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Acoustic emission of the Syracuse Athena temple: timescale invariance from microcracking to earthquakes

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Abstract. We show the results of acoustic-emission (AE) monitoring of the Cathedral of Syracuse in Sicily (Southern Italy), built around the surviving elements of a Doric temple dedicated to Athena from the 5th century BC.

We wired up a single pillar of the 2500-year-old cathedral for four months and then compared the AE data with earthquake records, observing a time correlation between the AE bursts and the sequence of nearby earthquakes and a similar scaling for the related magnitude distributions.

We found that the distribution of times between events—whether earthquakes or acoustic emissions—fell onto the same curve, over a wide range of timescales and energies, when scaled appropriately.

A similar 'universal scaling law' has been shown for collections of earthquakes of a range of sizes in different regions, so the new results appear to extend the law to the much smaller energy scales of a single pillar. These pieces of evidence suggest a correlation between the aging process and the local seismic activity, and that more careful monitoring of the cathedral is warranted.

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

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Contents

1. Acoustic-emission monitoring of Syracuse Cathedral and regional seismicity

Fracture of materials occurs as the culmination of progressive damage due to loading conditions or harsh environments. The growth of tiny cracks inside materials such as stone or concrete is accompanied by the spontaneous release of stored strain energy in the form of high-frequency vibrations (acoustic emission or AE) [1]–[3].

AE monitoring is used for the integrity assessment of materials and also large-sized structures [3, 4]. This predictive power can be exploited to protect cultural heritage exposed to seismic risk. Many structures may undergo accelerated aging and deterioration due to the action of small and intermediate earthquakes. In the seventh century the Cathedral of Syracuse (on the UNESCO World Heritage List since 2005) was built around the surviving elements of the Athena temple, and afterwards repeatedly modified as a consequence of damage caused by earthquakes. The structure currently exhibits an extended damage pattern, especially in four pillars at the end of the nave, showing repaired areas, replacements, and also several cracks. The AE activity in one of the nave pillars was monitored over a four-month period by means of six piezoelectric transducers working in the range of 50–500 kHz attached to the pillar surface.

After setting an appropriate detection threshold to filter out environmental background noise, we started data acquisition storing of two quantities for each AE signal: the arrival time, determined using the first threshold crossing of the signal, and the peak amplitude $V_{\max}$ (expressed in μV), which defines the magnitude of the AE event as $M = \mathrm{Log}(V_{\max}/1\ \mu\mathrm{V})$ [3].

Figure 1 displays the accumulated number of AE events, the AE instantaneous rate (averaged over 1 h) and the earthquake sequence as functions of time. Here, only earthquakes with hypocentral distance $\leq$60 km from Syracuse are considered (see figure 2 and [5]). There appears to be a correlation in time between AE activity on the Cathedral and local seismicity, as AE bursts often follow the occurrence of nearby seismic events.

