Acoustic Emissions in Fracturing Paper

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Abstract The fracture dynamics of heterogeneous materials is a rich subject with obvious practical interests, especially the subcritical fracture, where a material breaks through a series of successive, non-correlated and localized fracture events until the arriving to a critical situation where the whole material fails. Paper has been a common model material to study this phenomenon, and high-resolution and high-speed visualization are the usual ways to follow the dynamics of the process. However, visualization presents many limitations, especially for long experiences. That is one of the reasons why we are coupling acoustics to the measurements in an attempt to establish it as the main source of information. Acoustics presents a much better temporal resolution and captures a higher number of events than visualization. By thresholding the amplitude of the acoustic signal, it is possible to get similar activities in both measurements. The waiting times between events and the energy of the events are both distributed in power laws with exponents which are similar for the two different kind of measurements (visualization and acoustics), corroborating that the recorded acoustic data corresponds indeed to the fracture process.

Keywords Subcritical fracture, Acoustic emissions, crack propagation, scale invariance.

1. Introduction

Industrial designs evolve continuously toward thinner and lighter, however stronger structures, many of them submitted to a permanent stress. It is known that stresses intensify around a flaw in the material [1]; and even if the system resists at a particular instant, a micro-crack can start growing, in an intermittent manner (the case of heterogeneous materials), until reaching a critical length where the whole system fails. This process, denominated *subcritical fracture*, has captured the attention of scientist and engineers for more than half a century, and the progresses in experimental results are quite related to the technological advances in the period. Already in the sixties, some models based on thermally activated rupture were proposed [2, 3], supported by measurements of the lifetime of the sample as a function of the global stress and the temperature [2, 3]. In the nineties, during the early stages of the digital era, acoustics allowed the statistical analysis of the burst-like fracture events provoked by the intermittent growing of a crack [4, 5]. Power law distributions of amplitude and waiting time between fracture events were often interpreted as a signature of a "self-organized critical" process [6, 7]. In the latest years, high-speed and high-resolution video acquisition have played a major role in the study of the subcritical fracture of diverse materials [8-10]. Paper presents several good properties that have set it as a common model material: two-dimensionality, high degree of heterogeneity and variability, quasi-brittle character and a very low cost. Many different results have been obtained with direct observations in paper [8, 11, 12]. However, several issues seem favoring the implementation of acoustics measurements. Beyond lab limits, most objects are three-dimensional and non-transparent, thus analyzing their interior belongs mainly to the acoustics' domain. The earth's interior is one of their most relevant examples, and the statistical similitude between earthquakes and subcritical fracture [13] is an invitation to use the same source of information, i.e., acoustics. Also, in high-speed cameras there is a compromise between spatial resolution and frame rate, as well as size of the image vs. number of images. Having two characteristic frequencies in our study: one low, where a priori there is not much activity, and another very high, taking place during a local fracture event, direct observation may result in a lost of information. We are coupling acoustic to the measurements in an attempt to establish it as the main source of information. The main aim of this paper is to verify the agreement between acoustics and direct observation. By thresholding the amplitude of the acoustic signal, we get a very similar temporal activity in both measurements. The waiting times between events and the energy of the events are both distributed in power laws with exponents which are similar for the two different kind of measurements (direct observation and acoustics), corroborating that the recorded acoustic data corresponds indeed to the fracture process. Earlier studies have used acoustic as the main source of information to analyse a fracture process in paper [14-15]; however, as far as we know, this is the first report validating the results of the acoustic measurements through simultaneous direct observations.

We also discuss the advantages and challenges of the use of acoustics in our experiment. Some experiments have been done to study the acoustic emission of fracturing paper [14-15], but as far as we know this is the first time that acoustics are compared to another observation method-direct visualization of fracture propagation.

