Health Monitoring of Medieval Masonry Towers by an Acoustic Emission Approach

Article *in* Key Engineering Materials · August 2019

DOI: 10.4028/www.scientific.net/KEM.817.586

Giuseppe Lacidogna
Politecnico di Torino

Key Engineering Materials
ISSN: 1662-9795, Vol. 817, pp 586-593
doi:10.4028/www.scientific.net/KEM.817.586

Submitted: 2019-03-08
Revised: 2019-05-14
Accepted: 2019-05-15
Online: 2019-08-16

Health Monitoring of Medieval Masonry Towers by an Acoustic Emission Approach

Giuseppe Lacidogna[1,a,*], Gianni Niccolini[1,b], Alberto Carpinteri[1,c]

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

[a]giuseppe.lacidogna@polito.it, [b]gianni.niccolini@polito.it, [c]alberto.carpinteri@polito.it

Keywords: masonry, acoustic-emission monitoring, non-destructive testing, flat-jack, size-effects, seismic hazard, fractals, natural time analysis, *b*-value.

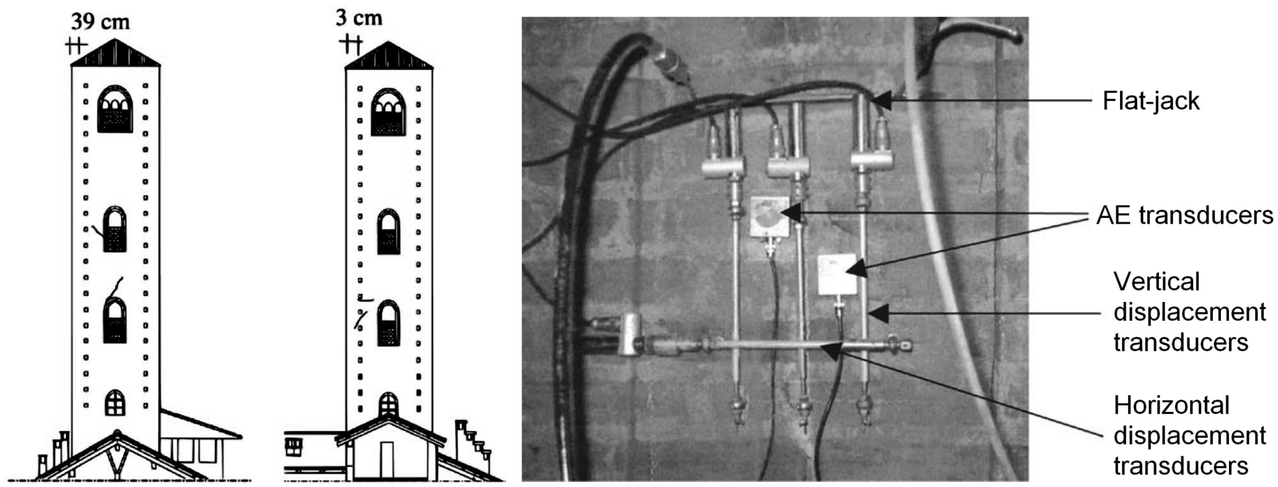
Abstract. Non-destructive tests were performed to assess cracking evolution in two medieval masonry buildings, Sineo and Asinelli towers rising respectively in the Cities of Alba and Bologna, in Italy. As regards the case study of Alba, *in situ* compressive flat-jack tests on small-sized elements of the tower were conducted in conjunction with acoustic emission (AE) monitoring. At the same time, crack patterns taking place in large volumes of the tower were likewise monitored through the AE technique. As for the case study of Bologna, a masonry wall of the Asinelli tower was monitored during a period of intense seismic activity. The observed correlation between the AE activity in the monitored structural element and local earthquakes points out a significant dependence of deterioration processes in the tower on the action of nearby earthquakes. In both cases, the trends of two evolutionary parameters, the *b*-value and the natural time (NT) variance κ_1, were derived from the AE time series to identify the approach of the monitored structures to a *critical state* in relation to the earthquake occurrence.

