Fracmeet 2021: Understanding Material Failure: One Hundred Years of Griffith's theory

Speaker: **Stefano Zapperi**
Title: *Predicting the failure of silica glasses*

Abstract: Glass represents the quintessential brittle material, shattering in pieces with little deformation. Yet at the nanoscale, silica glass becomes ductile and deforms plastically like metals. This behavior was observed experimentally in amorphous silica nanofibers, but its origin was unclear.

We investigated the problem by extensive atomistic simulations. The results show that the observed small sample size enhanced ductility is primarily due to diffuse damage accumulation. For larger samples, however, damage coalesce in extended cracks leading to brittle catastrophic failure. Surface effects such as boundary fluidization also contribute to ductility at room temperature by promoting necking, but are not the main driver of the transition. We then identify two distinct types of elementary plastic events, one is a standard quasilocalized atomic rearrangement while the second is a bond-breaking event that is absent in simplified models of fragile glass formers. Our results show that both plastic events can be predicted by a drop of the lowest nonzero eigenvalue of the Hessian matrix that vanishes at a critical strain.

Speaker: **Michael Zaiser**
Title: *Fracture behavior of hierarchically architectured materials: How to beat size effects in brittle fracture*

Abstract: Disordered materials suffer from statistical size effects (weakest-link behavior). All materials in presence of cracks suffer from classical fracture mechanical size effects as established by Griffiths. We demonstrate that, by endowing a material with a hierarchical architecture that interrupts load transmission and prevents supercritical crack growth, it is possible to mitigate against crack growth without falling prey to statistical size effects. To this end we present simulations of random fuse and random beam networks as well as experiments on hierarchically patterned paper and polystyrene sheets.

Speaker: **Thibaut Divoux**
Title: *Nonlinear viscoelasticity and generalized failure criterion for polymer gels*

Abstract: Polymer gels display a multi-scale microstructure that is responsible for their solid-like properties. Upon external deformation, these soft viscoelastic solids exhibit a generic nonlinear mechanical response characterized by pronounced stress- or strain-stiffening prior to irreversible damage and failure, most often through

macroscopic fractures. Here we show on an acid-induced protein gel that the nonlinear viscoelastic properties of the gel can be described in terms of a "damping function," which predicts the gel mechanical response quantitatively up to the onset of macroscopic failure. Using a nonlinear integral constitutive equation built upon the experimentally-measured damping function in conjunction with power-law linear viscoelastic response, we derive the form of the stress growth in the gel following the start up of steady shear. We further couple the shear stress response with Bailey's durability criteria for brittle solids in order to predict the critical values of the critical stress and strain for failure of the gel, and how they scale with the applied shear rate. Our work provides a consistent framework to describe the failure of polymer gels in a range of different deformation histories explored under external applied shear rate or shear stress.

Speaker: **Alex Hansen**
Title: *Life Time Distribution of Stretched Polymers*

Abstract: Stretch an ensemble of polymers using a constant external force and they will fail one by one due to thermal fluctuations. Some fail quickly, others live longer. What is the statistical distribution of life times? Even though each link in a given polymer obey Boltzmann statistics, this does not tell us anything directly about the link that fails. At any time there will be a link which is the most stretched and if this stretch is too large, the polymer fails. The statistics of the most stretched link is different from Boltzmann statistics. Rather, the stretch of the most stretched link follows extreme value statistics. By implementing this idea, we are able to find the behavior of the tail of the life time distribution. It turns out to have a power law tail with exponent -2, see Charan et al., Phys. Rev. Lett. 126, 085501 (2021).

Speaker: **Sivasambu Mahesh**
Title: *Fracture of unidirectional composites with fibre breakage and matrix failure*

Abstract: Physical composite failure is strongly affected by the matrix and fibre-matrix interface, in addition to the characteristics of fibre breakage. This is revealed by even a casual comparison of the fracture surface of a carbon-epoxy composite with that of a glass-epoxy composite.While the carbon composite fracture surface is typically flat, that of the glass composite is brush-like, with plenty of fibre pull out events revealed. This difference has been difficult to capture in fibre failure models.