There appear to be some seismic events which follow AE bursts and, then, which do not trigger AE activity on the Cathedral. The occurrence of increased AE activity was observed in some case histories from Italy before large earthquakes [4, 6]. In these cases, AE bursts apparently indicate crustal stress crises affecting areas of a few hundred kilometres radius during the preparation of a seismic event. In spite of intrinsic difficulties in high-frequency propagation through disjointed media (in particular
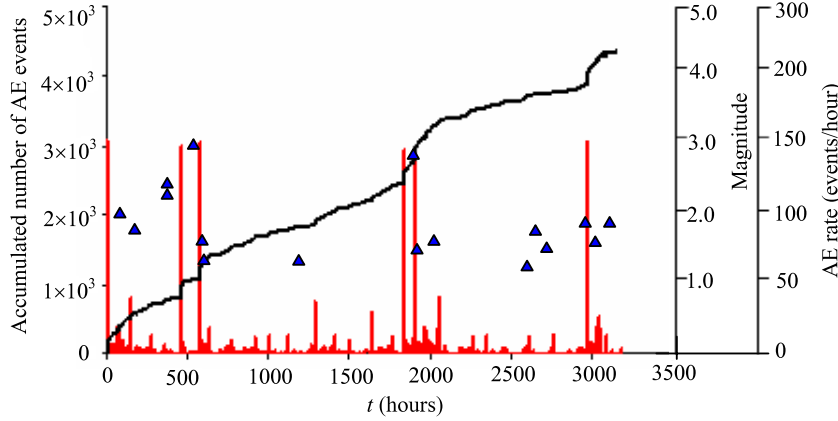
Figure 1. Accumulated number (black line), instantaneous AE rate averaged over 1 h (red line) in the temple pillar, and nearby earthquake occurrence (triangles) as functions of time.
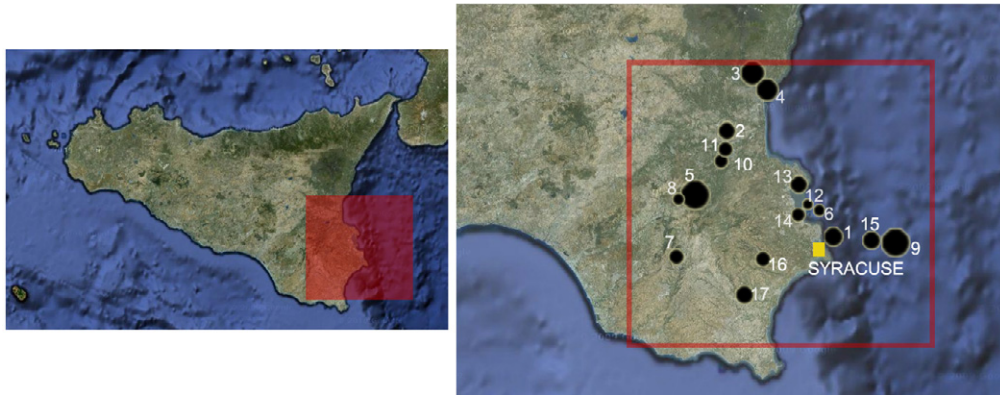

Figure 2. Map of Sicily showing location of the monitored site (yellow square) and epicentres (black circles) of nearby earthquakes (listed in [5]) occurring during the monitoring period.

at the ground/building foundation interface), part of the AE activity from the structures might derive from precursive microseismic activity. A rigorous investigation of causal relationships between AE bursts and earthquakes would require simultaneous operation of suitable arrays of AE monitoring sites, adequately placed in the territory, e.g. in the order of $\sim$1000 over a large regional area.

Several studies established that the total rate of damage, as measured for instance by the accumulated AE released energy, increases as a power law of the time to failure on the approach to the structural collapse [7, 8]. Here, while the data show evidence of the existence of a damage process, with two episodic abrupt increments in the accumulated number of AE events in time after $\sim$1800 and 2900 h (see again figure 1), there is no evidence of an accelerating damage rate, and thus no indication of imminent failure on the timescale of a year or so.

Because of large statistical fluctuations which affect the damage process, more precise conjectures about the criticality of the damage process, i.e. the distance from a critical
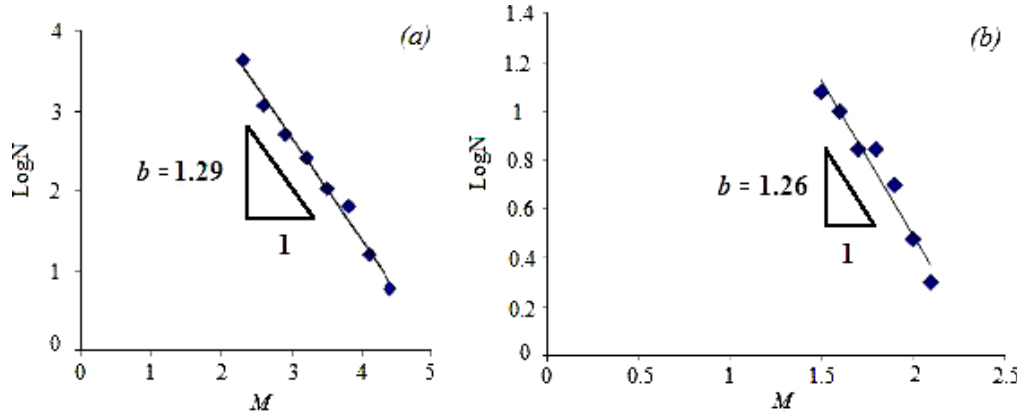
Figure 3. GR distribution of magnitudes for AE events in the pillar (a) and nearby seismicity (b). The magnitude of AE events is defined by the relation $M = \text{Log}(V/1 \ \mu\text{V})$ where V is the peak amplitude (expressed in volt) of AE signals, while M means the Richter magnitude for earthquakes.

