Frequency signal and natural time analyses from acoustic emission monitoring of an arched structure in the Racconigi Castle

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Abstract. The stability of an arch as a structural element in the thermal bath of King 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 possible entrance point to a critical state of the monitored structural element. Finally, possible influence of the local seismic and micro-seismic activity on the stability of the monitored structure was investigated. The criterion to select relevant earthquakes was based on the estimation of the size of earthquake preparation zones. The presented results suggest the use of AE technique as a tool for detecting both ongoing structural damage processes and micro-seismic 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 give an insight into the evolution of microcrack networks in laboratory experiments and possibly a tool for understanding the occurrence of fractures at larger scales (Mogi, 1962). Since 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, as it provides information on the internal state of a material without altering state of conservation of statues, monuments and fine artworks, seems to be suitable for this kind of structural monitoring.

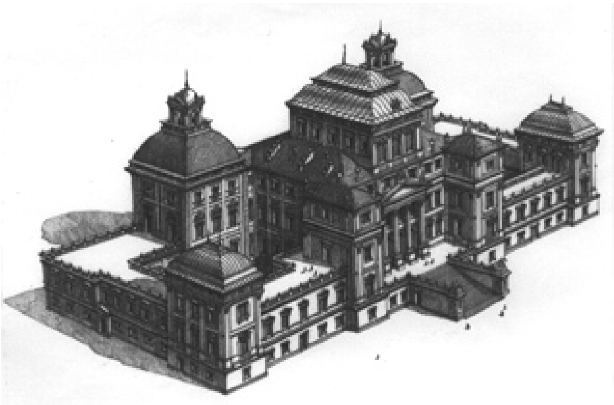
A relevant case study is here illustrated by the Racconigi Castle (origin dating back to the XIII century), whose original structure of medieval fortress was transformed over the centuries into a royal residence, becoming the southernmost of the Savoy Residences and one of the most important monuments in northwestern Italy. The moment of increased activity and restoration occurred between 1831 and 1848 during the reign of 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 Carlo Alberto, located in the ground floor of the Racconigi Castle, as a part of the complex planned by Pelagi on the Roman style and inspired by the "balnea" of the Pompeian villas. The wing of the castle containing this room is currently being restored.

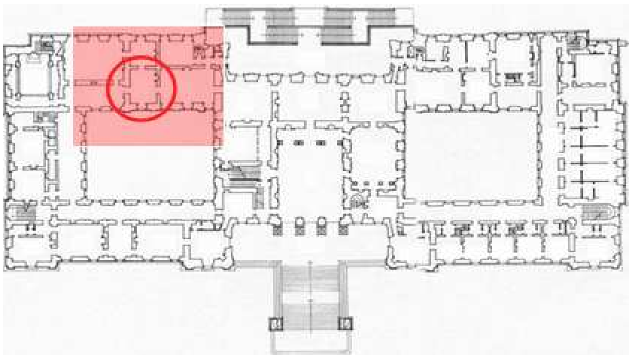
On the other hand, besides the disruptive power of strong earthquakes, Italian historic buildings and monuments suffer the action of small and intermediate earthquakes whose effects, though not immediately or clearly visible, eventually result in increased vulnerability to stronger earthquakes with catastrophic 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 an increased AE activity may be signature of crustal stresses redistribution in a large zone during the preparation of a seismic event (Gregori et al., 2004; Gregori et al., 2005; Carpinteri et al., 2007; Niccolini et al., 2011). According to previous research studies performed by Dobrovolsky et al. (Dobrovolsky et al., 1979), it can be assumed that the preparation zone is a circle with the centre in the epicenter of the impending earthquake. The radius r of the circle, called ‘strain radius’, is given by the relationship $r = 10^{0.433M + 0.6}$, where M is the earthquake magnitude and r is expressed in km. All the seismic precursors, including AE, are expected to fall into this circle.

