Nat. Hazards Earth Syst. Sci., 17, 1025–1032, 2017
https://doi.org/10.5194/nhess-17-1025-2017
© Author(s) 2017. This work is distributed under
the Creative Commons Attribution 3.0 License.

Natural Hazards and Earth System Sciences
Open Access
EGU

Signal frequency distribution and natural-time analyses from acoustic emission monitoring of an arched structure in the Castle of Racconigi

Gianni Niccolini[1], **Amedeo Manuello**[1], **Elena Marchis**[2], **and Alberto Carpinteri**[1]

[1]Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[2]Department of Architecture and Design, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin, Italy

Correspondence to: Gianni Niccolini (gianni.niccolini@polito.it)

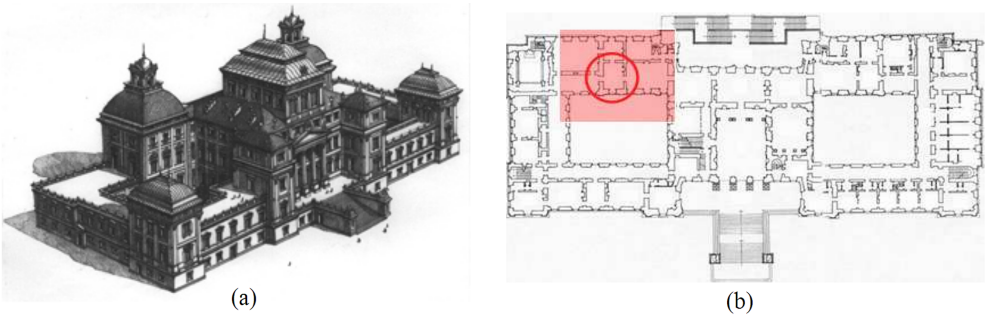
Received: 18 November 2016 – Discussion started: 18 January 2017
Revised: 12 April 2017 – Accepted: 1 May 2017 – Published: 4 July 2017

Abstract. The stability of an arch as a structural element in the thermal bath of King Charles Albert (Carlo Alberto) in the Royal Castle of Racconigi (on the UNESCO World Heritage List since 1997) was assessed by the acoustic emission (AE) monitoring technique with application of classical inversion methods to recorded AE data. First, damage source location by means of triangulation techniques and signal frequency analysis were carried out. Then, the recently introduced method of natural-time analysis was preliminarily applied to the AE time series in order to reveal a possible entrance point to a critical state of the monitored structural element. Finally, possible influence of the local seismic and microseismic activity on the stability of the monitored structure was investigated. The criterion for selecting relevant earthquakes was based on the estimation of the size of earthquake preparation zones. The presented results suggest the use of the AE technique as a tool for detecting both ongoing structural damage processes and microseismic activity during preparation stages of seismic events.

1 Introduction

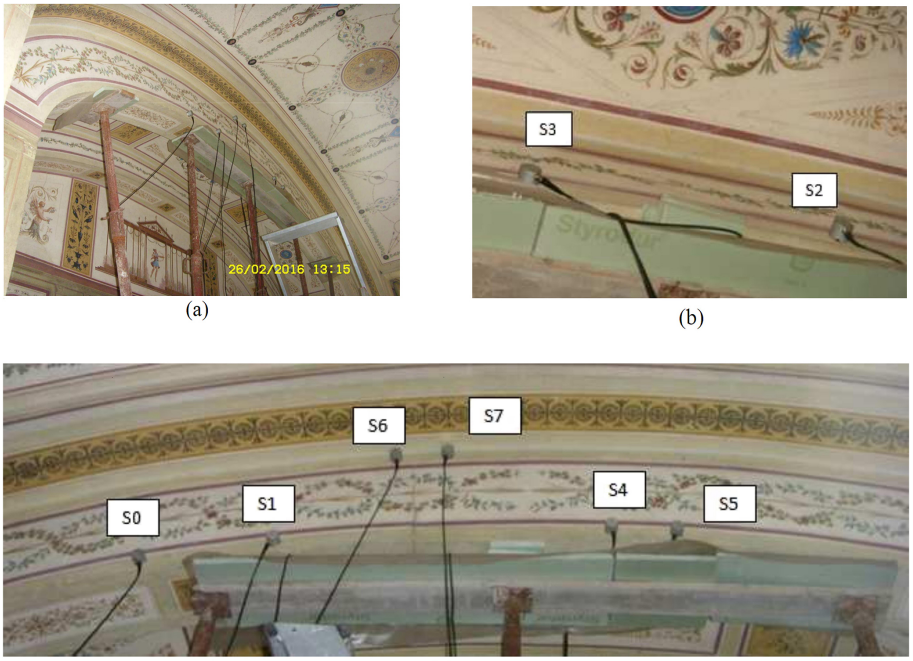
Fracture in heterogeneous materials is a complex phenomenon which involves a wide range of time, space and magnitude scales, from microcracking to earthquake ruptures, including structural failures (Omori, 1894; Richter, 1958; Kanamori and Anderson, 1975; Aki, 1981). Thus, acoustic emission (AE) monitoring during loading experiments gives insight into the evolution of microcrack networks in laboratory experiments and is possibly a tool for understanding the occurrence of fractures at larger scales (Mogi, 1962). Over the last decades, this approach has provided the opportunity to develop universal scaling laws reflecting the scale invariance and the self-similarity of fracture processes from the laboratory to the fault scale in time, space and magnitude domains (Turcotte, 1997; Bonnet et al. 2001; Bak et al., 2002; Tosi et al., 2004; Corral, 2006; Davidsen et al., 2007; Kun et al., 2008). These studies should hopefully contribute to solving the main problems of earthquake prediction and the remaining life assessment of structural elements. In particular, the latter is a crucial issue for researchers involved in restoration projects of historic monuments with damaged and cracked structural elements, which can benefit from the use of nondestructive monitoring techniques for the structural integrity assessment (Carpinteri et al., 2011; Schiavi et al., 2011; Lacidogna et al., 2015a). AE monitoring seems to be suitable for this kind of structural monitoring as it provides information on the internal state of a material without altering state of conservation of statues, monuments and fine artworks.