We have recently developed a fast stress analysis model based on the FFT to analyse such failures. We have also developed an algorithm to detect brush-like failure in such computer models. We will present these models, and discuss 3D composite statistics obtained from them. We will connect these statistics with those of 2D models.

Speaker: **Mikko Alava**
Title: Fracture: extreme values, statistics, lifetimes

Abstract:

How and when material samples fails must also be considered as a stochastic phenomenon. I will discuss what we know of statistical fracture, both in terms of the (extremal) statistics distributions and in terms of factors affecting those. Next part of my overview concerns with the question of lifetimes, when such samples are subjected to e.g constant creep loadings.

Speaker: **Ian Main**
Title: *Shear band localization in a brittle porous medium: sound and vision*

Ian Main[1], Alexis Cartwright-Taylor[1], Maria-Daphne Mangriotis[1], Ian Butler[1], Florian Fusseis[1], Andrew Curtis[1], Andrew Bell[1], Martin Ling[2], Edward Andò[3], Roberto Rizzo[1], Sina Marti[1],

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The localisation of structural damage along an emergent fault plane is the key driving mechanism for catastrophic failure in brittle porous media. However, due to the speed at which stable crack growth transitions to dynamic shear rupture, the precise mechanisms involved in fault formation are poorly constrained. Understanding these mechanisms is critical to understanding and forecasting earthquakes, including induced seismicity, landslides and volcanic eruptions, as well as failure of man-made materials and structures. Here we used time-resolved synchrotron x-ray microtomography to image *in-situ* damage localisation at the micron scale in a new x-ray tranparent deformation cell that allows simultaneous acoustic measurements. By controlling the rate of acoustic emissions (AE) recorded during a triaxial deformation experiment, we slowed the strain localisation process from seconds to minutes as failure approached, at bulk axial strain rates down to 10^{-7} s^{-1}. The resulting time-resolved microtomography images demonstrate a strong intrinsic correlation between microstructures associated with shear and dilatant strain in the localised zone, with bulk shear strain accomodated by the nucleation and rotation of en-echelon tensile microcracks within a grain-scale shear band. Rotation is accompanied by sequential synthetic then antithetic shear sliding of neighbouring crack surfaces as they rotate. The evolving 4D strain field inferred from incremental digital volume correlation of sequential 'snapshots' independently confirm the correlation between shear and dilatant strain and show how strain localises spontaneously, first through exploration of several competing shear bands at peak stress before transitioning to failure along the optimally-oriented final fault plane. It also shows the characteristic strain relaxation after slip on a throughgoing fault that

might be expected from the ‘elastic rebound’ hypothesis. The distribution of strain is bimodal, with a strongly peaked structure at early times, and a with a fatter tail emerging at longer times as deformation progresses. We locate AE events in 3D using the two sensors placed on either end of the sample by combining the elliptical locus of possible source locations with the strain increment in the same time interval. The temporal and spatial statistics of AE signatures and the inferred strain field in the samples show that most AE locations are in strain zones undergoing mixed-mode (shear and dilational) strain, and confirm that there is a large fraction of aseismic deformation in the shear band itself.

Speaker: **Koushik Viswanathan**
Title: Opposite moving detachment waves mediate stick-slip friction at soft interfaces

Abstract:
Intermittent motion, called stick--slip, is a friction instability that commonly occurs during relative sliding of two elastic solids. In adhesive polymer contacts, where elasticity and interface adhesion are strongly coupled, stick--slip results from the propagation of slow detachment waves at the interface. Using \emph{in situ} imaging experiments at an adhesive contact, we show the occurrence of two distinct detachment waves moving parallel (Schallamach wave) and anti-parallel (separation wave) to the applied remote sliding. Both waves cause slip in the same direction and travel at speeds much lesser than any elastic wave speed. We use an elastodynamic framework to describe the propagation of these slow detachment waves at an elastic-rigid interface and obtain governing integral equations in the low wave speed limit. These integral equations are solved in closed form when the elastic solid is incompressible. Two solution branches emerge, corresponding to opposite moving detachment waves, just as seen in the experiments. A numerical scheme is used to obtain interface stresses and velocities for the incompressible case for arbitrary Poisson ratio. Based on these results, we explicitly demonstrate a correspondence between propagating slow detachment waves and a static bi-material interface crack. Based on this, and coupled with a recently proposed fracture analogy for dynamic friction, we develop a phase diagram showing domains of possible occurrence of stick--slip via detachment waves vis-\'a-vis steady interface sliding.