2 Experimental results

Damage assessment in an arch of castle's thermal bath (Fig. 1) has been carried out by 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 non-invasive, 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 broad-band 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 8-channel acquisition system AEmission® which implements algorithms for automatic analysis of AE signal parameters, i.e., arrival time (determined with accuracy of 0.2 μs), duration, amplitude and counts number (total number of signal threshold crossings). The stored AE parameters can be wireless transmitted to a receiver allowing long-distance remote and real-time monitoring.

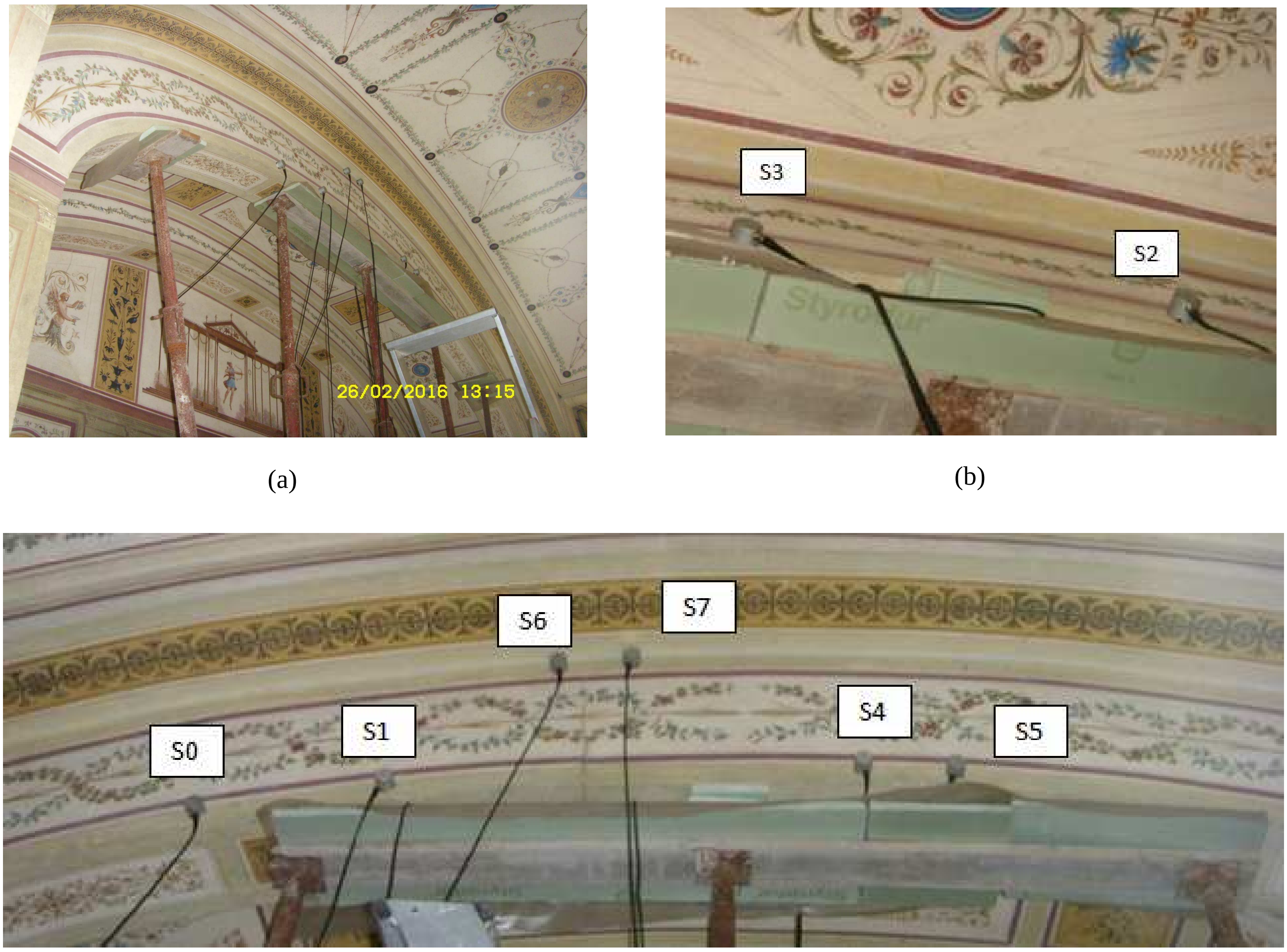


(a)