acceleration towards failure, would require AE monitoring over periods longer than 4 months (which represents $\sim$1/7500 of the total lifetime of the structure).

Damage assessment in the pillar is performed considering the statistical distribution of the AE signal magnitudes fitted by the Gutenberg–Richter (GR) law [9]:

$$\text{Log } N \ (\geq M) = a - bM, \tag{1}$$

where N is the number of AE events with magnitude greater than M, and a and b (or b-value) are fitting parameters. The b-value is an important parameter for damage assessment of structures as it decreases during damage evolution, reaching final values close to 1.0 when the failure is imminent [3]. The computed b-value, $b = 1.29$, is in accordance with the bad state of preservation of the pillar. The b-value analysis is repeated with the series of nearby earthquakes. The results, plotted in figure 3, show a remarkable similarity between the AE ($b = 1.29$) and seismic ($b = 1.26$) b-values.

2. Scaling and correlation of acoustic-emission and earthquake waiting-time distributions

Space-time organization of AE and the earthquake source process is ruled by different power laws, among them, the above-mentioned GR law for the magnitude distribution, the Omori law for the rate of aftershocks as a function of time from the main shock [10], and the fractal distribution law for the epicentres [11]. However, power laws and critical exponents are not the only scaling predictions for fracture processes.

Starting from the pioneering work of Bak *et al* [12], Corral found that the distributions of waiting times between consecutive earthquakes follow a universal scaling law in different regions of the world and earthquake catalogues if appropriately rescaled [13]. There has been an ongoing debate in the seismological community about the extent to which universal scaling of earthquake temporal occurrence applies to AE time series in laboratory fracture [14]–[18]. This suggests that timing of fractures might be self-similar over a larger range of magnitude than had been suggested earlier.

Here, the rescaling and collapsing procedure for waiting-time distributions in a sequence of rupture events is illustrated. We select the $N(M_{\text{th}})$ events with magnitude M above a certain threshold M_{th}. The sequence is transformed into a point process where events occur at times t_i with $1 \leq i \leq N(M_{\text{th}}) \equiv N$ and, therefore, the waiting time between consecutive events can be obtained as $\tau_i \equiv t_i - t_{i-1}$. Thus, we compute the waiting-time probability density function (PDF) as $p_{M_{\text{th}}}(\tau) \equiv \text{Prob}(\tau \leq$ waiting time $< \tau + \text{d}\tau)/\text{d}\tau$. Measuring the time in units of the mean waiting time $\langle\tau\rangle_{M_{\text{th}}} \equiv (t_N - t_1)/(N-1)$, i.e. performing the transformation $\tau \to \tau/\langle\tau\rangle_{M_{\text{th}}}$, also changes the units of the PDF, $p_{M_{\text{th}}}(\tau) \to \langle\tau\rangle_{M_{\text{th}}} p_{M_{\text{th}}}(\tau)$. This rescaling procedure is applied to PDFs obtained for several values of M_{th}. If all the rescaled PDFs collapse onto a single curve f, we can establish the fulfilment of a scaling law [13]:

$$p_{M_{\text{th}}}(\tau) = f(\tau/\langle\tau\rangle_{M_{\text{th}}})/\langle\tau\rangle_{M_{\text{th}}}. \tag{2}$$

The scaling function f is well approximated by a generalized gamma distribution, which is a common parameterization for all fracture systems from microscopic scale (AEs) to seismic scale (earthquakes) [13]–[16]:

$$f(\theta) \propto \theta^{-(1-\gamma)} \exp[(-\theta/x)^n], \tag{3}$$

where θ is the rescaled waiting time, $\theta \equiv \tau/\langle\tau\rangle_{M_{\text{th}}}$.

