Failure of porous materials under compression: statistical aspects of labquakes.

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There are profound analogies between fracture experiments and earthquakes; however, few works attempt a complete characterization of the parallels between these so separate phenomena. We have studied the acoustic emission (AE) events produced during the compression of porous SiO$_2$ (Vycor). The distribution of avalanche energies (Gutenberg-Richter law), the rate of aftershocks (modified Omori’s law), and the law of aftershock productivity hold for a minimum of 5 decades. These laws are independent of the compression rate, and keep stationary for all the duration of the experiments. The waiting-time distributions fulfils a unified scaling law with a decaying power-law exponent close to 1.0 for short times and close to 2.5 for long times. Results for other porous materials will also be discussed.

Figure 1: Sequence of repeated compression cycles up to greater and greater loads of a Vycor sample. Left-hand panel shows the sample height against the applied load. Right-hand panel shows sample height against time. Black circles indicate the energies of the detected AE signals.

References:

Depinning of a 2D visco-elastic interface: multiple magnitude-area scaling regimes in earthquakes

François Landes

Independently from the geophysical applications, time-delay mechanisms have recently triggered interest in the amorphous materials community. Better quantitative characterization of the behaviour of this kind of model helps understand the extent of their generality. In the geophysics community, the relation between seismic moment and fractured area is subject to debate: experimental catalogs show a multiple scaling behavior, of which the origin is unclear.

First, I will quickly show why classical spring block models completely fail at capturing this multiple scaling. I will then show how the visco-elastic depinning framework, taking into account heterogeneous friction and the visco-elastic nature of faults [1], combined here with finite-size effects [2] allows to reproduce the different scaling regimes observed. The origin of the two crossovers are shown to be controlled both by the geometry and the bulk dynamics.

References:


Deformation localization processes in amorphous materials - statistical mechanics and continuum mechanics

Michael Zaiser

TBA
Avalanches in wood compression

Markus Ovaska

We study avalanches in small wood samples under uniaxial compression by using acoustic emission monitoring and digital image correlation. The distributions of acoustic event energies and waiting times follow power laws, and in analogy to earthquakes, we find that large events (mainshocks) are followed by aftershocks according to Omori's law. Damage localization occurs in the form of collapsing softwood layers, which we see as regions of high local strain using digital image correlation. The sudden collapses are accompanied by bursts of high acoustic activity [1].

We also explore the predictability of acoustic events in two scenarios. First, we use a fast signal processing setup to make online predictions of aftershocks during compression experiments. We then study the predictability of mainshocks based on thresholding the acoustic event rate.

References:

Avalanches, non-Gaussian fluctuations and intermittency in fluid imbibition

Jordi Ortin

We review our work on the invasion of a model open fracture by a viscous wetting fluid, in the context of research on the spatiotemporal dynamics of fronts in disordered media. The model consists on a Hele-Shaw cell with randomly-distributed dichotomic variations of gap thickness. Distortions of the advancing front produced by fluctuations in capillary pressure and permeability are damped by interfacial tension and fluid viscosity. Competition of forces at different length scales makes that an initially flat front undergoes a kinetic roughening process, leading to a statistically-stationary state characterized by critical interfacial fluctuations and a collective avalanche dynamics. Using fast and high-resolution imaging we are able to track the evolution of the advancing front in space and time with high accuracy. The motion of the front takes place by localized bursts whose lateral sizes, areas and durations are found to be power-law distributed--up to a cutoff scale which diverges as the capillary number of the displacement $\mbox{Ca} \to 0$, a limit corresponding to a critical depinning transition. A scale-dependent statistical analysis of the temporal behavior of the spatially-averaged velocity of the front reveals the presence of non-Gaussian fluctuations, strongly intermittent dynamics and global avalanches.
Liquid foams, such as chocolate mousse and shaving foams are soft materials that we all use in our everyday life. Their multi-scale biphasic structure of gas bubbles within a liquid phase leads to a dual mechanical behaviour: they behave as solids at rest while they can flow like liquids above a given critical yield stress. Such peculiar rheological properties are at the root of their use in diverse applications, ranging from food, cosmetics and pharmaceutical industries, to mineral extraction, oil recovery or soil remediation. For those last applications, understanding and controlling the flow of liquid foams in disordered fractured media appears of tremendous importance. Therefore, in the present work, we investigate both experimentally and numerically such process. Experimentally, we designed a set-up that allows the direct observation and characterization of a 2D liquid foam (composed of a bubble monolayer) forced to invade a model fracture. Our model fracture consists on a Hele-Shaw cell (15 cm wide, 50 cm long and 1 mm gap), with localized defects (of a few cm²), where the gap thickness of the cell is reduced (of hundreds of microns). We investigate the influence of the geometrical properties (height and spatial extent) of such defects on the foam imbibition dynamics – pinning and depinning of the bubbly liquid front as well as the bubbles’ rearrangements characterized by neighbours’ swapping.

