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From the dynamics of cracks to the forecasting of catastrophic failures

The damage and fracture of materials under various types of loading conditions is a very important scientific problem with a broad spectrum of industrial applications. Recently, experimental and theoretical investigations have revealed that the disorder, omnipresent in natural and most of the artificially made materials, plays a crucial role in fracture processes. Both on the micro- and macro-scales fracture processes are described by universal scaling laws having strong analogies to phase transitions and critical phenomena. The main objective of our project was to investigate how the amount of materials' disorder affects the fracture of heterogeneous materials including the mechanical response and ultimate strength on the macroscale, and the statistical and dynamical features of crackling noise accompanying failure processes on the micro-scale. We wanted to extend the phase transition description of fracture and fragmentation phenomena, and to understand the evolution of fracture patterns and their relation to the shape of fragments. As an ultimate challenge of the statistical physics of fracture, we were searching for signatures of imminent failure that can be exploited for forecasting of the catastrophic collapse of the system. The present report provides an overview of the most important outcomes of our project.

1.Fiber bundle modelling of the mechanical response and crackling noise of materials

Figure 1: An avalanche of breaking fibers in three dimensions. The color code indicates the time evolution of spreading.

To understand the role of the heterogeneous stress field in fracture processes, we investigated how the dimensionality of the embedding space affects the microscopic crackling dynamics and the macroscopic response of heterogeneous materials. Using a fiber bundle model with localized load sharing, we performed computer simulations from one to eight dimensions slowly increasing the external load up to failure. The failure thresholds of fibers were sampled from an exponential distribution. Analyzing the constitutive curve, fracture strength, and avalanche statistics of bundles we demonstrated that a gradual crossover emerges from the universality class of localized behavior to the mean field class of fracture as the embedding dimension increases. Simulations revealed that the average temporal profile of crackling avalanches evolves with the dimensionality of the system from a strongly asymmetric shape to a symmetric parabola characteristic for localized stresses and homogeneous stress fields, respectively. Increasing the dimensionality of the bundle implies a decreasing stress concentration along crack fronts by increasing the connectivity of the system. As a consequence, stress fluctuations have a diminishing role with increasing dimension giving more room for the quenched disorder of fibers' strength. Our study has the important consequence that the upper critical dimension of the fracture of heterogeneous materials is infinite. We gave numerical evidence that the critical exponents change as an exponential function of the dimension. The results were published in Physical Review E where our paper was highlighted in the Kaleidoscope of the journal [5].

There are a large variety of systems with a complex micro-structure which respond to external loading by local rearrangements, for instance, of particles like in granular materials and in agglomerates of dipolar particles, or by an activation of internal stored length such as spider silk. The stick-slip mechanism plays also an essential role in the shrinkage induced fracture of thin layers attached to a rigid substrate. We proposed an extension of fiber bundle models to describe the mechanical response of systems which undergo a sequence of stick-slip cycles taking into account the changing stiffness and the fluctuating number of slip events of local material elements. In the model, after completing all stick-slip cycles allowed, fibers can either ultimately break or can keep their final stiffness leading to softening or hardening of the bundle, respectively. Under the assumption of global load sharing we derived analytic expressions for the constitutive response of the bundle with both quenched and annealed disorder of the failure thresholds where consecutive slips occur. Our calculations revealed that on the macro-scale the bundle exhibits a plastic behavior, which gets more pronounced when fibers undergo a higher number of stick-slip cycles with a gradually degrading stiffness. We found that the macroscopic response of hardening bundles is more sensitive to fluctuations of the number of stick-slip cycles allowed than of the softening ones. The quenched and annealed disorder of failure thresholds give rise to the same qualitative macro-scale behavior, however, the plastic response is found to be stronger in the annealed case [12,15].

Fracture of heterogeneous materials is governed by the competition of their disordered local strength and the evolving inhomogeneous stress field around nucleating and growing cracks. As the next step of the project, based on our fiber bundle model we showed that this competition leads to the emergence of a strength-neighborhood correlation where locally weak regions are protected by surrounding strong ones. We demonstrated that rearranging the micro-structure to introduce spatial anti-correlation of local strength results in a substantial improvement of the overall damage tolerance and ultimate strength of heterogeneous materials. The reason is that patches of dissimilar strengths in anti-correlated micro structure can stabilize breaking avalanches, arresting growing cracks. The mechanism is more effective for smaller quenched strength disorder where stress concentrations dominate the fracture process giving rise to quasi-brittle constitutive behavior. The stabilization requires the correlation length to be greater or equal to the range of load redistribution after local failure events. The results can have applications in developing novel methods of materials manufacturing. The manuscript presenting the results has been submitted to Physical Review Letters.