Introduction

The reliability assessment of historical and monumental structures is a complex problem that can be solved only by the use of innovative technologies. An optimal solution should take into account the entire life-cycle of these buildings, where monitoring procedures are used to evaluate damage process and the efficiency of the rehabilitation interventions. Among the non-destructive-testing methods for historical structures, the Acoustic Emission (AE) technique is one of the most suitable as a passive detection method of spontaneous elastic energy released in the form of transient (AE) waves [1-5]. Basically, materials under stress or harsh environment are subjected to internal changes such as crack growth and local deformation, which are generally accompanied by acoustic emissions. These waves, that provide information on the internal state of the material, are detected by suitable sensors which converts the surface movements of the material into an electric signal. Detection and location of AE sources allows the identification of internal cracks, which may either gradually come to an arrest or propagate at an increasingly fast rate. Then, damage evolution of the monitored structure towards stability or instability conditions can be evaluated, also in seismic regions by subjecting the AE time series to statistical analyses, such as the two approaches proposed in the paper.

AE monitoring of the Sineo Tower

The Sineo tower is 39-meter-high, deviating from verticality by about 1% (Fig. 1(*a*)), and characterized by *a sacco* bearing walls, whose thickness ranges from 2 m at the foundation level to 0.8 m at the top. Up to a height of 15 m, the tower is incorporated in a later building. The tower exhibits a cracking pattern which is schematically represented in Fig. 1(*a*). The stress state and cracking evolution in the tower were assessed respectively through the following non-destructive techniques: flat-jack tests on different-sized masonry elements tested to failure, and Acoustic Emission (AE) monitoring [1,2] of some portions of the tower. The AE activity in the tower was correlated with analogous AE activity recorded on the tested elements through a size-independent energetic damage parameter (Fig. 1(*b)*) [3-5]. Taking the tested specimens as representative of the state of tower (see Fig.2) [4,5], an estimate of actual damage levels and residual lifetime seems to be possible from AE data, as explained in the following. In situ double flat-jack tests were conducted on the Sineo tower to assess the deformability properties and the compressive strength of load bearing masonry walls [3-5]. Flat-jacks measuring 24 × 12 cm^2 were inserted at the base of a masonry wall into two cuts made in horizontal mortar joints about 30 cm apart for the smaller specimens, for the purpose of conducting tests under uniaxial compression. The stress–strain relationship of the masonry was determined increasing progressively the pressure applied by the flat-jacks during three loading–unloading cycles [4]. The compressive strength was obtained from the load–displacement diagram, when the latter became highly nonlinear, denoting imminent failure of the considered element. Three different-sized masonry volumes (Fig. 2(*a*)) were tested according to 1991 ASTM procedures [6,7], except for the vertical cuts made to eliminate the influence of the adjacent masonry portions. The damage evolution in each tested volume was monitored by AE monitoring, where the cumulative number of AE ring-down counts is plotted as a function of time. Overlaying the loading cycles diagram shows the well-known Kaiser effect, whereby the material emits AE energy when the stress level reached previously is exceeded (Fig. 2(*b*) top).



(a) *(b)*

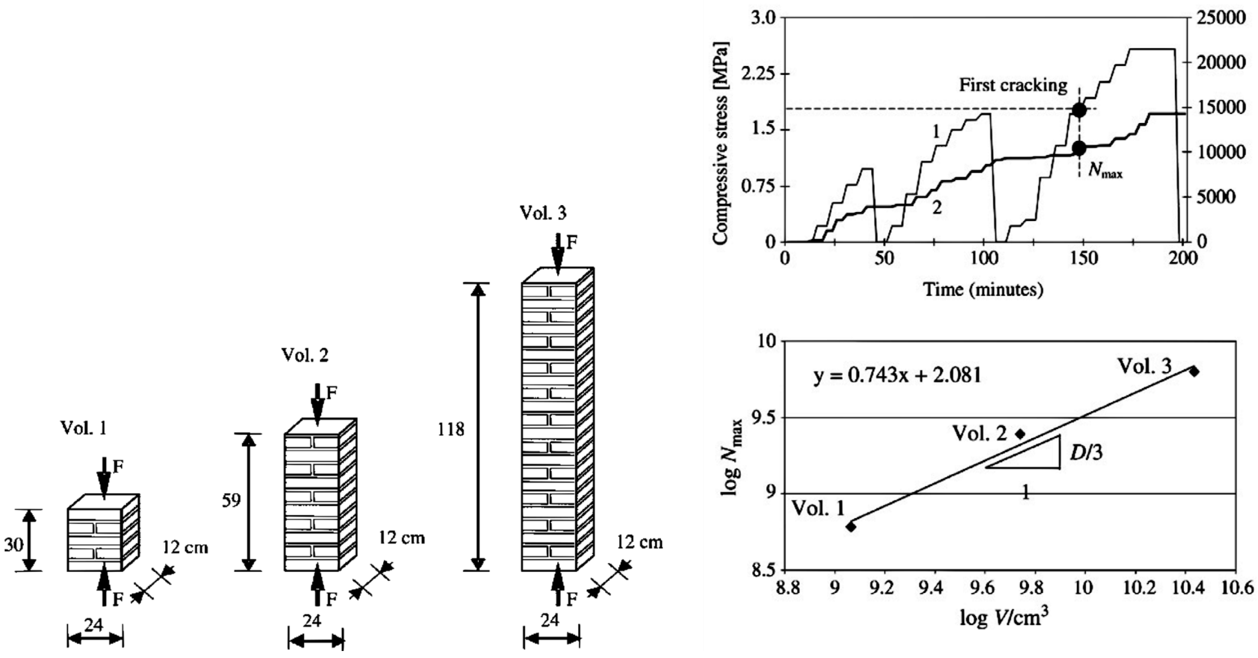
Fig. 1. Fig. 1. Elevations of the Sineo tower, the West side is on the left, the South side is on the right, showing the crack pattern and the deviation from verticality (a); combined flat-jack test and AE monitoring (b) (both pictures reprinted from [4]).

