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Acoustic emission monitoring of Italian historical buildings and the case study of the Athena temple in Syracuse

Giuseppe Lacidogna[a]*, Amedeo Manuello[a], Gianni Niccolini[b] and Alberto Carpinteri[a]

[a]*Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino 10129, Italy;* [b]*National Research Institute of Metrology – INRIM, Strada delle Cacce 91, Torino 10135, Italy*

Historical buildings often show diffused crack patterns due to different causes in relation to original function, construction technique and loading history. Non-destructive testing methods applied as *in situ* monitoring systems allow reliable evaluation of the state of conservation of these structures and its evolution in time. At first, in this paper different case studies are briefly presented to show the acoustic emission (AE) technique capability on damage evolution assessment in ancient brick and stone artworks, and to understand the most probable cause of evolving damage. Therefore, the specific case of the Syracuse Athena Temple, located in Sicily (Italy), is shown in detail. In this study, the AE technique was used to assess the evolution of damage in a pillar, which is part of the vertical load-bearing structure. By applying the AE source localization method, it proved possible to identify the microcrack initiation points inside the pillar, showing the presence of a damaging phenomenon that is evolving slowly but progressively. Finally, considering the AE data and the seismic records in a ray of 50 km from the Syracuse Athena Temple, a strong correlation between AE and the sequence of nearby earthquakes has been observed. This suggests that AE structural monitoring coupled with the analysis of local earthquake activity can be a tool of crucial importance in earthquake damage mitigation.

Keywords: acoustic emission; cracking evolution; damage localization; masonry constructions; structural assessment

Introduction

For some years, the authors have been conducting research through the application of a material and structure control method based on the spontaneous emission of pressure waves from evolving defects. With the acoustic emission (AE) monitoring technique, the ultrasound signals emitted by damage phenomena are received by wide-band piezoelectric sensors, that is, sensors calibrated for a frequency range between 50 and 800 kHz (Carpinteri and Lacidogna 2006, 2007a, 2007b, 2008, Anzani *et al.* 2008).

The AE technique is non-invasive and non-destructive and therefore is ideally suited for use in the assessment of historic and monumental structures that are subjected to high, long-term loads or cyclic loads, or, more generally, are exposed to seismic risk. Having to identify the fractured or damaged portion of a structure, it is possible to evaluate its stability from the evolution of damage, which may either gradually come to a halt or propagate at an increasingly fast rate (Shiotani *et al.* 1994, Ohtsu 1996, Carpinteri and Lacidogna 2006). Moreover, if the position of the defects is not known to begin with, it can be located by making use of a multiplicity of sensors and by triangulation, prior to assessing the stability of a structure based on the evolution of damage phenomena (Shah and Li, 1994, Grosse *et al.* 1997, Carpinteri *et al.* 2006).

Using the AE technique, the authors have acquired considerable experience in the monitoring of historical buildings and monuments (Carpinteri and Lacidogna 2006, 2007a, 2007b, 2008, Anzani *et al.* 2008, Carpinteri *et al.* 2009a, 2009b, 2012, Niccolini *et al.* 2011). At first, different case studies are briefly presented to show the AE technique capability on damage evolution assessment in ancient brick and stone artworks.

An interesting study focused on the structural stability of the medieval towers of Alba, a characteristic town in Piedmont (Italy). In particular, for the ‘Sineo Tower’, leaning on the north side by about 1%, the stability under the influence of dead loads was investigated, whereas the impact of earthquakes on damage evolution was assessed for all the towers (Carpinteri and Lacidogna 2006, 2007a). However, the AE technique is ideally suited not only to control the evolution of structural damage caused by pulse phenomena, such as wind and seismic actions, but also by repetitive phenomena, such as the action of vehicle traffic. With this aim, the AE data were used to assess the stability of the ‘Asinelli Tower’ in Bologna (Italy) (Carpinteri *et al.* 2012). Another original application of the AE technique, which the authors are currently carrying on, is on the evaluation of the state of conservation of mural paintings and their mural supports. In particular, this study is in progress

*Corresponding author. Email: giuseppe.lacidogna@polito.it

on the painting surfaces of the Monte Tabor Chapel, in the UNESCO Reserve of 'Sacro Monte' of Varallo in Piedmont (Italy) (Riserva Naturale Speciale, 2012).

Therefore, the specific case of the Syracuse Athena Temple monitoring – actually the Syracuse Cathedral – located in Sicily (Italy) is shown in detail (Carpinteri *et al.* 2009a, 2009b, Niccolini *et al.* 2011). The Cathedral, placed in the higher zone of the Ortigia island, has been included in the UNESCO World Heritage List since 2005. It presented different evidence of criticism in correspondence to the ancient pillars situated in the central nave of the monument. The Cathedral in fact, is the result of the transformation of the ancient Athena's Greek Temple (fifth century BCE), with modifications that have also been the consequence of the damage caused by earthquakes. At the present time, the structure shows an extended damage pattern, especially in four of the nave pillars (Privitera 1863, Russo 1991, Agnello 1996, Binda *et al.* 2004).

In this study, the AE technique was used to determine the damage level in a pillar that was part of the vertical bearing structure of the Cathedral. By applying the AE source localization method, it proved possible to identify approximately 50 microcrack initiation points inside the pillar, showing the presence of a damaging phenomenon that is evolving slowly but progressively. The damage evolution in the stonework structure of the pillar is described by a power law characterized by a non-integer exponent, β_t. In this way, the time dependence of damage is evaluated by working out the β_t exponent and making a prediction of the stability conditions of the monitored element. Finally, we analyse the time correlation between the AE bursts from the pillar of the Temple, and the occurrence of nearby earthquakes.

