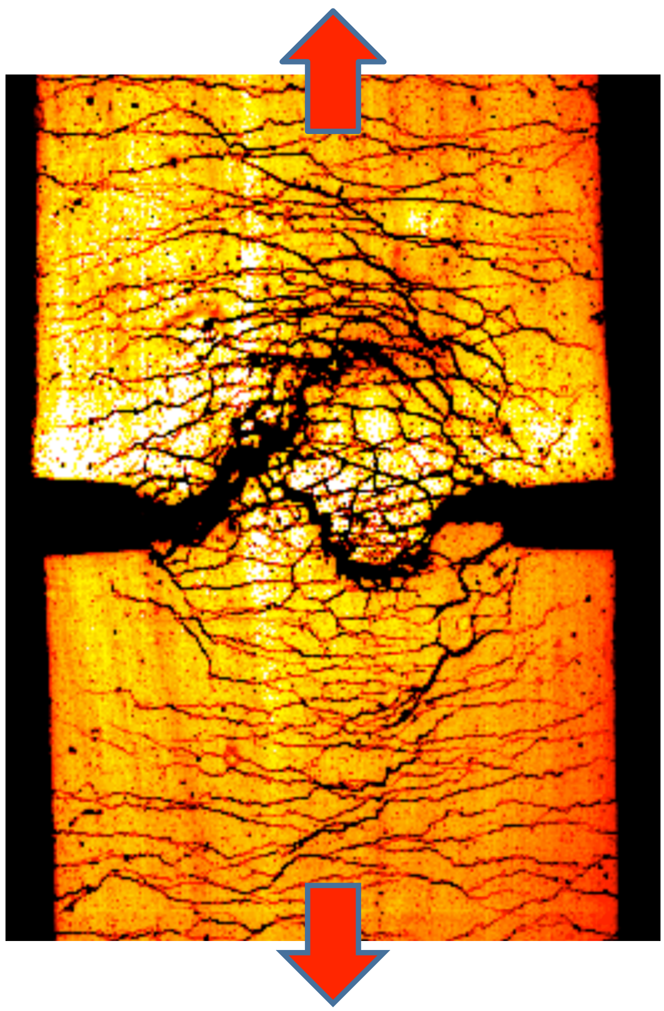
To counteract the challenges of crumbing civil infrastructure and climate change, a new ductile concrete (ECC) has been developed at the University of Michigan. ECC has over 300 times the tensile ductility of normal concrete, resisting the everyday crack-induced deterioration problems and suppressing catastrophic failures under extreme loading. In this presentation, I will share the design basis of ECC and highlight the contributions of fracture mechanics in general, and the J-integral in particular, to addressing the grand challenges to humankind. I will also touch on our recent research on carbon sequestration in ECC to induce carbon circularity in our built environment.

This presentation is dedicated to Professor James R. Rice and Dr. Renata Dmowska. They have major influences on my education and professional development.



Earthquake rupture barrier and possible slow slip on East Pacific Rise transform faults

Yajing Liu[1], Jefferey J. McGuire[2], and Mark D. Behn[3]

[1]McGill University, [2]US Geological Survey, [3]Boston College

Oceanic transform faults display a unique combination of seismic and aseismic slip behavior, including a large globally averaged seismic deficit, and the local occurrence of repeating magnitude (M) ~ 6 earthquakes with abundant foreshocks and seismic swarms, as on the Gofar transform of the East Pacific Rise and the Blanco Ridge in the northeast Pacific Ocean. However, the underlying mechanisms that govern the partitioning between seismic and aseismic slip and their interaction remain unclear. Here we present a numerical modeling study of earthquake sequences and aseismic transient slip on oceanic transform faults. In the model, strong dilatancy strengthening, supported by seismic imaging that indicates enhanced fluid-filled porosity and possible hydrothermal circulation down to the brittle–ductile transition, effectively stabilizes along-strike seismic rupture propagation and results in rupture barriers where aseismic transients arise episodically. The modeled slow slip migrates along the barrier zones at speeds ~ 10 to 600 m/h, spatiotemporally correlated with the

observed migration of seismic swarms on the Gofar transform. Our model thus suggests the possible prevalence of episodic aseismic transients in M ~ 6 rupture barrier zones that host active swarms on oceanic transform faults and provides candidates for future seafloor geodesy experiments to verify the relation between aseismic fault slip, earthquake swarms, and fault zone hydromechanical properties.

