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Crackling noise and universality in fracture systems

G Niccolini[1,3], G Durin[1], A Carpinteri[2], G Lacidogna[2] and A Manuello[2]

[1] Istituto Nazionale di Ricerca Metrologica, Strada delle Cacce 91, I-10135 Torino, Italy
[2] Politecnico di Torino, Corso Duca degli Abruzzi 24, I-10129 Torino, Italy
E-mail: g.niccolini@inrim.it, g.durin@inrim.it, alberto.carpinteri@polito.it, giuseppe.lacidogna@polito.it and amedeo.manuellobertetto@polito.it

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Abstract. We have analysed the temporal properties of crackling noise arising from two fracture systems at very different scales: the sequence of Italian earthquakes for the years 1984–2002 and the AE time series from a laboratory fracture experiment on a concrete specimen. In both cases the rescaled waiting-time distributions, obtained for several threshold event sizes, exhibit scaling collapse, thus reinforcing the idea that fracture of heterogeneous materials has similar scaling properties than earthquakes. The obtained results essentially agree with recent findings for fracture phenomena in rocks at the laboratory and at the geological scale. However, the existence of a unique scaling function valid for all fracture processes, irrespective of time, length and magnitude scales, remains a problem not completely solved.

Keywords: critical exponents and amplitudes (experiment), renormalization group, fracture (experiment)

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[3] Author to whom any correspondence should be addressed.

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Contents

1. Gutenberg–Richter law and scale invariance in the timing of ruptures

The fracture of materials is a complicated phenomenon which occurs according to two broadly defined scenarios. In the first one, a homogeneous solid subjected to loading will fail in a perfectly brittle manner (without any warnings announcing the incipient failure) with the sudden propagation of a single fracture. This 'one-crack' mechanism is perfectly realized in the presence of a perfect crystalline lattice with a pre-existing crack or notch to concentrate the applied stress.

In the second scenario, which applies to heterogeneous materials such as fibre composites, rocks and concrete under loading, the structure progressively deteriorates, first in an uncorrelated way reflecting the intrinsic heterogeneities (dislocations, flaws, etc) or disorder. As the density of microcracks increases with the increasing loads, the stress fields of the microcracks interact and the microcracks become correlated. In these systems, the microcracks may coalesce to form a through-going fracture as the culmination of progressive damage. This second kind of behaviour, called quasi-brittle, is characterized by well-defined precursors including progressive decay of the Young's modulus, changes in transport, electric properties, etc, announcing an imminent failure [1]–[4].

In particular, acoustic emission (AE) due to microcrack growth precedes the macroscopic failure of rock and concrete samples under constant stress or constant strain rate loading [5, 6].

In his search for earthquake precursory phenomena, Mogi [7] emphasized the analogy between the AEs emerging from microcracks in heterogeneous materials and earthquakes despite the vastly different scales involved: they both are elastic energy released by developing cracks inside a medium. Because of this and the similarity in their statistical behaviour, AEs can be considered analogous to earthquake sequences. The temporal, spatial and size distribution of AEs follow a power law, just as it is commonly observed for earthquakes.

Traditionally, the most important of these phenomenological laws is the Gutenberg–Richter (GR) law [8, 9]. The GR law determines that, in a fixed region and during a sufficiently long period of time T, the number $N(S_{\rm th})$ of events generated by rupture areas $S \geq S_{\rm th}$ decays according to a power law as we raise the threshold value $S_{\rm th}$, $N(S_{\rm th}) \propto S_{\rm th}^{-b}$ [10]. Exploiting the relation between the magnitude M of an event and its

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source rupture area S [11], $M \propto \mathrm{Log}\, S$, the GR law can be expressed as

$$R(M_{\mathrm{th}}) = \frac{N(M_{\mathrm{th}})}{T} = R_0 10^{-bM_{\mathrm{th}}}, \tag{1}$$

where $R(M_{\mathrm{th}})$ is the mean event rate, defined as the total number of events with $M \geq M_{\mathrm{th}}$ in the fixed region divided by the considered time window T, and R_0 is the hypothetical mean rate for $M_{\mathrm{th}} = 0$ (the dependence on the selected region as well as that on T will not be explicitly indicated).

