POSTER REFERENCE: ICF100630PR

STATISTICS OF ACOUSTIC EMISSION IN PAPER FRACTURE

L.I. Salminen[1], A.I. Tolvanen[1], M.J. Alava[1], and K.J. Niskanen[2]

[1]Laboratory of Physics, Helsinki University of Technology, P.O. Box 1100,
FIN-02015 HUT, Finland
[2]KCL Science and Consulting, P.O. Box 70, FIN-02151 Espoo, Finland

ABSTRACT

Experiments on acoustic emission during the tensile failure of paper are reported. These support the idea that the AE activity is correlated with a decrease in the elastic modulus which reduces the stored elastic energy. Tests with different strain rates indicate that in general the AE statistics depend quite weakly on the rate. This is demonstrated for the intervals between individual events. They follow for large intervals a power-law probability distribution independent of the strain rate, with the exponent close to unity. The event energy distributions have power-law tails, too.

KEYWORDS

acoustic emission, fracture, paper, power law, energy release, time interval, crack propagation

INTRODUCTION

Acoustic emission (AE) is a phenomenon whereby transient elastic waves are generated by the rapid release of energy from a localized source within a material. Therefore it is a experimental technique that can be applied to following damage and fracture development in disordered materials. In such systems the acoustic emission should follow the formation of microcracks. There are intriguing observations of power-law -like scaling laws in the AE statistics from various experimental situations [1, 2, 3]. It seems that e.g. the distribution of the released energy can follow such a power-law -like probability distribution. Understanding such scaling behavior in terms of the statistical mechanics of fracture is still an open question [4, 5, 6, 7, 8].

The structure of paper is strongly heterogeneous on two lengthscales. The characteristic dimensions of the building blocks, fibers vary between 1 μm and 1 mm. The fibers form flocs, which in the manufacturing process are organized in a random manner to assemble a paper sheet. The local areal mass density has a typical coefficient of variation of the order of 10 %. Likewise, the local fracture properties (strain, stress, ductility) vary even more. Unlike in most composite materials, the properties of fibers have a large quantitative effect on the structure they constitute. Both the properties of the furnish (fiber raw-material) and the network are difficult to connect to fracture.

The microscopic origins of AE release in paper are not known in detail. Whatever the actual source, AE can be considered as an indication of elementary rupture events. As an analogy, in fiber composites four methods of energy dissipation exist: 1) plastic elongation of fibers, 2) breaking of fibers, 3) breaking of bonds, and 4) fiber-to-fiber friction when fibers pull-out. Bond breakages are considered as the primary microscopic breaking

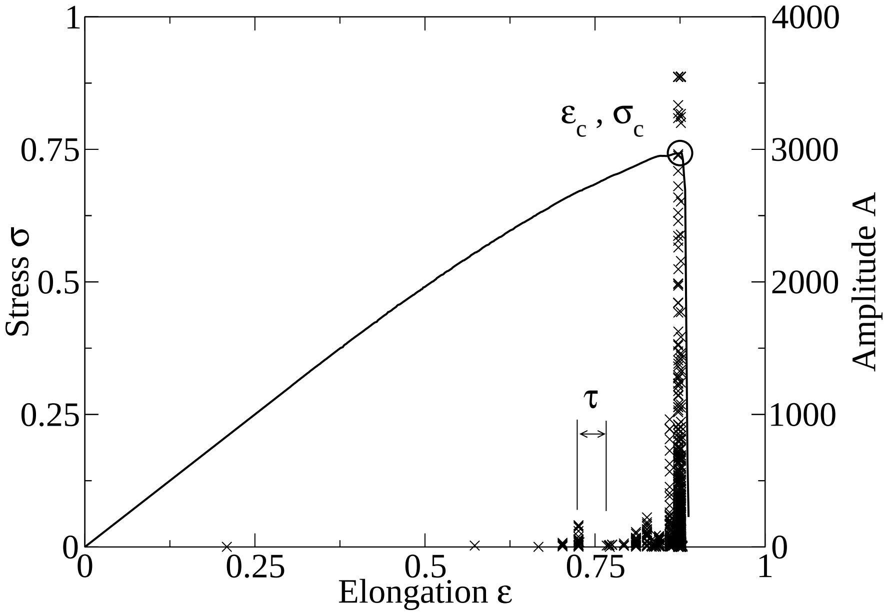

Figure 1: Example of a tensile test and acoustic emission in paper fracture. The crosses are the amplitudes A of acoustic emission, the solid line is the stress-strain curve, ϵ_c,σ_c denote the position of maximum load. τ is the silent interval between two events. (MD dry, rate of elongation 10 %/mm).