Storage particle cracking, solid electrolyte surface roughening and solid-state dendrite formation in lithium ion batteries

Robert M. McMeeking[1,2,3], Markus Ganser[4], and Markus Klinsmann[4]

[1]University of California, Santa Barbara, [2]University of Aberdeen, Scotland, [3]INM – Leibniz Institute for New Materials, Saarbrücken, Germany, [4]Robert Bosch GmbH, Stuttgart, Germany

Storage particles in lithium-ion batteries swell upon insertion of lithium, generating elastic stresses sufficient to crack them. This phenomenon is studied using a phase field method for fracture encompassing elasticity, lithium insertion and extraction, and lithium diffusion within the particle. It is shown that high C-rates, large particles and large swelling strains motivate particle fracture and comminution. In addition, a model is developed for the redox kinetics at an interface between a single ion conducting solid electrolyte and a lithium metal anode with inclusion of the effect of the mechanical stress across the interface, thereby extending the Butler-Volmer equation. This formulation is then used to assess the morphological stability of sinusoidal roughness on the surface of the lithium metal electrode when it is being plated from the single ion conducting solid electrolyte to which it is bonded. It is found that long wavelength roughness exceeding a critical value will always grow in amplitude. The critical value of the wavelength is proportional to the elastic shear modulus of the electrolyte, and inversely proportional to the current density in and the resistivity of the solid electrolyte. Therefore, any wavelength of roughness can be induced to increase in amplitude if the current density is high enough. The extended Butler-Volmer equation is also used to assess cracking of the solid electrolyte caused by insertion of lithium into a pre-existing flaw. It is found that lithium insertion from the solid electrolyte into the pre-existing flaw causes the lithium to yield plastically, and that pressure in the lithium in the crack builds up very rapidly. This pressure can cause the crack to propagate, thereby inducing dendrite growth that can short circuit the cell. This will occur unless the pressure in the lithium in the crack blocks the redox reaction that is inserting the lithium into it. In addition, the question of whether the lithium can extrude from the crack into the lithium electrode is investigated. It is found that it is likely that the lithium is contained within the crack, thereby enabling it to propagate the dendrite-flaw.

Thermal controls on ice stream shear margins

Colin R. Meyer[1], Brent M. Minchew[2], Alan W. Rempel[3], Marianne Haselof[4], Pierce Hunter[3]

[1]*Dartmouth College,* [2]*Massachussets Institute of Technology,* [3]*University of Oregon,* [4]*Northumbria University*

Ice in Antarctica primarily drains from the continent into the ocean through narrow, fast-flowing conduits known as ice streams. The nearly stagnant ice flow region outside of an ice stream is called the ridge, and the rapid transition between fast flow and the ridge is the ice stream shear margin. As drawn schematically in Schoof (2004), an ice stream shear margin is an antiplane crack, where slip occurs under the ice stream and the ice is frozen to the bed under the ridge. Jim and Thibaut Perol asked the question: how does deformation heating affect the temperature profile in a shear margin? Using a one-dimensional advection-conduction temperature model forced by observed shear strain rates in the Siple Coast, Antarctica, Thibaut found temperatures above the pressure-melting point for ice, thereby predicting a zone of temperate ice to exist in shear margins (Perol & Rice, 2015). Building on their foundational work, Meyer & Minchew (2018) derived a one-dimensional analytical model for the temperate zone height and forced the model using remote sensing observations from all of Antarctica to predict the temperate zone heights. Here, we present a two-dimensional (three velocity component), steady-state model designed to explore the thermal controls on ice stream shear margins. Sweeping through a parameter range that encompasses conditions representative of ice streams in Antarctica, we show that modeled steady-state velocity has a modest response to different choices in forcing up until temperate zones develop in the shear margins. When temperate zones are present, velocity is much more sensitive to changes in forcing. We identify key scalings for the emergence of temperate conditions in our idealized treatment that can be used to identify where thermomechanical feedbacks influence the evolution of the ice sheet. Jim's pioneering insight into shear margin processes has changed the way that glaciologists view ice sheet thermomechanics and the role of shear margins in ice sheet evolution.