Besides, we develop a model of foam imbibition, using a particle-based dynamic approach based on the Durian model (D. J. Durian Phys. Rev. Lett. 75, 4780 (1995)). We show that such numerical model can reproduce qualitatively our experimental observations.
Oscillatory instability of ultra-high speed brittle cracks in nonlinear elastic solids

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Experiments in thin gels have revealed that cracks can attain extreme speeds approaching the shear wave speed when micro branching, which limits propagation to smaller speeds in thick samples, is suppressed. They have further revealed the existence of an oscillatory instability with an intrinsic wavelength above a threshold speed. This talk will discuss progress to model this instability using a phase-field model of rapid fracture that bridges the short-scale physics of materials failure inside a microscopic process zone around the crack tip and macroscopic elastodynamics. Simulations of this model yield crack oscillations above a ultra-high speed threshold for neo-Hookean, but not linear, elasticity. Oscillations have an intrinsic wavelength that scales with the size of the nonlinear zone surrounding the crack tip, which can be much larger than the process zone size, and bear striking similarity with observed oscillations in thin gels. The results highlight the importance of nonlinear elasticity and associated emergent length scales in dynamic fracture instabilities. This work was carried out in collaboration with Chih-Hung Chen and Eran Bouchbinder and his supported by a grant from the US-Israel Binational Science Foundation.
The mechanical energy radiated as acoustic emission (AE) in externally stressed materials diverges when approaching to catastrophic failure. Different metastable models predict such result from the presence of an out-of-equilibrium critical point. Recent experimental results have reported a good agreement between the statistics of slip avalanches in granular and plastic materials and the mean-field (MF) critical failure of simple micromechanical models \[1, 2\], rendering a unified picture of critical failure within a universality class. However, the scale-free behaviour of the AE recorded during soft uniaxial compression tests \[3–5\] seem stationary instead of displaying a singular critical point. Detailed analysis of the AE registered during the soft uniaxial compression of artificial and natural silica (SiO \(_2\)) samples reveals trademarks of criticality in certain intervals. Such behaviour is compatible with critical failure in the MF model if the following constrains are lifted. First, we need to consider that quasistatic avalanches are split in aftershock sequences as already reported in such experimental results. Secondly, instead of a single failure stress, we observe that the material fails in a multifragmentation process associated to multiple potential localization bands. In the framework of the MF model, both effects can be implemented as an structured hardening-weakening coupling associate to quasi-brittle failure and a transient hardening associated to viscoelastic fracture or velocity-hardening friction.

References:


In ferroelectric materials, the structure and stability of domains with different polarisation depends crucially on both external boundary conditions and internal defects which together determine the screening of depolarising fields, nucleation thresholds, and domain wall pinning [1,2]. Here, we explore their combined effects on polarisation orientation, switching dynamics, domain wall roughness, and domain wall conduction, using scanned probe microscopy and structural characterisation of epitaxial ferroelectric thin films and heterostructures under different relative humidity, ultrahigh vacuum, and with different defect densities.

In PbTiO₃ thin films we show a reversal of the intrinsic polarisation orientation and the sign of the imprint as a function of growth temperature, under varying electrostatic screening, and relate the observed effects to oxygen vacancy gradients. In Pb(Zr₀.₂Ti₀.₈)O₃ thin films, we show slow growth and significantly increased roughening of domains when decreasing relative humidity and increasing oxygen vacancy density. We numerically probe the relative contributions of surface adsorbates and disorder, in good agreement with the experimental observations. Using a “pump-probe” approach we also explore the earliest stages of domain switching, demonstrating an unexpectedly long term (over 100 ms) metastability of the (sub)critical nucleus formed under very short repeated bias pulses at the probe tip [3].