A relevant case study is here illustrated by the Castle of Racconigi (origin dating back to the 13th century), whose original structure of a medieval fortress was transformed over the centuries into a royal residence, becoming the southernmost of the Savoy Residences and one of the most important monuments in northwestern Italy. The moment of increased activity and restoration occurred between 1831 and 1848 dur-



(a) (b)

Figure 1. Axonometric view of the castle in the contemporary configuration **(a)**; plan of the first floor: localization of the monitored bearing structure inside the thermal bath **(b)**.



(a) (b) (c)

Figure 2. The monitored arch **(a)** and the transducers positions **(b, c)**.

ing the reign of Charles Albert (Carlo Alberto), who commissioned the extension of this residence to Ernesto Melano (1784–1867) and its decoration to Pelagio Pelagi (1775–1860).

The castle, with its bearing walls decorated by frescoes, represents an extraordinary benchmark for the definition of conservation methods exploiting new technologies (Lacidogna et al., 2011; Niccolini et al., 2014). This paper presents the results of AE monitoring of an arch in the thermal bath of King Charles Albert, located in the ground floor of the Castle of Racconigi, as a part of the complex planned by Pelagi in the Roman style and inspired by the "balnea" of the Pompeian villas. The wing of the castle containing this room is currently being restored.

Besides the disruptive power of strong earthquakes, Italian historic buildings and monuments suffer from the action of small and intermediate earthquakes, whose effects, though not immediately or clearly visibly, eventually result in increased vulnerability to stronger earthquakes with catastrophic human and economic costs. In this framework, over the recent years there has been an increasing interest in AE monitoring related to environmental phenomena. Several case histories in the Italian territory and previous studies support the hypothesis that increased AE activity may be a signature of crustal stresses redistribution in a large zone during the preparation of a seismic event (Gregori and Paparo, 2004; Gregori et al., 2005; Carpinteri et al., 2007; Niccolini et al., 2011). According to previous research studies performed by Dobrovolsky et al. (1979), it can be assumed that the preparation zone is a circle with its center at the epicenter of the impending earthquake. The radius r of the circle, called the "strain radius", is given by the relationship $r = 10^{0.433M+0.6}$,

where M is the earthquake magnitude and r is expressed in kilometers. All the seismic precursors, including AE, are expected to fall within this circle.

2 Experimental results

Damage assessment in an arch of the castle's thermal bath (Fig. 1) has been carried out using the AE technique, as a first step to plan possible restoration interventions. Among all structural elements, arches and vaults made of stone or brick, be they bearing or not, are the most prone to degradation and stress caused by seismic events, changes in acting loads and foundation sinking, which cause the structure to lose its original mechanical properties. Because these elements are of great historic and architectural value, they need to be consolidated in a noninvasive, compatible and consistent way with regard to their special features. The examined architectural element, currently supported by a steel frame structure, is a masonry arch with a span of 4 meters exhibiting a relevant crack pattern. The propagation of one visible macrocrack has been investigated by an array of eight broadband piezoelectric transducers (working in the range 10 kHz–1 MHz) fixed on the arch surface as shown in Fig. 2. The AE transducers have been connected to a eight-channel acquisition system, AEmission®, which implements algorithms for automatic analysis of AE signal parameters, i.e., arrival time (determined with an accuracy of 0.2 µs), duration, amplitude and count number (total number of signal threshold crossings). The stored AE parameters can be wirelessly transmitted to a receiver, allowing long-distance remote and real-time monitoring.