AE monitoring of historical buildings and monuments

It has been said in the Introduction that the AE technique was very usefully adopted by the authors in order to investigate a wide series of structural problems related to brick and stone masonry artworks. In particular, it has been used to assess the damage evolution in important Italian monuments, to understand the residual capability of ancient brick masonry under loading, or to evaluate the reliability of reinforcing techniques employed in historical bearing structures (Carpinteri and Lacidogna 2006, 2007a, Anzani *et al.* 2008, Carpinteri *et al.* 2009a, 2009b, Niccolini *et al.* 2011, Ris. Nat. Spec., 2012).

The leading-edge equipment adopted by the authors consists of six units unit for storage acoustic emission monitoring (USAM) that can be synchronized for multichannel data processing. The most relevant parameters acquired from the signals (frequencies in a range between 50 and 800 kHz, arrival time, amplitude, duration, number of events and oscillations) are stored in the USAM memory and then downloaded to a PC for multi-channel data processing. Microcracks localization is performed from this

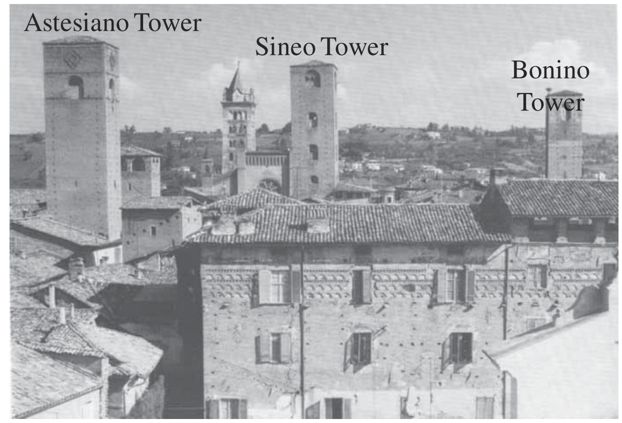

Figure 1. Astesiano, Sineo and Bonino Towers in the skyline of the City of Alba.

elaboration and the condition of the monitored specimen can be determined (Shah and Li 1994, Carpinteri *et al.* 2006).

In particular, the medieval towers of Alba have been monitored by the AE technique. These masonry buildings from the XIIIth century are among the tallest and mightiest medieval towers preserved in Piedmont (Figure 1). Sineo Tower is square, 39 m high, and leans to a side by about 1%. Wall thickness ranges from 2 m at the foundation level to 0.8 m at the top. The bearing walls are a sacco, that is, consist of brick faces enclosing a mixture of rubble and bricks bonded with lime and mortar. Over a height of 15 m, the tower is incorporated in a later building. Astesiano Tower has a similar structure, but has a rectangular base. The total height is about 36 m and the tower does not lean on any side. Torre Bonino, just under 35 m high, is the least imposing of the towers analysed, but the square-shaped structure has been incorporated in a valuable building from the Italian Art Nouveau period.

For the Sineo Tower, through AE monitoring, two cracks were detected in the inner masonry layer at the seventh floor level (Figures 2a and 2b). The monitoring process revealed an ongoing damaging process, characterized by slow crack propagation inside the brick walls. In the most damaged zone, crack spreading had come to a halt, the cracks having achieved a new condition of stability, leading towards compressed zones of the masonry. In this particular case, it can be seen that, in the monitored zone, each appreciable crack advancement is often correlated to a seismic event. In the diagram shown in Figure 2d, the cumulative AE function relating to the area monitored is overlaid with the seismic events recorded in the Alba region during the same time period; the relative intensity of the events is also shown (Carpinteri and Lacidogna 2006, 2007a).

A similar behaviour was observed for the Astesiano Tower. This structure was monitored by means of two transducers applied to the inner masonry layer of the tower, at the fourth floor level near the tip of a large vertical crack. The results obtained during the monitoring period are summarized in Figure 2e. It can be seen how the damage to

