MONITORING THE STRUCTURES OF THE ANCIENT TEMPLE OF ATHENA INCORPORATED INTO THE CATHEDRAL OF SYRACUSE

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SUMMARY

Some of the most significant architectural works are monumental masonry constructions, in stone or bricks. Among these, the Cathedral of Syracuse can be viewed as a fundamental element in the history and the cultural heritage of Europe. For the preservation of these monuments it is necessary to assess their durability by taking into account cumulative damage and cracking conditions in the structures, and the evolution of time-dependent phenomena such as creep. The adoption of the most advanced and innovative monitoring techniques is taking on ever greater importance in the analysis of this problem. The paper describes the methods used by the authors to determine the conditions of the materials and crack patterns in the structures of the Cathedral.

INTRODUCTION

In recent years, the authors have been working on the development of a method for the assessment of materials and structures based on the spontaneous release of pressure waves originated by the evolution of damage. This monitoring technique, referred to as Acoustic Emission (AE), is non invasive and non destructive and therefore is ideally suited for the control of historic and monumental structures in seismic areas (Carpinteri and Lacidogna 2006a, 2006b, 2007). With this technique, if it is not known, the initial position of the damage can be determined with the aid of a multiplicity of sensors and through triangulation (Carpinteri et al. 2006a). Once the damaged portion of a structure has been located, it becomes possible to evaluate the stability of the evolving damage, which may either come gradually to a halt or propagate at an ever faster rate.

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 of Syracuse (Sicily).

The pillars of the central nave, obtained cutting the walls of the temple cell, show a complex situation of damage and repairs. Remembering the partial collapse of the Noto Cathedral and its causes (Binda and Saisi, 2003a) the Superintendent M. Muti of the Syracuse C.H. Office supported an experimental and analytical research on the state of the Cathedral.

DESCRIPTION OF THE SYRACUSE CATHEDRAL

In the 6th century AD, the 5th century BC Greek temple of Athena in Syracuse, was transformed into a Catholic Church, and successively became the Cathedral of the city; the building was frequently modified along the centuries until the present configuration (Agnello, 1950; Agnello, 1996; Privitera, 1863; Russo, 1991; Russo, 1992).

Several styles and structural details belonging to the different times can be recognised: (i) in the external walls the ancient Greek columns and the filling wall between them of the Byzantine time, (ii) the baroque façade, (iii) the added apse and chapels. Furthermore, being Syracuse in a seismic area, the Cathedral was damaged, repaired or partially rebuilt several times (Agnello, 1950; Agnello, 1996). Figures 1 shows the evolution of the Cathedral plan along the centuries.