Before starting the monitoring, the background noise was checked for a representative period of time, i.e. 24 h, in order to determine the level of spurious signals. Thus, after identifying a signal detection threshold of 1.5 mV, a 1-month monitoring period started. In order to suppress possible voltage spikes, acquired AE signals with duration < 3 µs and count number < 3 were filtered out. Spatial identification of the arch's damaged zones was performed by applying triangulation equations to the received AE signals in order to localize the AE sources as active and propagating crack tips (Shah and Li, 1994; Shiotani et al., 1994; Grosse et al., 1997; Guarino et al., 1998; Ohtsu et al., 1998; Colombo et al. 2003; Turcotte et al., 2003; Aggelis et al., 2013).

The 3-D diagrams shown in Fig. 3 suggest that the arch experiences damage on one side, despite the use of reinforcing elements. Since all possible noisy signals in the frequency and amplitude range of measurement have been minimized, the burst of AE activity, marked by a vertical dashed line in the top diagram of Fig. 4, can be reasonably correlated with a sudden increase in damage accumulation.

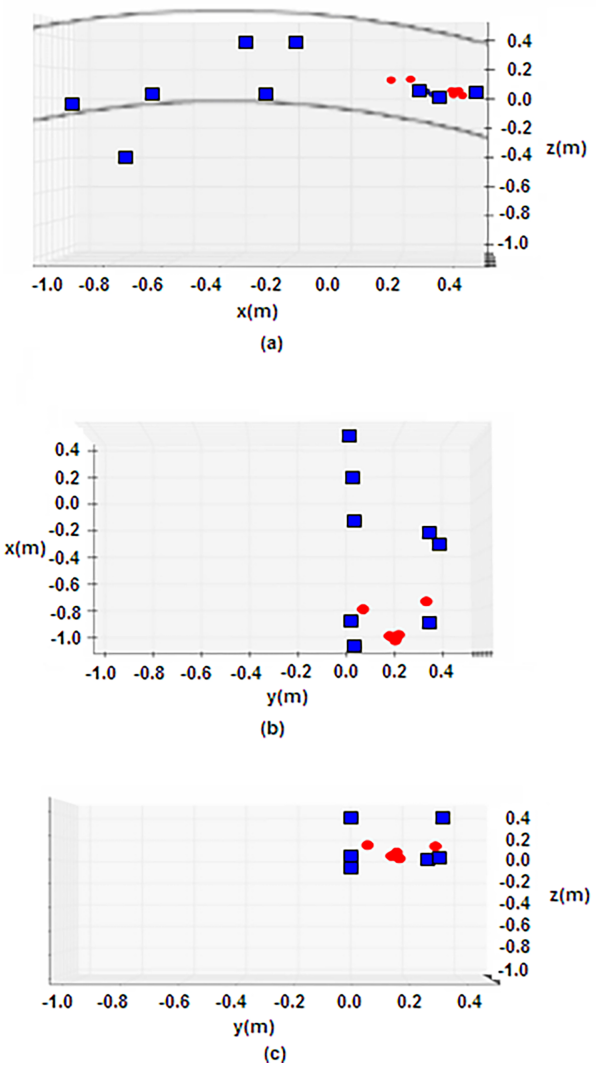


Figure 3. 3-D map showing the positions of transducers (blue squares) and localized AE sources (red dots): front **(a)**, upper **(b)** and side view **(c)**.

3 Frequency and natural-time analysis of AE time series and correlation with nearby seismicity

In the frame of critical phenomena (Bak and Tang, 1989; Stanley, 1999), the fracture process is viewed as a critical state of a dynamical system, and the problem of early detection of fracture precursors in structural elements long before the final collapse is transformed in the investigation of indicators revealing the entrance to a "critical state".

Recently, a noteworthy approach to identifying when a complex system enters a critical state has been developed, based on the time-series analysis of N events read in a new time domain, termed natural time χ (Varotsos et al., 2001, 2011a, b, 2013), where the time stamping is ignored and only the natural time, $\chi_k = k/N$, as a normalized order of occurrence of the kth event, and the energy Q_k