2. Experimental procedure

We use fax paper samples from *Alrey* having a thickness of 50 μm and effective dimensions 21 cm × 4 cm, being fixed along the longer sides and free in the perpendicular direction. An initial crack of length l_0 is prepared at one free side of the sample, both in a parallel direction and equidistant from the fixed borders. Experiments are performed by applying a constant force F perpendicularly to the direction of the initial crack. By adjusting $l_0 = 4.75$ cm and $F = 200$ N, the crack grows reaching a critical length, $l_c \sim 8$ cm, approximately between 10 minutes and 30 minutes after the application of the force. The critical length l_c separates the slow dynamics from the quasi-instantaneous rupture. Two piezoelectric transducers of diameter 2.3 mm (*Valpey Fisher VP-1.5*) are placed in contact with the paper at 5 cm and 9 cm from the free side containing the initial crack and at 1 cm from the fixed border (which also corresponds to a 1 cm distance to the direction of the initial crack). An ultrasonic gel guarantees a good contact between the sensor and the sheet of paper. The acoustic signals are amplified 64 db and recorded continuously during the whole experience by a *NI USB-6366* card at 2 MHz. A high-speed camera (*Photron FASTCAM SA4*) takes images in a rectangular area containing the advancing crack at a frequency of 10 Hz and a spatial resolution of 100 μm / pixel. All experiences have been performed under the same conditions. The temperature and relative humidity were 26.5 ± 1 °C and 45 ± 2% respectively. A scheme of the experimental setup with the crack and the position of the sensors is represented on figure 1.

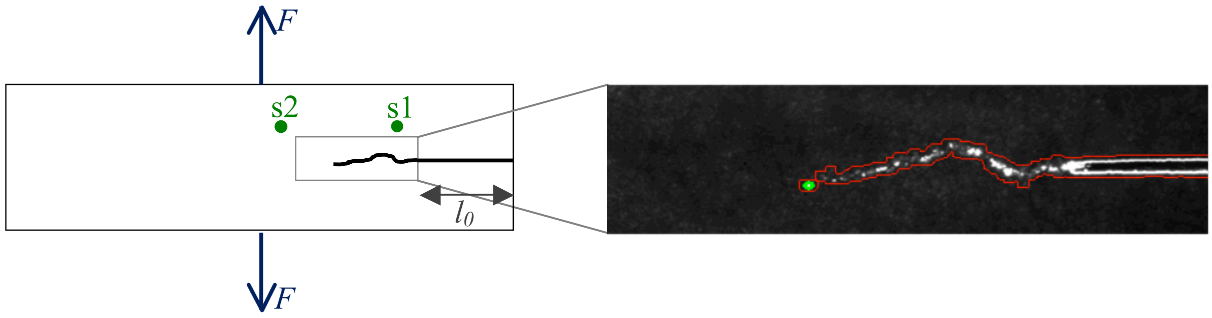

Figure 1. On the left, scheme of the experimental setup. l_0: initial crack length, s_l: projection of the crack length on the initial crack direction, F: applied force, s1 and s2: positions of the piezoelectric transducers. On the right, experimentally obtained image of the crack with the extracted crack contour (red line) and crack tip (green).

The amplitude of the acoustic signal depends on the contact between the transducer and the sheet of paper, which varies between different realizations. In order to compare events from different experiences, a calibration was performed. It consisted of the averaged response of each sensor to six localized rupture events produced on every sample (by piercing it with a computer controlled thin needle of 250 μm of diameter) before complete loading. Additional series of experiments were performed in order to study the attenuation of the acoustic waves in paper. 10 to 20 localized rupture events were induced on a sheet of paper submitted to a force of 200 N, but with no initial crack so to be sure that no uncontrolled rupture would occur. The events were made on a line parallel to the longer sides of the paper, in the same direction as the fracture in previous experiments. The acoustic signal was recorded by two sensors placed at 4 cm from each other.

2.1. Data Analysis

Images: crack contours are extracted using a digital image analysis routine. For each image the position of the crack tip is found (figure 1). Three variables are defined: s, the real length of the interface of the fracture created between two consecutive images; the size of the jump s_S, defined as the distance between the crack tip of two successive images, and s_l, defined as the projection of s on the initial direction of the crack.