The adopted AE equipment consisted of eight piezoelectric (PZT) transducers of the Atel series, sensitive in the frequency range 50-500 kHz and connected to as many control units. The detected AE signals were amplified with a gain 20 $\log_{10} A_u/A_i$ =60 dB, being A_u/A_i the ratio between the input and the output signal voltage. The signals were then processed by ring-down counting [8], i.e., counting the number N_0 of times each signal exceeded a given threshold voltage A_{th} , properly fixed at 100 μV to filter out the noise. Each unit was able to count up to 255 ring-down counts every 120 s [9]. The number of counts is assumed to be proportional to the signal amplitude, and then to the amount of energy emitted in each crack advancement.

Fragmentation theories have shown that elastic energy is dissipated by micro- and macro-cracking over a fractal domain comprised between a surface and the specimen volume V [4,10,11]. Furthermore, a surplus of energy is emitted through acoustic emissions during crack growth. Since the emitted energy is assumed to be proportional to the number N of AE ring-down counts, the following relationship can be stated [3,4]:

$$\Gamma_{AE} = N_{max} / V^{D/3}, \quad (1)$$

where N_{max} is the total number of AE counts at the critical stress σ_u, corresponding to the onset of macro-cracking (see Fig. 2(*b*) top), D is the fractal dimension of the damage domain, and the critical density Γ_{AE} of AE counts can be considered as a size-independent parameter by analogy with the renormalized fracture energy $\mathcal{G}_F^*$ [12,13].



(*a*) (*b*)

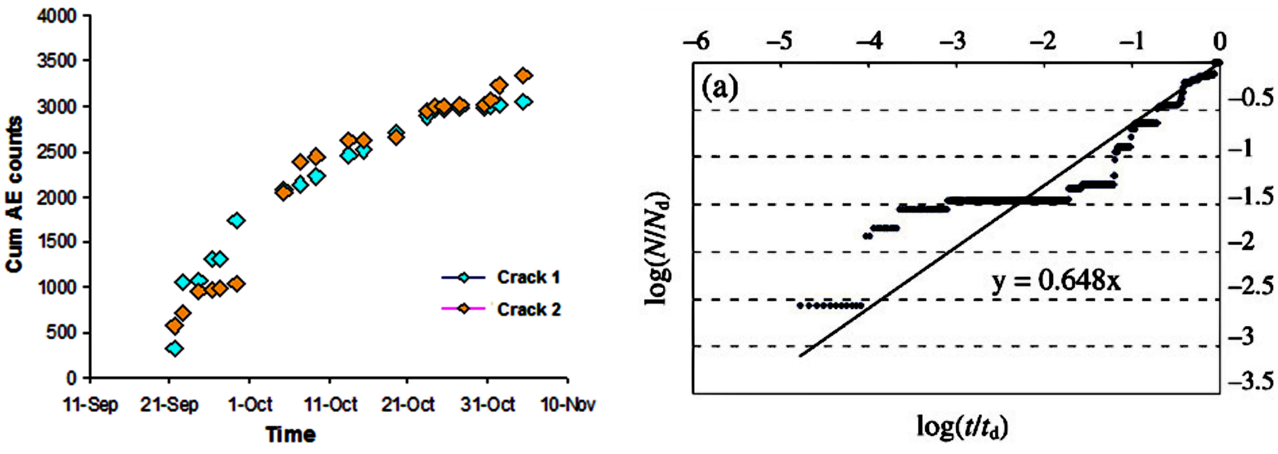
Fig. 2. Masonry elements tested in compression by means of double flat-jacks and AE sensors (*a*); test results on Vol. 2: cumulative number of AE counts vs cyclic loading and volume effect on N_{max} (*b*) (both pictures reprinted from [4]).