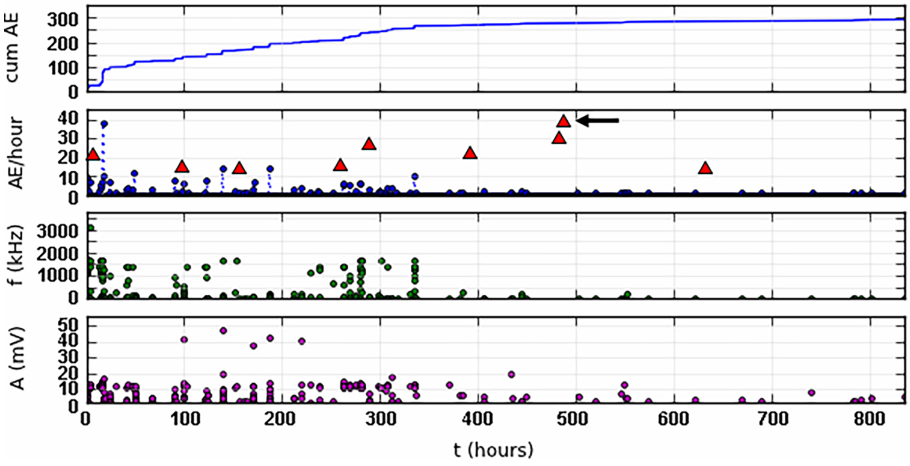


Figure 4. From top to bottom: accumulated number of AE signals ("hits"): the dashed line indicates a critical point revealed by the natural-time analysis; AE count rate and sequence of nearby earthquakes marked by red triangles (the arrow points to the strongest one); time series of signal frequencies and amplitudes.

are preserved. In natural-time analysis the evolution of the pair $(\chi_k,\ Q_k)$ is considered, by introducing the normalized power spectrum $\prod(\omega) \equiv |\Phi(\omega)|^2$, defined by $\Phi(\omega) = \Sigma_{i=1}^{N} p_k \exp(i\omega k)$, where ω stands for the angular natural frequency and $p_k = Q_k/\Sigma_{i=1}^{N} Q_i$ is the normalized energy of the kth event. It was found that all the moments of the distribution of the p_k can be estimated from the Taylor expansion $\prod(\omega) = 1 - \kappa_1\omega^2 + \kappa_2\omega^4 + \ldots$, where the values of the coefficient κ_1, which is just the variance of natural time χ, i.e., $\kappa_1 = \Sigma_{k=1}^{N} p_k\chi_k^2 - (\Sigma_{k=1}^{N} p_k\chi_k)^2 \equiv < \chi^2 > - < \chi >^2$, are useful in identifying the approach of a dynamical system to a critical state. The variance κ_1 varies when a new AE event ("hit") occurs, as $(\chi_k,\ p_k)$ are rescaled as natural-time χ_k changes from k/N to $k/(N+1)$ and p_k changes to $Q_k/\Sigma_{i=1}^{N} + 1Q_i$. Thus, the evolution hit by hit of κ_1 is shown along with that of the entropy S, which in the natural-time domain is defined as $S = < \chi \ln \chi > - < \chi > \ln < \chi >$, where $< \chi \ln \chi > = \Sigma_{k=1}^{N} p_k\chi_k \ln \chi_k$.

It has been successfully shown for a variety of dynamical systems that entering the critical state occurs when the variance κ_1 converges to 0.07 (Varotsos et al., 2001, 2011a, b), even if a theoretical derivation of the general validity of the $\kappa_1 = 0.07$ condition for criticality still remains an open issue. Two criteria have been defined to identify the entrance of a system to a true critical state (Varotsos et al., 2008): (1) the parameter κ_1 must approach the value 0.07 "by descending from above", and (2) the entropy S must be lower than the entropy of uniform noise, $S_u = 0.0966$, when κ_1 converges to 0.07.

Here, the damage evolution of a structural element is investigated by analyzing the AE time series using two different methods and comparing the results. First, the evolution of variance κ_1 and entropy S of the natural-time transformed time series $\{\chi_k\}$ is studied, where the energy Q_k associated with the AE event amplitude A_k is given by $Q_k = A_k^{1.5}$, similarly to seismology (Kanamori and Anderson, 1975; Turcotte, 1997). The second method used is the analysis of evolving AE signal frequencies over the monitoring time (Gregori and Paparo, 2004; Gregori et al., 2005; Schiavi et al., 2011).

First, the evolution of natural-time variance κ_1 and entropy S as functions of the accumulated number N of hits, i.e., as they change with the addition of every new hit, is plotted in Fig. 5. Thus, it is possible to easily reveal the possible entrance point to a critical state, corresponding to the fulfillment of criticality conditions (1) and (2) (Vallianatos et al., 2013; Hloupis et al., 2015, 2016). It is worth noting that the criticality initiation point (marked with a vertical line at the $N = 104$ hit number in Fig. 5) corresponds exactly to the abrupt jump in the AE rate highlighted in Fig. 4 and amounts to about 100 hits. This result, though obtained from a relatively small data sample, apparently confirms the potential of the AE natural-time analysis to reveal the onset of criticality in fracture systems.

Second, the AE signal frequency analysis has been correlated with the nearby seismicity within a radius of 100 km from the monitoring site (see Fig. 4 with the earthquake time series marked by red triangles). In particular, it has been found that AE activity vanishes at the end of a seismic sequence culminating in a magnitude 3.0 earthquake (pointed to by the black arrow), suggesting that part of the detected AE activity might be rather due to diffused microseismic activity falling in the preparation zone of the considered earthquake (strain radius > epicentral distance from the monitoring site) according to the criterion proposed by Dobrovolsky et al. (1979) (see Table 1 and Fig. 6).

