Intermittency in brittle cracks: Model experiment in artificial rocks

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Abstract

Stress enhancement in the vicinity of brittle cracks makes the macroscale failure properties extremely sensitive to the microscale material disorder. As a result, crack propagation is sometimes observed to display a jerky dynamics with seemingly random sudden jumps spanning a broad range of scales, reminiscent of earthquakes. This so-called crackling dynamics cannot be captured via standard continuum fracture theory. The understandings of the key processes that drive such a dynamics then represent a crucial step toward predictive statistical models for heterogeneous brittle failure.

In this context, we designed an experimental setup which permits to drive brittle cracks in opening mode at adjustable velocity throughout model materials of adjustable microstructure. During the fracture, both the mechanical behavior and the acoustic emission are recorded in real time, and *post-mortem*, the morphology of the fracture surface is obtained by profilometry. Accurate statistical analysis of these experimental data and their interplay is believed to provide a deeper understanding of the key mechanisms responsible for crackling in heterogeneous brittle fracture.

Keywords

Brittle crack, Experiment, Crackling dynamics, Model rock, Acoustic

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1. Introduction

The effect of materials heterogeneities onto their failure properties remains far from being understood (see [1,2] for reviews of recent progresses in this field). In particular, in heterogeneous materials under slow external loading, cracks growth sometimes displays a jerky dynamics, with sudden jumps spanning a broad range of lengthscales. Such a complex dynamics, also referred to as crackling noise [3] was directly imaged in interfacial crack experiments [4]. It was also suggested from the acoustic emission accompanying paper peeling experiments [5], from the anomalous activity recorded in some calorimeters for high energy physics experiments [6], and - at much larger scale - from the seismic activity associated to earthquakes [7,8]. The salient features of such a crackling dynamics is to exhibit universal scale free statistical features reminiscent of self-organized-criticality [3].

Standard continuum approaches fails to describe such a crackling dynamics. Conversely, recent theoretical and numerical works suggested that some of the approaches developed in statistical and non-linear physics may be relevant. In this context, it has been proposed to identify the crack front with a long-range elastic line [9,10] and to map crack destabilization with a critical depinning transition [11,12]. By subsequently extending this formalism to stable crack growth, it then becomes possible to reproduce a crackling dynamics [13], and to precise the conditions required to observe it [14]. Still, these models are derived by invoking very restrictive assumptions (1D line moving within a 2D random potential) and lack for quantitative comparisons with real fracture experiments (i.e. breaking of bulk 3D solids). One need also to further understand how the crackling statistics predicted theoretically translates into the acoustic emission and seismograph signals analyzed in fracture and earthquake problems.

The goal of the experiments described thereafter is to fill this lack.

2. Experimental setup

Slow stable cracks are driven via the wedge-splitting geometry [15] sketched in Fig. 1. Specimens were prepared from rectangular plates of size 12x14cm^2 and thickness 1.5cm. A notch is machined in each of the specimens i) by cutting out a 2.5x2.5cm^2 square from one side; ii) by subsequently adding a 8mm long thick groove with a diamond saw; and iii) by finally introducing a seed crack (~2mm-long) with a razor blade. The resulting specimens are loaded by placing two steel jaws equipped with roller bearing (to avoid friction) on both sides of the cutout and by pushing a steel wedge (semi-angle of 15°) in between. The opposite side is also made laid on a pivot to avoid friction when breaking. This geometry permits a stable propagation of the crack tip splitting the sample in two symmetric halves.