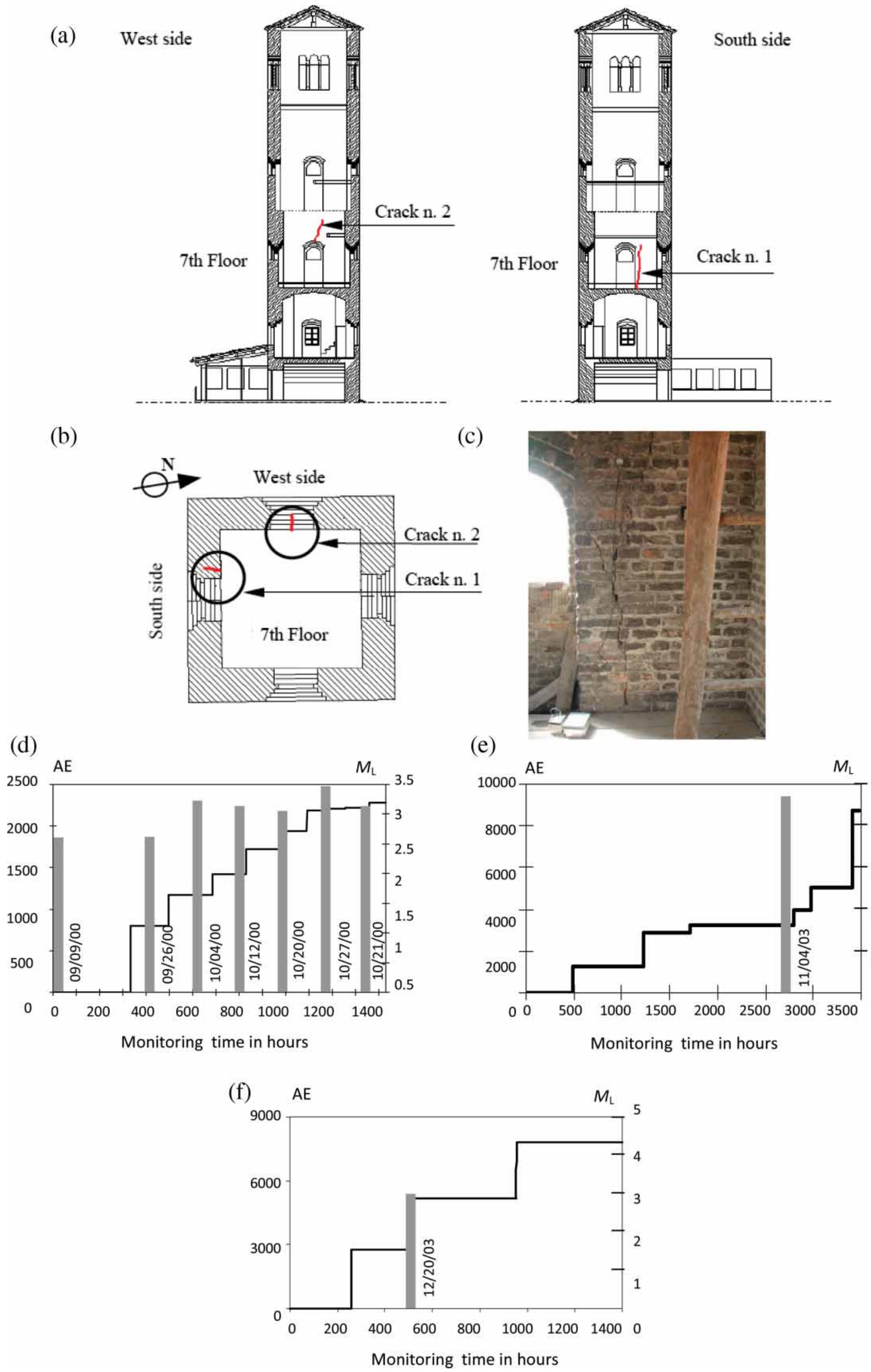

Figure 2. Cross-sections of the Sineo Tower (a), plan of the monitored zone (b), photo taken during the monitoring of crack no. 1 (c). AE counting number and seismic events in local Richter scale magnitude (M_L). Torre Sineo (d), Torre Astesiano (e) and Torre Bonino (f).

the masonry and the propagation of the cracks, as reflected by the cumulative number of AE counts, evolved progressively over time. A seismic event of magnitude 4.7 on the Richter scale occurred during the monitoring period: from the diagram we can see how the cumulative function of AE counts grew rapidly immediately after the earthquake. For Torre Bonino, monitored at first floor level, a progressive release of energy is observed under constant loading, this is

Figure 3. Photos of the Asinelli Tower and the Garisenda Tower in the city centre of Bologna.

due to a pseudo-creep phenomenon in the material. A seismic event of magnitude 3.0 on the Richter scale occurred during the monitoring period (Figure 2f).

During the observation period, the towers behaved as sensitive earthquake receptors. Thus, as can be seen, the AE technique is able to analyse state variations in a certain physical system and to identify, well in advance, the premonitory signals that precede a ‘catastrophic’ event (Gregori and Paparo 2004, Gregori *et al.* 2005, Niccolini *et al.* 2011).

The AE technique was also used to assess the structural stability of the Asinelli Tower, the tallest building in the city of Bologna (Italy), which, together with the nearby tower, named Garisenda, is the renowned symbol of the city (Figure 3) (Carpinteri *et al.* 2012). The Asinelli Tower was built in the early XIIth century, and it rises to a height of 97.30 m above the ground. It has a square cross-section, tapering along its height, the sides measuring ca 8.00 m at the base and 6.50 m at the top.

Studies conducted in the early twentieth century revealed that the Asinelli Tower leaned westward by 2.25 m, other recent studies have confirmed that its leaning is of 2.38 m: this is the reason why it is known as the tallest leaning tower in Italy.

AE monitoring began on 23 September 2010 and ended on 28 January 2011. It was carried on for ca 2915 h, corresponding to 122 consecutive days. From the monitoring process carried out on a significant part of this tower, it was possible to evaluate the incidence of vehicle traffic, seismic activity and wind action on the progress of fracture and damage phenomena within the structure. As regards the effects of vehicle traffic, it was observed that the structure is sensitive to traffic action in the areas surrounding the tower, particularly in the hours when it is most intense, that is, between 3:00 and 4:00 PM. Moreover, during the monitoring period a correlation between peaks of AE activity in the structure and regional seismicity was

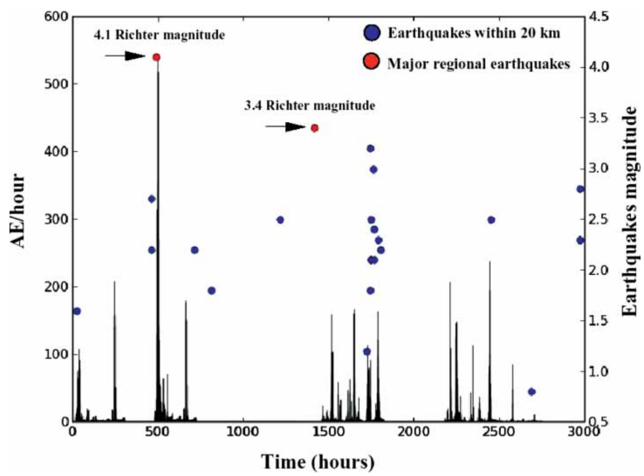

Figure 4. Historic series of the AE differential count and the earthquakes detected within a 20-km radius from the Bologna city centre. The chart also shows the two strongest regional earthquakes, which occurred in the Rimini area and in the Modena Apennines. This chart refers to the entire monitoring period.

found (see Figure 4) (Carpinteri *et al.* 2012). The tower, in fact, as in the case of the medieval towers of Alba, is very sensitive to earthquake motions.