(b)

Fig. 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)

Fig. 2: The monitored arch (a) and the transducers positions (b) and (c)

Before starting the monitoring, the background noise has been checked for a representative period of time, i.e. 24 hours, in order to determine the level of spurious signals. Thus, after identifying a signal detection threshold of 1.5 mV, a one-month monitoring period started. In order to suppress possible voltage spikes, acquired AE signals with duration < 3 μs and counts number < 3 have been filtered out. The spatial identification of arch's damaged zones has been 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 3D 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 sudden increase in damage accumulation.

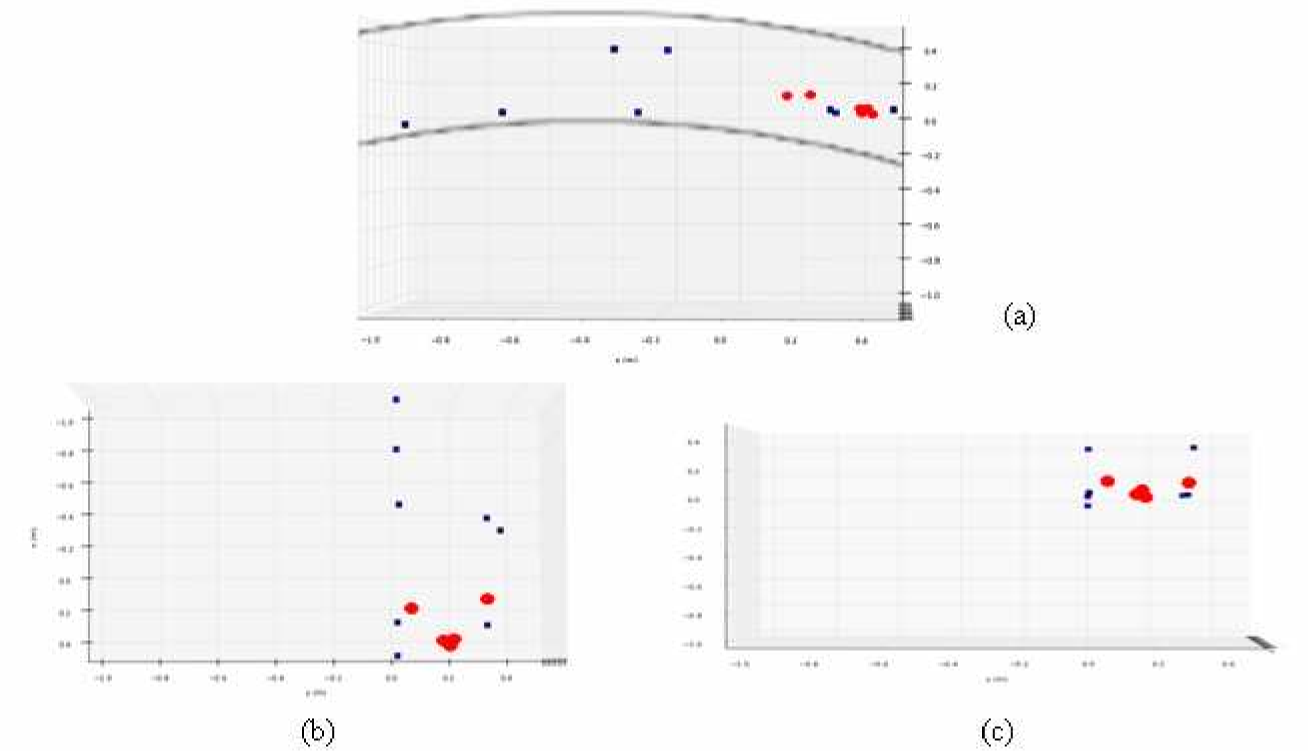


Figure 3: 3-D map showing the positions of transducers (blue squares) and localized AE sources (red dots): front (a), upper (b) and side view (c).