Limits on Eshelby Transformation Strain set by Non-negative Dissipation and Dissipation Rate

Alan Needleman[1], Amine Benzerga[1], Manish Vasoya[1] and Babak Kondori[2]

[1]*Texas A&M University,* [2]*SpaceX*

Eshelby transformations are used in a wide variety of deformation phenomena including deformation of various composite and heterogeneous materials, phase transformations, plasticity of amorphous solids, earthquake stress drops, irradiation induced disorder and residual stress evolution. An Eshelby transformation involves an elliptical region (an inclusion) in a linear elastic solid undergoing a uniform strain that would be stress free if not for the constraint of the surrounding material. Eshelby (Proc. R. Soc. Lond. A 241, 376, 1957; Proc. R. Soc. Lond. A 252, 561, 1959) showed that the resulting stress and strain fields in the inclusion are uniform and provided a framework for calculating the stress and strain fields inside and outside the inclusion. The dissipation and the dissipation rate (the energy release rate) associated with the transformation can be expressed as the product of a configurational force, analogous to Rice’s J-integral for cracks and the Peach-Koehler force for dislocations, times the transformation strain (dissipation) or transformation strain rate (dissipation rate). The transformation relaxes the stress levels inside the inclusion but increases the stress levels outside the inclusion so that neither the dissipation nor the dissipation rate are necessarily non-negative. Analyses (Vasoya et al., J. Appl. Mech, 86, 051005, 2019; J. Mech. Phys. Solids, 136, 103699, 2020) will be mentioned that show that requiring either non-negative dissipation or non-negative dissipation rate significantly limits the magnitude of the Eshelby transformation strain that can occur.

Dynamic earthquake sequence simulation with a spectral boundary integral equation method without periodic boundaries

Hiroyuki Noda[1]

[1]*Kyoto University*

Dynamic earthquake sequence simulation is an important tool for investigating the behavior of a fault that hosts a series of earthquakes because it solves all interrelated stages in the earthquake cycle consistently, including nucleation, propagation and arrest of dynamic rupture, afterslip, locking, and interseismic stress accumulation. Numerically simulating and resolving these phenomena, which have different time and length scales, in a single framework is challenging. Rice’s group contributed a lot in developing the earthquake sequence simulation. Quasistatic simulations were presented by Tse and Rice (1986), and Rice (1993) introduced the impedance effect (radiation damping term) to formulate the “quasidynamic” simulation, and finally the fully dynamic simulation were presented by Rice and Ben-Zion (1996) and Lapusta, Rice, and Ben-Zion (2000), for example. A spectral boundary integral equation method (SBIEM) that makes use of a fast Fourier transform is widely used because it reduces required computational costs, even though it can only be used for a planar fault. The conventional SBIEM has a periodic boundary condition as a result of the discretization of the wavenumber (k) domain with a regular mesh; thus, to obtain an approximate solution for a fault in an infinite medium, it has been necessary to simulate a region much longer than the source distribution. Here, I propose a new SBIEM that is free from this artificial periodic boundary condition. Cochard and Rice (1997) showed that the periodic boundary condition can be removed for simulation of dynamic rupture by expressing the distributions of slip and traction as Fourier series for functions defined in a twice longer region than the fault of interest. They executed the integral with respect to k without discretizing by a regular mesh. In the present method, the trick by Cochard and Rice (1997) was adopted to the dynamic earthquake sequence simulation. The integration kernel for the elastostatic effect without the artificial periodic boundary condition, which reaches infinitely far from the source, is expressed analytically and replaces the one in the conventional SBIEM. The new method requires simulation of a region only twice as long as the source distribution, so the computational costs are significantly less than those required by the conventional SBIEM to simulate a fault in an infinite medium. The effect of the distance λ between the artificial periodic boundaries was investigated by comparing solutions for a typical problem setting between the conventional and proposed SBIEM. The result showed that the artificial periodic boundaries cause overestimation of the recurrence interval that is proportional to λ^{-2}. If λ is four times the fault length (Lapusta, Rice, and Ben-Zion 2000), the interval is overestimated by less than 1%. Thus, the artificial periodic boundaries have only a modest effect on the conclusions of previous studies.