We combine these observations with parallel conductive-tip atomic force microscopy current measurements, which show highly localised variations in conductance, and highlight the key role played by oxygen vacancies and surface adsorbates, whose redistribution allows the reversible transition between insulating and conducting transport behaviour at the domain walls [4].

References:

Universal pinning energy barrier for driven domain walls in thin ferromagnetic films

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In presence of impurities, ferromagnetic domain walls slide only above a finite external driving field. Close to this depinning threshold, the wall proceeds by large and abrupt jumps, called avalanches, while, at much smaller field, it creeps by thermal activation. We report a comparative study of magnetic field driven domain wall creep motion in thin films made of different magnetic materials for a wide range of magnetic field and temperature. The full thermally activated creep motion, observed below the depinning threshold, is shown to be described by a unique universal energy barrier function. Our findings should be relevant for other systems whose dynamics can be modeled by elastic interfaces moving on disordered energy landscapes.
Creep, disorder and the dynamics of magnetic domain walls in films and wires with perpendicular anisotropy

Gianfranco Durin

Magnetic thin films and wires with perpendicular anisotropy are promising systems in spintronics, for instance, as a new family of non-volatile memories. The key element is the possibility to stabilize the type of domain wall (Bloch or Neel) using the Dzyaloshinskii-Moriya-interaction (DMI) which occurs in case of coupling of the ferromagnetic layer with a high spin-orbit material (such as Pt).

Creep dynamics is highly affected by the DMI, and different groups have tried to determine its value from experiments, even if the situation is far to be clear. Here we present our method for a reliable determination of the interaction, pointing out the problems in the experiments and in the theoretical interpretation of the creep dynamics.
Amorphous materials show intriguing flow and arrest phenomena that are of fundamental scientific interest and importance in engineering applications. Recent years have witnessed exciting universal scaling relations in the flow of amorphous solids, and soft glassy model systems have largely contributed to measure these relations on large length and time scales. In particular, colloidal and granular model systems have advanced our understanding of internal relaxation mechanisms of strained glasses by direct imaging of the internal particle-scale dynamics. The emerging picture is that flow and flow instabilities are related to nonequilibrium phase transitions from a rigid, solid-like to a flowing, liquid-like state of the material. In this talk, I will present evidence from colloidal and granular systems: the direct imaging of particle structure and dynamics together with stress measurements reveal intriguing signatures of first and second-order transitions in the deformation of amorphous materials. Furthermore, our real-space data of arresting attractive suspensions shows that even gelation can be understood as a nonequilibrium transition from a dispersed to an aggregated phase.
Analytical calculation of displacement correlation tensor: toward Lagrangian mode-coupling theory unifying liquid-based and solid-based approaches to colloidal glasses

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In search of methodological advances in theoretical treatment of jamming, plasticity and glass transition, we present our recent approach to statistical theory of two-dimensional colloidal systems modeled by interacting Brownian particles [1,2].

There have been at least two different theoretical approaches to this kind of systems: the liquid-based mode-coupling theory (MCT) [3] and the solid-based normal-mode analysis [4]. The standard MCT describes the caged dynamics of the colloidal particles in terms of two-time correlation of the microscopic density field. Since density is scalar, it lacks a direct access to directional aspects of the slow dynamics, such as vortical cooperative motion of the particles. Contrastively, the normal mode analysis reveals vortical motion directly as collective displacement of the particles, but its analytical treatment seems to be more difficult than in the case of MCT.

In the present talk, we show that the displacement correlation can be calculated analytically [1,2]. The key idea is a good choice of variables: instead of the standard density field, we adopt the deformation gradient tensor as the basic field variable, and at the same time we switch to what is called the Lagrangian description in fluid mechanics [5], which means that we use a time-dependent curvilinear coordinate system that moves together with the particles everywhere. A linear analysis already reveals vortical cooperative motion. We will also discuss how to develop a nonlinear version of the theory on the line of MCT, aiming to incorporate some important ingredients of the glassy dynamics, such as interaction between the non-affine deformations and the breaking of cages.

References:

Microscopic dynamics during the creep of a colloidal gel

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The mechanical properties of amorphous solids such as glasses or gels are currently a topic of intense research, with implications in material science as well in fundamental condensed matter physics. At the macroscopic scale, a distinctive feature of these materials is the slow plastic deformation that is observed when they are subject to a step stress. Remarkably, this slow creep regime is often interrupted by the sudden failure of the material, with no macroscopic precursors.