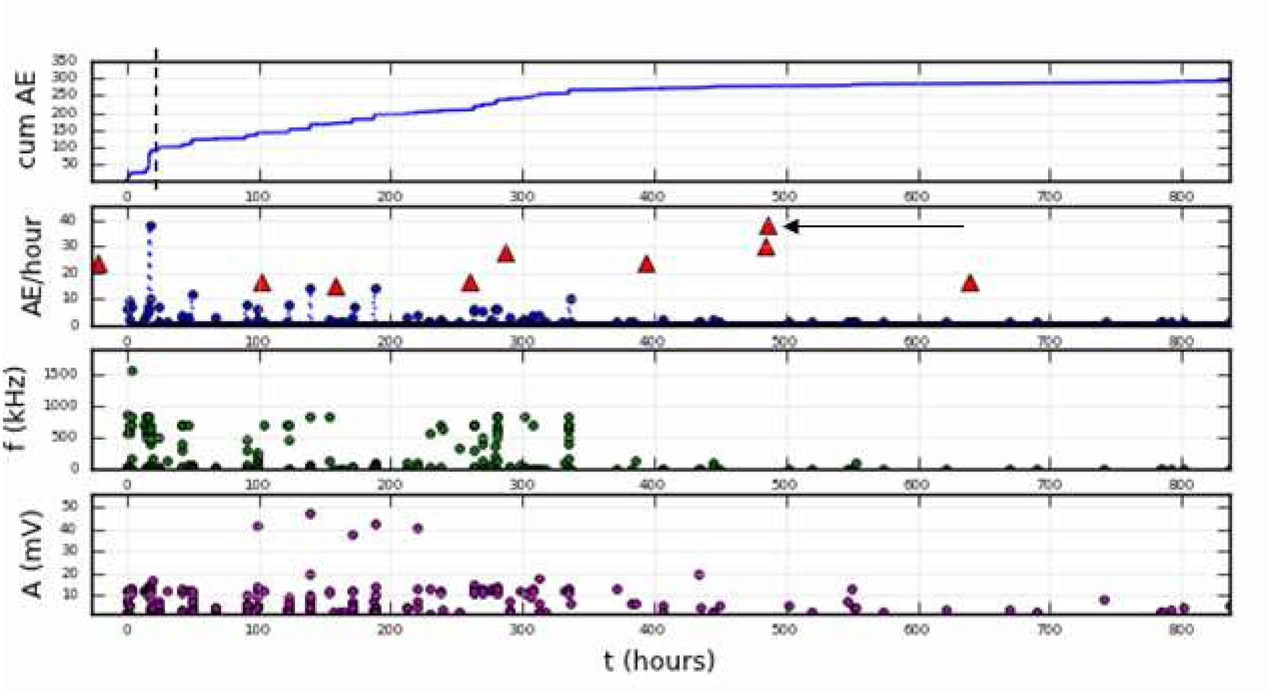


Figure 4: From top to bottom: accumulated number of AE signals ("hits"): the dashed line indicates a critical point revealed by the natural time analysis; AE count rate and sequence of nearby earthquakes marked by red triangles (the arrow points the strongest one); time series of signal frequencies and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

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

In the frame of critical phenomena (Bak et al., 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 along before the final collapse is transformed in the investigation of indicators revealing the entrance to a "critical state".

Recently, a worth of mentioning approach to identify 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; Varotsos et al., 2011a; Varotsos et al., 2011b; Varotsos et al., 2013), where the time stamping is ignored and only the natural time, $\chi_k = k/N$, as a normalized order of occurrence of the *k*-th event, and the energy Q_k are preserved. In natural time analysis the evolution of the pair (χ_k, Q_k) is considered, by introducing the normalized power spectrum $\Pi(\omega) \equiv |\Phi(\omega)|^2$, 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 k-th event. It was found that all the moments of the distribution of the p_k can be estimated from the Taylor expansion $\Pi(\omega) = 1 - \kappa_1\, \omega^2 + \kappa_2\, \omega^4 + \ldots$, 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 (χ_k, p_k) are rescaled as natural time χ_k changes from k/N to $k/(N+1)$ and p_k changes to $Q_k / \Sigma_{i=1}^{N+1} Q_i$. 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; Varotsos et al., 2011a; Varotsos et al., 2011b), 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 true critical state (Varotsos et al., 2008): 1) the parameter κ_1 must approach the value 0.07 "by descending from above"; 2) the entropy S must be lower than the entropy of uniform noise, $S_u = 0.0966$, when κ_1 coincides 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 { χ_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 et al., 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 "critical state", corresponding to the fulfillment of criticality conditions 1) and 2) (Vallianatos et al., 2013; Hloupis et al., 2015; Hloupis et al., 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 amounting 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 3.0-magnitude earthquake (pointed 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).