As can be seen from Fig. 2(*b*) (bottom), the critical number N_{max} increases with increasing the specimen volume V, obeying the scale effect predicted by Eq.(1) for specimens tested to failure. From the experimental data, the fractal dimension D of the damage domain results to be 2.23, i.e. between 2 and 3 as predicted by fragmentation theories.

During the observation period of the Sineo Tower, from 16th September to 7th November 2000, two cracks in the inner masonry layer at seventh floor level were monitored by recording the AE activity versus time [4,9]. The trend of the cumulative AE count (Fig. 3(*a*)) revealed an ongoing damage process, characterized by slow crack propagation inside the brick walls, which finally stopped as the cracks achieved a new condition of stability, presumably reaching compressed zones of the masonry. The damage level in the tower can be worked out correlating the AE monitoring results with the AE data recorded on the specimens tested to failure by flat-jacks. Since the monitored volume of the tower is roughly $V = 1.2 \times 10^7$ cm^3 (see Ref. [4], pag. 1577), inserting $D = 2.23$ and $\Gamma_{AE} = 8.00$ cm$^{-2.23}$ into Eq.(1) gives a critical AE number of $N_{max} = 1.46 \times 10^6$. The ratio of the actual number of recorded AE counts $N = 2250$ to N_{max} yields:

$$\eta = N/N_{max} = 0.154\% \ , \qquad (2)$$

that estimates in percentage terms, the amount of emitted energy with respect to the energy expected to cause ultimate failure of the monitored volume of the tower.



(a) *(b)*

Fig. 3. Cumulative AE activity vs time related to cracks 1 and 2 (*a*); temporal damage evolution (*b*) (last picture reprinted from [4]).

The assumption underlying these predictions is that the damage level observed in the reference specimens before flat-jack testing is representative of the level reached in the entire structure before the monitoring [4]. Indications on the damage growth rate to predict lifetime of the zone analyzed are obtained considering a damage parameter $\eta(t)$:

$$\eta(t)= N/N_d=(t/t_d)^{\beta_t}, \tag{3}$$

expressed as the ratio of the cumulative number N of AE counts recorded until time t to the number N_d at the end of the observation period t_d = 50 days. Correlating AE data by Eq.(3) gives $\beta_t = 0.648$ as a fitting parameter (Fig. 3(*b*)), that points out a stabilized damage process (values of $\beta_t > 1$ would point out unstable damage growth). Introducing the critical number N_{max} into Eq.(3) written in the form $N_d/N_{max} = (t_d/t_{max})^{\beta_t}$, with $\beta_t = 0.648$, gives $t_d/t_{max} = 4.678 \times 10^{-5}$, yielding a lifetime t_{max} of some thousands of years. Such prediction confirms the condition of stability for the monitored portion of the tower, unless significant environmental actions intervene to alter the actual trend.
However, as mentioned in the Abstract, the Sineo tower was monitored during a seismic swarm (see Tab. 2, pag. 3 in Ref. [9]) that hit the area of the city of Alba. In this respect, the approach of the monitored structure to critical conditions in relation to earthquake occurrence is also investigated by means of the Natural Time (NT) analysis [14-16] applied to the n surveys of the AE activity, considered as so many events. In the NT context, the natural time $\chi_k = k/n$ is ascribed to the k-th event of energy Q_k, which is given by the number N_{0k} of ring-down counts at each survey. The set of the normalized energies $p_k = Q_k/\Sigma_{i=1}^{n} Q_i$ can be regarded as the probability distribution of the discrete variable χ_k whose variance κ_1 is:

$$\kappa_1= \Sigma_{i=1}^{n} p_k \chi_k^2 - (\Sigma_{i=1}^{n} p_k \chi_k)^2 \equiv <\chi^2> - <\chi>^2. \tag{4}$$

Since χ_k and p_k rescale upon the occurrence of any additional event, κ_1 turns out to be an evolutionary parameter. Two universal criteria were defined to identify the entrance of different dynamical systems to a critical condition [14-16]:
1) κ_1, evolving event by event, must approach the value 0.07 "by descending from above";
2) the entropies S and S_{rev} (entropy upon time reversal) must be lower than the entropy of uniform noise, S_u= 0.0966, when κ_1 coincides to 0.07. The entropy S is defined as:

$$S \equiv <\chi \ln\chi> - <\chi> \ln<\chi> \ , \text{ with } <\chi \ln\chi> = \Sigma_{i=1}^{n} p_k \chi_k \ln\chi_k. \tag{5}$$