As cracking is a multi-scale phenomenon in the Earth's crust, the frequencies of AE waves related to microseis-

Table 1. List of nearby earthquakes that occurred during the AE monitoring; the event with the preparation zone encircling the monitoring site is written in bold.

Time origin (UTC)	Time delta (h)	Lat (°)	Long (°)	Depth (km)	Dist. (km)	Magnitude	Radius (km)
10 December 2015 16:31:56.990	−22.46	44.561	7.161	11.2	46.8	1.9	26.5
15 December 2015 11:21:44.070	102.73	45.087	7.163	7.9	53.6	1.3	14.5
18 December 2015 05:36:07.740	158.6	44.549	6.775	5.6	75.3	1.2	13.2
22 December 2015 07:10:41.190	259.68	44.93	6.874	10.4	65.7	1.3	14.5
23 December 2015 13:45:30.560	286.75	44.651	6.84	6.8	67.3	2.2	35.7
28 December 2015 01:11:29.380	394.18	44.45	7.289	11.8	46.8	1.9	26.5
31 December 2015 19:16:48.900	484.26	44.548	6.756	9.1	76.8	2.4	43.6
31 December 2015 20:42:01.000	**485.7**	**44.765**	**6.76**	**9.4**	**71**	**3.0**	**79.2**
7 January 2016 05:41:23.000	638.68	45.07	6.57	10	93.2	1.3	14. 5

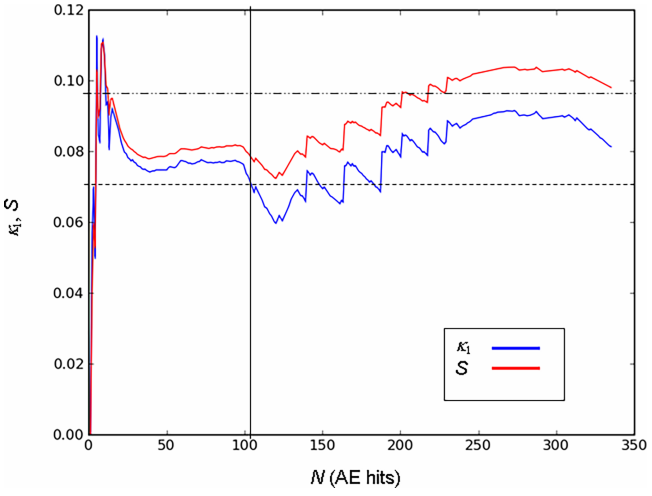


Figure 5. Evolution of natural-time quantities κ_1 (blue line) and S (red line) as functions of accumulated AE hit number N. The horizontal dashed line indicates the value $\kappa_1 = 00.07$, while the vertical line indicates the corresponding criticality initiation hit ($N = 104$). The upper dash-dot line indicates the entropy limit $S_u = 0.0966$.

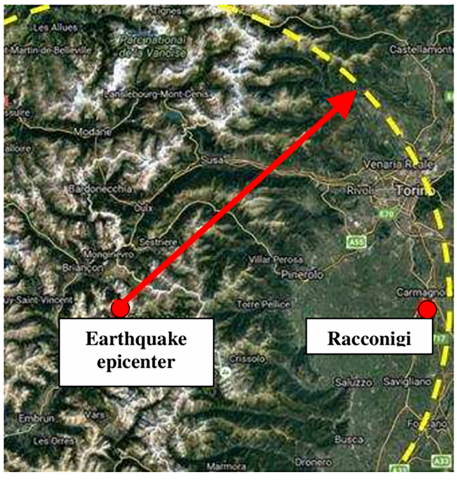


Figure 6. Map showing the epicenter of the magnitude 3 earthquake that occurred on 31 December 2015 and the related preparation zone encircling the monitoring site in Racconigi.

mic activity are spread over a broad spectrum. At the earlier stages of the preparation of a seismic event, mainly microcracks, and therefore high-frequency AE (MHz), will be present and active, while finally large cracks and lower frequencies will prevail, reaching also the audible field (Hz) during the earthquake occurrence (Gregori and Paparo, 2004; Gregori et al., 2005; Carpinteri, 2015).