As mentioned in the Introduction, the authors are also successfully applying the AE technique, not only to evaluate the stability of the historical structures, but also to assess the state of conservation of mural painting and their supports.

This particular applications of the AE technique have been performed on the masonry structure of the Monte Tabor Chapel built in the XVIth century in the UNESCO Reserve of ‘Sacro Monte’ of Varallo in Piedmont, Italy (Figures 5a and 5b) (Riserva Naturale Speciale Ris. Nat. Spec., 2012). The preservation of mural painting heritage is a complex problem that requires the use of innovative non-destructive investigation methodologies to assess the

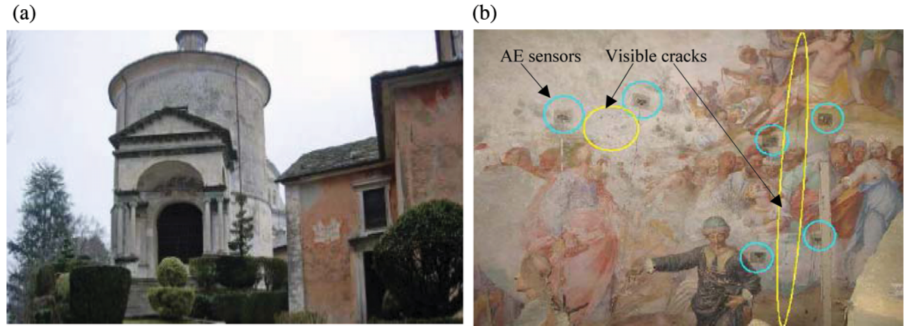

Figure 5. The Monte Tabor Chapel in the reserve of Varallo (a). Positions of the AE sensors applied into the internal wall of the chapel near visible cracks (b).

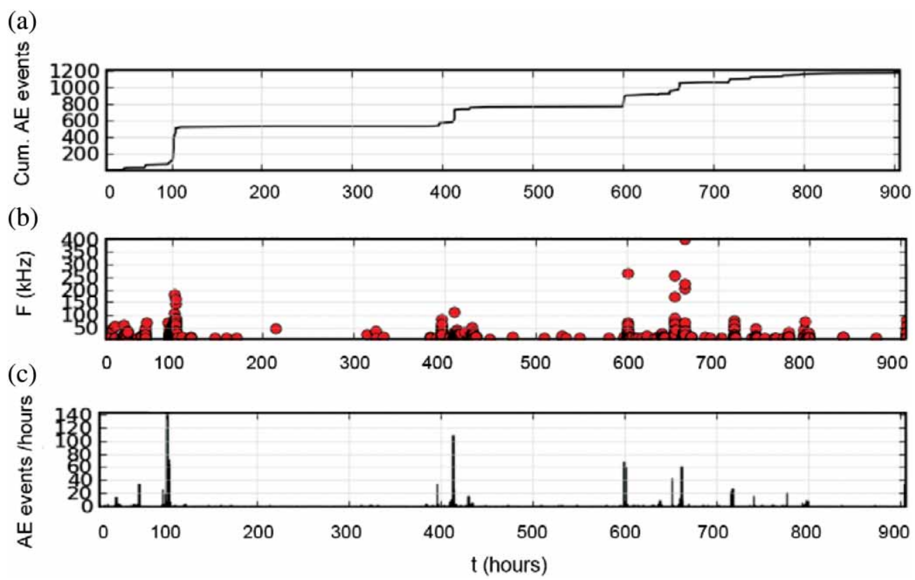

Figure 6. AE signals obtained during the internal decorated surfaces monitoring of the Monte Tabor Chapel. Cumulated AE events number (a), frequencies distribution (b) and AE count rate per hour (c).

integrity of decorated artworks without altering their state of conservation. The AE technique – giving a complete diagnosis of crack patterns on the external decorated surface and on the internal support – is particularly useful to avoid internal defects and damage phenomena that may suddenly degenerate into irreversible failure. Monitoring the support of a decorated surface by means of the AE technique, it becomes possible to detect the occurrence and evolution of surface vs. support separation and stress-induced cracks.

The AE signals, obtained during the monitoring of decorated surfaces inside Monte Tabor Chapel, are represented in Figure 6 in terms of cumulated AE events number, frequencies distribution and AE count rate per hour.

The Syracuse Athena temple

The Cathedral of Syracuse that presents a beautiful baroque façade (Figure 7a) shows in different parts of its structures traces of the destructive earthquake that struck the city of Syracuse in 1542 (see Figure 7b). In the sixth century AD, the fifth century BCE, the Greek temple of Athena in Syracuse, was transformed into a Catholic Church, and later became the Cathedral of the City; the building was frequently modified along the centuries until the present configuration (Figure 7c) (Privitera 1863, Russo 1991, Agnello, 1996, Binda *et al.* 2004). The internal pillars have a peculiar interest; they had been obtained from the stonework walls of the internal cell of the Greek temple. The pillars show several repaired areas and replacements, but also several cracks. In order to evaluate their state of preservation, the extension and the depth of the replacements and the presence of internal defects, an investigation programme was planned by the Superintendence of Syracuse and the Politecnico of Milan (Binda *et al.* 2004).

The crack pattern was classified and accurately documented and reported on the geometrical survey. Furthermore, a monitoring of the cracks development carried out for approximately 2 years showed an evident trend to increase their size in some cracks of the pillars positioned at the end of the central nave, which suggested a further check of the damage by acoustic emission (Carpinteri *et al.* 2009a, 2009b, Niccolini *et al.* 2011).