Here, the evolution of variance κ_1 and entropies S and S_{rev} of the natural-time transformed AE time series $\{\chi_k\}$ has been studied, where the event energy Q_k is defined by the ring-down counts number N_0 (≤ 255) previously introduced. The NT parameters are plotted as functions of the conventional time t to identify the transition to criticality of the AE activity (Fig. 4). As for crack 1, the AE activity enters the critical stage on October 27th (Fig. 4(*a*)), which is considered to be probably related to the 3.2-magnitude earthquake (at a hypocentral distance of 30.66 km from the tower) occurred in the same day. A critical point for the AE activity due to crack 2 propagation, being identified on September 26th (Fig. 4(*b*)), is analogously related to the 2.4-magnitude earthquake (at a hypocentral distance of 22.56 km) occurred in the same day. As reported in Ref.[9] (Tab. 2, pag. 3), the two considered seismic events are respectively the strongest and the closest to the monitoring site. Therefore, there are indications of a link between the nearby earthquakes and the AE activity, albeit stable, in the tower which thus behaved as a sensitive receptor of seismic activity.

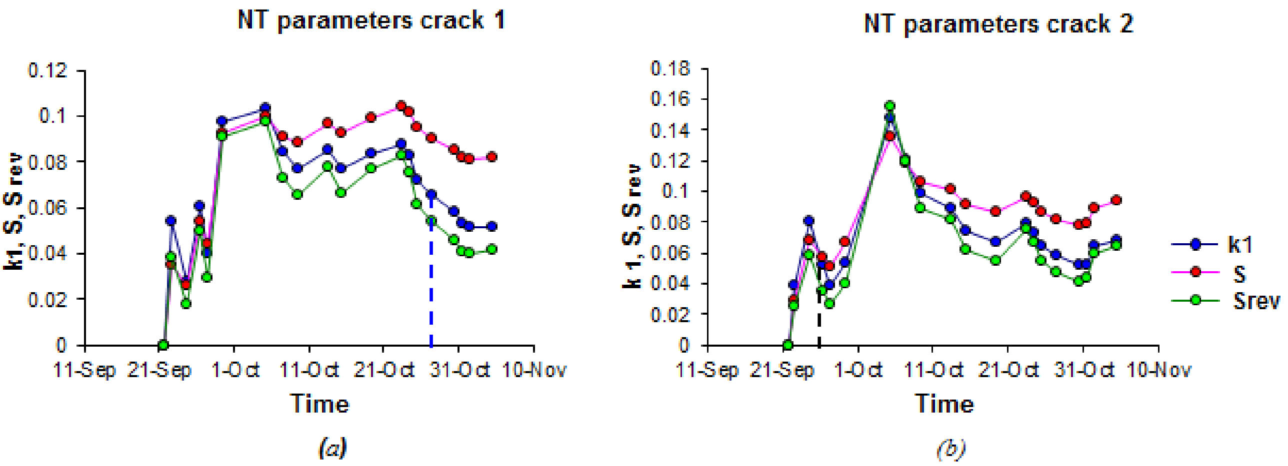


Fig. 4. Time evolution of natural-time quantities κ_1, S and S_{rev} extracted from the AE time series related to cracks 1 and 2: the dashed lines intercept the critical point on the time-axis, on 27th October and 26th September, respectively.