Hence, we have subjected the distribution of the AE signal frequencies (calculated by dividing the count number by the signal duration) to a statistical analysis, by partitioning the time window preceding the considered seismic event into three sub-intervals in order to describe the evolution of the frequency distributions over time. We have chosen the sub-intervals 0–50 h, 90–190 h and 260–485 h, which are characterized by different stages of the AE activity separated by quite long silent periods. The first interval (0–50 h) contains a sudden increase in the AE rate, followed by two in-

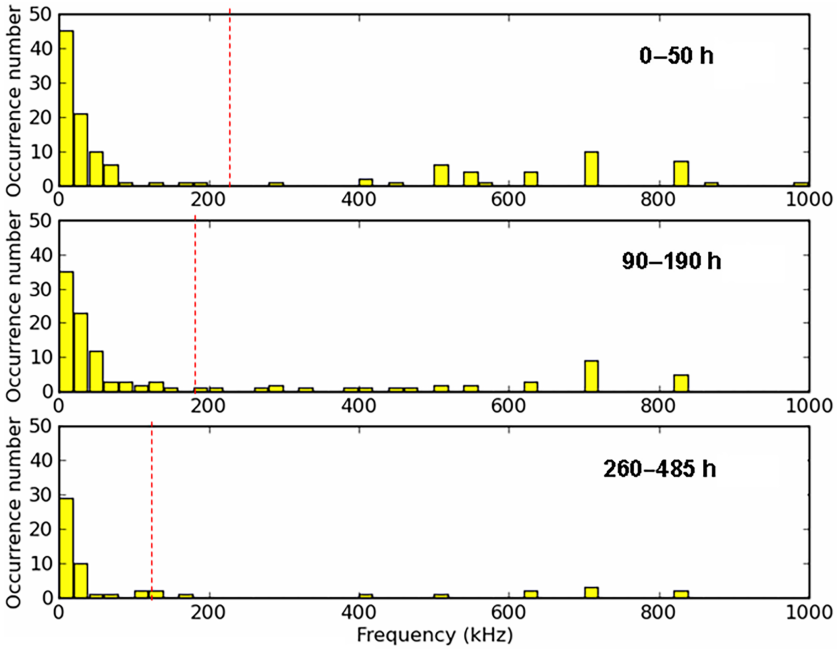


Figure 7. Histograms representing successive statistical distribution of the AE signal frequencies with bins 20 kHz wide starting at 10 kHz. The dashed lines represent the mean value of each distribution: 221, 193 and 141 kHz (top to bottom).

tervals (90–190 h and 260–485 h) with smoother AE rates. When comparing the plots of the corresponding distributions (Fig. 7), a progressive reduction of the highest frequencies, i.e., between 400 and 800 kHz, is observable as the seismic event was approaching. The reduction is given in percentage terms, 30, 22 and 16 % of the total amount of signals for each distribution. The frequency decay over time emerges also from the decreasing trend of the distributions' mean values, which are 221, 193 and 141 kHz.

4 Conclusion and prospectives

Structural monitoring based on the AE technique allowed active microcracks to be pointed out in an arched structure located in the Castle of Racconigi. Thus, 3-D localization of the ongoing damage process will result in more cost and time savings in the case of future maintenance and intervention programs. Furthermore, a preliminary investigation of critical-state indicators of the arch was carried out using the natural-time analysis applied to the AE time series. The obtained results apparently reveal the possibility of capturing the transition of this structural element to a critical state through the analysis of natural-time statistical parameters, such as the variance κ_1 and the entropy S.

On the other hand, the experimental evidence supports the hypothesis that a relevant part of AE activity emerging from the monitored element may be induced by evolving microseismicity falling into the preparation zone of a well identifiable earthquake according to the Dobrovolsky criterion. Indeed, the relatively small number of inner AE sources localized into the structure, compared to the total amount of recorded AE events, is compatible with the existence of a scattered source, i.e., the crustal trembling.

Finally, AE structural monitoring potentially provides twofold information in seismic areas: one concerning the structural damage and the other concerning the microseismic activity, propagating across the ground–building foundation interface, for which the building foundation represents a sort of extended underground probe (Gregori and Paparo, 2004; Gregori et al., 2005; Carpinteri et al., 2007). In this sense, structural monitoring in seismic areas could be usefully coupled with investigations of the local earthquake precursors (Niccolini et al., 2015; Lacidogna et al., 2015b).

Data availability. Data are not publicly accessible. However, the authors undertake to provide data to everyone who requests it.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. The previous director of the Polo Museale del Piemonte del Real Castello e Parco di Racconigi, architect Giuse Scalva, and the current director, architect Riccardo Vitale, are gratefully acknowledged for their assistance in the definition of the site and during the the monitoring phases.

Edited by: Filippos Vallianatos
Reviewed by: two anonymous referees

References

Aggelis, D. G., Mpalaskas, A. C., and Matikas, T. E.: Investigation of different fracture modes in cement-based materials by acoustic emission, Cement Concrete Res., 48, 1–8, 2013.

Aki, K.: A probabilistic synthesis of precursory phenomena, in: Earthquake Prediction, edited by: Simpson, D. W. and Richards, P. G., American Geophysical Union, Washington, D.C., USA, 566–574, 1981.

Bak, P. and Tang, C.: Earthquakes as a self-organized critical phenomenon, J. Geophys. Res., 94, 15635–15637, 1989.