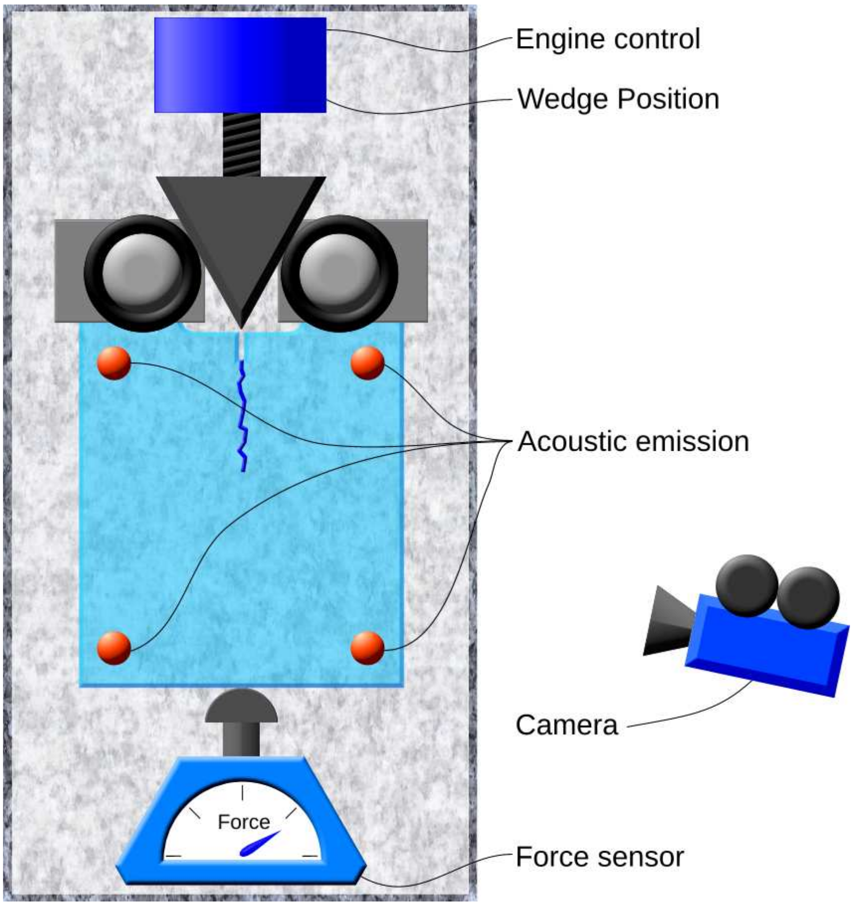


Figure 1. Experimental wedge-splitting device

Fracture experiments are performed on artificial rocks made from sintered polymer beads (Fig. 2D): Plexiglas or polystyrene monodisperse beads of an adjustable diameter (Fig. 2A) are heated up to a temperature slightly below glass transition (110° C), and then compressed in a rigid mold at a fixed pressure during 45min (Fig. 2B). An annealing process just above the glassy temperature during 1h is then applied to limit residual stress, and the so-obtained specimen is slowly cooled down (Fig. 2C).