AE monitoring of the Asinelli Tower

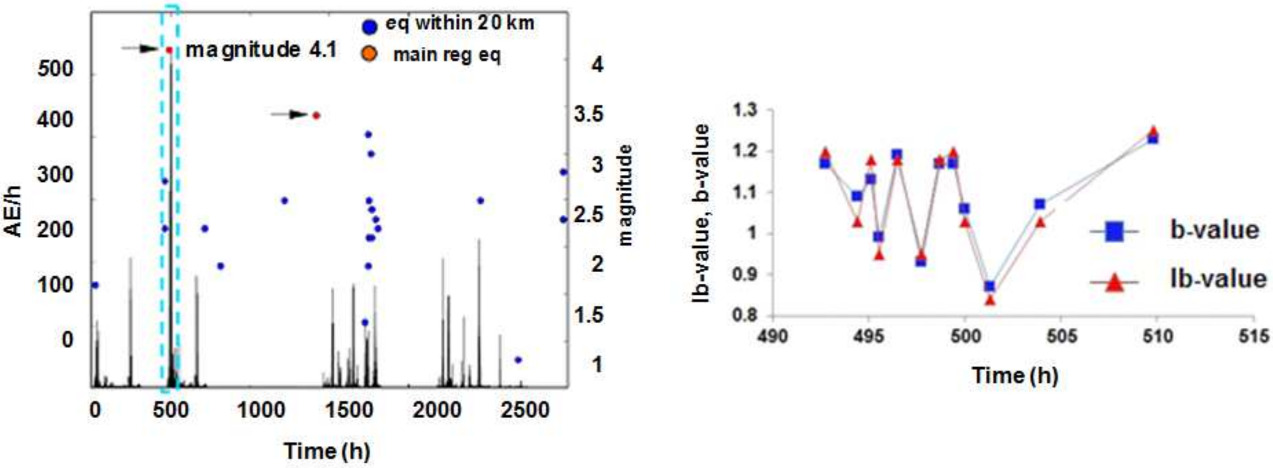
An array of six broadband AE transducers (sensitive up to 500 kHz) was fixed to the north-east angle of the Asinelli Tower at an average height of 9.00 m above ground level, and connected to a six-channel acquisition system to record arrival time, duration, peak amplitude, and ring-down count of each AE signal (see Fig. 5). The frequencies of interest in the old masonry, around 30 kHz, were detected by the used transducers. After a preliminary acquisition test, which permitted to identify a signal detection threshold of 100 μV, the AE monitoring began on September 23th 2010 until January 28 th 2011 [17,18], where the AE time history points out an ongoing damage process taking place in the masonry wall. Remarkably, the monitoring period was characterized by a strong regional earthquake (the magnitude 4.1 event occurred on 13th October with epicenter about 100 km far from Bologna) which was considered to be related to the densest AE cluster recorded (formed by 4000 signals and highlighted by the dashed frame in Fig. 6(*a*)). The comparatively longer duration of the AE cluster (occurred in the interval 490–510 h of the monitoring time) with respect the impulsive seismic event has been explained by a viscoelastic response assumed for masonry structures [19,20]. The entrance of the structural element to a critical state has been investigated by analyzing the temporal evolution of the Gutenberg-Richter (GR) *b*-value and the NT variance κ_1 of the AE time series. The GR law, initially introduced in seismology [21] and then extended to the statistics of the AE signals [22-24], is expressed by the relation:

$$\log_{10} N = a - bM, \tag{6}$$

where the magnitude $M \equiv \log_{10}(A_{max}/\ 1\mu V)\ 1$ is the logarithmic measure of the AE signal peak amplitude (ranging from 100 to 12800 μV for the detected signals), N is the number of signals with magnitude exceeding M, and a and b (termed as *b*-value) are fitting constants.

(a) *(b)*

Fig. 5. The Asinelli Tower showing the monitored portion (*a*); the masonry wall with the applied AE transducers (*b*), reprinted from [18].



(a) *(b)*

Fig. 6. Time series of the AE signals count rate and nearby earthquakes (*a*); time series of *b*-values and *Ib*-values (*b*) (reprinted from [18]).

In the present study, the analysis has been conducted by partitioning the AE time series in groups (formed by 300 signals), from each of which the *b*-value has been worked out. Thus, the *b*-value and improved *b*-value (*Ib*) time series result to exhibit similar trends with a global minimum close to 0.8-0.9 at 501 h (Fig. 6(*b*)). The recovery towards higher *b*-values demonstrates the stability of the masonry wall, where the unique damaging episode is considered to be related to a specific seismic event [18]. On the other hand, the evolution of variance κ_1 and entropies S and S_{rev} of the NT transformed AE time series $\{\chi_k\}$ has been analyzed, defining the event energy Q_k as a function of the signal amplitude A_k, $Q_k \sim A_k^{1.5}$ [10]. Looking at Fig. 7, an entrance point to a critical stage has been identified at time $t_{crit} = 492$ h by the vertical dotted line, i.e. 9 h before the minimum *b*-value (occurred at $t_{b\text{-min}} = 501$ h) [18]. This finding suggests that the NT variance κ_1 can be regarded as a pre-failure indicator, before the onset of non-reversible damage processes.

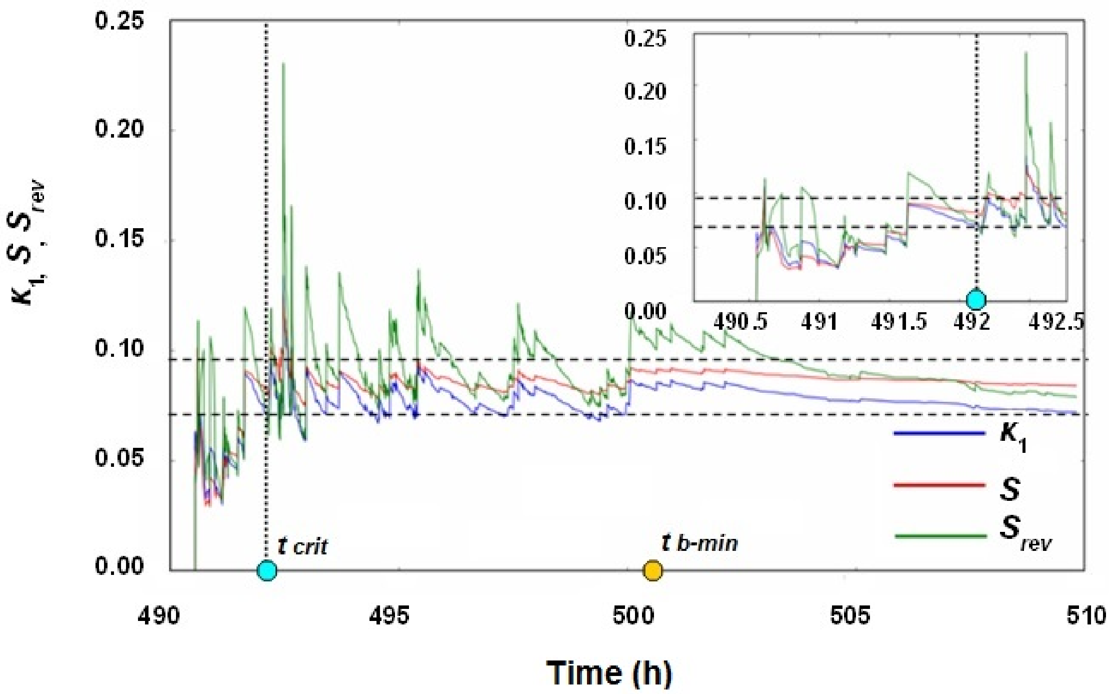


Fig. 7. Time evolution of natural-time quantities κ_1, S and S_{rev}. Horizontal dashed lines represent the characteristics value κ_1 = 0.07 and S_u = 0.0966 defining the criticality initiation time t_{crit}. Note the relative positions of t_{crit} and $t_{b\text{-}min}$ along the time-axis (reprinted from [18]).

Conclusion

An AE-based method of assessing the structural stability of two medieval masonry buildings, Sineo and Asinelli towers, has been proposed. In the former case, the results on specimens tested to failure allows to make inferences on the actual damage level and the remaining lifetime of the monitored structure. In both cases, the observed correlation between the AE time series and the nearby earthquakes [25] suggests that the local structural response is driven by the local seismicity. The onset of critical conditions in the monitored structural elements has been investigated by the *b*-value [17,18,26] and natural time analyses [14-16]. The influence of local earthquakes on damage processes taking place in this kind of structures would be hopefully analyzed by using seismometers, installed together with the AE system. In this way, the effectiveness of the AE monitoring technique for the seismic hazard mitigation could be extensively investigated. Furthermore, the AE technique could also be used to evaluate the effectiveness of restoration interventions once the damage has been repaired [27].

References

[1] S.P. Shah, S.P.; Z. Li, Localization of microcracking in concrete under uniaxial tension, ACI Mater. J. 91 (1994), 372-381.
[2] M. Ohtsu M., The history and development of acoustic emission in concrete engineering, Mag. Concrete Res. 48 (1996), 321-330.
[3] A. Carpinteri, G. Lacidogna, Structural monitoring and integrity assessment of medieval towers, J. Struct Eng-ASCE. 132 (2006) 1681-1690.
[4] A. Carpinteri, G. Lacidogna, Damage evaluation of three masonry towers by acoustic emission, Eng. Struct. 29 (2007) 1569-1579.
[5] A. Carpinteri, G. Lacidogna, N. Pugno, Structural damage diagnosis and life-time assessment by acoustic emission monitoring, Eng. Fract. Mech. 74 (2007), 273-289.