How knowing Jim Rice influenced my academic tastes

Ares J. Rosakis

California Institute of Technology

Freeform recollections and presentation of thoughts and images.

Under the Influence

John W. Rudnicki

Northwestern University

This talk will present anecdotes and discussion of Jim's enormous influence on my own work over the last 50 years.

J integral as a conservation law and its application for welded joints

Aleksandar Sedmak[1], Ružica Nikolić[2]

[1]*University of Belgrade, Faculty of Mechanical Engineering, Serbia*

[2]*University of Žilina, Research Center, Slovakia*

The J integral has been used extensively as the fracture mechanics parameter for more than 50 years, ever since it was defined by Rice in 1968, [1], as the conservation law for a two-dimensional (2D) cracked body. It has been proven by Rice that the J integral is path independent, can be identified with the crack driving force and describes the stress and strain fields around a crack. Anyhow, as stated in the Rice's original paper, the J integral is valid for the 2D non-linear elasticity in absence of the volume and thermal forces and for the homogeneous material, at least in the crack growth direction. Its application beyond these limitations has been questionable, but still successful, e.g. in the elastic-plastic fracture mechanics, without any modifications of the original expression. In some other cases, modified J integrals were introduced, e.g. for elastodynamics, [2] and 2D curved body, [3].

Here, one of the problems out of the limits of the original definition of J integral is presented and described in more details, as defined more than 20 years ago, [4]. It is a problem of the weldment heterogeneity, represented as a multibody with interfaces between regions with different properties. As follows from the original definition, the J integral is not path independent for a generally shaped weldment. However, its path independence can be recovered if the modified J integral is introduced, comprising the original J integral and line integrals along the weldment interfaces, Fig. 1. To this end, the modified J integral for a multi-material body, representing the welded joint with four different material regions (base metal - BM, weld metal - WM, coarse grain heat affected zone - CGHAZ and fine grain heat affected zone - FGHAZ), is defined as follows:

$$J = \int_{\Gamma} \left(W n_1 - \sigma^{ij} n_j \frac{\partial u^i}{\partial x^1} \right) ds - \sum_{a=1}^{6} \int_{l_a} \left(W n_1 - \sigma^{ij} n_j \frac{\partial u^i}{\partial x^1} \right) ds ,$$

where l_a (a =1…6) are interfaces, Fig. 1. Results for a chosen example are provided, confirming the soundness of this approach.

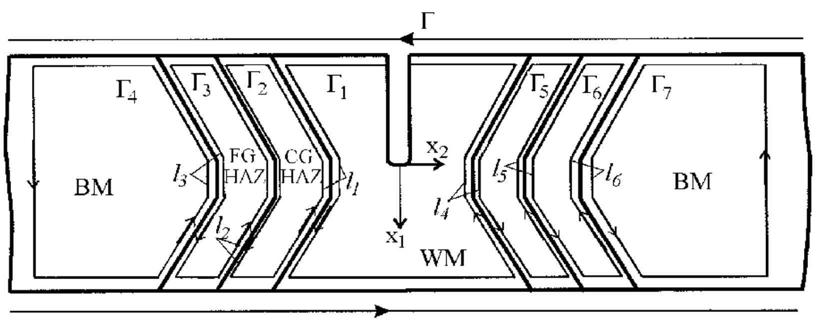


Figure 1. Integration paths for welded joint

1. J. R. Rice, A path independent integral and the approximate analysis of strain concentration by notches and cracks. J. Appl. Mech. 35, pp. 379-386, 1968.
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Repeating Caldera Collapse Events Constrain Fault Friction at the Kilometer Scale

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Fault friction is central to understanding earthquakes, yet laboratory rock mechanics experiments are restricted to at most, meter scale. Questions thus remain as to the applicability of measured frictional properties to faulting *in situ*. In particular, the slip-weakening distance d_c strongly influences precursory slip during earthquake nucleation, but scales with fault roughness and is therefore challenging to extrapolate to nature.