process in paper though fiber failures may also contribute. Plastic elongation produces probably no AE. The relative orders of magnitude of AE originating from these mechanisms are in any case unknown. Work by Yamauchi et al. implies that fiber and bond breakages could be distinguished by the amplitude spectrum[9].

EXPERIMENTS

The aim of the experiments was to use AE to resolve the dynamics of damage in mode I tensile tests on paper [10]. The main tool is statistical analysis which also allows a comparison to other statistical fracture results. We measured only one sample material, newsprint, a paper consisting of wide range of size of mechanically pulped fiber fragments. Basis weight (surface-mass) of paper was 44 g/m^2. Mode I tests were done in two principal sample orientations, the machine direction “MD” and the cross direction “CD”. The fiber orientation is strongly biased to MD. In MD we analyzed two moisture contents 8 %, (dry), and 16 %, (wet). The properties of wet MD are presumably in between dry MD and dry CD. The span length l_0 was 100 mm, the width w of strips 100 mm and a single edge notch of 15 mm was cut. Each measurement was repeated 20 times. We had 7 elongation rates in the range 0.1 mm/min - 100 min/min, ie. the rate was varied over three orders of magnitude.

The stress-strain behavior of paper has a few general features. If the stress is parallel to MD, the response is relatively brittle. The strain at break is always close to 1 per cent. The material obeys Hooke’s law i.e. the tangential modulus remains almost the same through the rising part. After the load maximum σ_c the load decreases and a crack propagates rapidly (Figure 1). In CD the functional behavior is much more ductile, the strain at break is 2 - 4 per cent and the elongation includes a plastic component from the very beginning. The tangential modulus may decrease by 50 per cent. The final crack propagates much slower and may even stop a few times.

The experimental apparatus consists of an AE transducer, an amplifier, and data acquisition and signal conditioning software. The transducer is a rubber faced piezoelectric transducer from Etalon Inc. The rest of the apparatus has been developed in the Laboratory of Physics at HUT. The time resolution by which individual AE events can be observed is 10 μs. In our geometry the source-to-transducer transmission time of AE is about

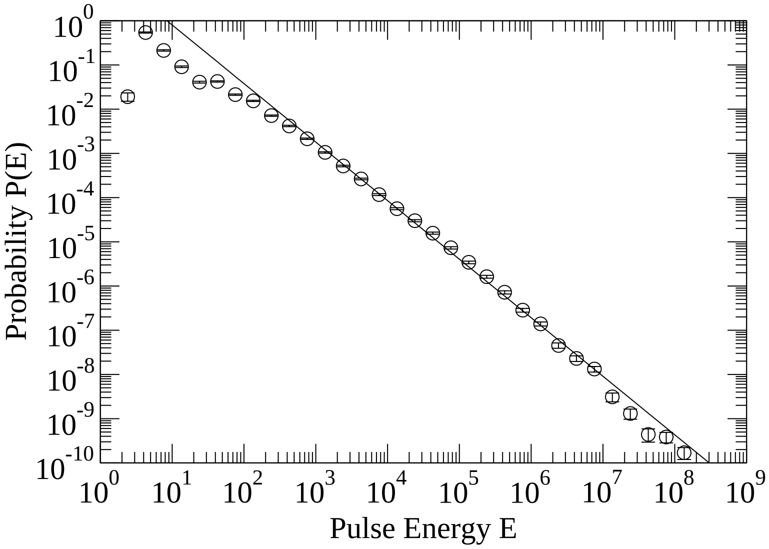

Figure 2: A power law fit for AE pulse energy $P(E) \sim E^{\gamma}$, with $\gamma = -1.3 \pm 0.2$. The circles are the experimental data. The error in E is equal to the bin-width, and only the errors in P are shown. (MD wet, 100 %/mm, a fast rate of elongation.)