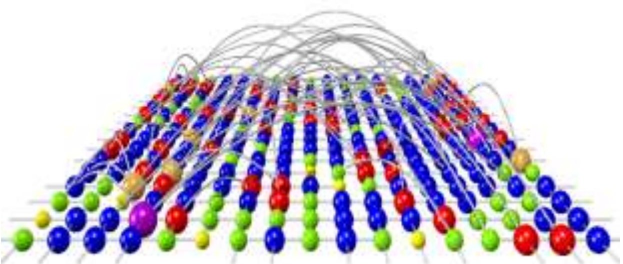

Figure 2: A rewired square lattice at the rewiring probability p=0.1. Fibers are the nodes of the network represented by spheres.

Besides fracture phenomena, cascading failure driven by the redistribution of load after local damage events of connected elements often occur in our technological environment. From the cascading blackouts of electric transmission grids to the failure avalanches of transportation and communication networks a large variety of failure phenomena can be mentioned which often have a strong economic impact. As a novel extension of our crackling noise studies, we investigated how the interplay of the topology of the network of load transmitting connections and of the randomness of the strength of the connected elements governs the temporal evolution of failure cascades. The fiber bundle model extensively used in our research can be considered as a generic modelling framework of avalanching failure triggered by local load redistribution. Starting from a regular square lattice of fibers we applied the Watts-Strogatz rewiring technique to introduce long range random connections in the load transmission network and analyzed how the ultimate strength of the bundle and the statistics of the size of failure cascades change when the rewiring probability is gradually increased. We showed that increasing the structural randomness of the network a transition emerges from the localized to the mean field universality class of FBMs. The degree of strength disorder of nodes of the network was found to have a substantial effect on the transition. In particular, we showed that the transition sets on at a finite value of the rewiring probability, which shifts to higher values as the degree of disorder is reduced. The transition is limited to a well-defined range of disorder, so that there exists a threshold disorder of nodes' strength below which the randomization of the network structure does not provide any improvement neither of the overall load bearing capacity nor of the cascade tolerance of the system. At low strength disorder the fully random network is the most stable one, while at high disorder best cascade tolerance is obtained at a lower structural randomness. We constructed an analytical argument which provided a reasonable description of the numerical findings [17].

As to the next, we demonstrated that on all network topologies the temporal evolution of cascades is described by a parabolic profile with a right handed asymmetry which implies that cascades start slowly then accelerate and eventually stop suddenly. The degree of asymmetry proved to be characteristic for the network topology gradually decreasing with increasing rewiring probability. Computer simulations revealed that both the size and duration of failure cascades are power law distributed on all network topologies with a crossover between two regimes of different exponents. Reducing the strength disorder, the exponents of the size and duration distribution of cascades increase in the localized regime of the failure process, while the localized to mean field transition becomes more abrupt. The consistency of the results is supported by a scaling analysis relating the characteristic exponents of the statistics and dynamics of cascades. The results were published in the journal Chaos, where it was highlighted as „Editor' pick" [16].

2. Effect of the amount of disorder on the fracture of heterogeneous materials

The degree of materials disorder has a substantial effect on the fracture of heterogeneous materials on both the micro-and macroscales. The ultimate strength of heterogeneous materials is found to be significantly lower than the value expected for homogeneous microstructures. Materials' disorder has also the consequence that strength is a stochastic quantity so that it can be characterized by a probability distribution. Additionally, the average strength of materials proved to decrease with increasing sample size. When subject to a slowly increasing external load, fracture proceeds in bursts which can be considered as precursors of global failure. Failure forecast methods (FFM) of the imminent catastrophic failure strongly rely on the bursting dynamics. It has been demonstrated experimentally that increasing amount of disorder gives rise to a more intensive precursory activity, which then improves the quality of forecasts. Motivated by these observations, during the project we investigated the effect of the amount of disorder on the microscopic dynamics of the fracture process of heterogeneous materials.