Speaker: **Lucas Goehring**
Title: *Cohesive Granular Media*

Abstract: A wide range of solid, porous materials, such as sandstone, concrete and snow, can be described as rigid particles with sticky, sintered or cohesive contacts. Here, we consider the general behavior of such cohesive granular media, and how they fail. We have recently developed a simple experimental realization of a cohesive granular material, consisting of glass beads bound together by narrow polymer (PDMS) bridges, which has tunable properties including its elasticity, fracture toughness, and permeability. In this talk I will describe and characterize this material and show how its macroscopic properties follow from the microscopic constitutive laws linking adjacent particles. Surprisingly, almost all of the material's response to strain is determined by the bonds between particles, which can be as little as one percent of the volume of the solid structure. I will also detail our minimal

model of these materials, which is fully constrained by experimental measurements. Under simple compression, this model shows a smooth transition from shear banding, to plastic deformation, to compaction banding (“anti-cracks”), as porosity decreases.

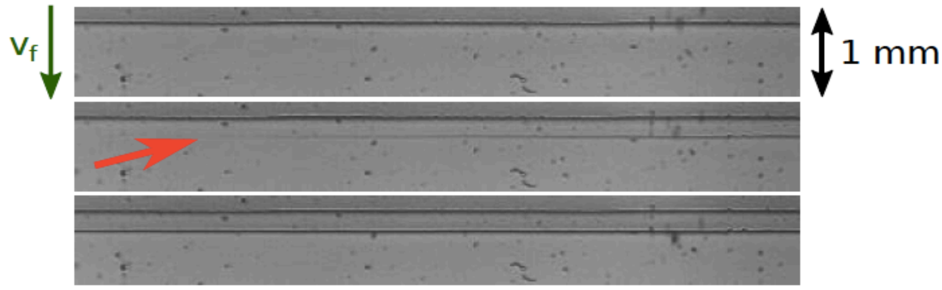
Speaker: **Takahiro Hatano**
Title: *Models for slow earthquakes*

Abstract: Quite a few attempts have been made on the earthquake statistics from a theoretical-physics perspective, but they mostly involve regular earthquakes. In recent years, a new category of earth-quakes, referred to as slow earthquakes, has been discovered. They emit only weak or no seismic signals, and have different statistics than those of regular earthquakes. Here we propose a physical model for tremors, which is a member of slow earthquakes, introducing two competing time scales in a model for self-organized criticality. Our model reproduces some observation results for tremors: enduring events, the moment-duration scaling, the size distribution, and the power spectrum of the moment rate function.

Inertial effects on the multi-scale stick-slip dynamics in adhesive tape peeling

Everyone has experienced the unpleasant screechy sound when peeling-off packing tape. This noise is the signature of a dynamical stick-slip instability, with periodic velocity oscillations of the peel front. Despite a large number of studies, such instability still causes industrial problems, bringing forward challenging questions. Recent studies have demonstrated that the unstable front dynamics is even a more complex process, involving a secondary instability at much smaller spatio-temporal scales than the macroscopic stick-slip.

Thanks to an extensive experimental study, we have been able to unveil the precise characteristics of this peel front micro-instability. In particular, the amplitude of this instability scales with its period as $A \sim T^{1/3}$, with a pre-factor evolving slightly with the peel angle, and increasing systematically with the bending modulus of the tape backing. A local energy balance of the detachment process shows that the elastic bending energy stored in the tape region that will detach during the micro-slip is converted into a kinetic energy increase of the peeled tape during a micro-stick-slip cycle.
Our model allows a quantitative description of the observed scaling-law linking amplitudes and periods of the micro-instability, and in particular its dependency with the peeling angle, as well as with the bending modulus and lineic mass of the ribbon.