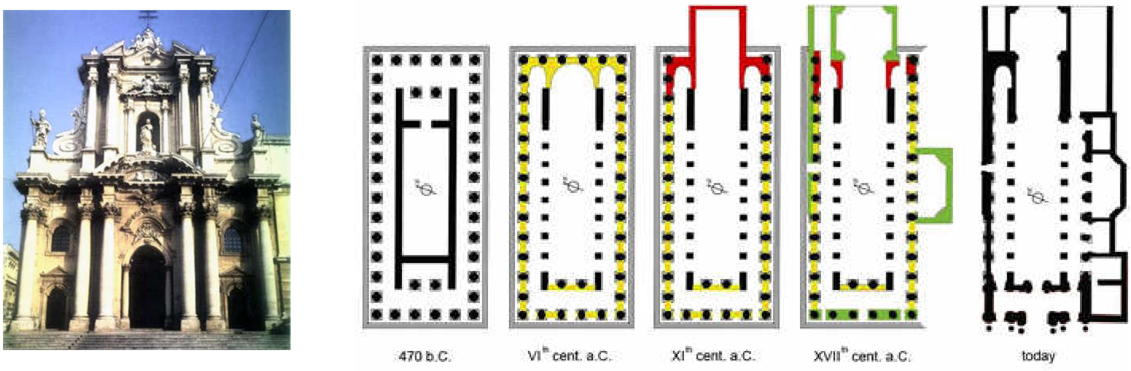


Figure1. The Cathedral and its evolution

The Cathedral pillars have a peculiar interest; they had been obtained cutting out the stonework walls of the internal cell of the Greek temple. The pillars show several repaired areas, 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 program was planned by the M. Muti and the Politecnico of Milan. As a first step, a survey of the pillars with an accurate mapping of the superficial materials, of the defects, of the cracks and of the morphology was carried out. The crack pattern was classified and accurately documented and reported on the geometrical survey Figure 2 gives an example of this documentation referred to two damaged pillars (see later also Figure 6). The cracks display frequently a vertical pattern due to compressive stresses, whose action is often combined with the compressive-bending stresses caused by frequent earthquakes. In some cases, the corners and part of the stone blocks were expelled. The mortar traces in these cases are trials to locally repair the damages. In the survey repaired cracks were cleared in order to evaluate the evolution of the damages.

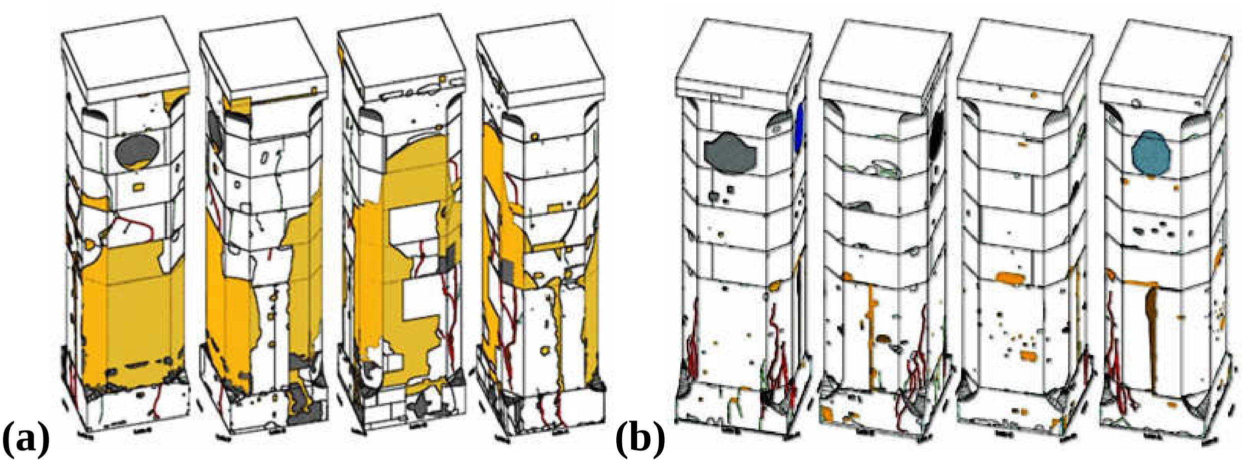


Figure 2. Cracks pattern survey of the pillars 19 (a) and 26 (b).

On the base of this detailed survey, NDT tests were performed in order to investigate the depth of the damage: (i) sonic and ultrasonic to find voids inside the pillars and the depth of the cracks respectively (in some cases up to 40cm), (ii) thermovision to detect the detachment of renders and repaired parts, (iii) radar to find internal cracks and inclusions (Figure 3).