Acoustics: The detection of acoustic events is made through the *spectral distance* calculation, which corresponds to the spectral distance between the recorded signal and the noise (the noise sample is recorded during the calibration, before the complete loading of the paper, so no cracks have occurred during it) over a temporal window of length w=100 μs. Spectral distances are usually calculated using the logarithms of the power spectra [16, 17], but we prefer using the power spectra directly so to obtain a distance that is directly proportional to the acoustic energy:

$$D(t) = \frac{1}{w}\int_{t-\frac{w}{2}}^{t+\frac{w}{2}} \langle S(t')\rangle - \langle \overline{N}\rangle \, dt' \qquad (1)$$

where $\langle S(t)\rangle$ is the mean value of the signal's power spectrum averaged over all the frequencies and $\langle \overline{N}\rangle$ the mean value of the noise's power spectrum averaged over time and frequency. Detecting acoustic events and determining their duration is done by thresholding the spectral distance. The energy of an event is calculated as the integral of the spectral distance over its duration. Thanks to the spectral distance the number of detected events is almost four times greater than by thresholding the raw data and we are able to detect events with slightly smaller energy.

3. Results

As the applied force is subcritical and the material heterogeneous, the initial crack propagates in an intermittent manner [8]: images show that the length of the fracture is constant for most of the time and increases by making fast discrete crack steps, denominated *jumps* or avalanches. The acoustic data shows discrete *bursts* with a finite duration. Each burst constitutes an acoustic event. First, we compared the number and occurrence times of jumps and acoustic events, without considering their energy value. For each experiment the number of acoustic events was significantly larger than the number of jumps, even when adjusting the acoustic time resolution to the images' frame rate. This is a clear indication that the acoustics is much more sensitive to crack propagation than the image analysis. Nevertheless, if we only consider acoustic events having an energy larger than a threshold value their number will decrease. By setting the threshold energy to an optimal value we can get the

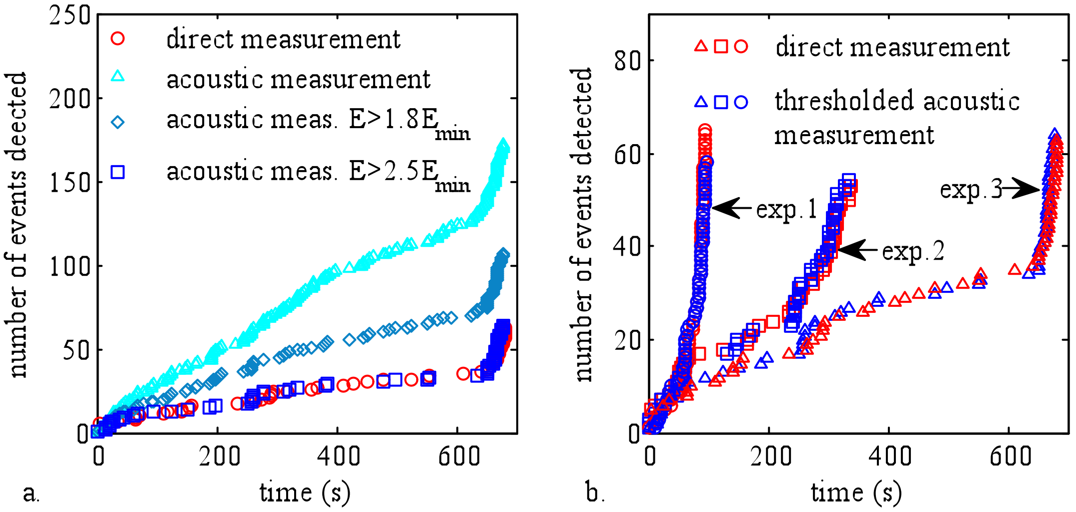

Figure 2. a. Activities obtained by direct observation (jumps) and acoustic monitoring for one experiment: acoustic monitoring results in much more events than direct observation. By considering only acoustic events with energy superior to a threshold value we get very similar activities for both methods. b. Comparison of activities obtained by direct observations and acoustic monitoring for three experiments.