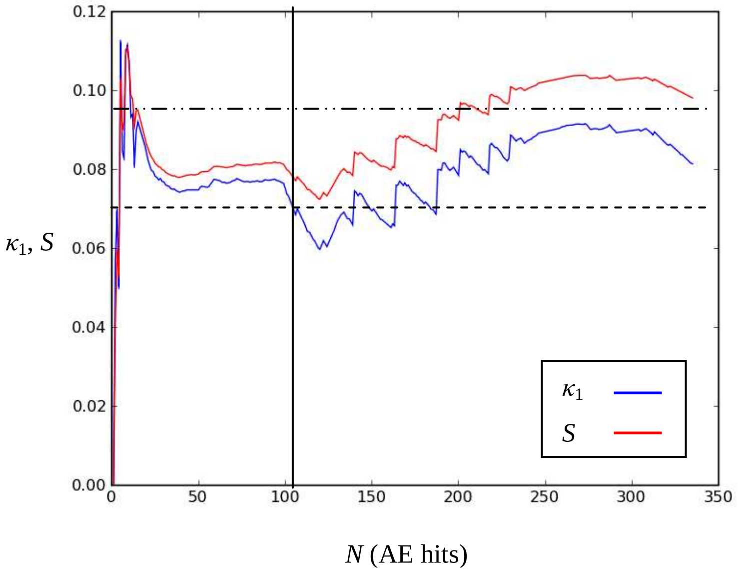


Figure 5: Evolution of natural time quantities κ_1 (blue line) and *S* (red line) as function of accumulated AE hit number *N*. The horizontal dashed line indicates the value κ_1 = 0 0.07, while the vertical line indicates the corresponding criticality initiation hit (*N* = 104). The upper dash-dot line indicates the entropy limit S_u = 0.0966.

Time Origin (UTC)	**Time Delta(h)**	**Lat (deg)**	**Long (deg)**	**Depth (km)**	**Dist. (km)**	**Magnitude**	**Radius (km)**
2015-12-10 16:31:56.990	-22.46	44.561	7.161	11.2	46.8	1.9	26.5
2015-12-15 11:21:44.070	102.73	45.087	7.163	7.9	53.6	1.3	14.5
2015-12-18 05:36:07.740	158.6	44.549	6.775	5.6	75.3	1.2	13.2
2015-12-22 07:10:41.190	259.68	44.93	6.874	10.4	65.7	1.3	14.5
2015-12-23 13:45:30.560	286.75	44.651	6.84	6.8	67.3	2.2	35.7
2015-12-28	394.18	44.45	7.289	11.8	46.8	1.9	26.5

01:11:29.380							
2015-12-31 19:16:48.900	484.26	44.548	6.756	9.1	76.8	2.4	43.6
2015-12-31 20:42:01.000	**485.7**	**44.765**	**6.76**	**9.4**	**71**	**3.0**	**79.2**
2016-01-07 05:41:23.000	638.68	45.07	6.57	10	93.2	1.3	14. 5