As a first step we studied the size scaling of the macroscopic fracture strength of heterogeneous materials when microscopic disorder is controlled by fat-tailed distributions. For this purpose, we constructed a fiber bundle model, where the strength of individual fibers was described by a power law distribution. Tuning the amount of disorder by varying the power law exponent and the upper cutoff of fibers' strength, in the limit of equal load sharing our computer simulations revealed an astonishing size effect: For small system sizes the bundle strength increases with the number of fibers, and the usual decreasing size effect of heterogeneous materials is restored only beyond a characteristic size. We showed by analytical calculations that the extreme order statistics of fibers' strength is responsible for this peculiar behavior. Analyzing the results of computer simulations, we deduced a scaling form which describes the dependence of the macroscopic strength of fiber bundles on the parameters of microscopic disorder over the entire range of system sizes. These results may be exploited for the design of special purpose materials [2].

On the micro-scale we demonstrated that the amount of disorder has a strong effect on the sequence of breaking bursts of fibers. In particular, we showed that for an infinite upper cutoff of fibers' strength, the sequence of bursts is stationary so that the system does not exhibit any sign of acceleration towards failure. Consequently, a power-law burst size distribution is obtained, where the disorder exponent only controls the cutoff burst size. For finite upper cutoffs there exists a well-defined critical point of global failure; however, it can be realized only in sufficiently large systems. This peculiar behavior gives rise to an astonishing dependence of the statistics of burst sizes on the size of the system: for small systems the burst sequence proved to be close to stationary, and hence, the burst size distribution coincides with the one corresponding to the infinite upper cutoff of fibers' strength. For large systems the initially stationary sequence is followed by an accelerating regime in the close vicinity of the critical point, which gives rise to a crossover between two power laws of the burst size distribution. The results have relevance for the design of laboratory experiments: when the microscale materials disorder has a rapidly (exponentially) decaying distribution, the sample size mainly affects the cutoff of the burst size distribution but not its functional form. However, for fat-tailed disorder the sample size has a strong effect on the functional form of the burst size distribution so that the size of laboratory specimens has to be sufficiently large to reproduce the acceleration of the burst sequence towards failure obtained in field measurements [7].

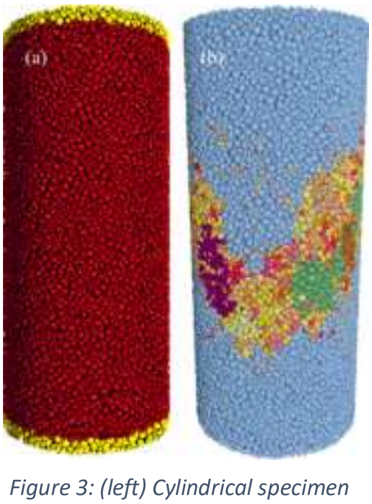

Figure 3: (left) Cylindrical specimen clamped at the two ends, which is then uniaxially compressed. (right) The damage band is highlighted by coloring the fragments.

As the next step, we focused on the fracture of sand stone most relevant for the emergence of earthquakes. We used our discrete element model of porous rocks to investigate the effect of disorder on the evolution of the fracture process of sand stone towards macroscopic failure. We performed computer simulations of the uniaxial compression of cylindrical shaped numerical sand stone samples in a strain controlled way. Most notably, we showed that as the system approaches failure, damage localizes in a narrow shear band or synthetic fault "gouge" containing a large number of poorly sorted non-cohesive fragments on a broad range of scales, with properties similar to those of natural and experimental faults [1,4]. We determined the position and orientation of the central fault plane, the width of the shear band, and the spatial and mass distribution of fragments. We demonstrated that the relative width of the shear band decreases as a power law of the system size, and the probability distribution of the angle of the central fault plane converges to around 30 degrees, representing an internal coefficient of friction of 0.7 or so. The mass of fragments is power law distributed, with an exponent that does not depend on scale, and is near that inferred for experimental and natural fault gouges. The fragments are in general angular, with a clear self-affine geometry. The very good agreement of our model with experimental and field results underlines the critical roles of preexisting heterogeneity, elastic interactions, and finite system size to grain size ratio on the development of shear bands and faults in porous media. The results were published in Physical Review E where our paper received the "Editors' suggestion" appreciation [1].

Faults and damage zone properties control a range of important phenomena, from the hydraulic properties of underground reservoirs to the physics of earthquakes on a larger scale. To control the amount of structural disorder in our simulations, model rock samples were numerically generated by sedimenting particles with a random size. Based on measurements on sedimentary rocks, we implemented a log-normal particle size distribution, where the standard deviation was varied. To obtain damage bands with a sufficiently large length along axis, we performed simulations of 'Brazilian'- type compression tests of cylindrical samples. In such a setup, as failure is approached, damage localization leads to the formation of two conjugate shear bands. The orientation angle of bands to the loading direction was found to increase with disorder, implying a decrease in the internal coefficient of friction. The width of the damage band scales as a power law of the degree of disorder. Inside the damage band, the sample is crushed into a large number of pieces with a power law mass distribution. The shape of fragments undergoes a crossover at a disorder-dependent size from the isotropy of small pieces to the anisotropic flattened form of the large ones. The results provide important constraints in understanding the role of disorder in geological fractures [8,4].

3. Signatures of the impending catastrophic failure – Towards failure forecasting

Forecasting failure is a long standing problem which has an utmost importance to mitigate the consequences of the collapse of engineering constructions and of natural catastrophes like landslides, earthquakes, volcanic eruptions, rock and snow avalanches. Failure forecast methods rely on the analogy of accelerating failure and critical phenomena which implies time-to-failure power laws of observables like the rate of breaking bursts, deformation rate, increasing average burst size, in the acceleration regime making possible to predict the lifetime of the system. However, such failure forecast methods have a limited reliability and a rather low precision.

3.1 Record statistics of bursts signals the onset of acceleration towards failure

To overcome the limitations of existing failure forecast methods, instead of the failure time, we focused on the onset of acceleration towards failure, which could be exploited as an early warning of the imminent failure. As an important methodological novelty, to quantify how the degree of disorder determines the predictability of failure, we investigated the internal structure of the sequence of breaking bursts analyzing the evolution of record size events. Records are bursts of size greater than any previous crackling event of the fracture process so that they can easily be identified by experimental techniques both in laboratory and in field measurements above the noisy background. Based on computer simulations of our fiber bundle model with power law distributed strength values, we demonstrated that the waiting time between consecutive record breakings, i.e. the lifetime of records, is very sensitive to the details of the fracture process providing a clear signal of the acceleration of the dynamics towards ultimate failure. In particular, we showed the existence of a characteristic record rank, which marks the onset of acceleration of record breaking: below this record, breaking slows down due to the dominance of disorder in the fracture process, while above it the stress redistribution gives rise

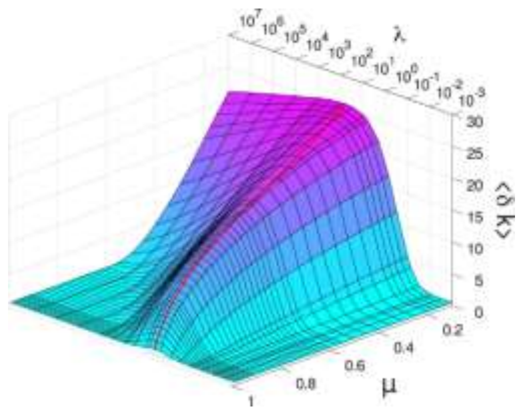

Figure 4: The average number record size events in the accelerating phase of the system. Failure can be forecasted when this quantity is significantly greater than one.

to an enhanced triggering of bursts after breaking events. Detecting the characteristic record, it can be exploited as an early signal of the imminent ultimate failure of the system, however, the significance of the accelerating regime strongly depends on the degree of disorder. Most notably, we showed that the highly brittle fracture of low disorder materials and the ductile failure of strongly disordered ones are both unpredictable due to the absence of accelerated record breaking. Our results imply the existence of a lower and upper bound of the amount of materials' disorder beyond which no meaningful failure prediction is possible, hence, refuting previous results of the literature [11].

To study how the competition of the disordered local strength and of the evolving inhomogeneous stress field affects the evolution of the series of breaking avalanches and the predictability of global failure, we performed localized load sharing simulations in our FBM tuning the degree of disorder with the exponent and cutoff value of the power law distribution of failure thresholds. Comparison of the results to their equal load sharing counterparts revealed that the accelerating regime is shorter than in case of a homogeneous stress field due to the higher degree of brittleness of the system, and additionally, in the presence of stress concentrations the stabilization of the system requires a higher degree of disorder [18].

3.2 Failure forecasting during unloading

Failure of materials can often occur under constant or slowly varying (decreasing, increasing, or periodically varying) external loads. For simplicity, we investigated separately the creep failure process emerging during unloading from a previously applied stress level. Such loading conditions can occur on large length and time scales at the emergence of earthquakes: crustal unloading due to near-surface mass redistribution (removal of water, ice, or quarried material) can affect the subsurface stress field, altering seismic activity and being also responsible for rupture activation and induced earthquakes. To consider this problem, we used a fiber bundle model of time-dependent deformation and rupture, which captures the slow damaging of loaded fibers and their immediate breaking when the local load exceeds the fibers' fracture strength. We showed that depending on the unloading rate the system has two phases: for rapid unloading the system suffers only partial failure and it has an infinite lifetime, while at slow unloading macroscopic failure occurs in a finite time. The transition between the two phases proved to be analogous to continuous phase transitions. Computer simulations revealed that during unloading the fracture proceeds in bursts of local breakings triggered by slowly accumulating damage. In both phases the time evolution starts with a relaxation of the bursting activity characterized by a universal power-law decay of the burst rate. In the phase of finite lifetime the initial slowdown is followed by an acceleration towards macroscopic failure where the increasing rate of bursts obeys the (inverse) Omori law of earthquakes. We pointed out a strong correlation between the time where the event rate reaches a minimum value and of the lifetime of the system which allows for forecasting of the imminent catastrophic failure of creeping systems [6].

4. Phase transitions in fracture and fragmentation

During the past decades experimental and theoretical studies have revealed that the fracture and fragmentation of disordered materials shows interesting analogies to phase transitions and critical phenomena. The importance of this analogy is underlined by the fact that it forms the basis of developing forecasting techniques of ultimate failure.

4.1 The damage to perforation transition as a continuous phase transition

Studies of the phase transition nature of fracture phenomena have mostly been focused on uniaxial quasi-static loading conditions. However, both the time evolution and the final outcome of fracture processes also depend on how the load is applied on the specimen. For instance, in the Charpy impact test widely used in engineering, a bar shaped specimen is clamped at the two ends and it suffers impact loading (a hit) in the middle. This boundary and loading condition results in a dynamically propagating crack which may stop or pass through the sample leading to perforation. We investigated the impact-induced fracture of a bar-shaped specimen with the aim to understand how perforation occurs as the impact energy is gradually increased at different degrees of disorder. In the modeling approach the bar is represented as two rigid blocks glued together with an elastic interface which can undergo damaging as the bar deforms. The interface is discretized in terms of a bundle of parallel fibers which allows for a simple representation of materials' disorder by the random strength of fibers. We implemented the loading condition commonly used in the Charpy impact test to determine the fracture toughness of materials. Our analytical and numerical calculations showed that depending on the imparted energy, the outcome of the impact process can be classified into two states: at low values of the impact energy the bar suffers only a finite deflection accompanied by damage, resulting in a partial failure of the specimen. However, exceeding a critical energy value the impact results in global failure breaking the specimen into two pieces. The transition between the damaged and perforated phases occurs at a well-defined critical energy. Numerical analysis revealed that the deflection rate diverges, while the fraction of surviving fibers goes to zero as power laws of the distance from the critical point analogous to continuous phase transitions. The power-law behavior holds for any degree of disorder with universal exponents [9].

4.2 Phase transitions in impact induced breakup processes

Impact induced breaking of solid bodies often occurs in nature e.g. in rock falls and debris flows, and it is broadly exploited by the industry for ore processing. It has been shown that single impact processes have two distinct phases depending on the imparted energy: when the energy is sufficiently high the solid gets fragmented, i.e. it rapidly breaks up into a large number of pieces significantly smaller than the original body. At low energies only small pieces break off the body so that a large dominant residue remains which only suffers some damage. Repeated low energy impacts are known to shape particles in sediment transport e.g. in river beds, playing a crucial role in the evolution of our geological environment. In order to obtain a deeper understanding of this process, we performed a thorough theoretical study of the phase structure of impact induced attrition processes. Based on realistic discrete element simulations of sequences of body-wall collisions, we showed that, instead of just two energy phases, one has to consider three distinct energy phases since the damage phase can be clearly separated into two further phases: At sufficiently low velocities repeated impacts result in abrasion of the body and lead to a finite asymptotic residual mass defining the abrasion energy phase. Above a first critical velocity, complete destruction is achieved within a finite number of repetitions (cleavage energy phase). The third, highest energy phase occurs above a second critical velocity where cracks span the entire body and the sample rapidly falls apart into a large number of small pieces corresponding to the original fragmentation phase of single impact processes. We demonstrated that the transitions between the abrasion, cleavage, and fragmentation phases occur at two well-defined critical velocities analogous to continuous phase transitions [14].

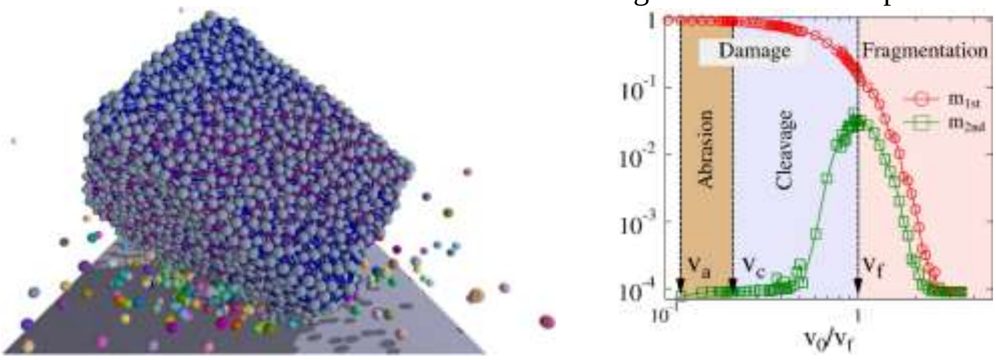

Figure 5:(left) Discrete element simulation of the impact of a rectangular body against a hard wall. (right) Phase diagram of impact induced breakup processes with the three energy phases of abrasion, cleavage, and fragmentation. The size of the largest and second largest fragments is plotted as a function of the impact velocity. The arrows indicate the transition points.

Our study revealed that the evolution of the mass and shape of the solid is governed by scaling laws in terms of the impact velocity. Most notably, in the abrasion phase the shape evolution of the sample is described by a universal scaling form with a power law dependence on the impact velocity predicting infinite sample lifetime at some finite, asymptotic mass. We also confirmed the existence of the two earlier observed geometric phases, thus our simulations serve as the first direct mechanical confirmation of curvature-driven partial differential equations as models of impact-driven abrasion processes. In the cleavage phase we found that the sample lifetime decreases as a power law of the impact velocity analogous to the Basquin law of sub-critical fracture [14].

5. Controlled generation of crack patterns – Structure of fracture networks

Shrinkage induced cracking of thin layers attached to a substrate raises the possibility of the controlled generation of crack patterns which has a high potential for microelectronic manufacturing. To explore the possibilities of controlled crack generation we developed discrete element modelling approaches in two and three dimensions which capture the essential mechanisms responsible for sequential cracking and for the emergence of isotropic and anisotropic crack patterns. Based on the 2D model we studied how the dynamics of cracking and the size of fragments of the layer evolve when the amount of disorder is varied. In the model a thin layer is discretized on a random lattice of Voronoi polygons attached to a substrate. The cohesive interaction of polygons is represented by beam elements which can break due to shrinkage. The polygons are attached to the substrate by elastic springs which do not break during the simulations. Two sources of disorder are considered: structural disorder captured by the local variation of the stiffness, and strength disorder represented by the random strength of cohesive elements between polygons. Increasing the amount of strength disorder, our calculations revealed a transition from a cellular crack pattern, generated by the sequential branching and merging of cracks, to a disordered ensemble of cracks where the merging of randomly nucleated micro-cracks dominate. In the limit of low disorder, the statistics of fragment size is described by a log-normal distribution; however, in the limit of high disorder, a power-law distribution is obtained. The results were published in Physical Review E where our paper received the “Editors’ suggestion” appreciation [3].

Recently, experimental investigations of our collaborator Akio Nakahara demonstrated that introducing anisotropy into the mechanical properties of drying pastes before desiccation sets on, e.g. by mechanical shaking or by applying an external magnetic field on a paste doped with dipolar particles, the orientation of cracks and their spacing can be controlled. To capture the effect of this initial anisotropy and explore possibilities of controlled crack patterning we extended our discrete element model:

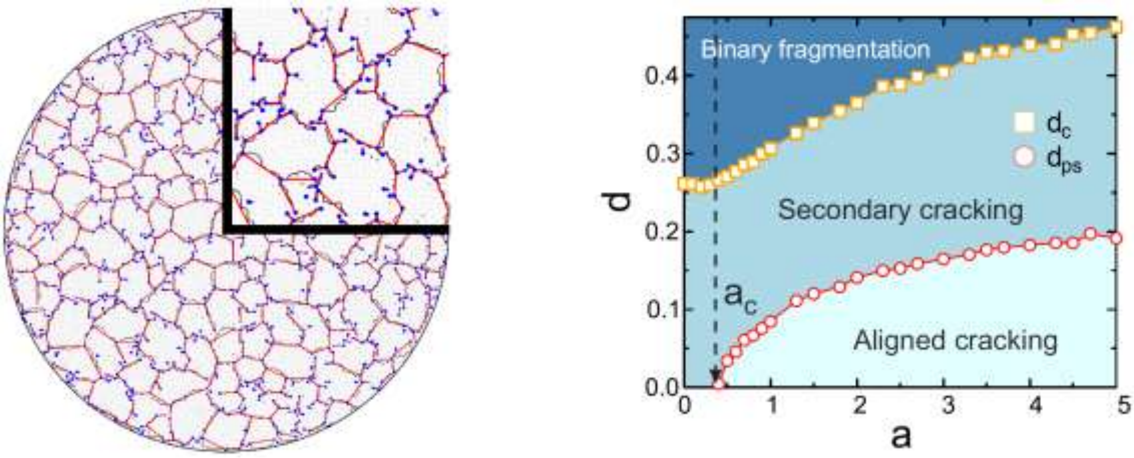

Figure 6: (left) Cellular crack pattern generated in an isotropic layer by computer simulations. (right) Phase diagram of anisotropic cracking on the parameter plane of the amount of structural disorder ***a*** *and damage* ***d****.*

in the model a homogeneous material was considered with an inherent structural disorder where anisotropy is captured by the directional dependence of the local cohesive strength. We demonstrated that there exists a threshold anisotropy below which crack initiation and propagation is determined by the disordered micro-structure, giving rise to cellular crack patterns. When the strength of anisotropy is sufficiently high, cracking was found to evolve through three distinct phases of aligned cracking which slices the sample, secondary cracking in the perpendicular direction, and finally binary fragmentation following the formation of a connected crack network. We pointed out that the anisotropic crack pattern results in fragments with a shape anisotropy which gradually gets reduced as binary fragmentation proceeds. The statistics of fragment masses exhibits a high degree of robustness described by a log-normal functional form at all anisotropies. Our theoretical results proved to have a very good agreement with the experimental findings. The paper presenting the results was published in Soft Matter and it was selected for the cover of the corresponding issue of the journal [13]. To study the magnetically controlled memory effect of pastes, we performed discrete element simulations of the drying process of our 3D model paste doped with particles having a permanent magnetic moment. We demonstrated that chains of dipolar particles, formed under a homogeneous magnetic field, act as reinforcing units in the paste making a preferred direction for desiccation induced cracking. Our simulations performed at different concentrations of the magnetic particles reproduced the experimentally observed crack patterns with a high degree of anisotropy. These calculations demonstrated that the presence of reinforcing particle chains is a sufficient condition for the emergence of the memory effect of pastes. The manuscript presenting the results was submitted to Physical Review E.

To get a deeper understanding of the shape of fragments generated by slow sequential fracturing, and by dynamic breakup process we introduced a very important methodological innovation. Namely, our approach focused on the global picture of the network of evolving fractures and derived the shape characteristics of fragments from the structure of the fragmentation pattern. Based on the mathematical theory of convex mosaics, we proposed a generic classification of all planar and spatial fragmentation patterns with polyhedral fragment shapes, i.e. where fractures are either straight/flat or can be approximated by straight/flat segments spanning over the typical fragment size. Our study revealed an astonishing robustness of fragment shapes, in particular, we demonstrated that on the average, the shape of polyhedral fragments agree with rectangles, and cuboids, in 2D and 3D fragmentation, respectively. Based on analytical arguments and computer simulations of a discrete stochastic model of breakup, and on field measurements on various types of fragmenting systems, we gave very strong evidences that although in a subtle, statistical manner, these features are universal among fragments. Both for planar and spatial fragmentation we identified two universality classes and show that the rectangular and cuboid classes are attractors of fragmentation phenomena, hence, they dominate natural fragmentation patterns including the shrinkage induced breakup of thin layers attached to a substrate. The results were published in PNAS and was highlighted by more than 30 news outlets [10].

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