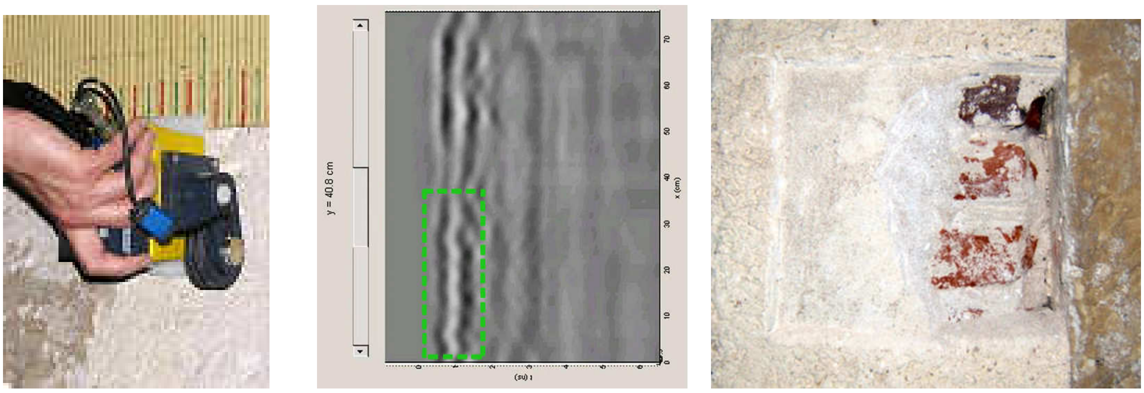


Figure 3. The radargram shows the presence of regularly spaced diffractions (about every 5-6 cm) at a depth of about 3-4 cm. The inspection proved that these pillars were sometimes repaired with bricks masonry instead of stone.

The complementarity of these NDTs already studied in (Binda et al., 2000; Binda et al., 2003b), could be successfully exploited to diagnose the state of damage of the pillars (Binda et al. 2006). Furthermore a monitoring of the cracks development carried out for approximately two years showed an evident trend to increase their size in some cracks of the pillars named 18, 19, 29 and 30, which suggested a further check of the damage by Acoustic Emissions.

THE STRUCTURE MONITORING

The monitoring process was performed on a pillar of the Cathedral of Syracuse. 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 2a, all the pillars and the columns inside the building are marked with a progressive number.