In the following we focus on two quantities to characterize each event: the time of occurrence—usually given by the initiation time—and the magnitude, disregarding the position of the hypocentre. For each M_{th} value, all the events with $M \geq M_{\mathrm{th}}$ define a point process in time where events occur at t_i with $1 \leq i \leq N(M_{\mathrm{th}})$, and therefore the time intervals between consecutive events—also referred to as waiting times or recurrence times—can be obtained as $\tau_i \equiv t_i - t_{i-1}$.

According to the approach introduced by Bak *et al* in seismicity and pursued by Corral, we consider, within a fixed space–time window, only events above a threshold magnitude M_{th} and study how the timing of events changes as a function of M_{th}. The main peculiarity of this approach to seismicity is that, after selecting an arbitrary region of the Earth, a temporal period and a detection threshold M_{th}, all the events in this space–time–magnitude window are taken into account without distinguishing among different kinds of events—foreshocks, main shocks or aftershocks—nor focusing on single fault segments [12]–[14].

Dealing with the timing of AE and earthquake occurrence, the only information provided by the GR law is the mean waiting time, $\langle \tau(M_{\mathrm{th}}) \rangle = R(M_{\mathrm{th}})^{-1}$. Obviously, the larger M_{th}, the less events there will be and the larger the mean time between them. However, since waiting times are broadly distributed (in seismicity they even range from seconds to years), the mean alone is a very poor temporal characterization of the process and it is inevitable to consider the probability density of waiting times τ, $D(\tau; M_{\mathrm{th}})$, defined as

$$D(\tau; M_{\mathrm{th}}) = \mathrm{Prob}[\tau < \text{waiting time} \leq \tau + \mathrm{d}\tau]/\mathrm{d}\tau, \tag{2}$$

where the space–time dependence of D is not explicitly indicated in this notation.

It was shown [13] that the waiting-time probability densities of earthquakes for several values of M_{th} can be described by a unique distribution if they are rescaled by their rates. In other words, measuring the waiting time in units of its mean, i.e. performing the transformation $\tau \to R(M_{\mathrm{th}})\tau$ and $D(\tau; M_{\mathrm{th}}) \to D(\tau; M_{\mathrm{th}})/R(M_{\mathrm{th}})$, all the distributions collapse onto a single curve f, illustrating the fulfilment of a scaling law:

$$D(\tau; M_{\mathrm{th}}) = R(M_{\mathrm{th}}) f(R(M_{\mathrm{th}})\, \tau), \tag{3}$$

where f is the scaling function.

Inserting explicitly equation (1), the scaling law takes the form

$$D(\tau; M_{\mathrm{th}})\, 10^{bM_{\mathrm{th}}} = \tilde{f}(10^{-bM_{\mathrm{th}}}\tau). \tag{4}$$

Now, considering events separated by waiting times τ for $M \geq M_{\mathrm{th}}$ and $\tau' \equiv 10^b \tau$ for $M \geq M'_{\mathrm{th}} \equiv M_{\mathrm{th}} + 1$, and inserting these particular arguments $(\tau'; M'_{\mathrm{th}})$ and $(\tau;\, M_{\mathrm{th}})$ into equation (4) it can be easily verified that the scaling law fulfils the following condition,

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suggesting self-similarity of the waiting-time distribution at different magnitude levels:

$$D(\tau; M_{\rm th}) = 10^b D(10^b \tau; M_{\rm th} + 1). \tag{5}$$

For instance, equation (5) relates the distribution of events in Italy for the years 1984–2002 with $M \geq 3$ separated by a waiting time $\tau = 100$ h with the distribution of events with $M \geq 4$ separated by a waiting time $\tau' = 10^b \tau = 1000$ h ($b \cong 1$ in the GR law for Italian seismicity). That relation holds no matter the value of τ, while the GR law describes only average temporal properties, saying that the number of events with $M \geq 4$ is about 1/10 of the number of events with $M \geq 3$ in the total time under consideration.