Bak, P., Christensen, K., Danon, L., and Scanlon, T.: Unified scaling law for earthquakes, Phys. Rev. Lett., 88, 178501, https://doi.org/10.1103/PhysRevLett.88.178501, 2002.

Bonnet, E., Bour, O., Odling, N. E., Davy, P., Main, I. P., Cowie, P., and Berkowitz, B.: Scaling of fracture systems in geological media, Rev. Geophys., 39, 347–383, 2001.

Carpinteri, A.: TeraHertz Phonons and Piezonuclear Reactions from Nano-scale Mechanical Instabilities, in: Acoustic, Electromagnetic, Neutron Emissions from Fracture and Earthquakes, edited by: Carpinteri, A., Lacidogna, G., and Manuello, A., Springer International Publishing Switzerland, Cham, Heidelberg, New York, Dordrecht, London, 1–10, 2015.

Carpinteri, A., Lacidogna, G., and Niccolini, G.: Acoustic emission monitoring of medieval towers considered as sensitive earthquake receptors, Nat. Hazards Earth Syst. Sci., 7, 251–261, https://doi.org/10.5194/nhess-7-251-2007, 2007.

Carpinteri, A., Lacidogna, G., and Niccolini, G.: Damage analysis of reinforced concrete buildings by the acoustic emission technique, Struct. Control Hlth., 18, 660–673, 2011.

Colombo, S., Main, I. G., and Forde, M. C.: Assessing damage of reinforced concrete beam using "b-value" analysis of acoustic emission signals, J. Mater. Civil Eng., 15, 280–286, 2003.

Corral, A: Statistical Features of Earthquake Temporal Occurrence, in: Modeling Critical and Catastrophic Phenomena in Geoscience, edited by: Bhattacharya, P. and Chakrabarti, B. K., Springer Lecture Notes in Physics, 705, Berlin, Germany, 191–221, 2006.

Davidsen, J., Stanchits, S., and Dresen, G.: Scaling and universality in rock fracture, Phys. Rev. Lett., 98 125502, https://doi.org/10.1103/PhysRevLett.98.125502, 2007.

Dobrovolsky, I. P., Zubkov, S. I., and Miachkin, V. I.: Estimation of the size of earthquake preparation zones, Pure Appl. Geophys., 117, 1025–1044, 1979.

Gregori, G. P. and Paparo, G.: Acoustic Emission (AE): A diagnostic tool for environmental sciences and for non destructive tests (with a potential application to gravitational a antennas), in: Meteorological and geophysical fluid dynamics, edited by: Schroeder, W., Science Edition, Bremen, Germany, 166–204, 2004.

Gregori, G. P., Paparo, G., Poscolieri, M., and Zanini, A.: Acoustic emission and released seismic energy, Nat. Hazards Earth Syst. Sci., 5, 777–782, https://doi.org/10.5194/nhess-5-777-2005, 2005.

Grosse, C. U., Reinhardt, H. W., and Dahm, T.: Localization and classification of fracture types in concrete with quantitative acoustic emission measurement techniques, NDT Int., 30, 223–230, 1997.

Guarino, A., Garcimartin, A., and Ciliberto, S.: An experimental test of the critical behaviour of fracture precursors, Eur. Phys. J. B, 6, 13–24, 1998.

Hloupis, G., Stavrakas, I., Pasiou, E. D., Triantis, D., and Kourkoulis, S. K.: Natural time analysis of acoustic emissions in Double Edge Notched Tension (DENT) marble specimens, Procedia Engineering, 109, 248–256, 2015.

Hloupis, G., Stavrakas, I., Vallianatos, F., and Triantis, D.: A preliminary study for prefailure indicators in acoustic emissions using wavelets and natural time analysis, Proc. Inst. Mech. Eng., Part L: J. Materials: Design and Applications, 230, 780–788, 2016.

Kanamori, H. and Anderson, D. L.: Theoretical basis of some empirical relationships in seismology, B. Seismol. Soc. Am., 65, 1073–1095, 1975.

Kun, F., Carmona, H. A., Andrade Jr., J. S., and Herrmann, H. J.: Universality behind Basquin's Law of Fatigue, Phys. Rev. Lett., 100, 094301, https://doi.org/10.1103/PhysRevLett.100.094301, 2008.

Lacidogna, G., Carpinteri, A., Manuello, A., Durin, G., Schiavi, A., Niccolini, G., and Agosto, A.: Acoustic and electromagnetic emissions as precursor phenomena in failure processes, Strain, 47, 144–152, 2011.

Lacidogna, G., Manuello, A., Niccolini, G., and Carpinteri, A.: Acoustic emission monitoring of Italian historical buildings and the case study of the Athena Temple in Syracuse, Architect. Sci. Rev., 58, 290–299, 2015a.