Although the parameterization of equation (3) is valid for all fracture processes, from AE in laboratory experiments to earthquakes, the values of fitting parameters γ, x, and n generally depend on the window of observation [12]. In particular, the power-law exponent $1 - \gamma$ indicates the clustering degree in times of events. For example, when aftershock sequences or earthquake swarms dominate the selected time window T, the power-law exponent is high ($1 - \gamma = 1.5$ [18] against 0.3 for stationary activity or slowly varying event rates [13]–[16]), indicating that earthquakes are close in time.

Previously, Kagan [18]–[20] in a different approach pointed out that the number of short waiting times between large earthquakes exceeds the number expected for memoryless Poisson recurrence. This behaviour, indicating clustering, is the opposite of the regularity or quasi-periodicity derived from the idea of the seismic cycle. A surprising consequence of clustering is the paradoxical result that the longer it has been since the last earthquake, the longer the expected time until the next [13, 19, 20].

Here, we use the scaling approach to study the AE events from the pillar and the Eastern Sicily earthquakes. The PDFs of rescaled waiting times are calculated for both time series, and appear in figure 4. The good quality of data collapse demonstrates that a common scaling law describes both AE and earthquake time recurrence (the fit yields $\gamma = 0.35 \pm 0.02$, $x = 1.15 \pm 0.42$, $n = 0.53 \pm 0.04$). This finding indicates the existence of a nontrivial correlation between small scale AE activity in the temple pillar and nearby earthquake activity [5].

3. Discussion

An apparent correlation in time between AE bursts and the occurrence of a nearby earthquake is found. Therefore, the structure of the temple might be particularly sensitive to the action of nearby earthquakes. The demonstration that a common scaling law describes temporal recurrence of AE and earthquake activities supports the conjecture
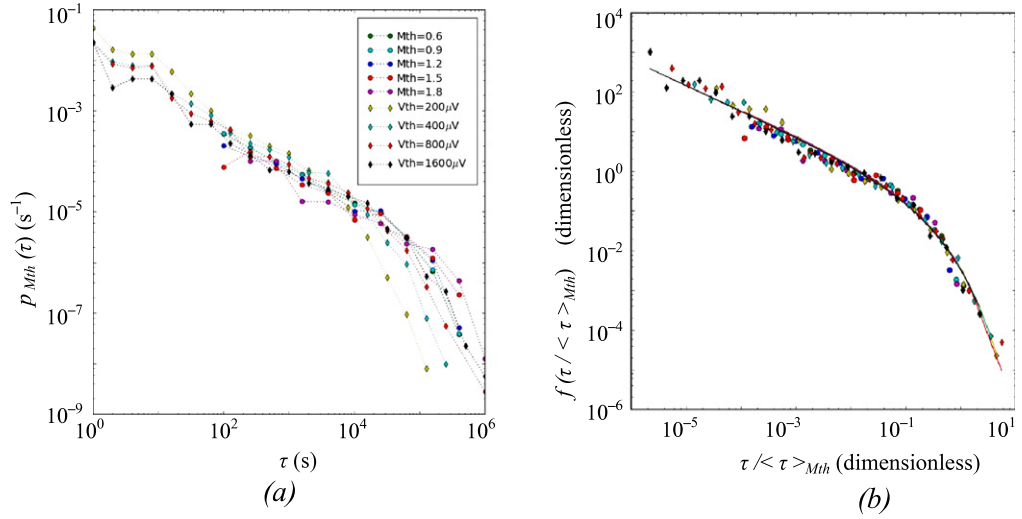
Figure 4. Waiting-time PDFs for five seismic magnitude thresholds M_{th} and four AE signal thresholds V_{th} (a), and their collapse onto a single curve illustrating the fulfilment of a common scaling law (b), where the fitting line is the scaling function of equation (3).

that both respond to critical values of stress in the same manner. The presented study suggests that the AE structural monitoring coupled with the analysis of local earthquake activity can be a tool of crucial importance in earthquake damage mitigation. The similarity between microfractures and seismicity could even have implications for understanding the triggering mechanism of earthquakes of all types by other earthquakes.

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