[6] ASTM. Standard test method for in situ compressive stress within solid unit masonry estimated using flat-jack measurements, ASTM C1196-91, Philadelphia; 1991.
[7] L. Binda, E. Bertocchi, D. Trussardi, Torri in muratura, Una metodologia per la valutazione della sicurezza, Recupero e Conservazione 18 (1997), 26-34 [in Italian].
[8] A.A. Pollock, Acoustic emission-2: Acoustic emission amplitudes, Non-Destructive Testing 6 (1973), 264-269.
[9] A. Carpinteri, G. Lacidogna, G. Niccolini, Acoustic emission monitoring of medieval towers considered as sensitive earthquake receptors, Nat. Hazards Earth Syst. Sci. 7 (2007) 251-261.
[10] D.L. Turcotte, Fractals and Chaos in Geology and Geophysics, Cambridge University Press, Cambridge, 1997.
[11] E. Bonnet, O. Bour, N.E. Odling, P. Davy, I.P. Main, P. Cowie, B. Berkowitz, Scaling of fracture systems in geological media, Rev. Geophys. 39 (2001), 347-383.
[12] A. Carpinteri, Scaling laws and renormalization groups for strength and toughness of disordered materials, Int. J. Solids & Structures 31(3) (1994), 291-302.
[13] A Carpinteri,. G. Lacidogna, F. Accornero, A. Mpalaskas, T.E. Matikas, D.G. Aggelis, Influence of damage in the acoustic emission parameters, Cement Concrete Comp. 44 (2013), 9-16.
[14] P.A.Varotsos, N.V Sarlis., E.S. Skordas, Natural Time Analysis: The New View of Time; Springer, Berlin/Heidelberg, Germany, 2011.
[15] P.A.Varotsos, N.V Sarlis., E.S. Skordas, Uyeda, S.; Kamogawa, M. Natural time analysis of critical phenomena. Proc. Natl. Acad. Sci. USA 108 (2011), 11361-11364.
[16] G. Hloupis, I. Stavrakas, E.D. Pasiou, D. Triantis, S.K. Kourkoulis, Natural time analysis of acoustic emissions in Double Edge Notched Tension (DENT) marble specimens, Procedia Eng. 109 (2015), 248-256.
[17] A. Carpinteri, G. Lacidogna, A. Manuello, G. Niccolini, A study on the structural stability of the Asinelli Tower in Bologna, Struct. Control Health Monit. 23 (2016), 659-667.
[18] A. Carpinteri, G. Niccolini, G. Lacidogna, Time Series Analysis of Acoustic Emissions in the Asinelli Tower during Local Seismic Activity, Appl. Sci. Journal 8(7) (2018), 1012-1021.
[19] A. Cecchi, A. Tralli, A homogenized viscoelastic model for masonry structures, Int. J. Solids Struct. 49 (2012), 1485-1496.
[20] R.H. Pritchard, E.M. Terentjev, Oscillations and damping in the fractional Maxwell materials, J. Rheol. 61 (2017), 187-203.
[21] C.F. Richter, Elementary Seismology, W.H. Freeman and Company: San Francisco, CA, USA, London, UK, 1958.
[22] T. Shiotani, K. Fujii, T. Aoki, K. Amou, K., Evaluation of progressive failure using AE sources and improved *b*-value on slope model tests, Prog. Acoust. Emiss. VII (1994), 529-534.
[23] P.R. Sammonds, P.G. Meredith, S.A.F. Murrel, I.G. Main, Modeling the evolution of damage in rock containing porefluid by acoustic emission, in: Proceedings of the Eurock'94, Delft, The Netherlands, 29–31 August 1994.
[24] S. Colombo, I.G. Main, M.C. Forde, Assessing damage of reinforced concrete beam using "*b*-value" analysis of acoustic emission signals, J. Mater. Civil Eng. ASCE 15 (2003), 280-286.
[25] G.P. Gregori, G. Paparo, M. Poscolieri, A. Zanini, Acoustic emission and released seismic energy, Nat. Hazards Earth Syst. Sci. 5 (2005), 777-782.
[26] A. Carpinteri, G. Lacidogna, G. Niccolini, N. Pugno, Morphological fractal dimension versus power-law exponent in the scaling of damaged media, Int. J. Damage Mech. 18 (2009) 259-282.
[27] A. Anzani, L. Binda, A. Carpinteri, G. Lacidogna, A. Manuello, Evaluation of the repair on multiple leaf stone masonry by acoustic emission, Mater. Struct. 41 (2008), 1169-1189.