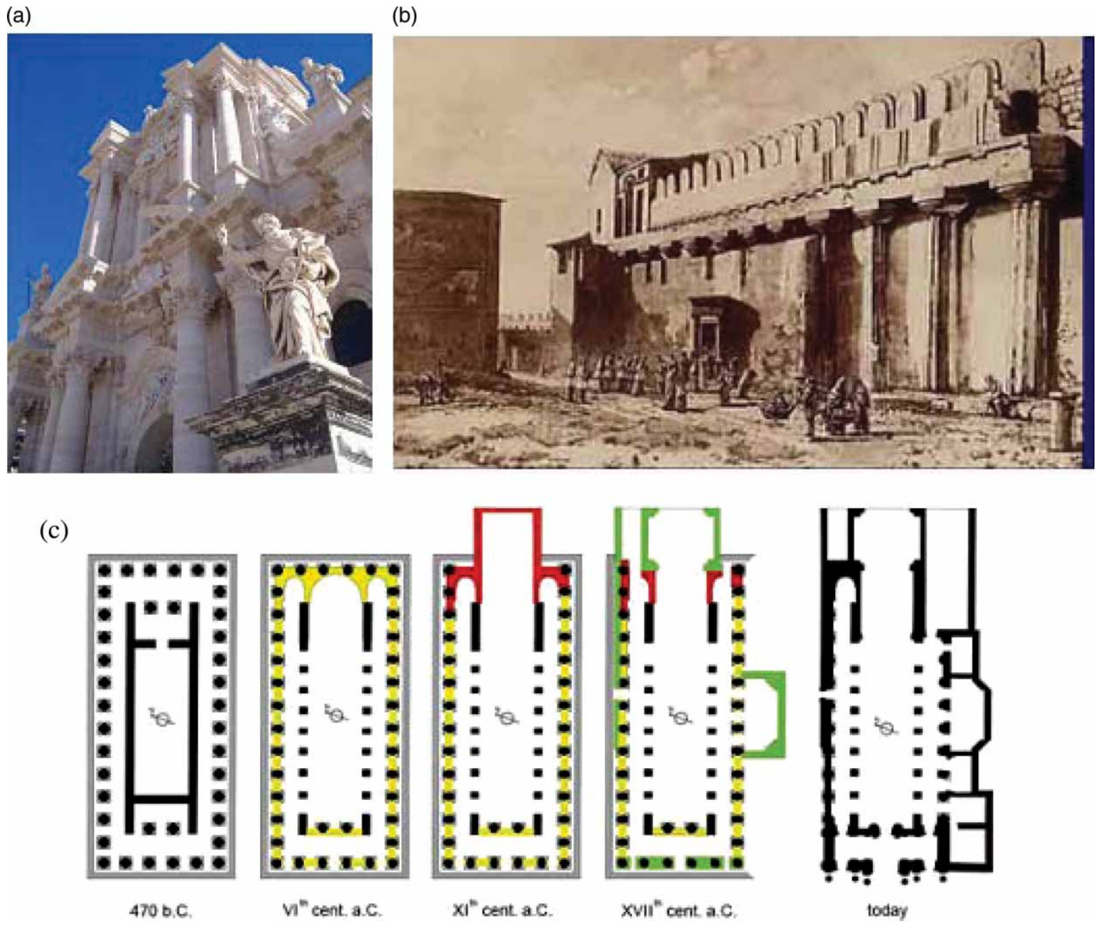

Figure 7. The façade of the Syracuse Cathedral (a). A historical view after the 1542 earthquake (b). The evolution of the plan along centuries (c) (Privitera 1863, Russo 1991, Agnello 1996, Binda *et al.* 2004).

AE monitoring of the ancient pillar

The AE monitoring process was performed on a pillar of the central nave (Figures 8a–8c). The temple had 14 columns along the sides and 6 at front, and some of them, belonging to the peristyle and the stylobate, can still be identified. In the layout of the Cathedral, shown in Figure 8a, the pillar selected for the application of the AE monitoring technique is indicated by a circle. On this element, situated towards the altar, serious damage is observed. It is important to stress the effects of the 1542 earthquake, which produced a great deformation of the perimeter wall close to the pillar.

The pillar, save for a few strengthening works performed – according to the Syracuse Superintendence for Cultural Heritage – during a restoration process in 1926 (see Figure 8d) was thought to be made of limestone blocks, probably installed during the initial construction of the temple dedicated to Athena in the fifth century BCE.

The AE equipment adopted by the authors consists of six units, USAM, synchronized for multi-channel data processing (Carpinteri and Lacidogna 2006, 2007a, 2007b, 2008, Anzani *et al.* 2008). The six AE sensors have been applied on the middle zone of the pillar (Carpinteri *et al.* 2009a, 2009b, Niccolini *et al.* 2011) (see Figures 8b and 8c). The monitoring process began at 11:00 a.m. of 19 September 2006 and ended at 12:20 p.m. of 21 January 2007. The data collected were analysed in order to interpret the evolution of damage and determine the position of AE sources within the pillar.

Cumulated AE events number, instantaneous AE rate averaged over 1 h in the temple pillar and nearby earthquake occurrence (triangles) as functions of time are reported in Figure 9, considering a region within a radius of ca 50 km around the city of Syracuse (Figures 9a and 9b). The most relevant seismic events, with the local magnitude value, occurring during the same period are indicated in the graph.