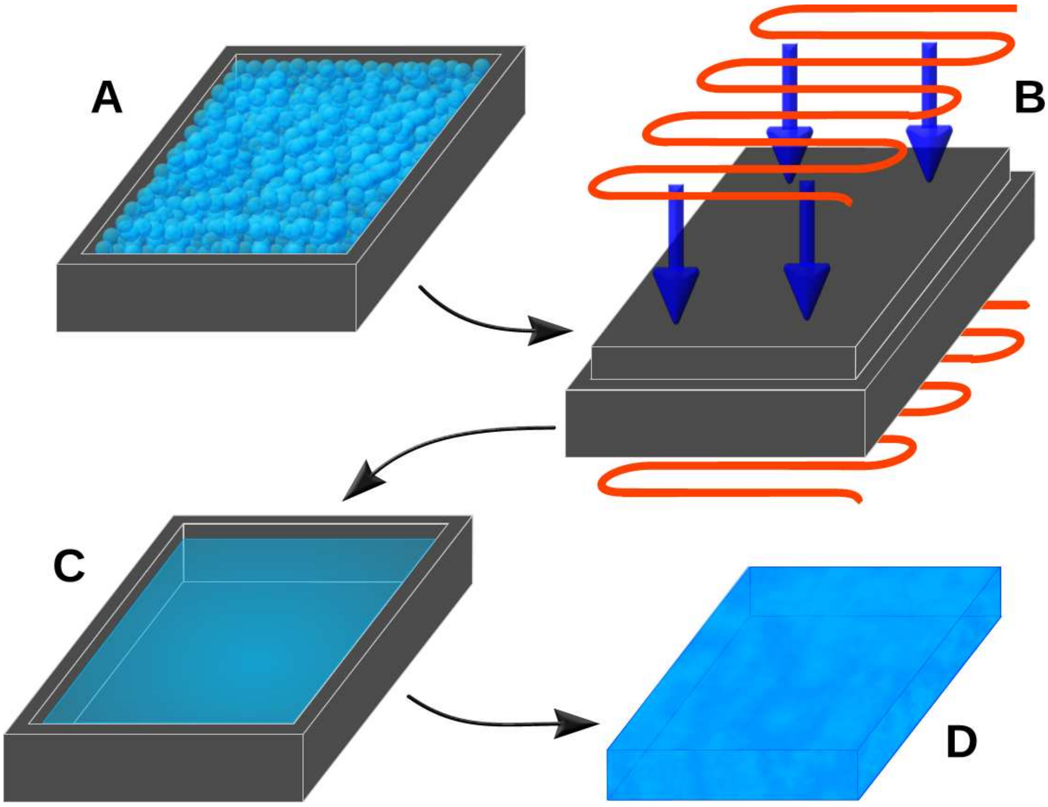


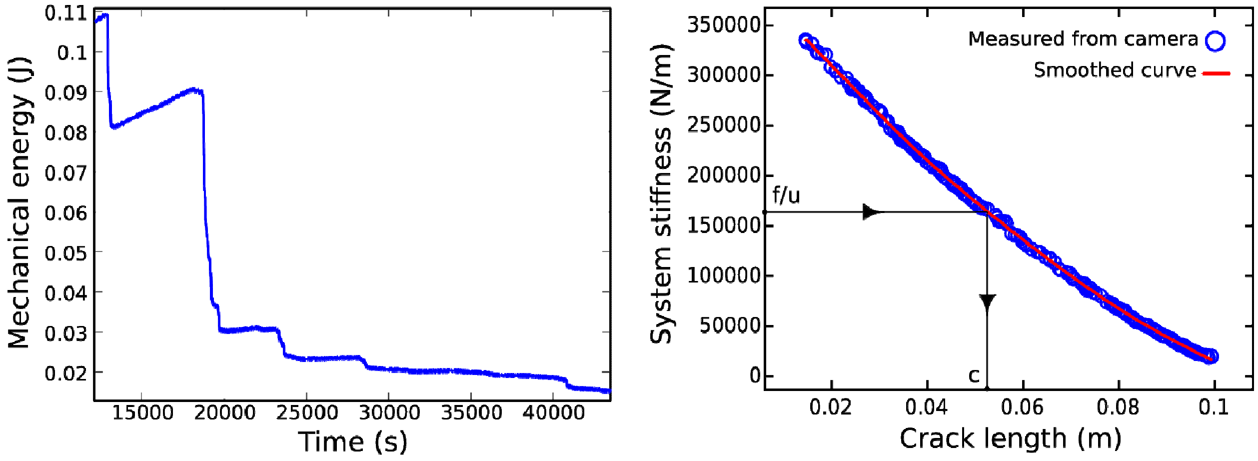
Figure 2. Protocol to synthesize artificial rock of adjustable microstructure

Bead diameters and sintering pressure have been varied, from 20 to 500μm and from 10 to 800kPa respectively, to modulate the microstructure length-scale and the porosity. Wedge speed was varied from 1.6 to 1600 nm/s to study the effect of driving rate. During the tests, a force sensor connected to the bottom of the sample (see Fig. 1) records in real-time the force f applyed on the specimen (acquisition rate of 50kHz with an accuracy of 1N). Similarly the wedge position u is recorded at each time step (acquisition rate of 1Hz) with nanometer precision. Crack propagation is imaged at the specimen surface (30 frames per second with a pixel size of 130μm) and 8 acoustic sensors (4 on both side of the sample) permit a record of the acoustic emission (and its further localization) with MHz acquisition rate and aJ precision.