The shape of the scaling function f is the same from worldwide to local scale, for different spatial regions, time windows and magnitude ranges if the analysis is restricted to periods of stationary seismicity, i.e. periods where pronounced activity peaks are absent and the mean rate in any subperiod is indistinguishable from the mean rate of the whole period, as observed in [13].

The waiting times between AEs in time series of laboratory rock fractures were analysed in the same way [14]. Still focusing on the periods of stationary activity, a scaling function was obtained compatible with that for stationary seismicity, suggesting the existence of a universal scaling law for fracture processes independent of time, space and magnitude scales. That apparently means that the behaviour exhibited by fracture systems is independent of microscopic and macroscopic details.

Later on, taking a catalogue of Italian seismicity and the AE time series from a laboratory concrete fracture experiment, we subject the obtained waiting-time distributions to a fitting procedure which realizes the best data collapse, in order to verify the scaling law in the form of equation (4). Therefore, we explore the universality in fracture processes by verifying the existence of a unique scaling law for the presented case studies.

2. Scaling laws for waiting-time distributions of Italian seismicity

First, we illustrate this procedure examining the earthquake catalogue of Italy covering the period $T = 1984$–2002 for $M_{\rm th}$ ranging from 2.5 to 5 (9096 events with $M_{\rm th} \geq 2.5$, for which the catalogue is complete).

The waiting-time probability densities D for several values of $M_{\rm th}$ are shown in figure 1 (left), where it can be seen that τ ranges from seconds to more than 100 days. The ranges of the distributions are different: the larger $M_{\rm th}$, the larger the mean waiting time, $\langle \tau(M_{\rm th}) \rangle$.

Therefore, we rescale the distributions performing a change transformation of the axes τ and D of the form, $\tau \to R_0 10^{-aM_{\rm th}} \tau$ and $D \to R_0^{-1} 10^{cM_{\rm th}} D$, and we use a generalized gamma distribution to model the scaling function f:

$$f(\theta) \propto \theta^{-(1-\gamma)} \exp[(-\theta/x)^n], \tag{6}$$

where $\theta \equiv R_0 10^{-aM_{\rm th}} \tau$ is the rescaled waiting time.

We fit the gamma distribution to the rescaled distributions where rescaling exponents a and c are also considered as fitting parameters. The fitting procedure yields an excellent data collapse with $a = 0.95 \pm 0.03, c = 0.96 \pm 0.03, \gamma = 0.36 \pm 0.02, x = 1.44 \pm 0.58$ and $n = 1.15 \pm 0.17$ (figure 1 (right)) in good agreement with the results obtained for other

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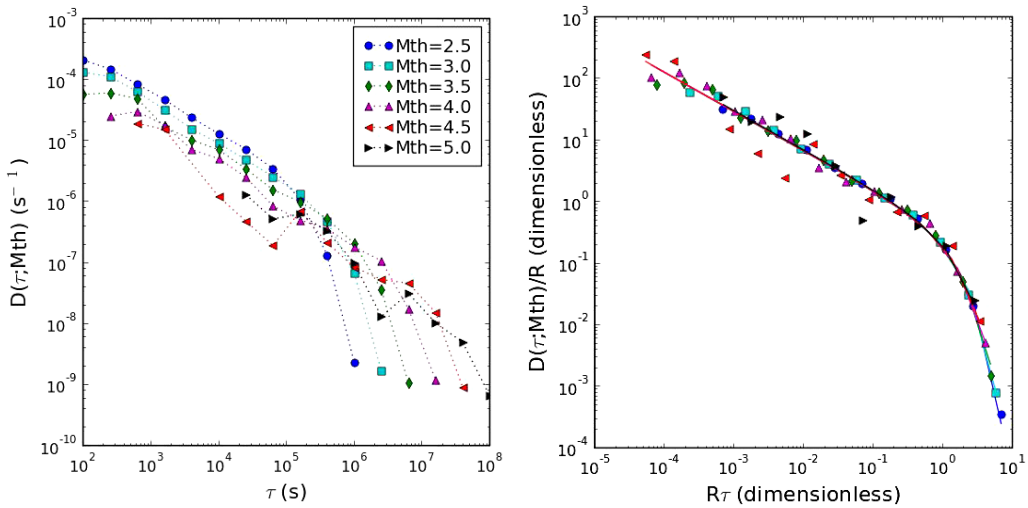