same number of events for both methods. In this situation, time intervals with many acoustic events correspond to the ones with many jumps (figure 2). This global similarity between the two activities confirms the relationship between the propagation of the crack (jumps) and acoustic events. However, when considering the events' energy, the relationship between jumps and acoustics events is not as obvious as previously. Large jumps are not always associated to high acoustic energy and the temporal correlation between the two signals is very poor. The temporal correlation between the two signals is also very poor in the case of not considering the energy values. This can be a consequence of the combination of two facts: the low acquisition rate of the images (10 Hz) and the fact that there is a temporal shift between the rupture of the material (acoustic event) and the macroscopic opening of the fracture (jump). This lack of correlation makes it impossible to match jumps and acoustic events individually, but our data is suitable for statistical analysis: each experiment results in approximately 50 jumps and few hundreds to few thousands of acoustic events, providing enough data for such approach. Here we will study and compare the probability distributions of two different variables characterizing subcritical fracture: waiting times and energies.

Waiting Times: For subcritical fractures the time between two discrete events, referred to as the waiting time, follows power-law distributions [18-20]. Figure 3 shows the probability distributions of waiting times between the events for the jumps and the acoustic data. Both waiting times are power law distributed (with a slight cutoff for long waiting times). The distributions were fitted as power laws within the domains delimited by the vertical lines on the figures, and the exponent obtained are very similar: 1.1 and 1.0 for the jumps and acoustic waiting times respectively.

The distributions are represented on the same plot in figure 4. Since acoustic data acquisition has a much better time resolution, acoustic waiting times spread on a larger set of values. To compare the two distributions we can adjust the distributions' normalization coefficients. Figure 4.a shows that with well-chosen coefficients the distributions collapse. Another solution is ignoring acoustic waiting times smaller than the image frame rate (0.1 s). In this case the two distributions also match (figure 4.b). The similitude between the two probability distributions indicates that the acoustic activity and the detected propagation of the fracture are indeed issued from the same mechanism.

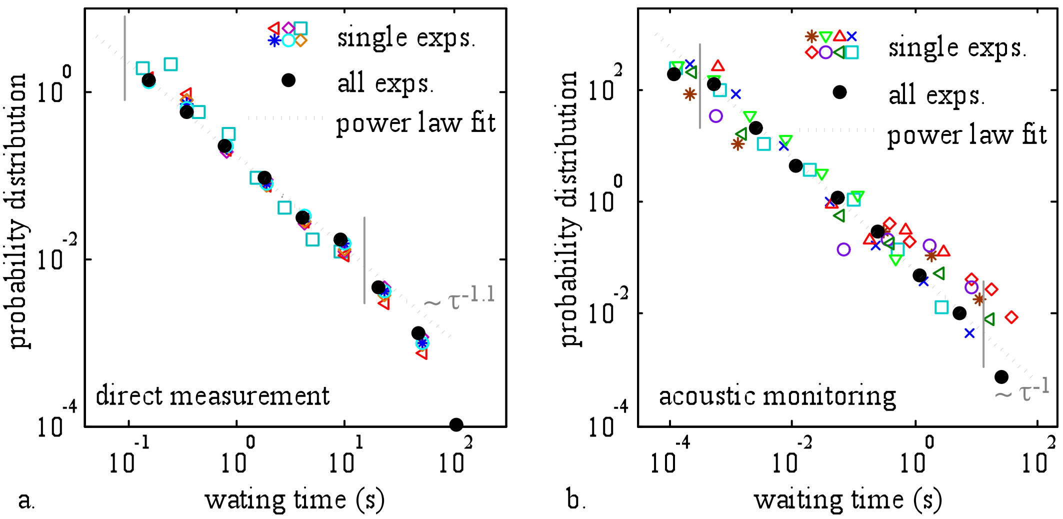

Figure 3. a. Distribution of waiting times determined by the direct observations (jumps). b. Distribution of waiting times determined by acoustic monitoring. Open symbols: waiting times of each experiment separately, solid symbols: waiting times of all the experiments, dotted line: a power law fit of the distribution of the waiting times of all experiments in a range limited by vertical lines.