If we examine the chart illustrating the differential function of AE counts, we can see sudden increases in the oscillation peaks occurring at certain intervals over time. It should be also noted that during the monitoring period, strong seismic actions were recorded in the area (see Figure 9c). Earthquake data for the period were obtained from the website: www.ct.ingv.it/Sismologia/GridSism.asp published by the Seismic Data Analysis Group of Catania (Gruppo di Analisi Dati Sismici – INGV-CT). From the wealth of data available, we selected the seismic events with a local magnitude (M_L) greater than 1.2 that had occurred

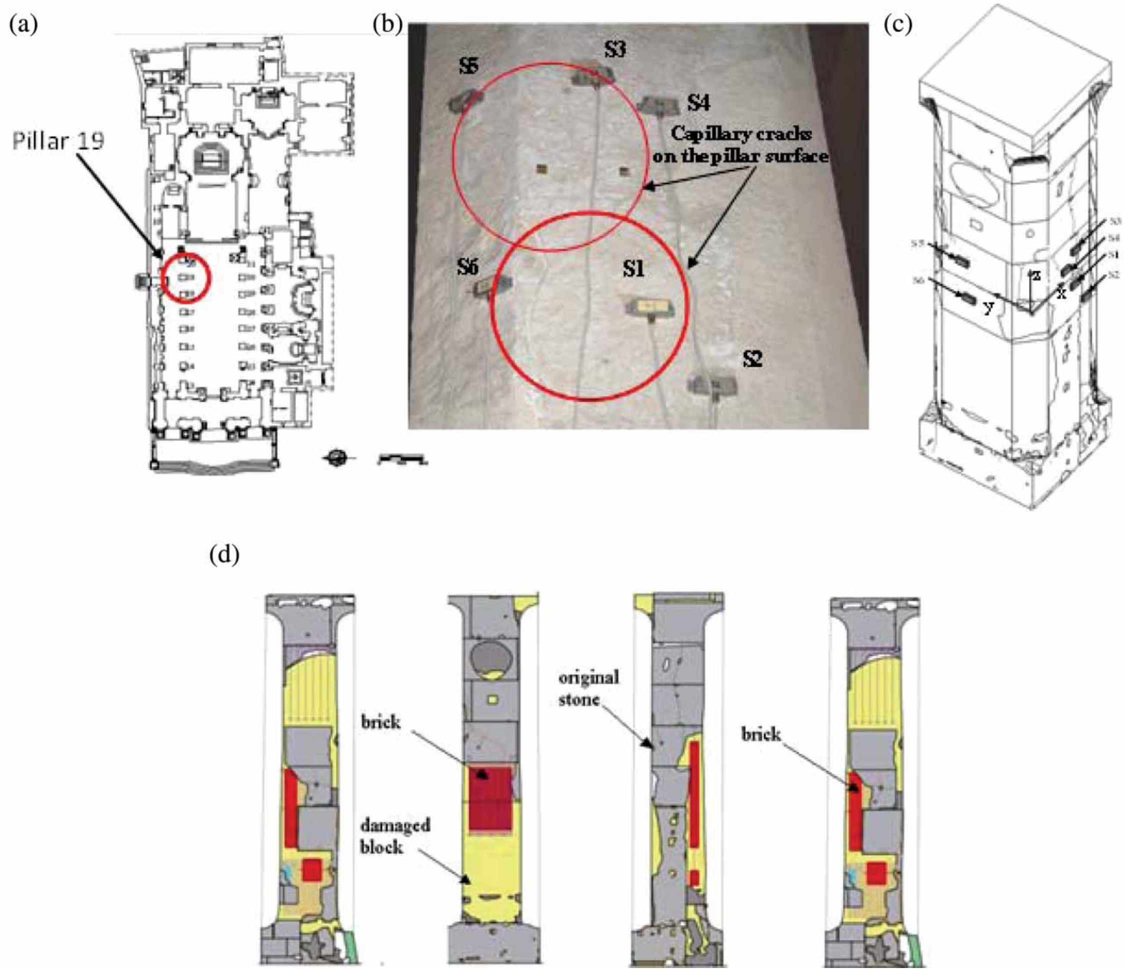

Figure 8. Plan of the Syracuse Cathedral with the indication of the monitored pillar (a). The AE sensors were applied on the external surface of the pillar at a high of about 4 m (b), (c). View of the four sides of the monitored pillar. In the figure various materials making the pillar are reported (d) (Binda *et al.* 2004, Carpinteri *et al.* 2009b).

during the monitoring period. These events are illustrated in Figure 9c, where the relative magnitudes are also given (Carpinteri *et al.* 2009a, 2009b).

The chart in Figure 9c, showing AE monitoring and regional earthquake data, reveals an interesting correlation between the AE activities determined experimentally and seismic events: the timing of the energy peaks measured by means of the AE differential counts is seen to coincide almost invariably with seismic shocks. This correspondence seems to show how the pillar monitored behaves in a pseudo-stable manner when subject to the vertical loads alone, but has a meagre capacity to respond elastically to horizontal or oscillatory actions.

Damage detection in the monitored pillar

During the monitoring of the pillar, the AE source localization was performed to identify the crack positions into the monitored structure. The first stage in the localization method consists in recognizing the data needed to identify the AE sources, followed by the triangulation procedure (Shah and Li 1994, Carpinteri *et al.* 2006). During the first stage, the groups of signals, recorded by different AE sensors, which fall into time intervals compatible with the formation of microcracks in the analysed volume, are identified. These time intervals, of the order of microseconds, are defined on the basis of the mutual distance of the sensors applied on the material surface. It is usual to assume that the amplitude threshold of 100 μV of the non-amplified signal is appropriate to distinguish between P-wave and S-wave arrival times. In fact, P waves are usually characterized by higher-amplitude signals (Shah and Li 1994). In the second stage, when the formation of microcracks in a three-dimensional space is analysed, the triangulation technique can be applied if signals recorded by at least five sensors fall into the time intervals.