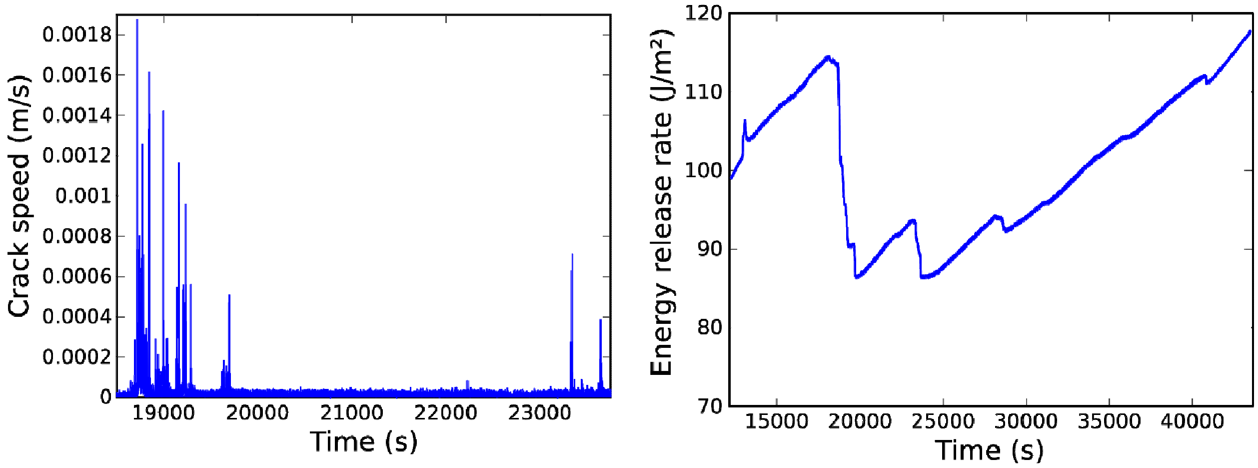
3. Experimental results

Measurement of the wedge position u and of the applied force f gives full access to the exact mechanical energy stored in the system at each time step (see Fig. 3A). It also provides the time variation of the specimen stiffness (f / u). This signal is plotted as a function of the crack length c