10 μs. During the test we do not threshold the signal in any way. The analysis is done completely off-line. The acoustic coupling between the transducer and the paper is lost at the end of test, so the final events are sometimes missing. Further details of the apparatus are described elsewhere. In our experiments the velocity of the crack is always slow so that the stress-field is close to static except during individual AE events, perhaps.

RESULTS

The occurrence of AE in paper is relatively rare so statistical analysis is needed. Here correlation analysis is not justifiable since the tensile test is not stationary in time. Logarithmically scaled histograms are capable of presenting the frequent and infrequent events in same figure, and eventual power laws $y \sim x^{-\alpha}$ are seen as straight lines on a log-log scale. One of the advantages of scaling analysis is its robustness concerning the experimental details like signal thresholding and pulse detection procedures. To benefit from power law analysis, large data sets are essential.

Tensile test and the crack propagation vs. AE

The experiments indicate that the properties of acoustic emission are not directly related to the critical strength or strain or the sample elastic modulus. The mean number of AE events before the rupture is about constant and has no correlation with $\dot{\epsilon}$, the rate of elongation. The number of events after the maximum load σ_c decreases roughly in an exponential manner as $\dot{\epsilon}$ increases. For elongation rates less than 10 mm/min most events happen during the crack propagation phase. It is possible that the same holds for higher elongation rates. The correlation of the number of events in the crack propagation phase and the strain rate implies that the fracture process zone (FPZ) may be reduced in size with $\dot{\epsilon}$. The newsprint is rather brittle, thus it is not surprising that the tensile index is found to be almost independent of $\dot{\epsilon}$. As $\dot{\epsilon}$ is varied the behavior of the average magnitude of the elastic modulus has a nice correlation with the average amplitude of AE. However for individual samples any direct correlation is absent. This reflects the statistical nature of AE.

Statistical laws

The energy probability distribution is found to follow a power-law behavior, in analogy with the Gutenberg-Richter scaling of earthquakes. The energy of an AE pulse E is defined as the integral of the squared amplitude of a pulse. We have used four alternative methods for pulse discrimination with no qualitative differences, to

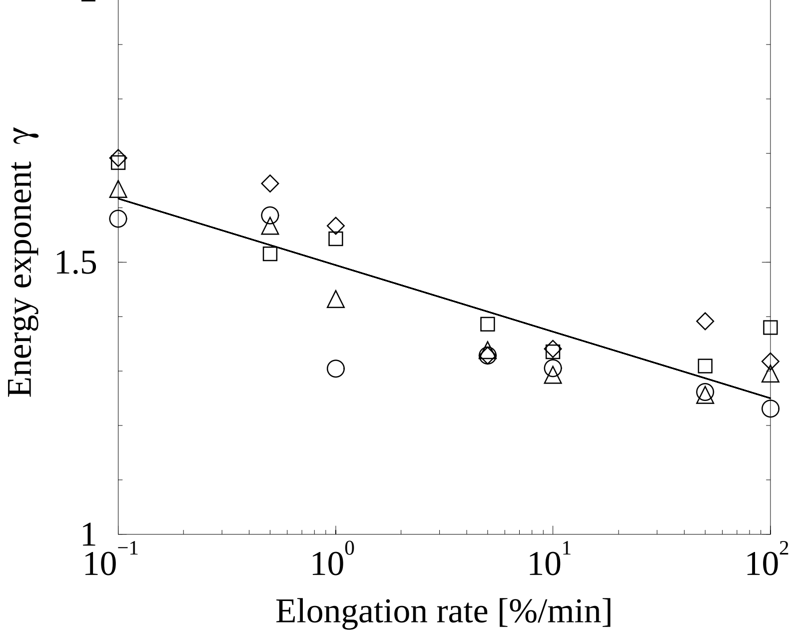

Figure 3: The energy exponent γ as a function of the rate of elongation $\dot{\epsilon}$. The four different symbols represent the energy scaling exponents γ of dry MD samples determined with four interchangeable methods. The power-law scaling regime extends always at least 2 decades in E. The line shows a least square fit ($\gamma \sim 1.5 + 0.05\% \times \log(\dot{\epsilon})$) to all the datapoints.