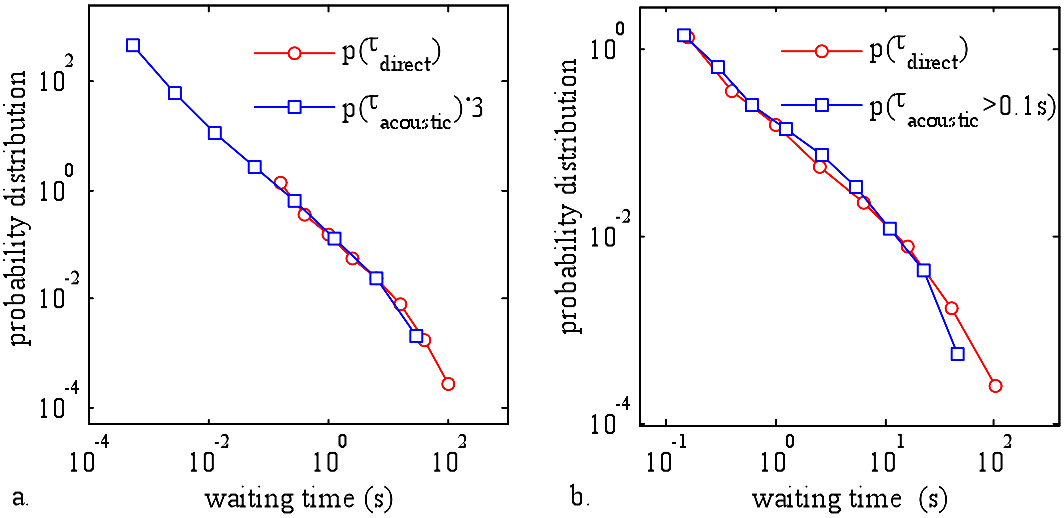

Figure 4. a. Distribution of waiting times of the jumps, obtained by direct observations (red circles) and distribution of waiting times obtained by acoustic monitoring multiplied by 3 (blue squares). b. Distribution of waiting times obtained by direct observations (red circles) and distribution of waiting times greater than the image frame fate (0.1 s) obtained by acoustic monitoring (blue squares).

Furthermore, some test showed that the acoustic waiting time distribution is not affected by thresholding the event's energy; and considering all the detected acoustic events, the same power law distribution is found. This result indicates that all the acoustic bursts correspond to fracture events.

Energies: in this two-dimensional system fracture energy scales as the fracture's length. Therefore, the normalized distribution of jump sizes is equal to the normalized distribution of jump energies. The probability distribution of s (the real crack length), s_s (the distance between crack tips on two successive images) and s_l (the projection of s on the initial direction of the crack), are represented in figure 5.a. The three distributions follow a power law over approximately a decade followed by a cutoff. We extracted power laws with exponent 1.2 for s_s and s_l and 1.0 for s. Because of the relatively small number of jumps and the limited span of the power law we must consider these results with precaution and will not discuss the differences between the probability distributions. We will rely on results from previous experiments: an exponent of 1.23 has been found previously for the power law distribution of s_l [8, 21], which matches our observations.