Recent works focus on the interplay between irreversible rearrangements at the microscopic level, resulting from an applied deformation or stress, and the macroscopic mechanical behavior. In fact, even though material failure is ubiquitous in our everyday life, the underlying microscopic mechanisms are still not well understood, mainly because the direct observation of its precursors at the particle level is experimentally very challenging in atomic or molecular materials.

In this work, we study the microscopic dynamics of a model colloidal gel under load, by coupling a small angle light scattering apparatus to a custom stress-controlled shear cell. We find that the gel creep consists of three regimes. Initially, non-affine displacements grow linearly with strain. These non-affine dynamics are fully reversible upon removing the applied stress, and are associated to heterogeneity of the local gel elasticity. In the second regime, non-affine displacements grow much slower with strain, but are associated to irreversible rearrangements. In the third regime, a sharp acceleration of the dynamics at small length scale is observed. These rearrangements are a dynamic precursor of material failure; remarkably they occur thousands of seconds before the macroscopic yielding of the gel.
Scale-free avalanche dynamics and transformation-induced structural defects are two key traits of phase transforming materials. We have recently developed a theory that explains the crucial interplay between these two factors and solves an existing controversy in martensitic transformations which confronted self-organised and tuned criticality. Our model starts from a mesoscopic description of crystal deformations which is then reduced to a spin model of the random field type with zero-temperature metastable dynamics. The heterogeneous fields represent transformation-induced slip disorder which co-evolves with the phase transition, obeys heavy-tailed distributions and exhibits long-range spatial correlations. Scale-free response is only observed in the vicinity of a critical manifold in the space spanned by the driving parameter (temperature) and disorder (slip). In spite of that, evolving disorder makes scale-free response more robust than in plain tuned criticality since the critical manifold can be crossed without extrinsic tuning of disorder.
The structural complexity of metamaterials is in principle limitless, although in practice, most designs comprise periodic architectures leading to materials with spatially homogeneous features. More complex tasks dealing with spatially textured functionalities require aperiodic architectures. However, a straightforward implementation of such structural complexity invariably leads to frustration, which prevents coherent operation and impedes functionality. Here we introduce a combinatorial strategy for the design of aperiodic yet frustration-free metamaterials, whom we show to exhibit spatially textured functionalities. We implement this strategy using cubic building blocks which deform anisotropically, a local stacking rule which guarantees that deformed building blocks fit as in a 3D jigsaw puzzle, thus allowing cooperative shape changes, and 3D printing. We show that, first, these aperiodic metamaterials exhibit long-range holographic order, where the 2D pixelated surface texture completely dictates the 3D interior voxel arrangement. Second, they act as programmable shape shifters, morphing into spatially complex but predictable and designable shapes when uniaxially compressed. Third, they perform mechanical computations on externally supplied patterned textures. Combinatorial design thus opens a new avenue towards metamaterials with unusual order and machine-like functionalities.
Fracture size-effects in nanoscale materials

Stefano Zapperi

The failure of disordered systems is often ruled by extreme value theory: the weakest element is determining the failure of the entire system, leading to non-trivial size scaling of the failure distributions. The problem becomes particularly complex, however, when elements are coupled (e.g. by elastic interactions) or in presence of thermal fluctuations or rate-dependent effects. Here I discuss recent results that address these issues in full generality and present applications to the failure of nanoscale materials.
Statistical physics of the yielding transition in soft matter

Kirsten Martens

Steadily sheared disordered systems that yield in an athermal way (like foams, emulsions or granular systems) provide excellent examples for the study of driven disordered systems reaching an out-of-equilibrium steady state. The interesting feature of these type of systems is that fluctuations are solely introduced through the mechanical response itself. And the challenge is thus to describe this mechanical noise in a self-consistent correct manner. In this talk I will show that in this situation usual effective temperature based concepts, like Arrhenius type dynamics, should not hold [1, 2].