account for the possible lack of temporal resolution which would result in several AE events being joined together. The pulse energy probability scales as $P(E) \sim E^{-\gamma}$, where γ defines the energy exponent (Figure 2 shows an example of a fit). For amplitudes the same scaling law reads $P(A) \sim A^{-\beta}$, with $\frac{1+\beta}{2} = \delta$.

In our experiments the exponent γ varies slightly with the rate of elongation (shown Figure 3) and also with the test direction. The rate-dependence seems to be a logarithmic function of $\dot{\epsilon}$, irrespective of the discrimination method. High elongation rates give lower values of the exponent γ. With wet MD the scaling region is shorter and the exponents are higher than for dry MD. Experiments in CD give the highest and least reliable values of γ. In practice these results imply that the microcrack tolerance of paper increases in the order MD dry - MD wet - CD dry. To compare, for infinitely slow elongation rates i.e. in a creep test in cellular glass the measured exponent γ is found to be 1.5[1]. For high pressure tanks the energy exponent is 2.0[12]. For AE experiments in volcanic rocks the exponent $\gamma = 1.5 \pm 0.1$[11]. As a function of reduced stress $\frac{\sigma_c - \sigma}{\sigma_c}$ we found no power-law for the cumulated energy $\int E$. In wood and fiberglass Guarino et al. reported a proportionality of $\int E \sim \left(\frac{\sigma_c - \sigma}{\sigma_c}\right)^{-\eta}$, with $\eta \approx 0.26$[2].

The inter-pulse times τ ('dead time') between AE events obey an an Omori-type power law for large τ, similarly to earthquake data. This means that the probability $P(\tau)$ is proportional to $\tau^{-\kappa}$. Within the statistical errors the exponent κ is uncorrelated with the rate of elongation $\dot{\epsilon}$ and the value is close to 1.0 (Figure 4). For creep experiments on cellular glass κ has been reported to be 1.3 [1] and in volcanic rocks $\kappa = 1.2 - 1.3$[11]. The apparent stochasticity in the time delays between AE events before critical crack growth can be interpreted as a lack of correlation between consecutive events. Slight caution should be applied since the temporal resolution of the system may not be sufficient during the most active time span. This does not however affect the large-τ tail of P and the conclusions drawn from it.

CONCLUSIONS

In paper, a disordered two-dimensional material, relatively few AE events occure before the crack initialization, in agreement with the fact that the elastic modulus should decrease only modestly. After the crack starts to propagate we observe strong simultaneous AE activity. In contradiction to creep tests in perhaps more