Assuming that the AE waves propagate spherically reaching the AE sensors glued at the surface of the pillar, the solving equations for the crack localization can be trivially derived (see also Figure 10):

$$d_i - d_j = v_p \Delta t_{ij} \tag{1}$$

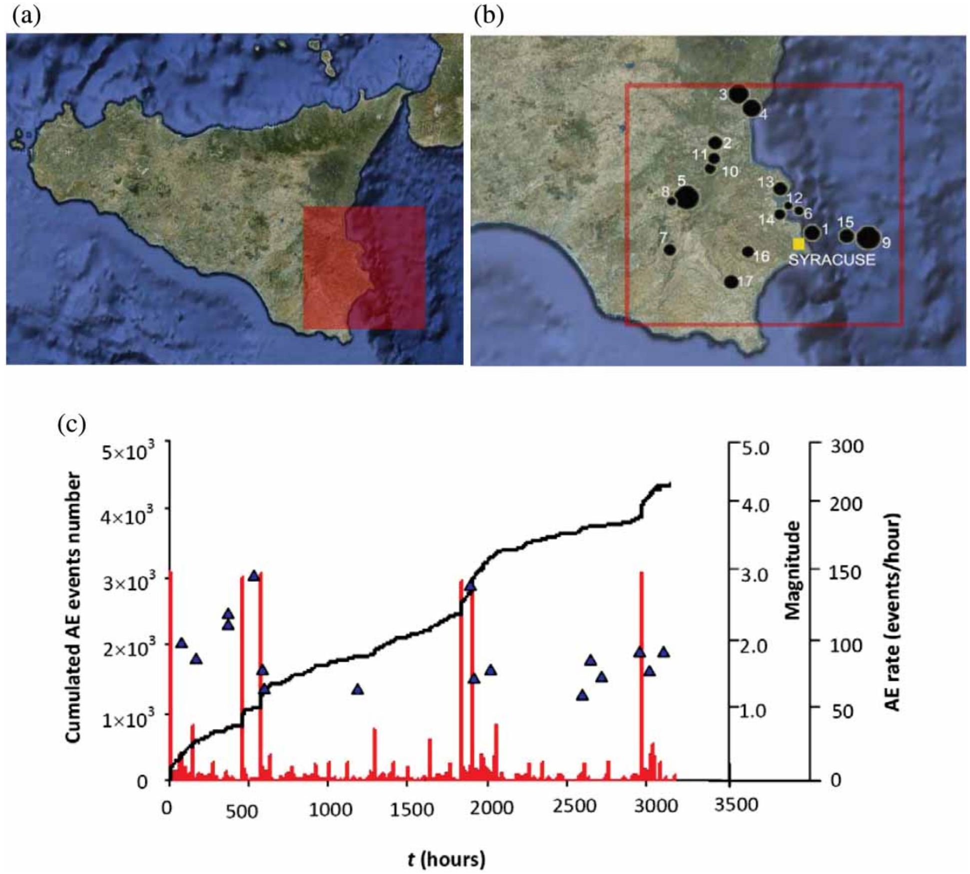

Figure 9. Map of Sicily showing the location of the monitored site (yellow square) and epicenters (black circles) of nearby earthquakes that occurred during the monitoring period (a), (b). Cumulated AE events number, instantaneous AE rate averaged over 1 hour in the temple pillar and nearby earthquake occurrence (triangles) as functions of time. The most relevant seismic events, with the local magnitude value, occurring during the same period are indicated in graph (c).

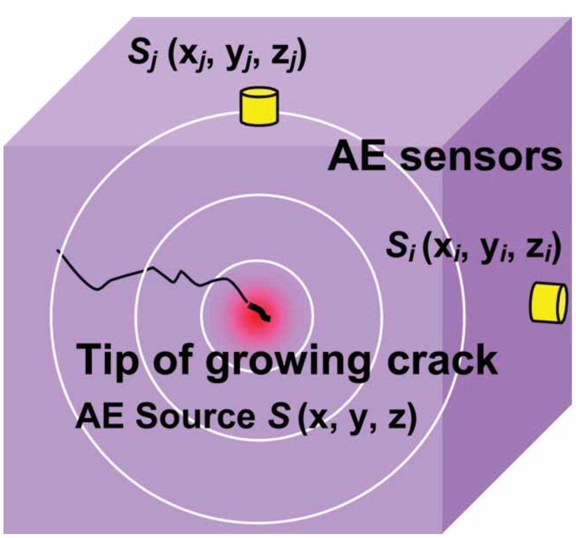

Figure 10. The first wave motion generated at t_0 in S (an AE event generated by an opening microcrack) propagates spherically and reaches the sensor S_i at time t_i and S_j at t_j.

where d_i is the Euclidean distance between the AE crack source and the ith sensor S_i:

$$d_i = \left[(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2\right]^{1/2} \qquad (2)$$

while $\Delta t_{ij} \equiv t_i - t_j$ is the measured arrival time difference for the first wave motion recorded at S_i and S_j.

Thus, with the procedure synthesized by Equations (1) and (2), it is possible to define both the position of the microcracks in the volume and the speed of transmission of P waves. The localization procedure was also performed through numerical techniques using optimization methods such as the least squares method (Carpinteri *et al.* 2006).

By applying the localization method described above more than 50 AE sources have been localized in the pillar with a high confidence level. The localized sources and the cracking pattern are represented in Figure 11. It can be noted that the localized sources are concentrated near the more visible crack paths. The localization of these source concentrations and the oscillation counting denounce that the pillar is subject to a damaging phenomenon in slow but progressive evolution.