The 2018 eruption of Kilauea volcano, Hawai`i, caused 62 repeatable collapse events in which the summit caldera dropped several meters, accompanied by M_W 4.7-5.4 Very Long Period (VLP) earthquakes. Collapses were exceptionally well recorded by Global Positioning System (GPS) and tilt instruments and represent unique *in situ* kilometer-scale friction experiments. We develop a lumped parameter model of a piston collapsing into a magma reservoir. Pressure at the piston base and shear stress on its margin, governed by rate and state friction, balance its weight. Downward motion of the piston compresses the underlying magma, driving flow to the eruption vents. Monte Carlo estimation of the system parameters validates laboratory friction parameters at the kilometer scale, including the magnitude of steady-state velocity weakening. The absence of accelerating pre-collapse deformation constrains d_c to be less than or equal to 10 mm, potentially much less. These results support the use of laboratory friction laws and parameters for modeling earthquakes under similar conditions.

We identify initial conditions and ranges of material and magma-system parameters that lead to episodic caldera collapse, revealing that small differences in the elevation of eruptive vents can lead to major differences in eruption volume and duration. Most historical basaltic caldera collapses were, at least in part, episodic implying that the conditions for stick-slip derived here are commonly met in nature.

From interface fracture to adhesion

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In 1989, I wrote my PhD thesis, titled Mechanics of Interface Fracture, under the direction of Professor John Hutchinson. Professor Jim Rice was on my thesis committee, but he was visiting Caltech at the time of my thesis defence. I was disappointed. My thesis was greatly influenced by his papers on subject. From Caltech he wrote me a kind email to apologize for the absence. He also offered to co-author a paper with me, and let his researcher associate, Dr. Jansheng Wang, work with me on an experiment. Jim's kindness meant to me enormously then, and even more as I grow older. He set an example as a creative researcher and a caring gentleman.

After I started my own research group, initially at UCSB, I promised myself not to study interface fracture again. How naïve I was! Years later, friends at Intel got me involved in the interface fracture in semiconductor devices. In more recent years, opportunities have come up for me to work on adhesion between soft materials, such as living tissues, hydrogels, and elastomers. Fracture and adhesion make a lot of sense to a Chinese brought up in a world full of spears and shields.

High-Frequency Earthquake Ground Motion from Structural Impacts in Complex Fault Zones

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A fundamental question of earthquake science is what produces damaging high-frequency ground motion. Earthquakes often occur within complex fault zones containing numerous intersecting fault strands, but this complexity poses a computational challenge for earthquake rupture models, which often simplify the fault structure to a single rough fault surface. Thus, the amount of high-frequency ground motion in simulations may not be captured correctly due to the lack of accounting for the physics related to the transfer of slip between many fault surfaces. Here we discuss an alternative to off-fault viscoplastic deformation for accommodating fault slip in a complex fault zone by accounting for the stochastic transfer of momentum between various structures within a fault zone. In this alternate model, the elastic collision of structures occurs in response to fault slip in the presence of geometrical incompatibilities, which promotes transfer of slip onto different fault strands on timescales mediated by elasticity. This elastic impact model predicts that the strength of high-frequency radiation is primarily due to fault zone geometry, that radiation patterns at high frequencies are more isotropic than otherwise expected, and that P/S radiated energy is higher than for fault slip. These predictions are more consistent with certain earthquake observations, including explaining why apparent stress drops of earthquakes vary significantly within a given fault zone but are relatively constant globally, and why high-frequency radiation patterns are more isotropic than standard rough-fault frictional models predict. High-frequency earthquake ground motions and damage may therefore be an outgrowth of fault-zone geometric structure rather than related to off-fault viscous behavior.