Even more interestingly these systems exhibit non-equilibrium phase transitions, that can be both continuous [3] and discontinuous [4], and are again not governed by usual temperature considerations, but other yielding dynamics related concepts. For the continuous transition we observe dynamical heterogeneities with diverging length and time scales, whereas in the discontinuous case we could show the existence of a phase coexistence between two dynamical phases. The existence of critical dynamics leads us to the question whether it will be possible to define different universality classes for the flow of yield stress materials, similar to what has been done in the field of the depinning transition [5]. Further we investigate the possibility of introducing mean-field descriptions to predict relations for macroscopic observables, such as the flow curve [2, 6].

References:


Avalanche statistics at the yielding transition of amorphous solids: driving rate dependence and inertial effects

Ezequiel E. Ferrero

We study stress time series caused by plastic avalanches in athermally sheared disordered materials. Using extensive simulations of a mesoscopic elastoplastic model, we analyze system size and shear-rate dependence of the stress-drop duration and size distributions together with their average temporal shape.

We find critical exponents different from mean-field predictions, and a clear asymmetry for individual avalanches. The probability distribution for local yielding and its driving rate dependence are also discussed in the marginal stability picture. We probe scaling relations for the rate dependency of the dynamics and we report a crossover towards mean-field results for strong driving.

By means of a finite-element extension of the model that allows for the control of damping, we additionally address the effects of inertia in the avalanche statistics.

References:

Driving Rate Dependence of Avalanche Statistics and Shapes at the Yielding Transition
Chen Liu, Ezequiel E. Ferrero, Francesco Puosi, Jean-Louis Barrat, and Kirsten Martens
Phys. Rev. Lett. 116, 065501
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Effects of inertia at the yielding transition of amorphous solids: a finite-element approach.
Kamran Karimi, Ezequiel E. Ferrero, Jean-Louis Barrat
(in preparation)
Spatio-temporal patterns in ultra-slow domain wall creep dynamics

*Alberto Rosso*

In presence of impurities, ferromagnetic and ferroelectric domain walls slide only above a finite external field. Close to this depinning threshold, the wall proceeds by large and abrupt jumps, called avalanches, while, at much smaller field, it creeps by thermal activation. In this work we develop a novel numerical technique that captures the ultra-slow creep regime over huge time scales. We point out the existence of activated events that involve collective reorganizations similar to avalanches, but, at variance with them, display correlated spatio-temporal patterns that resemble the complex sequence of aftershocks observed after a large earthquake. Remarkably, we show that events assembly in independent clusters owning the same scale-free statistics as critical depinning avalanches. This correlated dynamics should be experimentally accessible.
Crystal plasticity occurs by deformation bursts due to the avalanche-like motion of dislocations. In order to study the statistical properties of these avalanches, we have performed extensive numerical simulations of Al with three-dimensional dislocation dynamics code ParaDis [1]. We have modified the default version of the code by adding a quasistatic stress loading feature where the stress-rate is controlled by the average velocity of the dislocations. Our results show that dislocation avalanches are power-law distributed and display peculiar stress and sample size dependence: The average avalanche size grows exponentially with the applied stress, and the amount of dislocation activity increases with the system size. These results suggest that intermittent deformation processes in materials with FCC crystal structure exhibit an extended critical-like phase in analogy to glassy systems, instead of originating from a non-equilibrium phase transition critical point.

References:

Stick-slip instability during adhesive tape peeling

Vincent de Zotti

We present an experimental study of the peeling of an adhesive tape at a constant velocity.

In a given range of imposed peeling velocity, the detachment front displays a jerky dynamic, alternating periodically fast and slow phases, characteristic of a Stick-Slip instability. Recent studies have evidenced the crucial role of the peeling angle [1] and the ribbon inertia [2] on such unstable motion, as well as its multi-scale nature [3,4]. Indeed, during the fast phase ("Slip") of the stick-slip cycles, a secondary stick-slip instability has been observed involving significantly smaller temporal and spatial scales.

We pursue those recent studies in the present experimental work. Using an high speed camera, we follow the unstable propagation of the detachment front of an adhesive tape, peeled from a flat surface at a constant velocity.

On one hand, we provide a detailed characterization of the multi-scale stick slip instability - amplitudes and durations of the slow and fast phases - as a function of the peeling velocity, peeling angle and peeled tape length.

On the other hand, we focus on the onset of the instability. We could indeed observe a quasi-periodic oscillatory peeling front motion occurring at the transition between the regular and the Stick-Slip peeling dynamics. Such oscillatory peeling front motion can be explained by considering inertial effects modeled recently [2].

References:


