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# Discrete Damage Modelling for Computer Aided Acoustic Emissions in Health Monitoring

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## 1. Introduction

This chapter is conceived as an essay on modern multiscale discrete damage modelling, providing a brief personal perspective about its foreseeable applications-implications for structural health monitoring purposes. In particular, it is argued that this sort of damage modelling could be potentially useful in damage detection by acoustic emissions (AE), which is a class of non-destructive techniques (NDT) used to capture damage evolution in a number of materials (e.g. from concrete systems such as bridges and beam elements to composites in aircraft components and pressure equipments) and from a number of external actions (e.g. sustained load, monotonic testing, fatigue, corrosion, etc.) (Biancolini & Brutti, 2006 ; Carpinteri & Lacidogna, 2008 ; Grosse & Ohtsu, 2008). With AE it is possible to “hear” the microcracking phenomenon and characterize the location and magnitude of a single microcrack (of size and “strength”<sup>1</sup> beyond certain thresholds) acting as an acoustic source. Hence, it is routinely possible to plot the released energy of each crack as a time series or to map them over a 2D spatial domain by counting and locating individual acoustic events in time. Yet the analysis of this type of output is not straightforward and major difficulties exist, let alone sensitivity issues of equipment, material dependence, and other practical issues. The scope of this discussion covers two issues of general interest:

1. the randomness of the AE signal,
2. the need for structure-property relations as companion to AE monitoring.

The first problem is rooted in the very same nature of the collected signal, which is a highly random time series that needs to be analyzed and interpreted. How to do that is a non-trivial task and remains an open research topic to date. Of course, elimination of the outer noises is one of the most concerned aspects in the applications and is usually achieved by simply setting a minimum cut-off threshold (low enough to retain all relevant information

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<sup>1</sup> Here, the term “strength” alludes figuratively to the energy released by a microcrack during formation, which is linked to the amplitude of the collected signal and can largely differ between cracks of equal size (e.g. consider grain boundary microcracks with different orientation).

but above the noise level), by a band-pass filtering, or by a post-analysis of the data<sup>2</sup>. However, more importantly, even when the external noise could be filtered out completely, the AE data would retain a highly complex and random structure due to the inherent nature of the damage process and to material inhomogeneities, as depicted in Fig.1. A fundamental question, then, is whether the whole detected signal is essential to health monitoring and failure prediction, or criteria can be derived to discern what is relevant from what is not in the dataset. This is one main aspect to be explored later by discrete damage modelling. The development of such a filtering capability would have an impact, enabling not only greater understanding, but also the discard of the unwanted signals in favour of simplified time-series and optimal hardware usage (e.g. data storage, transmission facilities, longer monitoring period, etc.).

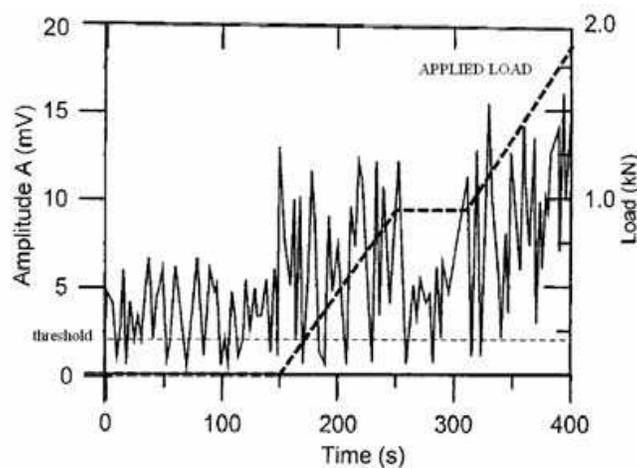


Fig. 1. Preliminary AE test for noise detection and quantification in a sintered ceramics loaded according to the dashed ramp. The cut-off threshold is indicated (after Palma & Mansur, 2003).

The second problem is the impossibility to correlate the AE output with the actual microstructure of the material without pairing AE with microscopy<sup>3</sup> to cross-correlate and perform a companion microstructural characterization. Macroscale observations (e.g. AE measures) render partial information that captures only the overall effect of microstructural phenomena happening at a much finer scale and not normally observable in field applications. It is nowadays well recognized that the material cannot be regarded as a black-box in the study of damage and strain localization phenomena (including failure analysis), which require thorough understanding of the structure-property relations. Likewise, the consideration of the deformation mechanisms active in a given material microstructure and triggered by a certain load configuration may indeed be crucial for the interpretation of AE signals and for the estimate of the current damage state. Unfortunately, with the exception of LOM and despite a few field trials for AFM (by INAIL(IT) private communication), it is

<sup>2</sup> Noises sometimes have similar frequency contents and amplitudes to AE signals, or sources of the noises are unknown. Then noises characteristics have to be estimated and modelled prior to measurement in order to separate the actual AE signals from raw data. The use of filters is very useful also in this respect, e.g. for determining the proper frequency range.

<sup>3</sup> For example, scanning electron microscopy (SEM), optical microscopy (LOM), atomic force microscopy (AFM), electron backscattered diffraction (EBSD), focus ion beam (FIB), etc.

not easy to perform these auxiliary microscopic investigations *in-situ* at present. As a matter of fact, in alternative to LOM for field metallurgy, industry relies on surrogate NDTs, such as the “replication” technique<sup>4</sup> (VGB, 1992; Rinaldi et al., 2010). Also in this context, discrete damage modelling seems to offer a possible route to overcome experimental limitations and establish the correct (micro)structure-property relationships of a desired material by means of accurate numerical simulations<sup>5</sup>.

We should now move on to clarify how discrete damage modelling can be used to address the aforementioned AE problems, after a brief overview of AE facts. The outline of the discussion is as follows:

- Data collection, seismic similarity, and statistics in AE
- Discrete mechanical models for damage and fracture
- Lattice model highlights and AE
- Closing remarks

## 2. Data collection, seismic similarity, and statistics in AE

AE signals are electrical signals generated by fracture phenomena. After acquisition, the characteristics of AE parameters are used to infer fracture or physical phenomena. The following definitions (ref. ISO 12716 2001) refer to some popular signal parameters (Grosse & Ohtsu, 2008).

1. Hit: a signal that exceeds the set minimum threshold and causes a system channel to accumulate data;
2. Count: the number of times the waveform (signal) exceeds the given threshold within a hit;
3. Amplitude: a peak voltage of the signal waveform is usually assigned. Amplitudes are expressed on a decibel scale instead of linear scale.

The one waveform in Fig. 2 corresponds to one hit or to nine counts. “Hits” are the classical data used to show AE activity by means of the accumulated number  $n$  (parameter-based approach). Also “counts” can be employed (signal-based approach) to quantify the AE activity in place of “hits” but have several cons, as they require more acquisition capability, more consuming/sophisticated data analysis, and depend strongly on selected threshold and operating frequency<sup>6</sup>. For the sake of this discussion, the scope can be limited to

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<sup>4</sup> Essentially a technique to collect a copy of the actual material surface *in-situ* for afterwards examination in laboratory. It is used for example for microstructural monitoring in low-alloy carbon steels subject to creep.

<sup>5</sup> Structure-property relationships in solid mechanics represent a multidisciplinary research topic, sitting primarily at the crossroad of material science and engineering. Its widespread recognition and popularity is best witnessed by the growing number of scientists and engineers that have engaged in multiscale modeling of damage processes of all kinds and in all kinds of materials over the past ten years (check mechanics journals; JMPS, Acta Mater, Mech Mater., etc.). The development of microstructure-based models is indeed a major trend in solid mechanics research. A great effort is also been directed in scaling laws able to predict the behaviour of materials in components of different size, trying to model the sample-size effects of damage, structural failure and other properties existing in real material systems. (Krajcinovic, 1996; Krajcinovic & Rinaldi, 2005, Carpinteri & Lacidogna, 2008).

<sup>6</sup> Approaches in recording and analyzing AE signals can be divided into two main groups: parameter-based (classical) and signal-based (quantitative) AE techniques. Both approaches are currently applied with success for different applications. Rapid developments in microelectronics over the last few

classical parameter-based approach with no loss of generality. In that case, the waveforms like Fig.2 are measured but only simpler parameters are stored, such as hits and corresponding amplitudes *vs.* time. As an example, Fig.3 shows actual AE monitoring in ceramics (Palma & Mansur, 2003) during controlled tensile test. One plot (left) correlates the amplitude and number of AE signals at each strain with the force response of the material specimen throughout the test. The second plot (right) reports the cumulative number of hits  $n$  *vs.* time, along with the force signal. Both pictures clearly render an increased activity, both in terms of signal amplitude and signal density (i.e.  $dn/dt$ ) at well defined points, namely the end of the elastic regime and prior to failure. The force signal indicates the substantial loss of load bearing capability of the material in correspondence to these (transition) points.

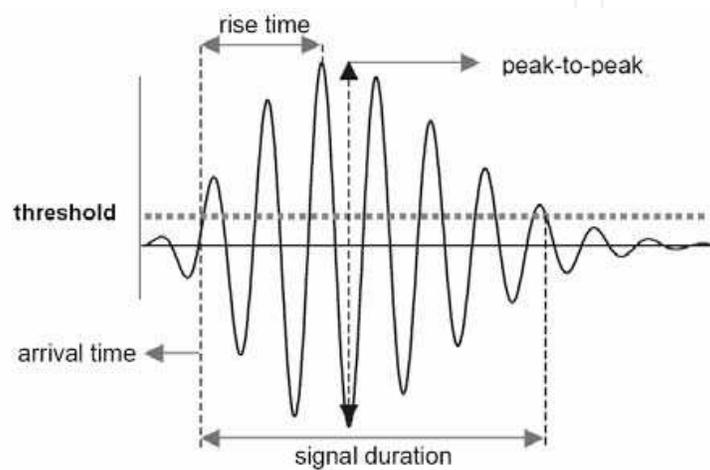


Fig. 2. Example of typical 'AE parameters' according to international and national standards (ASTM E610, 1982; Berger, 1977; DGZFP SE-3, 1991).

decades are largely responsible for the existence of two approaches. In the past, it was not possible to record and store a large number of signals over a sufficiently short period of time. Despite significant technical advances in recent years, it is still not possible to use signal-based techniques to monitor large structures and buildings. In addition, the relatively high financial costs and the time required to apply modern signal-based techniques are a sufficient reason for why parameter-based techniques are still popular. It should be emphasized that the discrepancies between the two approaches are becoming smaller and that devices intended for the classical AE technique are now able to store entire waveforms of the detected AE signals, even though this is not the primary function of these devices. Instead, applications using signal-based analysis techniques rely on equipment based on transient recorders, which facilitate the use of custom software tools to extract AE parameters for statistical analyses. In fact, in that case, not only "counts" but also other parameters can be chosen, e.g. "counts to Peak" (i.e. counts between the triggering time over the threshold and the peak amplitude, equal to four in Fig. 2), the arrival time (defined as the first crossing of a given amplitude threshold), the rise time (defined as the duration between the arrival time and the time where the maximum amplitude is recorded) and the duration (defined by the last crossing of a given amplitude threshold) (ref. ASTM E610 1982; CEN 1330-9 1999). The signal-based approach, so-called quantitative AE technique, record and store as many signals as possible after converting waveforms from analogue-to-digital (A/D) signals, which enables a comprehensive and time-consuming analysis of the data but usually only in a post-processing environment and not in real-time (Scruby 1985; Sachse and Kim 1987). The next generations of instruments will tend to be universal and adapt to different applications, capable either of recording waveforms if a signal-based approach is being taken or storing a large number of events  $n$  if a parameter-based approach is being taken requiring the statistical analysis of many events.

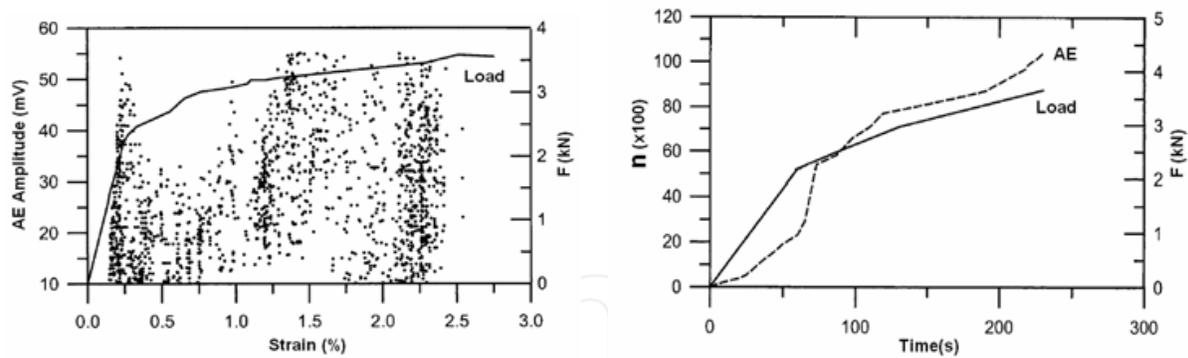


Fig. 3. (left) Correlation between AE amplitude and deformation in a sintered material. (right) Number of threshold crossings  $n$  vs. time. Damage localization points are seen as discontinuity in the force response and step increase in AE activity (Palma & Mansur, 2003)

Another noteworthy feature of AE data is the similarity with seismology. AE and seismological techniques are very affine because they basically exploit the same concept but at a different scales. An AE signal is defined as the spontaneous release of localized strain energy in stressed material and, as such, it can be regarded as a form of microseismicity generated during the failure process as materials are loaded. AE transducers (sensors) placed on the materials surface sense and record this energy release due to microcracking, just like seismographers measure earthquakes. In turn, there is a well established theory connecting earthquakes and fracture processes in (micro)structural elements near failure (Mogi, 1967), which are both described by the Gutemberg-Richter law

$$\text{Log } N = a - b m \tag{1}$$

expressing the empirical relation between a certain magnitude  $m$  to the number  $N$  of events exceeding  $m$  in a earthquake (or a failure). By further assuming the magnitude to be related to the energy level as  $m = \text{Log } E$ , Eq.(1) can be rewritten as

$$\text{Log } N = a - b \text{Log } E \tag{2}$$

which implies a linear relation between  $N$  and  $E$  in a log-log plane (Fig.4a) and, equivalently, a power law relationship " $N \sim E^{-b}$ " for the decay of number of seismic/microcracking events of larger energy. These equations state that major fracture events (leading to catastrophic failure) are expectedly preceded by many events of smaller

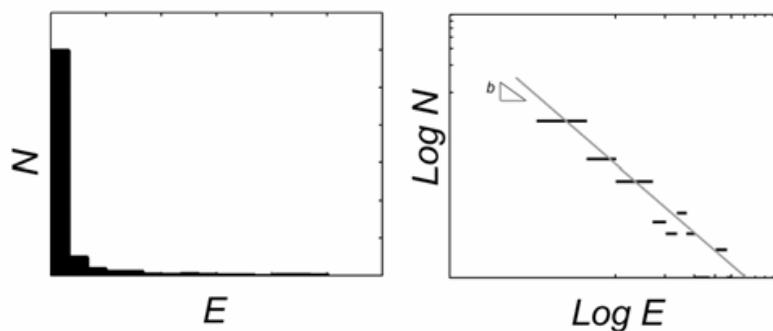


Fig. 4. Statistical distribution of microcracking events valid for seismic and AE data (left). The number of events  $N$  scale with energy (magnitude) according to a power law (right).

entity. For what said, this same framework and expectation apply to AE monitoring and explain why the AE technique is in principle suited to detect a failure at a very early stage, long before a structure completely fails.

### 3. Discrete mechanical models for damage and fracture

Now, discrete damage modelling is briefly addressed in consideration of the experimental facts just recalled. The importance of having a theoretical model to analyze AE measures was pointed out in the introduction, but no universal damage modelling has emerged to date. The goal of damage mechanics is to develop predictive models for damage tolerant design and failure prevention, just as AE monitoring. Damage models can be continuum or discrete (Krajcinovic, 1996). Continuum models, which represent the mainstream tool in solid and structural mechanics, are very commonly used in industry but are unsuited in this case. Most continuum damage models are derived from micromechanics via one of the many homogenization or coarse graining techniques available. The “representative volume element” (RVE) is the traditional basic instrument of micromechanics to convert a disordered (i.e. randomly microcracked) material into an equivalent continuum model and, as depicted in Fig. 5, it represents the smallest specimen volume of disordered matter that can be considered as statistically homogeneous (and, hence, in thermodynamic equilibrium) under the action of nearly-uniform tractions at its boundaries. This formal definition simply means that a continuum model takes in consideration an idealized material that is mechanically equivalent to the real one and has properties obtained from averaging local micro-properties over the RVE domain. But this procedure, although numerically convenient, poses severe limitations and overheads, because details of the microstructure that are fundamental to the damage process (e.g. the grain and grain boundaries of a polycrystalline metal - Fig.5) are completely discarded. Further more, an RVE may not even exist sometimes, rendering the continuum approach ill-posed and not applicable. This is typically the case at the onset of damage localization and failure pointed out in Fig.3. In extreme synthesis, the good candidate model needs to have a resolution length of the same order of the relevant microstructure (e.g.  $l$  in Fig.5).

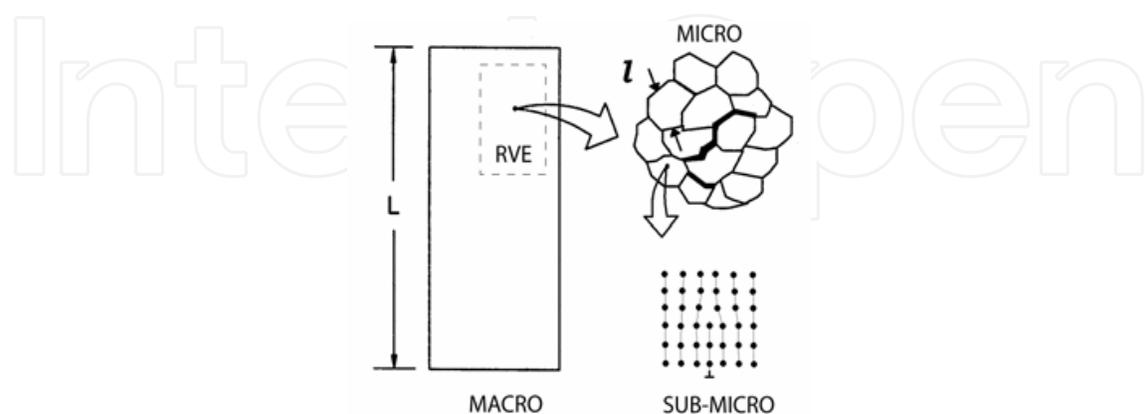


Fig. 5. Example of hierarchy of length scales associated to a damage problem in a polycrystalline material. The scope of damage mechanics does not conventionally entail sub-microscale for the estimate of residual life (i.e. unless nanoscale components of nanotechnology are involved) but necessitates direct consideration of the microscale.

In that regard, modern discrete damage modelling, also known as statistical damage mechanics (SDM), appears to be a better option to bridge such a theoretical gap. SDM is a new branch of damage mechanics (and more at large of solid mechanics) (Rinaldi, 2010). Unlike the continuum modelling (e.g. micromechanics but also non-local continuum theory), SDM is natively a multiscale approach, where discrete statistical models accurately reproduce the random microstructure of a material with a sufficient degree of detail, incorporating the relevant random microscale properties via statistical distributions. Such discrete models are applicable over the entire damage evolution, regardless of whether damage is homogeneously dispersed or localized in the material (following a transition), near and away from failure. SDM offers a fertile ground for the application of advanced statistical methods and non-standard mathematical method (e.g. fractal theory) to obtain innovative physically-based constitutive relations and damage theories that effectively reckon subtle aspects (e.g. such as sample-size effects, localization threshold, intrinsic variability of mechanical properties, and damage-induced anisotropy), which has important implications for the study of sound localization, as we shall see.

In damage mechanics, the modelling problem consists of determining the proper damage variable  $D$  that fully encapsulates the complexity of the stochastic damage process and is a random variable ranging from 0 in pristine conditions to 1 at failure. Damage is a weakening transformation of the microstructure that is driven by one or more external causes (i.e. quasi-static load, fatigue, corrosion, impact, etc. or a combination) and consists of microcracks formation, growth, and coalescence into a final fracture, which is perceived as a depletion of the elastic stiffness at the macroscale. The material response, as damage accumulates under the action of an increasing load  $\sigma$ , is generally expressed by

$$\sigma = E^*(D)\varepsilon_e = E_0(1-D)\varepsilon_e \quad (3)$$

where  $E_0$  is the initial Young modulus,  $D$  is the damage parameter,  $\varepsilon_e$  is the elastic strain and  $E^*$  is the secant stiffness, both measurable during unloading in a ductile material. This relation states that the damage parameter is equal to the normalized loss of secant stiffness  $D = \Delta E^*/E_0$ , which is the sum of each damage increment associated to the  $i$ -th event  $\Delta D = \Delta E^*_i/E_0$  (the stiffness decrement normalized to the pristine stiffness), such that after  $n$  random microcracks it is

$$D = \frac{\sum_{i=1}^n \Delta E^*_i}{E_0} \quad (4)$$

Of course the evaluation of Eq.(4) is not trivial, since the  $\Delta E^*_i$  is unknown a priori and is a complicated random function of microstructure and applied load(or generalized action).

### 3.1 One dimensional SDM: fiber bundle model

The problem (4) has been investigated and solved exactly long time back (see my paper and reference therein) only for 1D fiber bundle models (FBM). As an example, consider the brittle FBM in Fig. 6 made of  $N$  parallel fibers (ideally representing actual fibers as well as springs, rods, bars, ropes, etc.) endowed with finite elasticity and connected to two transversal bus-bars loaded under tension. The disorder is typically quenched in the system

by sampling the fracture displacements of each fiber from a given distribution  $p_f(u)$ , which is a characteristic attribute of the microstructure. If the fibers do not interact locally (e.g. limited cross-linking) and the end-bars are rigid, the rupture of a fiber (mimicking a microcrack) produces a “democratic” load redistribution over all extant fibers. When fibers have equal stiffness  $k$ , the force-displacement response of an instance bundle at the  $n$ -th rupture is given by

$$F = \sum_{i=1}^{N-n} f_i = \sum_{i=1}^{N-n} ku_i = K_0 \left( 1 - \frac{n}{N_{TOT}} \right) u = K_0 (1-D)u \quad (5)$$

which is the FBM counterpart of Eq.(3) in terms of force vs. displacement, with the Young’s moduli being replaced orderly by the bundle stiffness  $K_0$  and  $K$  in pristine and serviced conditions. The damage parameter is the mentioned order parameter, i.e. a random variable taking values from zero (in pristine state) up to 1 (at failure), and linking microscale disorder and macroscale structural degradation during the whole damage process. Because all fibers have equal applied displacement but fracture thresholds randomly sampled from  $p_f(u)$ , the expected value of  $D$  can be readily obtained at any damage state (sometimes analytically) as

$$D = \frac{n}{N_{TOT}} = \int_0^n \frac{dn}{N_{TOT}} = \int_0^u p_f(u) du = P(u) \quad (6)$$

Notably, the knowledge of  $D$  allows expressing the mean response of this class of FBM as

$$F = K_0 (1-D) \cdot u \quad (7)$$

As a numeric example of this model, consider the results in Fig. 6 (right) for the case of a uniform distribution  $p_f$ , where the damage curve (6) is a straight line and the force response (7) is a parabola.

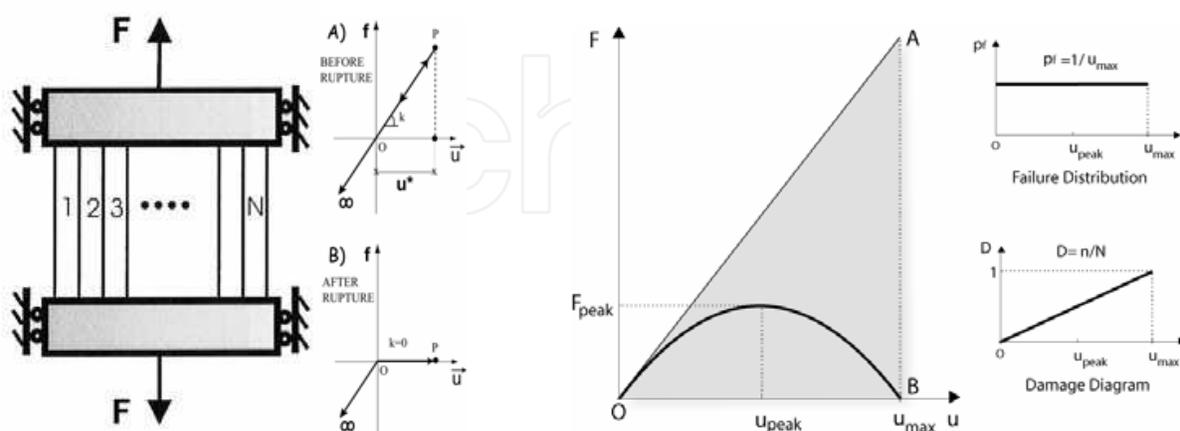


Fig. 6. FBM damage model and micro constitutive law of one bar (left), showing the tensile response prior and after rupture. Uniform strength distribution, corresponding damage curve, and average force response are shown on the right. The grayed area AOB represents the domain of all possible FBM responses.

### 3.2 Two dimensional SDM: lattice model

The above result is not only a rational mathematical model of intrinsic theoretical value, but has also several engineering applications (e.g. steel rope design, EN 12385-6:2004; EN 13414-3:2003; ISO 4101:1983). However, it only applies to 1-D structural systems that resemble a FBM and is of little usage for AE purposes. Most materials, despite their discrete nature, are multidimensional systems, with a high degree of interconnection between near-neighbour elements, e.g. polycrystalline or multiphase microstructures. Unfortunately, the damage process is much more complex in these systems and no rational theories have been formulated, with one notable exception being the 2-D lattice model in Fig. 7.

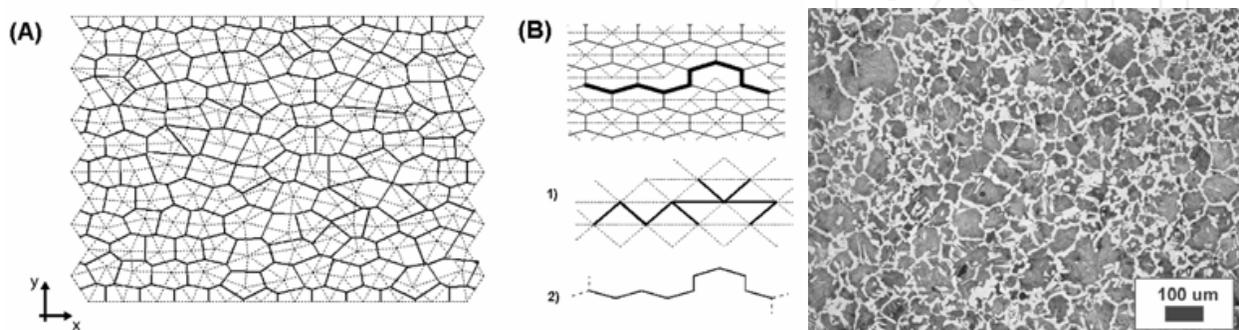


Fig. 7. (a) Sample lattice model obtained as the Delaunay network associated to a Voronoi froth approximating a polycrystalline microstructure. (b) Damage (microcracks) representation in Voronoi and Delaunay representations. An example of an actual network of ferrite (bright signal) framing pearlite grains (dark signal) in a C55 steel, as observed after metallographic attack (utmost right).

This mechanical lattice consists of a disordered spring network and provides a first order approximation of a polycrystalline microstructure (and an exact representation for actual as truss structure), where each spring represents a grain boundary (GB) normal to it in pristine condition. It has been investigated for decades to understand the physics of the damage mechanics underlying brittle failures (not just in brittle materials but in some ductile ones too) from inter-granular microcracking (Krajcinovic & Rinaldi 2005, Krajcinovic, 1996, and references therein). This model is the natural multidimensional extension of the FBM model from Fig. 6 but the damage process is different because of the local load redistribution effect and the geometrical disorder. In fact, when all springs have stiffness  $k$  and micro-strength sampled from a given  $p_f(u)$  in strict similarity with the previous FBM, the rational model for the lattice subject to uniaxial load is demonstrably (Rinaldi & Lai, 2007; Rinaldi, 2009)

$$D(\varepsilon) = \frac{k}{E_0} \left( \frac{\ell}{L} \right)^2 \left[ \sum_{i=1}^{n(\varepsilon)} (1 + \eta_p) \left( \frac{\varepsilon_i^*}{\varepsilon} \right)^2 \right] \quad (8)$$

Compared to Eq.(6), the damage parameter (8) depends on a number of extra parameters:

- i. the ratio  $\ell / L$  between the average grain size and the lattice overall dimension;
- ii. the “strain energy” redistribution parameter  $\eta$  characteristic of the given microstructure and dependent on coordination number (i.e. the average number of grain boundaries of a grain), and orientation of the failed GBs with respect to the applied load;

- iii. the kinematic parameter  $\bar{\varepsilon}^*/\bar{\varepsilon}$  expressed by the ratio of the critical microstrain at spring failure (i.e. a microcrack forming at a grain boundary) over the corresponding macroscopic strain applied to the lattice (marked with a bar sign for clarity).

The fact that these variables are random may seem discouraging at first but they were demonstrated to actually exhibit a structure (Rinaldi, 2009), rendering the mathematical problem indeed tractable and allowing the formulation of approximate closed-form solutions of Eq.(8). The mathematical derivation and extensive discussion of each parameter is outside of the present scope and the interested reader is referred to the original scientific papers. Instead we shall focus on the aspects relevant to AE applications and to what is new in the SDM model, trying to keep math and technical jargon at a minimum.

#### 4. Lattice model highlights and AE

The principal merit of the rationale model (8) is perhaps the disclosure of the “mathematical structure” of the brittle damage process, not just for the lattice problem that only served as a convenient setting for the proof. The problem of computing  $D$  in a higher dimensional system, i.e. most real materials, evidently requires the determination of several micro-variables, here  $\eta$ ,  $\bar{\varepsilon}^*(\bar{\varepsilon})$ , and  $n(\bar{\varepsilon})$ . Remarkably, this type of SDM models allows an unprecedented insight of the damage process at the microstructure level, which is one of the two main advocated limitations of AE in the introduction. To that end, some relevant results of the lattice model are illustrated in the remaining of this section. However, for the sake of argument, the concepts are discussed in the context of the “perfect” lattice example shown in Fig. 8, which consists of two classes of springs with orientation  $0^\circ$  or  $\pm 60^\circ$  during a tensile test along  $0^\circ$ . The same figure (Fig.8(B)) reports the simulated tensile response  $\sigma$  vs.  $\bar{\varepsilon}$  for an instance lattice, where the peak response at  $\bar{\varepsilon} = 2.7 \cdot 10^{-3}$  marks the damage localization, usually accompanied by a large microcracks avalanche (analogous to increased AE activity).

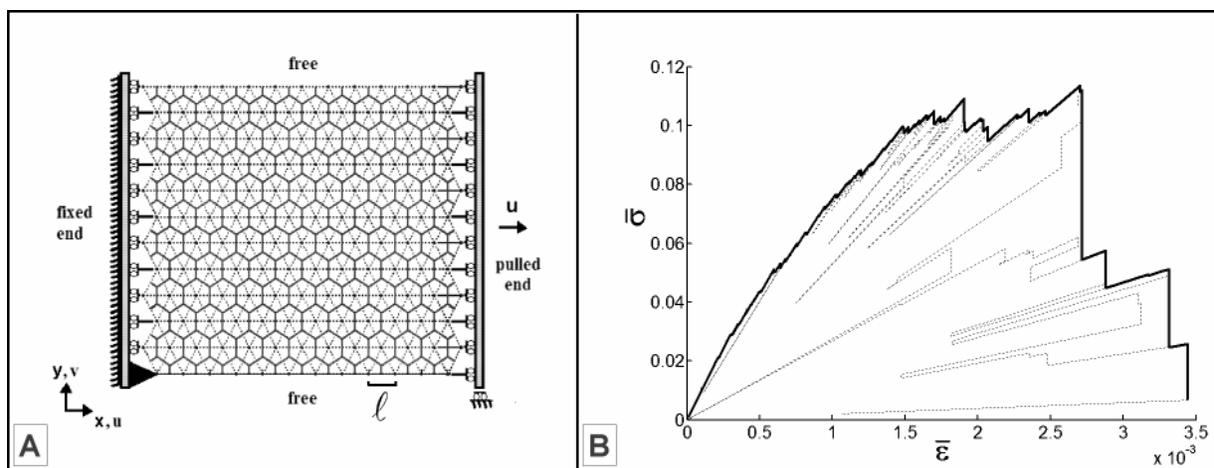


Fig. 8. (A) Perfect lattice with springs (GBs) orientated at  $0^\circ$  or  $\pm 60^\circ$  during a tensile test along  $0^\circ$ . (B) Simulated lattice response from tensile test (stress values reflects an arbitrary numerical scale). Dotted lines relate to the formation of either isolated or avalanche of microcracks.

The first practical result is the clear demonstration of the non-linearity between the damage parameter  $D$  and the number of microcracks  $n$ . This is implicitly stated by Eq.(8) but is more

readily verified by visual examination of the corresponding  $n$  and  $D$  data in Fig. 9 for the same tensile test in Fig.8(B). The marked difference of  $n$  vs.  $D$  is of consequence. Primarily, since  $n$  and  $D$  are not proportional, the damage parameter  $D$  cannot be deduced by a simple count of AE events as often attempted (i.e.  $n$  in Fig.3). Instead, such evaluation requires, as a prerequisite, that each AE event could be properly weighted to fit into a theoretical model similar to Eq.(8), after tailoring it for the material under consideration of course. We speculate that this might be somehow achieved practically by using the AE amplitude data to quantify the weights. Secondly, Fig. 9 features a spectral decomposition of the  $n$  and  $D$  data into three components, each accounting for ruptures of springs with same orientation (recall that only  $0^\circ$  and  $\pm 60^\circ$  are possible here). This breakdown of pooled data reveals that the horizontal springs in the perfect honeycomb lattice tend to break at a fastest pace and to contribute most to the damage parameter. Note in fact that, while diagonal ruptures happen (i.e.  $n_{2,3} \neq 0$ ) since early in the damage process, they have a null effect in terms of damage (i.e.  $D_{2,3} = 0$ ) and play a secondary role. After the transition at  $\varepsilon = 2.7 \cdot 10^{-3}$ , the situation reverses and there is a crossover between  $n_1$  that levels off and  $n_{2,3}$  that rises, becoming dominant. This means that

- the importance of the springs (i.e. GBs in general) in the damage process heavily depends on their orientation relative to the load;
- the formation of (secondary) microcracks can be of minimal or negligible importance to  $D$ , such that these events can be classified as secondary;
- the relative importance of GBs with different orientation may change during the damage process, before and after damage localization.

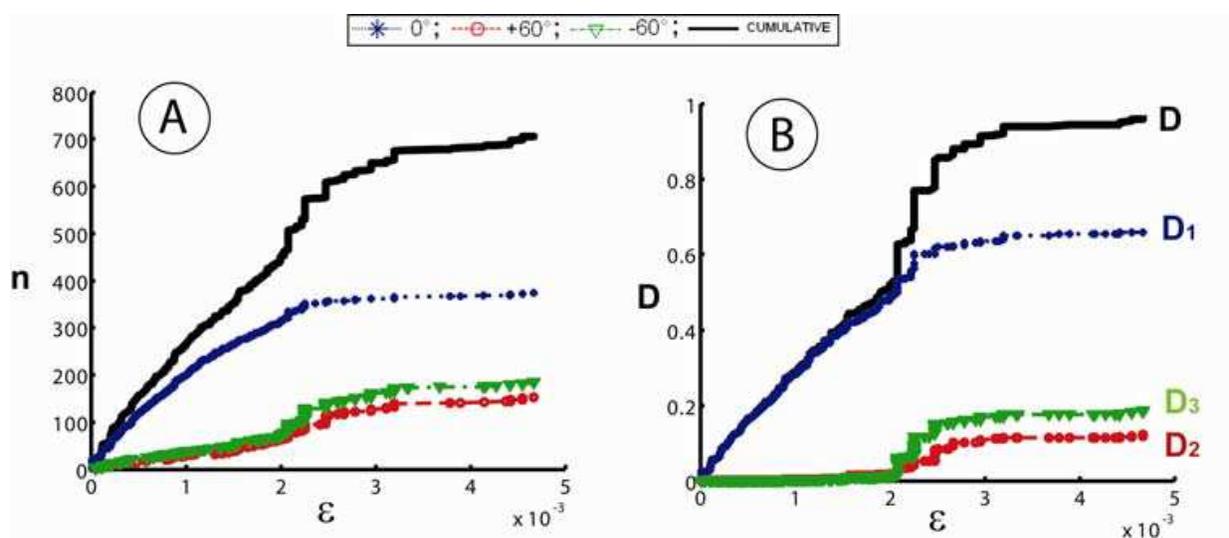


Fig. 9. (A) Cumulative microcracks  $n$ , as well as partition for GBs with orientation normal to  $0^\circ$  and  $\pm 60^\circ$  for the tensile test in Fig.8(B) (the cumulative curve is a typical AE output); (B) likewise, the damage parameter  $D$  and the spectral decomposition  $D_i$ . The comparison shows that only one type of GBs is relevant before damage (i.e. sound) localization.

These facts make immediately sense but are actually hard to quantify with classical modelling tools during cooperative phenomena, such as microcracks interaction at the onset of localization. This evaluation is also very hard experimentally and would require the advanced microscopy investigation (e.g. SEM, TEM, AFM, etc. ) invoked in the introduction.

Next, consider the problem from another angle, by examining the simulation data shown in Fig. 10 about the critical strains series  $\varepsilon_p^*$  vs.  $\varepsilon$  of the  $p$ -th broken springs, presented both in aggregate form (A) and as partitioned into two groups (B), as per spectral decomposition. Monitoring  $\varepsilon_p^*$  during the simulation is a meaningful idea because it is a means of tracking the strain (and stress) fluctuations induced by damage in the lattice microstructure. Fig. 11(A) readily demonstrates that both the mean value and the scatter tend to increase progressively with  $\varepsilon$  (i.e. applied load) until the transition (load localization) is reached and a sudden burst occurs. This is fine and very interesting, also because this type of output, in the aggregate form, is very similar to the random signal from AE (ref. AE magnitude Fig.3(A)) - after all the energy released by a microcrack (spring here) is related to  $\varepsilon_p^{*2}$ . Yet, the aggregate form yields only a partial view of the microstructural phenomenon, as demonstrated by the spectral decomposition in Fig. 11(B). Then, it becomes very understandable that before the transition the rupture with higher  $\varepsilon_p^*$  (i.e. bearing more energy) corresponds almost exclusively to the horizontal springs, whereas afterwards large values of  $\varepsilon_p^*$  comes from springs of any orientation, which is consistent with the scenario drawn from Fig.9.

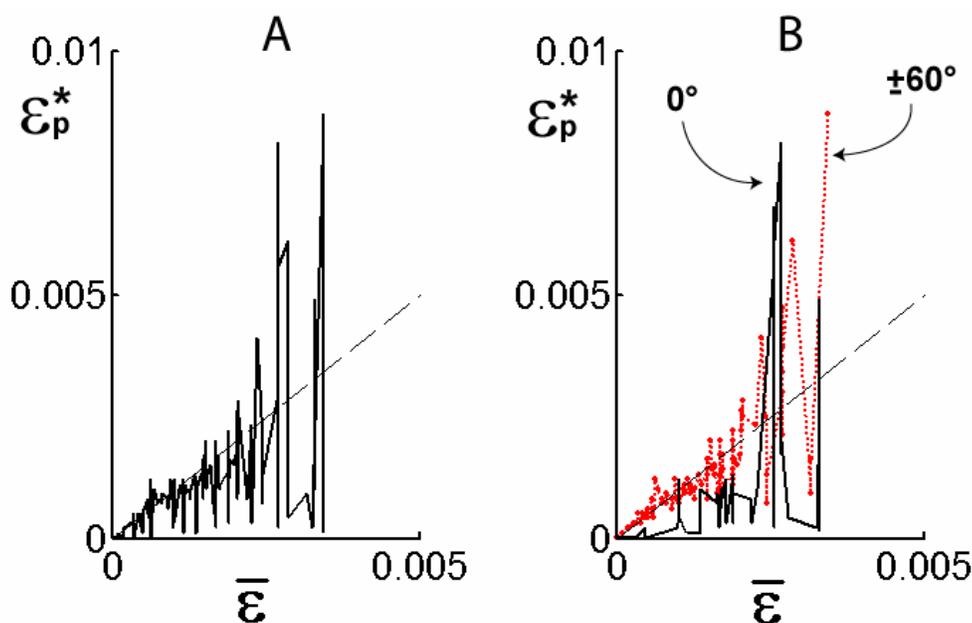


Fig. 10. Critical strains  $\varepsilon_p^*$  vs.  $\varepsilon$  of broken springs (i.e. GBs) subdivided in aggregate form (A) and partitioned into two groups (B), based on orientation relative to tensile axis. The peak response in Fig.8(B) has damage localization at  $\varepsilon = 2.7 \cdot 10^{-3}$ , which happens with a large microcracks avalanche - a signature of the transition. As opposed to misaligned GBs, the GBs normal to the pulling action are more prone to damage before the localization because they carry most of the load and involve also stronger springs. After localization, damage formation involves GBs of any strength and orientation.

As far as the AE technique in polycrystalline materials, this result suggests that the whole AE signal may not be essential and that before sound localization (i.e. damage localization) it may possibly be filtered to extract the higher energy AE part that mostly governs the damage process, i.e. that part associated to GBs "favourably" oriented with the load and carrying large portions of strain energy, then released upon cracking. In other words, the

present finding represents a potential basis to design a partition of AE data based on a microstructural interpretation of low and high energy events. At the same time, as far as failure prediction for field applications, the onset of damage localization could be detected by monitoring the spread in the AE amplitude signal, or in alternative by detecting rising trends in the low energy events, anticipating the cited crossover. By this viewpoint, modern discrete models theory seems like a viable route to device filters aimed at breaking the complexity of random AE signal and aiding in its interpretation.

As a last result of the section, we linger a little longer on the lattice problem to examine in greater detail the physical mechanism for the lattice transition in Figs. 9 and 10, a phenomenon observed phenomenologically in most brittle materials and failures. Based on our analysis, the damage localization at the onset of failure can be explained in terms of the stress amplification in the microstructure due to the local load redistribution induced by the previously accumulated microcracks. With reference to the perfect triangular lattice model in Fig.8, it can be shown that diagonal GBs would initially carry a near-zero stress until in pristine condition but, if one horizontal spring fails, this produces an overstraining influence that immediately raises the load level in the diagonals (inducing actually a strain-gradient). Fig. 11 shows graphically this effect in terms of percent strain perturbation on the  $ij$ -th extant spring between the  $i$ -th and  $j$ -th grains defined as

$$\% \text{ Strain Perturbation} = \frac{\varepsilon_{(ij)} - \varepsilon_{(ij)}^{REF}}{\varepsilon_{(ij)}^{REF}} \times 100 \quad (9)$$

where  $\varepsilon_{(ij)}^{REF}$  is the reference strain in pristine condition. The magnitude of the perturbation decays away from the damaged location but the maximum tensile perturbation induced on diagonal GBs is  $10^3$  % to  $10^4$  %, against the modest 20% of the horizontal springs. Such a remarkable magnification of the strain field is responsible for triggering the ruptures in the otherwise weakly loaded diagonal GBs. Eventually, as more microcracks form, the microcracking probability of unfavorably oriented GBs keeps increasing, to the point that the initial order in damage formation breaks down and a sudden transition ushers in a new mode, involving microcracking of GBs of any orientation. Of course this phenomenon is

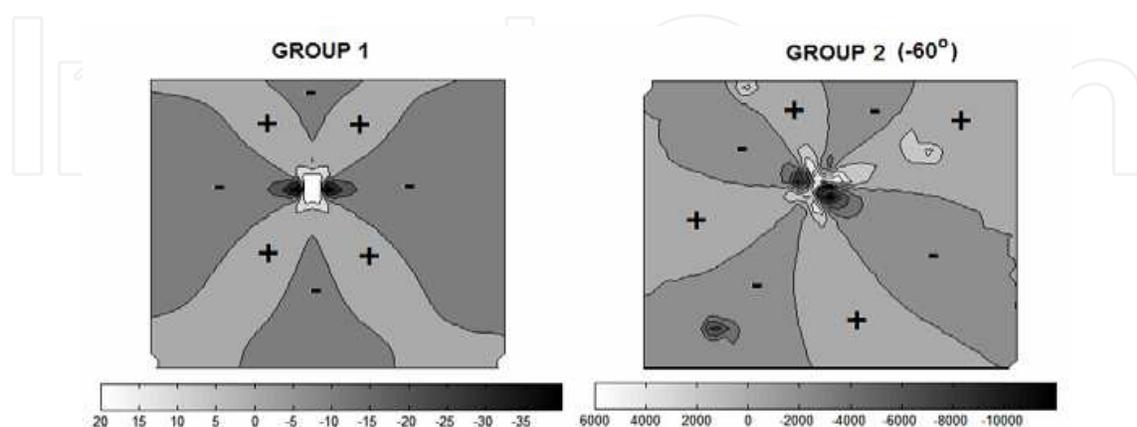


Fig. 11. Percent perturbation fields on horizontal (Group 1) and diagonal (Group 2) extant springs for a sample lattice with  $\sim 600$  grains loaded as in Fig.8 and containing just one horizontal rupture. The magnitude of the perturbation on secondary spring is 1000-folds.

dependent on the loading direction, as the differential rupturing of GBs is tied to their orientation relative to the load. This is the root cause behind the damage-induced elastic anisotropy experienced by a damaged solid. The latter consists of the reduction of the elastic stiffness moduli only for the constants related to those GBs that participate to the damage process, leaving the elastic moduli in other directions only slightly affected. This is appreciated in Fig. 12, showing the different failure patterns for the same lattice from four uniaxial loading schemes, the ultimate evidence of the anisotropic damage evolution.

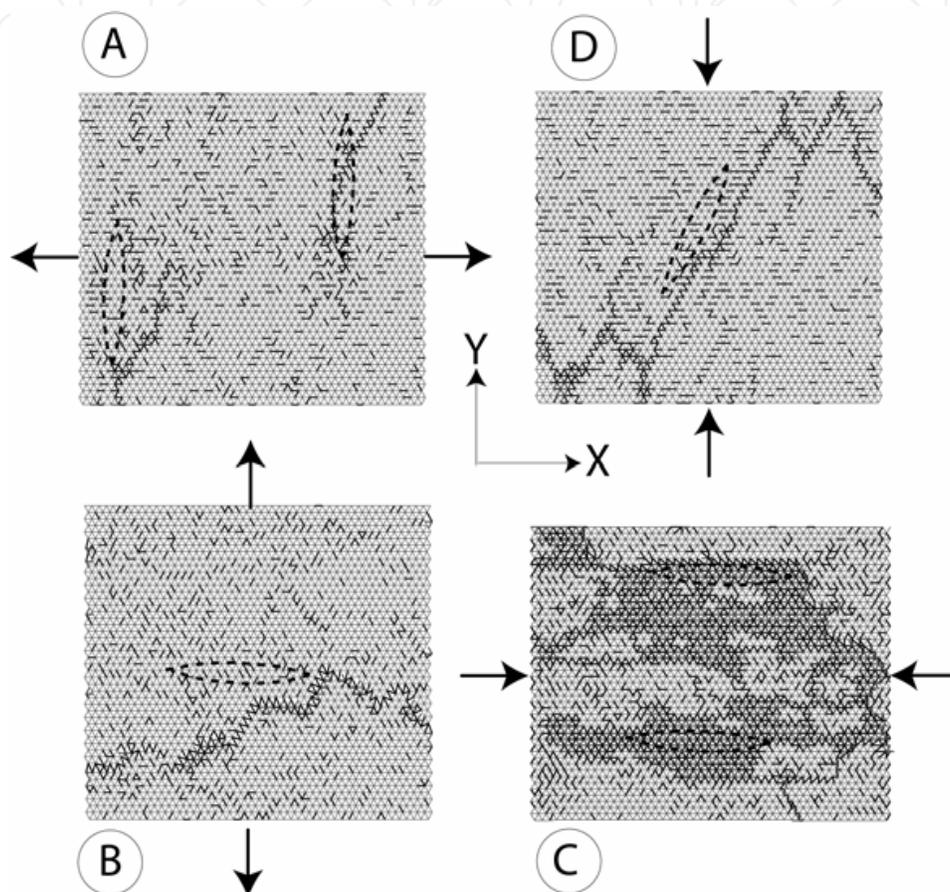


Fig. 12. Failure patterns for four load cases, revealing different failure modes. In agreement with experimental evidence on rock, concrete, and other brittle materials, tensile schemes are linked to cracks formation whether compressive loads produce shear banding and split (after Rinaldi, 2009).

## 5. Concluding remarks

Recent advances in discrete modelling were discussed in the context of AE monitoring. Starting from the limitations of AE stemming from the intrinsic randomness of AE data and from lack of knowledge/consideration of the microstructure, it was argued why SDM discrete modelling could become a companion tool for computer aided AE analysis. From the analysis of mechanical lattices we illustrated how SDM

1. can lead to an exact expression for the damage parameter, this proof-of-concept being a template to formulate physically-inspired damage models of  $D$  from parameter-based AE experimental data;

2. can capture the role of microstructural texture in the damage process and damage localization, demonstrating that knowledge of actual microstructure cross-correlate with AE signal, aiding its interpretation.

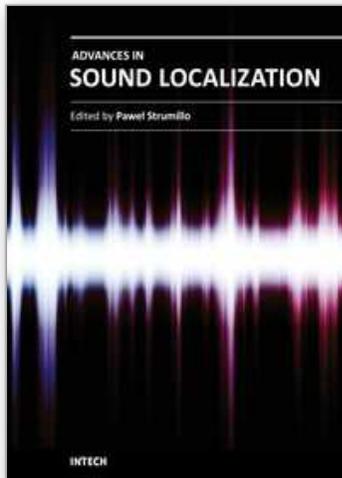
Thus, SDM is a powerful tool to look into structure-property relationships for damage and fracture. The featured analysis of the lattice model proved that the driving force in the fracture of heterogeneous matter resides in the stress amplification induced in the microstructure by the previously accumulated damage, following local load redistribution. This type of insight about the damage process could not be gained by classical continuum mechanics in such a straight forward manner. However, although the discussion supports the potential of the computational approach for damage assessment and AE structural monitoring, especially as far as the issues highlighted in the introduction, presently this remains a perspective, primarily because of the conceptual stage of the SDM theory for higher order structural system and calibration issues. Further research is on demand to validate these results on many real systems beyond lattice and customize them specifically for AE (field and lab) applications. On the other side there is a strong demand for modern computational tools for AE, which appear particularly welcome in consideration of the ever broadening range of AE applications that span from the determination of mechanical damage in metallic constructions (cracks, pits, and holes) to corrosion monitoring, from composites to concrete.

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## **Advances in Sound Localization**

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Sound source localization is an important research field that has attracted researchers' efforts from many technical and biomedical sciences. Sound source localization (SSL) is defined as the determination of the direction from a receiver, but also includes the distance from it. Because of the wave nature of sound propagation, phenomena such as refraction, diffraction, diffusion, reflection, reverberation and interference occur. The wide spectrum of sound frequencies that range from infrasounds through acoustic sounds to ultrasounds, also introduces difficulties, as different spectrum components have different penetration properties through the medium. Consequently, SSL is a complex computation problem and development of robust sound localization techniques calls for different approaches, including multisensor schemes, null-steering beamforming and time-difference arrival techniques. The book offers a rich source of valuable material on advances on SSL techniques and their applications that should appeal to researches representing diverse engineering and scientific disciplines.

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