Figure 1. (Left): Probability densities of waiting times of Italian earthquakes with magnitude $\geq M_{\rm th}$ during the period 1984–2002, for $M_{\rm th}$ ranging from 2.5 to 5. (Right): The same distributions rescaled by their mean seismic rate. The data collapse is the signature of the scaling law. The fitting function is the scaling function f in equation (6).

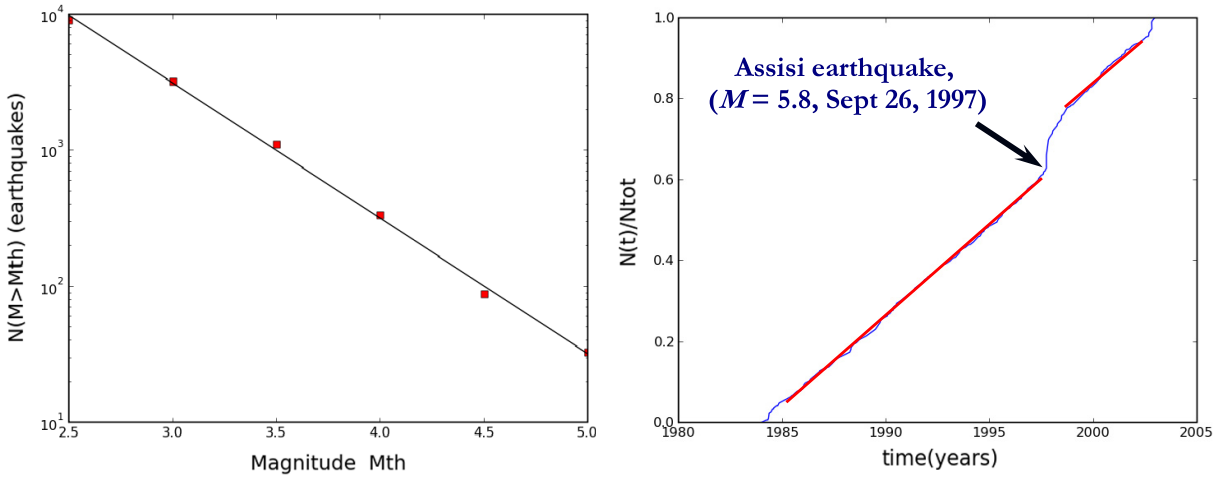

Figure 2. (Left): Diagram of the number of earthquakes in Italy for the period 1984–2002 as a function of their magnitude, displaying the GR law, with $b \cong 0.99$ given by the negative slope of the line. (Right): Accumulated number of earthquakes as a function of time; note the abrupt increment in 1997 after the Assisi earthquake.

earthquake catalogues. We remark that the obtained values for a and c are compatible with the GR b value (as plotted in figure 2 (left)), confirming the scaling law of the form of equation (4) proposed in [13].

Therefore, as displayed by the plot, we have a decreasing power law with exponent $1-\gamma \cong 0.64$ over four decades up to the largest values of the argument θ, where the behaviour changes to an exponential decay. This behaviour, indicating clustering, means

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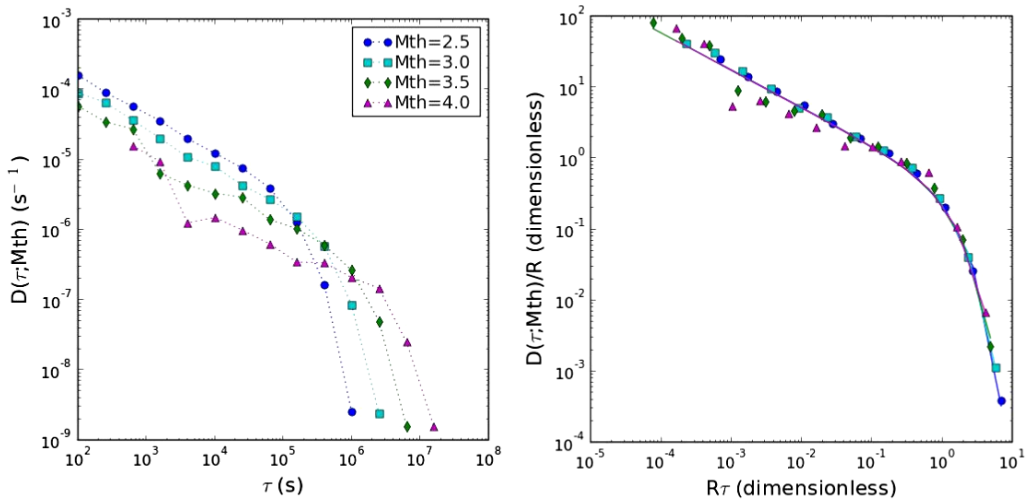

Figure 3. (Left): Probability densities of waiting times for the stationary periods explained in the text. (Right): The same probability densities after rescaling.

that there are more earthquakes separated by short waiting intervals than what correspond to a (memoryless) Poisson process with the same rate, i.e. $D(\tau; M_{\rm th}) = R\exp(-R\tau)$. In other words, the risk of occurrence is higher right after an earthquake, and then decreases for long times, which leads to the formation of clusters of events.

Now, we consider the accumulated number of earthquakes as a function of time, displayed in figure 2 (right), which exhibits a nonlinear behaviour due to episodic abrupt increments, in particular the period dominated by the aftershock sequence which followed the Assisi earthquake ($M = 5.8$, 26 Sept. 1997).

After removing such sequences, we verify the fulfilment of the universal scaling law for stationary seismicity, i.e. the existence of a universal exponent $\gamma \cong 0.7$ for all space–time windows and magnitude ranges considered under stationary conditions. The remaining nearly stationary periods, 1985.1–1997.4 and 1998.9–2002.7 marked in red in figure 2 (right), yield a power law, shown in figure 3 (right), flatter than the one for the whole period 1984–2002—indicating that the clustering degree is smaller in this case, in comparison, but it still exists—although less than expected. In this case, the fit yields $a = 0.95 \pm 0.04$, $c = 0.96 \pm 0.04$, $\gamma = 0.47 \pm 0.03$, $x = 1.39 \pm 0.64$ and $n = 1.13 \pm 0.18$, still in agreement with some recent findings (reported later on) for stationary seismicity except for the parameter value γ (we obtain a lower value). The reason for such a discrepancy is not completely understood; it may depend on difficult identification of real stationary periods and will be discussed in the final section.

3. Scaling laws for waiting-time distributions in concrete fracture

Now, we investigate if the results presented here for earthquakes are representative of somehow related processes at a much smaller scale. We analyse the waiting times between AEs emerging from a $100 \times 15 \times 15$ cm^3 fibre-reinforced concrete (FRC) beam loaded up to failure according to the three-point bending test geometry and subjected to AE monitoring [6]. The beam had a central 5 cm notch cut into it beforehand to ensure a

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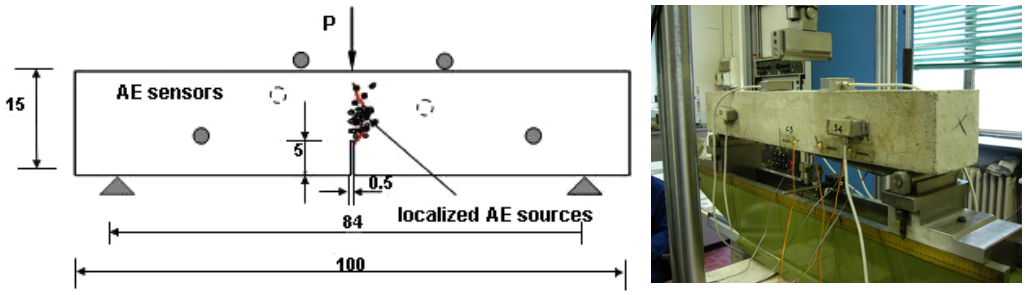

Figure 4. (Left): Three-point bending point test geometry and identification of the fracture process zone by AE source location. (Right): Test rig and instrumented beam in the structural laboratory.

centre crack (figure 4) with a fibre content of 40 kg m^{-3} for a resulting Young's modulus of 35 GPa. The test was performed in displacement control by imposing a constant displacement rate equal to 10^{-3} mm s^{-1}. In the presented case study, we used an array of USAM® transducers which exploit the capacity of piezoelectric (PZT) crystals to transform elastic vibrations into electrical signals. These sensors are of the resonant type, particularly sensitive in the range between 50 and 800 kHz. From each signal we record the arrival time, determined with an accuracy of about 0.5 μs, and the amplitude, i.e. the peak voltage of the signal itself.

Six transducers were fitted to the specimen at points shown in figure 4 (left). During the loading test, the AE source location procedure was successfully applied to identify the fracture process zone. In this way, AE clusters are seen to propagate with increasing load, following satisfactorily the growth of the central crack (see again figure 4 (left)).

We take only AE data associated with effective source locations—requiring event detection by two or more transducers—and characterize each AE event by means of the occurrence time and the amplitude V (the output is a voltage signal); therefore, even in this case hypocentre positions are disregarded. As shown in figure 5 (left), the accumulated number of AEs filtered in this way grows roughly linearly in time, without displaying the avalanche behaviour which typically precedes the imminent failure.

With the adopted transducers the indication of the amplitude changes at discrete steps: $V_i = (100 \times 2^i)$ μV, with $i = 0, 1, 2, \ldots$. For instance, if the detected signal has an amplitude included between 200 and 400 μV, the measured output indicates 200 μV. We consider the waiting-time probability densities for three threshold amplitudes $V_{\rm th}$, 200, 400 and 800 μV. Expressing the recorded signal amplitudes in the logarithmic scale, we have the GR law for AE events, $\log N(M_{\rm th}) \propto -bM_{\rm th}$, with $b = 0.58$, as shown in figure 5 (right).

The fitting procedure described above for the earthquakes yields now a satisfactory AE data collapse, shown in figure 6 with the parameter values $a = 0.60 \pm 0.11, c = 0.61 \pm 0.11, \gamma = 0.73 \pm 0.12, x = 1.45 \pm 1.26$ and $n = 1.24 \pm 0.41$—a and c are still very close to the present GR b value, confirming the scaling law of the form of equation (4)—in good agreement with recent findings for earthquakes ($\gamma \cong 0.7, x \cong 1.53$ and $n \cong 1$ in [13, 14]) and AEs ($\gamma \cong 0.8, x \cong 1.4$ and $n \cong 1$ in [15]) under stationary conditions. The quality of the collapse—not as good as that of earthquakes—is affected by the quite small amount of data (111 localized AE hypocentres).

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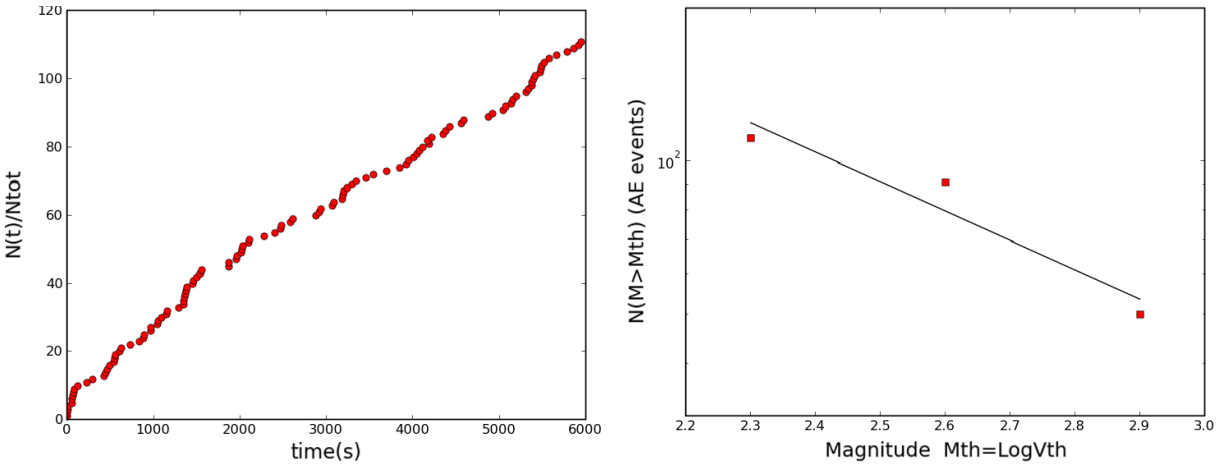

Figure 5. (Left): Accumulated number of AEs as a function of time. (Right): Number of AEs as a function of their magnitude ($M_{\rm th} = {\rm Log}V_{\rm th}$ with $V_{\rm th} = 200$, 400 and 800 μV). The line is the GR law, $\log N(M_{\rm th}) \propto -bM_{\rm th}$ with $b = 0.58$.

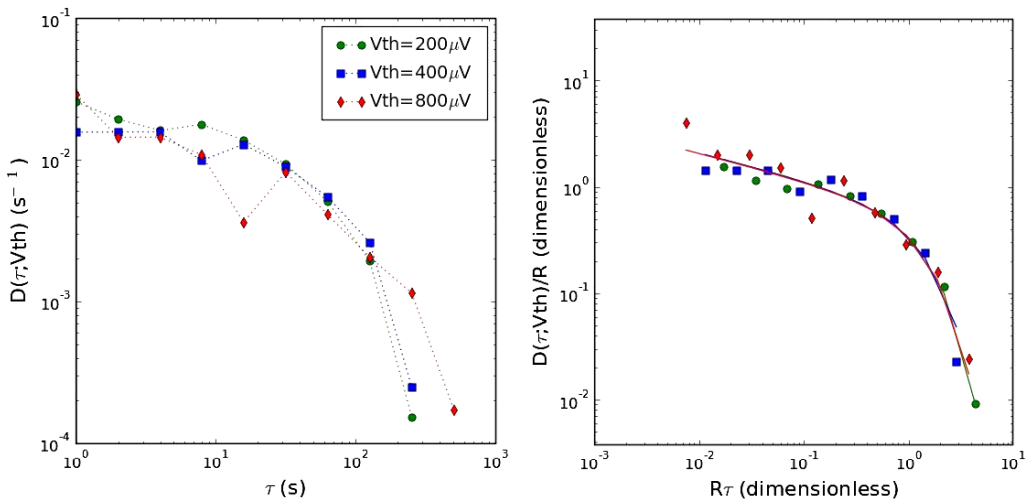

Figure 6. (Left): Probability densities of waiting times for fracture experiments on concrete. (Right): The same distributions rescaled by their mean rate. The solid line corresponds to the best fit according to equation (6).

4. Discussion

We have confirmed the existence of scaling collapse onto a single scaling function for various waiting-time distributions, implying the existence of scale invariance for waiting times over a broad range of space–time scales. By means of an integral fitting procedure, which involves also rescaling, we have verified that the GR law is included in this scaling law as well.

The uniqueness of the scaling function irrespective of time, size and magnitude scales, which would mean the existence of a universal scaling law for all fracture processes, from the laboratory to the geological scale, does not emerge in our analysis and apparently still remains an open issue.