Legend: Chrono-photography of the detachment front (time interval between each image is 20 µs) during a typical peel experiment (peel velocity 1 m/s, peel angle 90°, and peeled length 50 cm). The red arrow indicates the tip of the fracture kink, which propagates in the transverse direction across the tape width.

References:

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Thermal effects in material failure: is breaking through matter a hot matter? How to predict material failure by monitoring creep

Tom Vincent-Dospital[1,2], **Renaud Toussaint**[1,2], Alain Cochard[1], Eirik Grude Flekkøy[2], Knut Jørgen Måløy[2], Stéphane Santucci[3], Loïc Vanel[4], Daniel Bonamy[5], Lamine Hattali[5,6]

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In any domain involving some stressed solids, that is, from seismology to rock physics or general engineering, the strength of matter is a paramount feature to understand. The global failure of a mechanically loaded solid is usually dictated by the growth of its internal micro-cracks and dislocations. When this growth is rather smooth and distributed, the solid is considered to be in ductile condition. Alternatively, an abrupt propagation of localized defects leads to a brittle rupture of the full matrix.
It is then critical to understand what the physics and dynamics of isolated cracks are, when their tips are loaded at a given stress level. While the general elasticity theory predicts such stress to diverge, it is acknowledged that some area around the crack fronts is rather plastic. In other words, some dissipation of mechanical energy, in a so-called process zone around a crack tip, prevents the - unphysical - stress divergence and shields the fronts from excessive load levels.

Here, we focus on the local Joule heating, that significantly contributes to the energy dissipation. Analysing experimental data of the rupture of many materials, we indeed show that the scale for the thermal release around crack tips explains why the toughness of different media spans over orders of magnitude (we analysed materials spanning over 5 decades of energy release rate), whereas the covalent energy to separate two atoms does not.

We propose a model in which the local heat production around a crack tip generates a temperature elevation, which in turn affects the chemistry of molecular bond breaking and its rate, and thus the crack front velocity [1]. This is compared to two types of experiments, some on PMMA fractured in mode I, some in adhesive tape peeling. We show that the model predicts correctly the loading curve (G,v) relating energy release rate G and crack velocity v over 7 orders of magnitude in velocity (Fig. 1). This model also offers hints on a possible origin of phenomena like fractoluminescence in some materials (e.g. adhesive tape), that we relate to a predicted tip velocity exceeding 1000 °C in the fast rupture stages (Fig. 2). We also study how material disorder impacts the characteristics of fast propagating avalanches, in the low temperature regime [2].

We here discuss the ability of this simple thermally activated sub-critical model, which includes the auto-induced thermal evolution of cracks tips [1], to predict the catastrophic failure of a vast range of materials [3]. It is in particular shown that the intrinsic surface energy barrier, for breaking the atomic bonds of many solids, can be easily deduced from the slow creeping dynamics of a crack. This intrinsic barrier is however higher than the macroscopic load threshold at which brittle matter brutally fails, possibly as a result of thermal activation and of a thermal weakening mechanism. We propose a novel method to compute the macroscopic critical energy release rate of rupture, Gc macroscopic, solely from monitoring slow creep, and show that this reproduces the experimental values within 50% accuracy over twenty different materials (such as glass, rocks, polymers, metals), and over more than four decades of fracture energy (Fig. 3). We also infer the characteristic energy of rupturing bonds, and the size of an intense heat source zone around crack tips, and show that it scales as the classic process zone size, but is significantly (10^5 to 10^7 times) smaller.

Eventually, we show that this approach leads to describe brittle rupture as a first order phase transition, and the brittle/ductile transition, as it happens at the basis of the lithosphere, as a second order phase transition [4]. The critical exponents of the latter are derived.