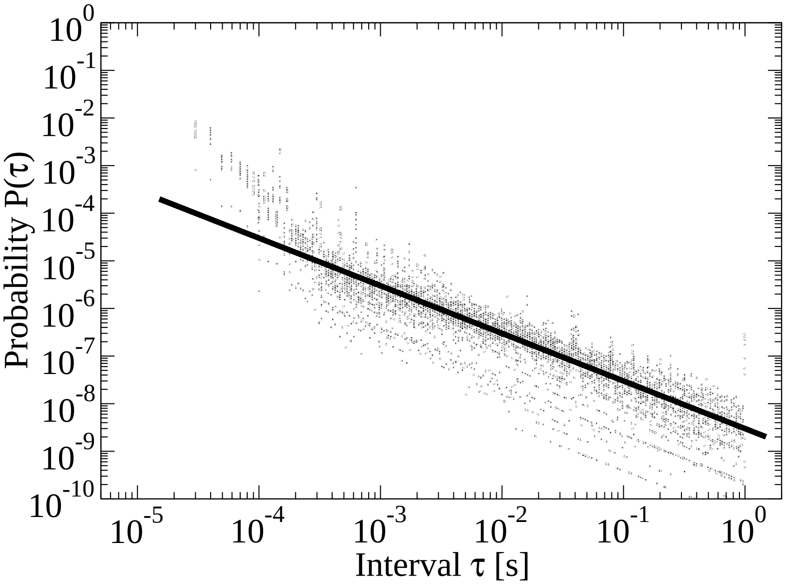

Figure 4: The distribution of time intervals τ obeys an Omori's law -like scaling $P(\tau) \sim \tau^{-1}$. The gray dots are experimental data, the thick line with slope -1 is a guide to the eye. For very short intervals ($\tau < 10^{-4}$s) the data can be skewed due to the accuracy of the experimental setup.

homogeneous materials we are unable to observe any reliable precursors of the critical crack (compare with the claims in ref. [12]). So even in ideal circumstances AE cannot be applied as predictive indicator of the web break. However, the results imply, that AE can be applied as an indirected way to measure drops in E_{mod}. Thus the technique should be of interest in comparing the microscopic damage processes in different papers and the roles of fiber and bond failure in the energy dissipation, while their relative importance can as such be analyzed with other methods than AE.

The experiments imply that the number of events decreases as the rate of elongation increases. Meanwhile, the mean amplitude of AE events remains the same. In our opinion this originates from a reduction of the size of the FPZ. As fracture becomes faster the fractureline may become less branched and fluctuate less. A concomitant decrease in microscopic damage would be expected. The behavior of the number of AE events implies that the way the energy dissipated in fracture process depends on the elongation rate.

We have also presented a brief analysis of AE energy and time-interval statistics [10]. One practical conclusion is, due to the large dynamic range of the apparatus which allows the detection of very small amplitude events, one can not discern between the two main failure processes, fiber and bond rupture, directly from the statistics, in contrast to some claims. The scaling laws indicate that in the failure of paper the viscoelastic relaxation processes do have an effect on the energy statistics, which nevertheless seem to follow rough power-law scalings. For large strain rates, ie. in the brittle limit, the energy exponent γ approaches unity which case should allow for the easiest comparison with theoretical models. On the other hand, the interval distributions show evidence of being invariant of the strain rate. Since the time between two acoustic events should only depend on the strain rate, the very fast relaxation of the stress field, and the internal processes typical of the material, we therefore conclude that the last ones determine the typical timescales.

REFERENCES

[1] C. Maes, A. Van Moffaert, H. Frederix, H. Strauven, (1998), Phys. Rev. B, 57, 4987.

[2] A. Guarino, A. Garcimartín, S. Ciliberto, (1998), Eur. Phys. Jour. B., 6, 13. A. Garcimartín, A. Guarino, L. Bellon, S. Ciliberto, (1997), Phys. Rev. Lett., 79, 3202.

[3] A. Petri, G. Paparo, A. Vespignani, A. Alippi, M. Costantini, (1994), Phys. Rev. Lett., 73, 3423.

[4] S. Zapperi, P. Ray, H.E. Stanley, A. Vespignani, (1997), Phys. Rev. Lett., 78, 1408.

[5] V.I. Räisänen, M.J. Alava, R.M. Nieminen, (1998), Phys. Rev. B, 58, 14288.

[6] S. Roux, (2000), Phys. Rev. E, 62, 6164.

[7] G. Caldarelli, F. D. Di Tolla, A. Petri, (1996), Phys. Rev. Lett., 77, 2503.

[8] M. Kloster, A. Hansen, P. C. Hemmer, (1997), Phys. Rev. E, 56, 2615.

[9] T. Yamauchi, S. Okumura, N. Noguchi, (1990), J. Pulp and Paper Science, 16, 45.

[10] A detailed analysis of the statistical aspects is reported elsewhere (L.I. Salminen et al., submitted for publication).

[11] P. Diodati, F. Marchesoni, S. Piazza, (1991), Phys. Rev. Lett., 67, 2239 .

[12] J.-C. Anifrani, C. Le Floc'h, D. Sornette, B. Souillard, (1995), J. Phys. I. France, 5, 631.