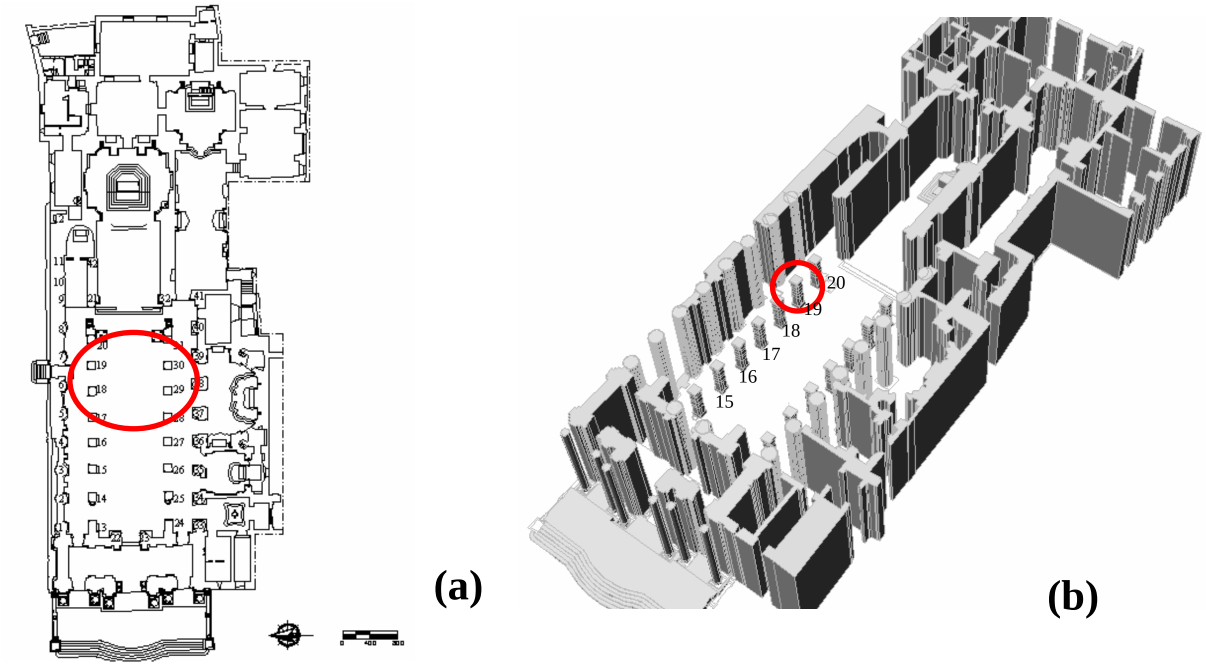


Figure 4. Plan of the Syracuse Cathedral. Pillars 19, 20, 30 and 31 are pointed out (a). Axonometric projection of the vertical bearing structures. Pillar 19 is indicated by a circle (b).

Basically, the Doric columns are marked with numbers in three ranges: 1-8; 22,23; 33-40; whereas the pillars, obtained from the calcareous stone masonry of the temple cell, are identified with the remaining numbers. As said above, from the survey of the cracks, it was determined that the pillars in the most critical conditions were nos. 18, 19, 29 and 30, all of them located near the end of the central nave (Figure. 4a). These pillars show an appreciable degree of deterioration, due to the presence of added layers of plaster and conspicuous cracks, which in some cases seem to cut the constituent stone blocks. Pillar no. 19, selected for the application of the AE monitoring technique, is shown in the axonometric view in Figure 4b.

The pillar (save for a few strengthening works performed – according to the Syracuse Superintendence for Cultural Heritage – during a restoration process in 1926) was thought to be made of limestone blocks, probably installed during the initial construction of the temple dedicated to Athena in the 5th century BC. The investigation revealed instead the presence of parts made with brick masonry and their lower stiffness is probably the cause of the damage developed in the stones.

APPLICATION OF THE AE TECHNIQUE

AE equipment and "in situ" applications details

Monitoring a structure by means of the AE technique proves possible to detect the occurrence and evolution of stress-induced cracks. Cracking, in fact, is accompanied by the emission of elastic waves which propagate within the bulk of the material. These waves can be received and recorded by piezoelectric (PZT) transducers applied to the surface of the structural elements. The signal is therefore analysed by a measuring system counting the emissions that exceed a certain voltage threshold measured in volts (V). The leading-edge equipment adopted by the authors for

the analysis on the vertical bearing structures of the Syracuse Cathedral consists of six units USAM®, that can be synchronized for multi-channel 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 a multi-channel data processing (see Figure 5). Microcracks localisation is performed from this elaboration and the condition of the monitored specimen can be determined (Carpinteri et al. 2006a, 2007a).

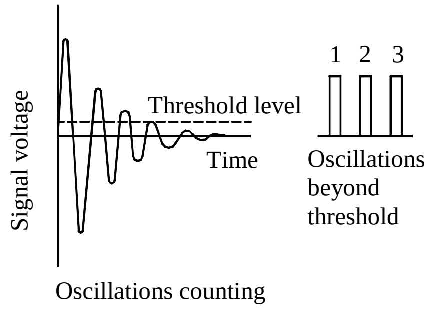
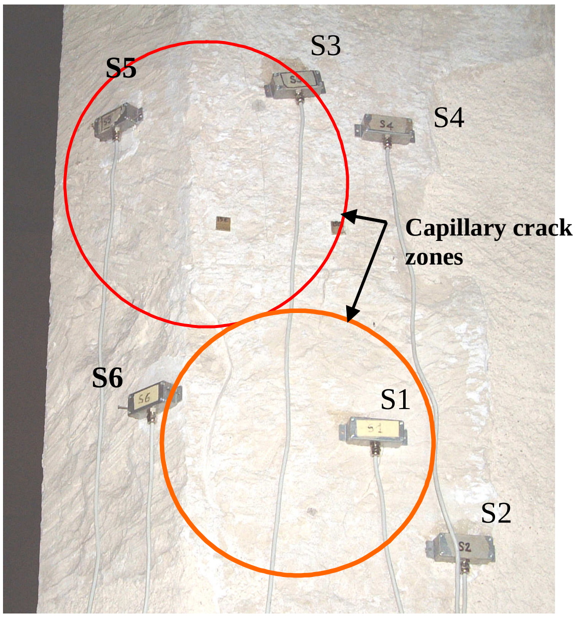