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

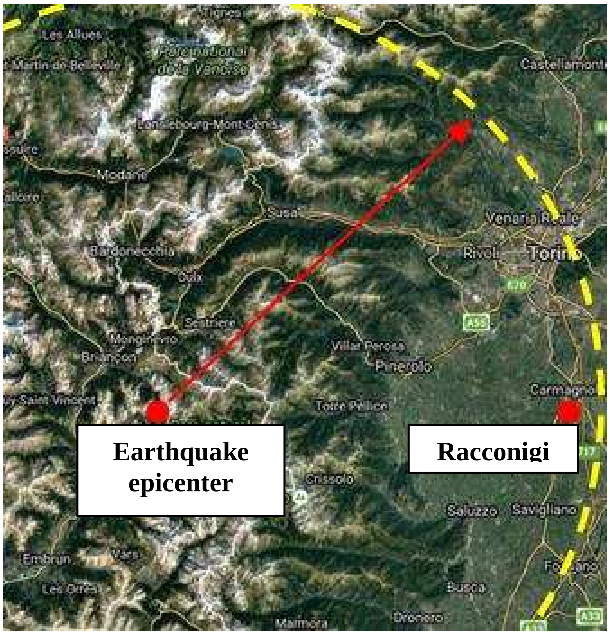


Figure 6: Map showing the epicenter of the magnitude 3 earthquake occurred on 2015-12-31 and the related preparation zone embedding the monitoring site in Racconigi.

As cracking is a multi-scale phenomenon in the Earth's crust, the frequencies of AE waves related to micro-seismic activity are spread over a broad spectrum. At the earlier stages of the preparation of a seismic event, mainly micro-cracks will be present and active and therefore high-frequency AE (MHz), while finally large cracks and lower frequencies will prevail, reaching also the audible field (Hz) during the earthquake occurrence (Gregori et al., 2004; Gregori et al., 2005; Carpinteri, 2015).

Hence, we have subjected the distribution of the AE signal frequencies (calculated by dividing the counts number to 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 the time. We have chosen the following sub-intervals: (0h, 50h); (90h, 190h); (260h, 485h) characterized by different stages of the AE activity separated by quite long silent periods. The first interval, (0h-50h), contains a sudden increase in the AE rate, followed by two intervals, (90h, 190h) and (260h-485h), with smoother AE rates. 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 approached. The reduction is given in percentage terms, 30%, 22% and 16% of the total amount of signals for each distribution. The frequency decay over the time emerges also from the decreasing trend of the distributions' mean values, which are 221, 193 and 141 kHz.

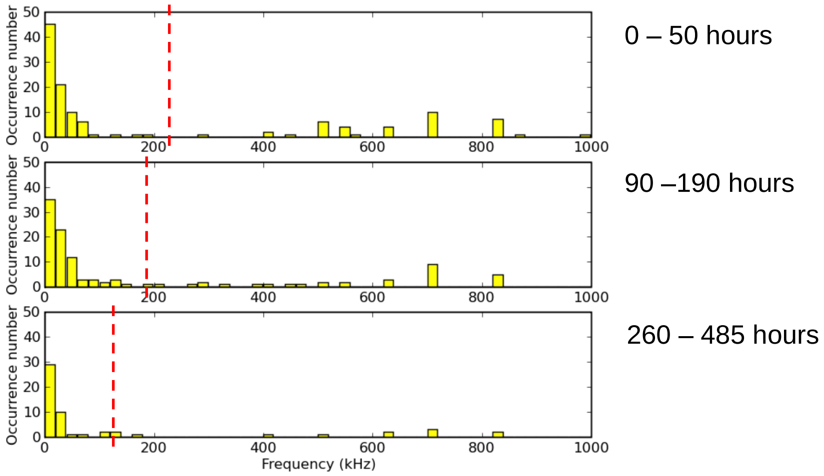


Figure 7: Histograms representing successive statistical distribution of the AE signal frequencies with bins 20 kHz wide starting at 10 kHz. The dashed lines represent the mean value of each distribution: 221, 193 and 141 kHz, respectively.

4 Conclusion and prospectives

Structural monitoring based on the AE technique allowed to point out active microcracks in an arched structure located in the Castle of Racconigi. Thus, the 3D localization of the ongoing damage process will result in more cost and time savings in case of future maintenance and intervention programs. Furthermore, a preliminary investigation of arch's critical state indicators 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 micro-seismicity 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 et al., 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).

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