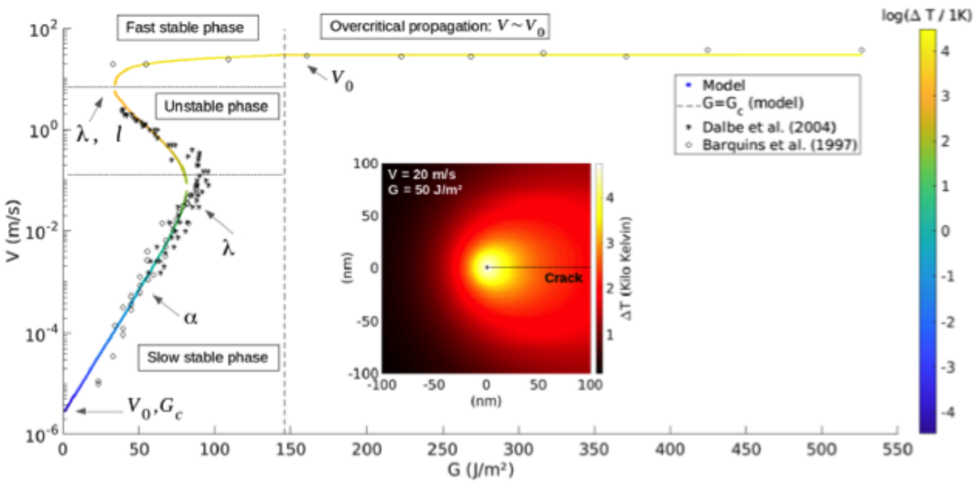

Fig. 1: Characteristic (G, v) predicted by the model fitted to experimental data (points) on fracture in tape glue, during tape peeling experiments. The unstable branch corresponds to $G(v)$ decreasing, its presence is associated to a stick-slip instability. The tip temperature is visible in the colour bar. The arrows indicate which model parameters control the different parts of the curve. The inset shows the modelled temperature field around the crack tip, at the onset of the instability, v=20 m/s [1].

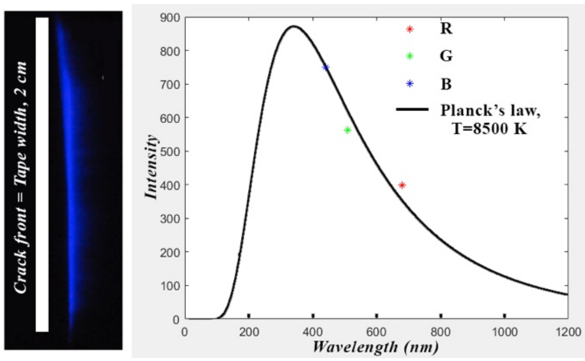

Fig. 2: : Stick-slip motion during tape peeling experiment monitored using an optical digital camera, where light is detected during the fast stages. The spectrum is compatible with a blackbody radiation at high temperature.

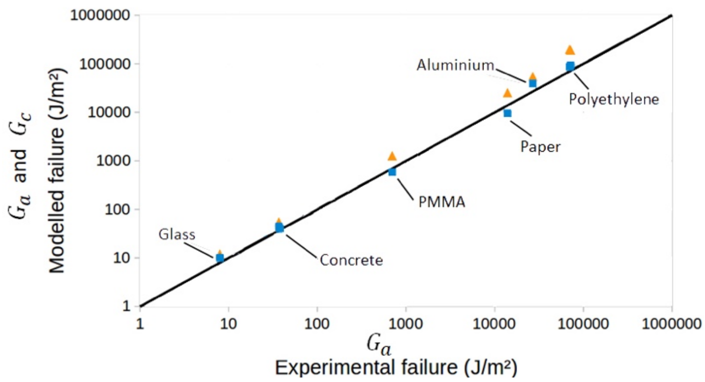

Fig. 3: Tests of the proposed theory on literature data, predicting macroscopic rupture from the creep motion, and comparing the prediction to the actual macroscopic critical energy release rate: from the slow velocity part of $G(v)$ curves, a microscopic critical energy release rate G_c can be computed. Taking into account local heating, a macroscopic critical energy release rate G_a can also be estimated. These theoretical estimations (in ordinate, blue squares: G_a and orange triangles: G_c) are here compared to the experimentally measured macroscopic energy release rate G_a (in abscissa). The values predicted are close to the experimentally realized ones [3].

References:

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