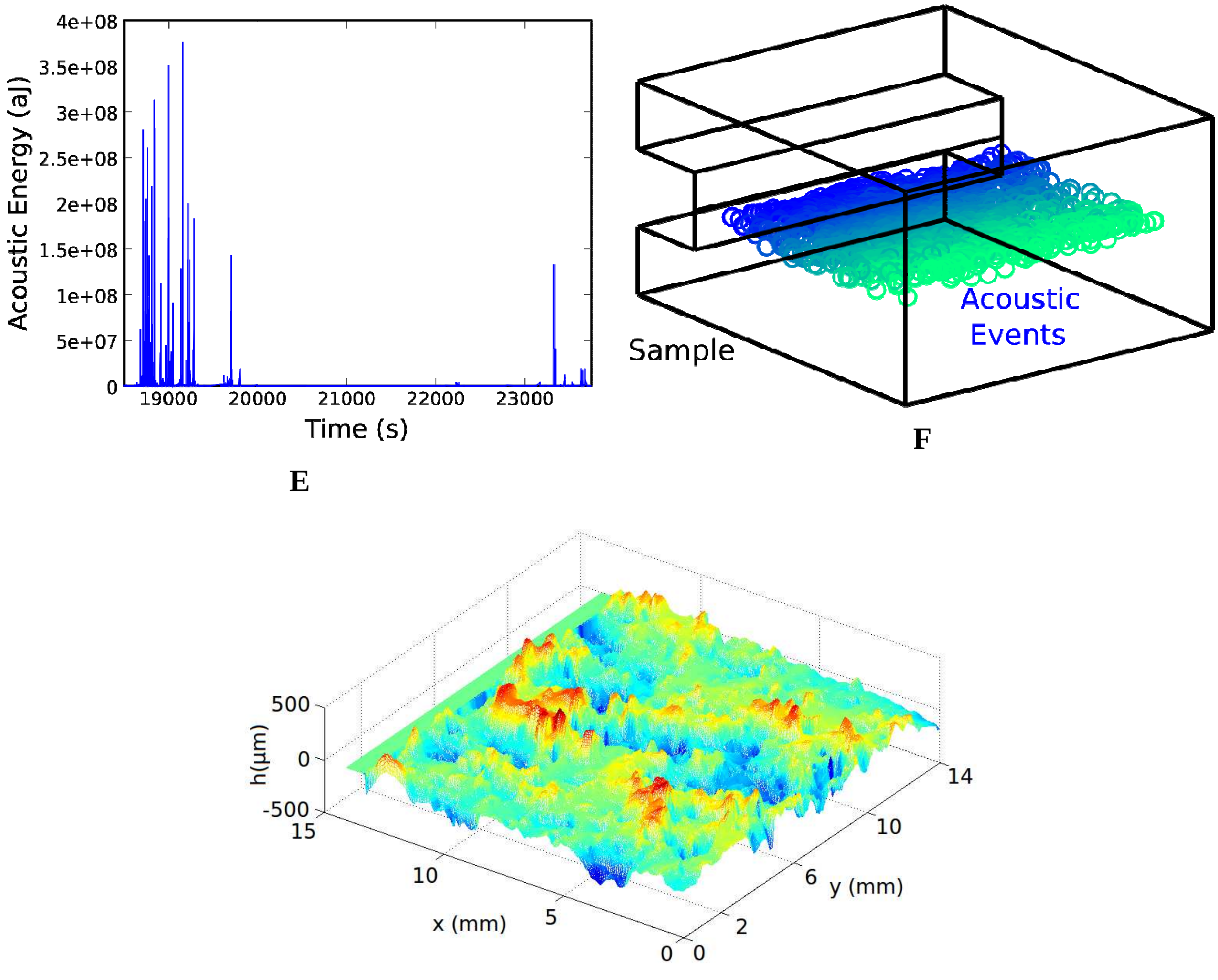
measured from the direct imaging of the surface (Fig. 3B). This curve is noisy, but since noise has no physical meaning in this case, the curve is smoothed and an accurate one-to-one measure of the crack length as a function of the stiffness and of the time is get (black arrows in Fig. 3B). The failure speed can then be directly deduced, with a fairly high signal to noise ratio, by differentiating these data (see Fig. 3C). By limiting friction and plastic dissipation in our experiments, we ensured that the fracture process zone at the tip of the propagating crack is the sole source of mechanical energy dissipation in the system. Hence, from the knowledge of the time evolution for stored elastic energy and crack length, one can compute the energy release rate *G* (see Fig. 3D). Acoustic sensors give access to the energy (see Fig. 3E) of the acoustic events and time delays permit to localize each acoustic source (see Fig. 3F). Finally, the fracture surface is analyzed post-mortem via profilometer (see Fig. 3G).



A **B**



C **D**



E

F

G

Figure 3. Graph of experimental results. A: Elastic energy stored in the whole system as function of time ; B: Crude and smoothed curve of the stiffness system as a function of the crack length measured by camera ; C: Speed of the crack front as a function of time ; D: Energy release rate as a function of time ; E: Acoustic energy of the fracture events ; F: Acoustic location of the fracture events in the sample geometry (colors correspond with time of occurrence) ; G: Post-mortem fracture surface of a piece of sample

As seen in Fig. 3, a crackling signal is observed in our experiments. The statistical analysis of the various signals and their interplay are currently underway and will be presented at ICF13.

4. Concluding discussion

The experimental setup presented here is the first one which permits to observe a crackling dynamics for the steady bulk crack propagation within a 3D brittle solid. A precise sintering protocol has been set up to build this material from mono-disperse polymer beads. Hence, all material parameters (microstructural texture, porosity, toughness) are tunable. The wedge-splitting experimental device set up to fracture this material controlling the loading permits to have access to an accurate measurement of the acoustic and mechanical parameters evolution.

The statistical analysis of these quantities and their interplay is currently in progress. It will allow qualifying the depinning approaches developed in statistical physics [8] to address the problem of brittle heterogeneous fracture.

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