Lacidogna, G., Borla, O., Niccolini, G., and Carpinteri, A.: Correlation Between Acoustic and Other Forms of Energy Emissions from Fracture Phenomena, in: Acoustic, Electromagnetic, Neutron Emissions from Fracture and Earthquakes, edited by: Carpinteri, A., Lacidogna, G., and Manuello, A., Springer International Publishing Switzerland, Cham, Heidelberg, New York, Dordrecht, London, 11–22, 2015b.

Mogi, K.: Study of elastic shocks caused by the fracture of heterogeneous materials and its relation to earthquake phenomena, Bulletin of Earthquake Research Institute, 40, 125–173, 1962.

Niccolini, G., Carpinteri, A., Lacidogna, G., and Manuello, A.: Acoustic emission monitoring of the Syracuse Athena Temple: Scale invariance in the timing of ruptures, Phys. Rev. Lett., 106, 108503, https://doi.org/10.1103/PhysRevLett.106.108503, 2011.

Niccolini, G., Borla, O., Accornero, F., Lacidogna, G., and Carpinteri, A.: Scaling in damage by electrical resistance measurements: an application to the terracotta statues of the Sacred Mountain of Varallo Renaissance Complex (Italy), Rendiconti Lincei Scienze Fisiche e Naturali, https://doi.org/10.1007/s12210-014-0353-6, 2014.

Niccolini, G., Borla, O., Lacidogna, G., and Carpinteri, A.: Correlated Fracture Precursors in Rocks and Cement-Based Materials Under Stress, in: Acoustic, Electromagnetic, Neutron Emissions from Fracture and Earthquakes, edited by: Carpinteri, A., Lacidogna, G., and Manuello, A., Springer International Publishing Switzerland, Cham, Heidelberg, New York, Dordrecht, London, 238–248, 2015.

Ohtsu, M., Okamoto, T., and Yuyama, S.: Moment tensor analysis of acoustic emission for cracking mechanisms in concrete, ACI Struct. J., 95, 87–95, 1998.

Omori, F.: On aftershocks, Rep. Imp. Earthquake Invest. Comm., 2, 103–109, 1894.

Richter, C. F.: Elementary Seismology, W. H. Freeman and Company, San Francisco, USA and London, UK, 1958.

Schiavi, A., Niccolini, G., Tarizzo, P., Carpinteri, A., Lacidogna, G., and Manuello A.: Acoustic emissions at high and low frequencies during compression tests of brittle materials, Strain, 47, 105–110, 2011.

Shah, S. P. and Li, Z.: Localization of microcracking in concrete under uniaxial tension, ACI Mater. J., 91, 372–381, 1994.

Shiotani, T., Fujii, K., Aoki, T., and Amou, K.: Evaluation of progressive failure using AE sources and improved b-value on slope model tests, Prog. Acoust. Emission, 7, 529–534, 1994.

Stanley, H. E.: Scaling, renormalization and universality: three pillars of modern critical phenomena, Rev. Mod. Phys., 71, 358–366, 1999.

Tosi, P., De Rubeis, V., Loreto, V., and Pietronero, L.: Space-time combined correlation integral and earthquake interactions, Ann. Geophys.-Italy, 47, 1849–1854, 2004.

Turcotte, D. L.: Fractal and Chaos in Geology and Geophysics, Cambridge University Press, Cambridge, UK, 1997.

Turcotte, D. L., Newman, W. I., and Shcherbakov, R.: Micro and macroscopic models of rock fracture, Geophys. J. Int., 152, 718–728, 2003.

Vallianatos, F., Michas G., Benson, P., and Sammonds, P.: Natural time analysis of critical phenomena: the case of acoustic emissions in triaxially deformed Etna basalt, Physica A, 392, 5172–5178, 2013.

Varotsos, P. A., Sarlis, N. V., and Skordas, E. S.: Spatio-temporal complexity aspects on the interrelation between seismic electric signals and seismicity, Pract. Athens Acad., 76, 294–321, 2001.

Varotsos, P. A., Sarlis, N. V., Skordas, E. S., and Lazaridou, M. S.: Fluctuations, under time reversal, of the natural time and the entropy distinguish similar looking electric signals of different dynamics, J. Appl. Phys., 103, 014906, https://doi.org/10.1063/1.2827363, 2008.

Varotsos, P. A., Sarlis, N. V., and Skordas, E. S.: Natural Time Analysis: The New View of Time, in: Precursory Seismic Electric Signals; Earthquakes and Other Complex Time-Series, Springer-Verlag, Berlin, Heidelberg, Germany, 2011a.

Varotsos, P. A., Sarlis, N. V., Skordas, E. S., Uyeda, S., and Kamogawa, M.: Natural time analysis of critical phenomena, P. Natl. Acad. Sci. USA, 108, 11361–11364, 2011b.

Varotsos, P. A., Sarlis, N. V., Skordas, E. S., and Lazaridou, M. S.: Seismic Electric Signals: An additional fact showing their physical interconnection with seismicity, Tectonophysics, 589, 116–125, 2013.