The energy of acoustic events is defined as the integral of the spectral distance (equation 1) over an event's duration. The event is the part of the spectral distance overcoming a chosen threshold. We prefer this definition to the maximal amplitude of the signal (or of the spectral distance) because acoustic events are not single punctual bursts: they sometimes have irregular shapes in time, presenting few local maxima as consequence of the fact that few fibers can break consecutively in a very small lapse of time, appearing as one single event. Taking into account only one of these maxima would result in neglecting a considerable proportion of the acoustic energy. Integrating the spectral distance rather than the square of the signal itself decreases the influence of the noise. This definition provides an estimation of the acoustic energy detected by the sensors, which does not exactly correspond to the energy at the event's source. This energy needs to be corrected by taking into account the attenuation of the acoustic waves, which can be scattered or absorbed by paper fibers. The experiments on crack-free paper provided data on the position and energy of about hundred events relative to the two different sensors. By comparing the energy ratio of signals detected by the two sensors, to the distance separating each event from the sensors, we obtained that the energy is attenuated exponentially with a characteristic length of 3.2 cm. To determine the position of the source of an acoustic event we use the images and suppose that it occurred at the position of the crack tip at the corresponding time. By knowing the distance between the source and the sensor, we can compute the attenuation of the energy. Figure 5.b shows the distribution of the estimated acoustic energy at the events' source. Energies follow a power law over more than three decades with an exponent of 1.3, very close to the one found for the distributions of jump sizes. Once again, the similarity between the power laws of jumps and acoustic energy indicates that acoustic emissions are a consequence of the paper's fracture.

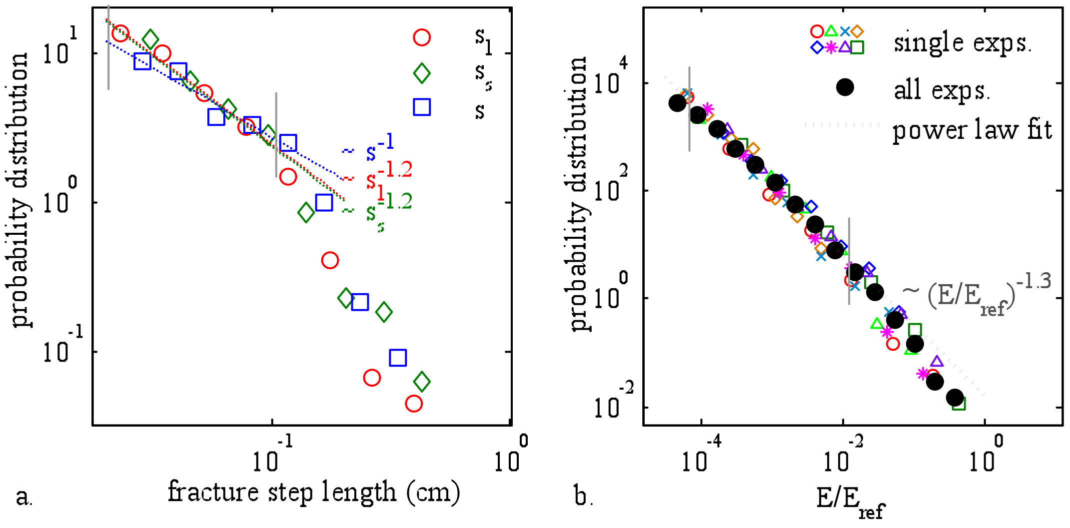

Figure 5. a. Probability distribution of fracture jumps (s, s_l and s_s) with power law fits in a range limited by vertical lines. b. Distribution of the energies of the acoustic events. Open symbols: energies of each experiment separately. Solid symbols: energies of all the experiments, dotted line: a power law fit of the distribution of the energies of all experiments in the signalized range.

4. Conclusion

We studied the subcritical crack growth of a single crack in a sheet of paper submitted to constant force. The system was observed directly by image analysis and indirectly by recording the acoustic emissions. Both methods show similar activities over time. Two variables, the waiting times between the events and the energy released at each event, were statistically analyzed. They both present power law distributions that are very similar for the two different measurements (direct or acoustic emissions), corroborating that the recorded acoustic data corresponds indeed to the fracture process. Having better time resolution and sensibility than image analysis, acoustic monitoring seems more promising for the future development of subcritical fracture in heterogeneous materials.

Acknowledgements

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