Evolution of Frictional State is Dominated by Changes in Contact Strength, not Changes in Contact Area

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Rate and state friction refers to the dependence of friction on the velocity of sliding, and on a 'state' of the frictional interface that has been poorly understood for fifty years (Dieterich, J. Geophys. Res., 1972, Pure Appl. Geophys.,1978, J. Geophys. Res., 1979; Ruina, J. Geophys. Res., 1983). Empirically, the state of a frictional interface evolves with slip and/or with time, but the microprocesses responsible for this evolution are still unclear.

Frictional interfaces are in contact only at numerous smaller areas called asperities and their real total area is less than the nominal total area (Bowden and Tabor, Clarendon Press, 1964). Frictional resistance only results from the shear strength of the contacts acting across the area of all the contacting asperities. It is commonly presumed that changes in state are due to changes in the total contact area of the asperities (Scholz, J. Geophys. Res., 1968; Scholz et al., J. Geophys. Res., 1972; Scholz and Engelder, Int. J. Rock Mech. Mining Sci, 1976; and Engelder and Scholz, Int. J. Rock Mech. Mining Sci, 1976; Dieterich, Pure Appl. Geophys., 1978; Dieterich and Conrad, J. Geophys. Res., 1984; Dieterich and Kilgore, Pure Appl. Geophys., 1994; Scholz, Cambridge University Press, 2002; Aharonov and Scholz, Jour. Geophys. Res., 2018). An alternative explanation is that changes in state are due to changes in the shear strength of the contact area, for example by changes in chemical bond strength or density (Li et al., Nature, 2011; Thom, et al., Geophys. Res. Lett., 2018; Liu and Szlufarska, Phys. Rev. Lett., 2012).

Here we show that the evolution of frictional strength in experiments involving sudden steps in normal stress cannot be understood in terms of changes in contact area alone and must be dominated by changes in contact strength. The important observation is that at the time of the step increase in normal stress contact area is inferred to undergo an essentially instantaneous step increase, and there is very little subsequent change in contact area. In dramatic contrast to the abrupt change in contact area when the normal stress step occurs, the shear stress undergoes only a gradual increase and approaches an eventual steady-state value after some slip. At the time of the normal stress step the load-point velocity V_0 is maintained constant, but the slip velocity V drops, due to an increase in the contact area and therefore total shear resistance. We use the observed slip velocity perturbation to infer the ratio of the shear strength per area of the new area created by the step increase in normal stress, as well as its subsequent evolution, to the strength per area prior to the normal stress step. In order to explain our observations, we find the newly formed contact area to have a strength per unit area that is initially only about 20% of the strength that the older contacts had prior to the normal stress step, irrespective of step size. We also show that this initial strength contrast is continually erased by interfacial slip in order for frictional strength to reach its pre-step steady state value.

By careful analysis of these normal-stress-step experiments we are finally able to show that the evolution in state cannot be due to changes in contact area alone, and must involve changes in contact strength as well. This lays a foundation for replacing our empirical descriptions of state evolution with an understanding of operative microprocesses that focuses on changes in contact strength rather than contact area.

Influence of Fluid-Assisted Healing on Fault Permeability Structure

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Microcracks in fault damage zones can heal under thermally controlled processes. If a flow communication exists between a fluid source and the fault damage zone, warm fluids can migrate into it, change its thermal conditions, and assist healing. The crack life span depends on the local temperature and is, thus, modified by the infiltration of warm fluids. The features of the initial fault architecture govern how the fluids will propagate within the fault damage zones. This affects the rate of healing and the rate of permeability reduction. The region infiltrated by fluids will then show a significant decrease in its permeability, as seen in many field examples like the Alpine Fault. Conventionally, the damage zones immediately near the fault core have a high permeability that decays as we go further away. However, the region adjacent to the fault core, in the Alpine Fault, New Zealand, has the lowest permeability in the current interseismic period. As shown by our simulations, this can be due to healing and sealing, favored by the localized high geothermal gradients (confirmed by the drilling data) and the upward fluid migration through the fault relay structure, which accelerated mass diffusion and minerals precipitation. Hence, the thermal and hydraulic conditions play an important role in the fault permeability structure and its evolution during the interseismic period. It is necessary to take that into consideration when studying the seismic cycles of the faults.