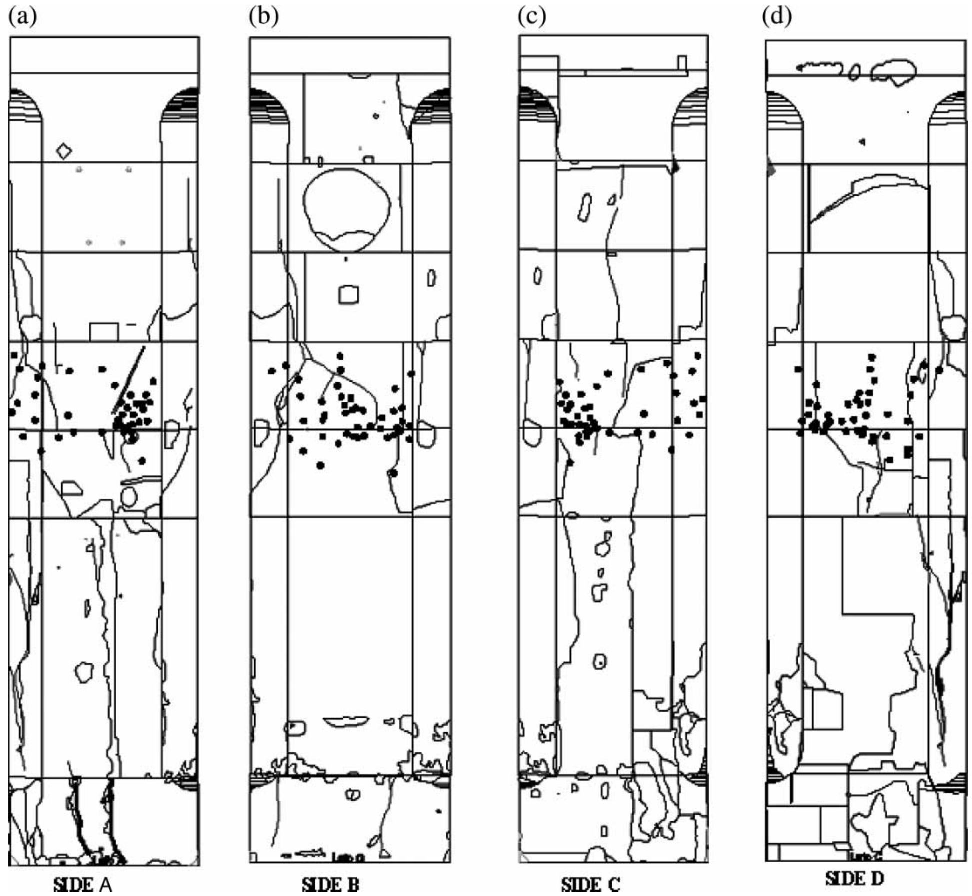

Figure 11. Cracking pattern and localization of AE sources for pillar.

The time dependence of the structural damage observed during the monitoring period, identified by parameter η, can also be correlated to the rate of propagation of the microcracks. If we express the ratio between the cumulative number of AE counts recorded during the monitoring process, N, and the number obtained at the end of the observation period, N_d, as a function of time, t, we get the damage time dependence on AE:

$$\eta = \frac{E}{E_d} = \frac{N}{N_d} = \left(\frac{t}{t_d}\right)^{\beta_t} \tag{3}$$

In Equation (3), the values of E_d and N_d do not necessarily correspond to critical conditions ($E_d \leq E_{\max}; N_d \leq N_{\max}$) and the t_d parameter must be construed as the time during which the structure has been monitored. By working out the β_t exponent from the data obtained during the observation period, we can make a prediction as to the structure's stability conditions. If $\beta_t > 1$, the damaging process slows down and the structure evolves towards stability conditions, in as much as energy dissipation tends to decrease; if $\beta_t > 1$ the process diverges and becomes unstable; if $\beta_t \cong 1$ the process is metastable, that is, though it evolves linearly over time, it can reach indifferently either stability or instability conditions (Carpinteri *et al.* 2009a, 2009b).

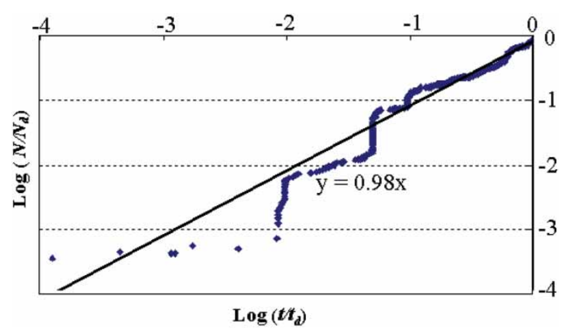

Figure 12. Evaluation of damage, β_t exponent for pillar.

During the observation period, which lasted about 84 days for the monitored pillar, the number of AE counts was $\cong$4300 (Figure 9c). In order to obtain indications on the rate of the damage process, as given in Equation (3), the data obtained with the AE technique were subjected to best-fitting in the bilogarithmic plane. This yielded a slant $\beta_t \cong 0.98$ as shown in Figure 12. The results confirm that the damage process in the pillar is in metastable conditions according to a quasi-linear progression over time.

Conclusions

After having briefly presented different case studies to show the AE technique capability on damage assessment of historical structures, the evolution of damage in a pillar that is part of the vertical bearing structure of the Syracuse Cathedral was evaluated.

The data collected were analysed in order to interpret the evolution of damage and to determine the positions of AE sources within the pillar. From the charts plotted for the differential and cumulative functions of the AE signal counts, it can be seen that the pillar is actually undergoing a damage process. Moreover, by applying the AE source localization procedure it was possible to identify approximately 50 emission points within the pillar. Within the stone blocks to which the sensors had been applied, the points were seen to concentrate along the cracks that could be discerned more clearly on the surface. The identification of these emission sources together with the oscillation counts shows that the pillar is indubitably undergoing a slow but incessant damage process.

Acknowledgements

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