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The large amount of studies in the field of statistical fracture show that the power-law exponents of the waiting-time distributions widely differ, ranging from 0.3 found in seismicity [13, 14] and in AE time series from laboratory rock fracture [15] up to 5.5 in similar experiments on the rock fracture [16], passing through intermediate values (1–1.3) for AE from different materials [17]–[20]. This wide range of exponent values represents a serious issue, in the light of searching for general scaling properties in fracture processes independent of material, time, space and event sizes.

A significant role in determining the exponent value is apparently played by the event rate, as emerges in some of the mentioned studies: when the rate is not stationary with an excess of very short waiting times—typically due to dominant aftershock sequences in seismicity or to foreshock sequences, which represent the damage acceleration before failure in fracture experiments—other power laws with particularly high exponent values have been observed (1 in small-sized seismic regions dominated by an aftershock sequence [20], or even 5.5 at the final stage of a rock fracture experiment [16]).

On the basis of the Corral rescaling method, a universal power-law exponent $1-\gamma = 0.3$ can be established focusing on periods in which the rate remains stationary, or with filtering of the data which selects a stationary sequence as done in our analysis. The universal exponent 0.3 for stationary seismicity is still found in the critical cases in which a stationary period may not exist, by replacing the mean seismic rate by the instantaneous seismic rate as the scaling factor in equation (3) [13].

Therefore, rescaling of the waiting times with the instantaneous event rate instead of the mean rate, in order to transform a sequence with a time-variable rate into a stationary sequence, could be the key to obtaining a robust, universal power-law exponent of general validity for the fracture of heterogeneous materials (including the study on Italian seismicity in the present work and the previous ones [17]–[20] whose results are in contradiction with the Corral scaling law).

A consistent fraction of the distributions present in the literature are pure power laws [17]–[20], without evidence of a cutoff. On the other hand, many authors find decreasing power-law distributions accelerated by an exponential term (cutoff) at long waiting times [13]–[15], [21, 22]. Such a discrepancy represents another serious issue as regards universal scaling in the field of statistical fracture.

Deviation at long waiting times from the power-law behaviour in seismicity was considered to be due to a regime of uncorrelated events, such as main shocks occurring in large regions including different tectonic environments. It was believed that for such large regions the occurrence of main shocks was totally random, i.e. with an exponential (Poisson) probability density function of the waiting times [23]. However, as already remarked, this viewpoint—separation of earthquakes into different processes, main shocks and aftershocks, following different statistical distributions—has been recently overcome by the Bak *et al* and Corral approaches. In particular, the latter [13, 14] showed that removal of earthquakes smaller than $M_{\mathrm{th}} = 6.5$ from worldwide seismicity does not lead to a Poisson, memoryless sequence, since the obtained waiting-time distribution still exhibits a decreasing power-law behaviour followed by a faster exponential decay for long times. Worth noting is [13], where the gamma distribution, combining both behaviours, comes from a (nonhomogeneous) Poisson process with a time-variable rate, but whose derivation is limited to Omori aftershock sequences.

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Also stochastic fracture models recently developed to support fatigue experiments have shown that the waiting times are power-law-distributed with an exponential cutoff, $\exp(-R\tau)$, depending on the constant external stress σ_0, $R \propto \sigma_0^{1+\gamma}$, where $\gamma > 0$ controls the rate of damage accumulation: the higher the parameter γ, the later damage develops [22, 24]. In general, γ is found to depend on both the material [22] and the load history—for instance, the damage develops much later when the external stress increases linearly with time than when it is instantaneously applied [24]—making the evidence of cutoff, controlled by R, dependent on experiments. That is confirmed by recent tensile experiments at a constant strain rate [25], in which the failure does not occur suddenly and γ is expected to be low. Thus, the observed power-law distributions without evidence of cutoff may be explained in terms of suitably small values of R, due to its dependence on γ, and then of $R\tau$.

To summarize, universal features in the timing of fracture processes should be emphasized considering rescaled times, preferably by means of the instantaneous rate. Indeed, evidence of cutoff is a less general feature, since it apparently depends on experimental conditions.

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