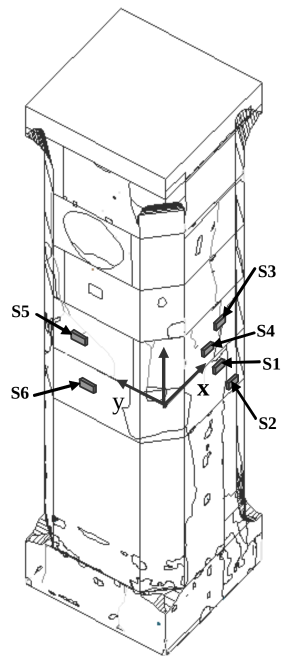
Figure 5. AE signal identified by the transducer.

On each side of element 19 an evident cracking pattern is observed. The AE sensors have been applied on the middle part of the pillar as shown in Figure 6a and b. In the Figure 6a the zones with capillar vertical cracks are indicated by circles.

The AE sensors arrangement is represented in Figure 6a according to the scheme reported in Figure 6b. The sensors were glued with silicone resin on two faces of the pillar. These resins are good ultrasound conductors and have the advantage of reducing to the minimum the attenuation of signal perception in the layer between the specimen surface and the applied sensor. The positions of applied sensors are listed in Table 1**.** The reference frame for the sensors position coordinates is shown in Figure 6b.

(a)





(b)

Figure 6. View (a) and axonometric projection (b) of the of AE sensor applied to the pillar 19.

Table 1 – Arrangement of the sensors applied to the pillar 19

AE Sensors	x [mm]	y [mm]	z [mm]
S1	539.7	0.00	–285
S2	679.7	0.00	–455
S3	434.7	0.00	335
S4	394.7	0.00	265
S5	0.00	410	330
S6	0.00	300	–220

RESULTS OF THE MONITORING PROCESS

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 positions of AE sources within the pillar.

The AE signal received by the transducers is processed by an analyser which counts the oscillations exceeding a certain voltage threshold. This makes it possible to plot cumulative curves reflecting the count number as measured continuously throughout the monitoring period. This method, referred to as *Ring-Down Counting*, is widely used for defect detection purposes (see Figure 5). As a first approximation, in fact, the count number *N*, i.e., oscillations per unit time (differential function) can be compared with the quantity of energy released during the monitoring process, and the relative sums (cumulative function) may be assumed to increase proportionately with the widening of the damaged zone. Needless to say, this assumption applies only if the damage evolves slowly (Brindley et al. 1973, Pollock 1973, Swindlehurst 1973, Carpinteri and Lacidogna 2006a).

Figure 7 shows the diagrams of the differential and cumulative functions obtained from the count numbers measured per day on pillar 19. These charts were plotted starting from the date of application of the sensors to the pillar up to the time when they were definitively removed. During the monitoring period, the threshold level for the input signals from the PZT transducers was always set to 100 μV. Based on the authors’ experience, this threshold level is the most significant for the reception of AE signals during a damage process in non-metal materials such as concrete and masonry (Carpinteri and Lacidogna 2006a, Carpinteri et al. 2007a, 2007b).

From the charts it can be seen that the pillar is actually undergoing a deterioration process. 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. These sudden increments are matched by leaps in the cumulative functions of AE counts. The AE counts in other time intervals seem to evolve in a virtually linear manner. It may therefore be assumed that the discontinuities in the cumulative function reflect the critical moments during which the amount of energy released – due to the evolution of damage in the structure – is highest.

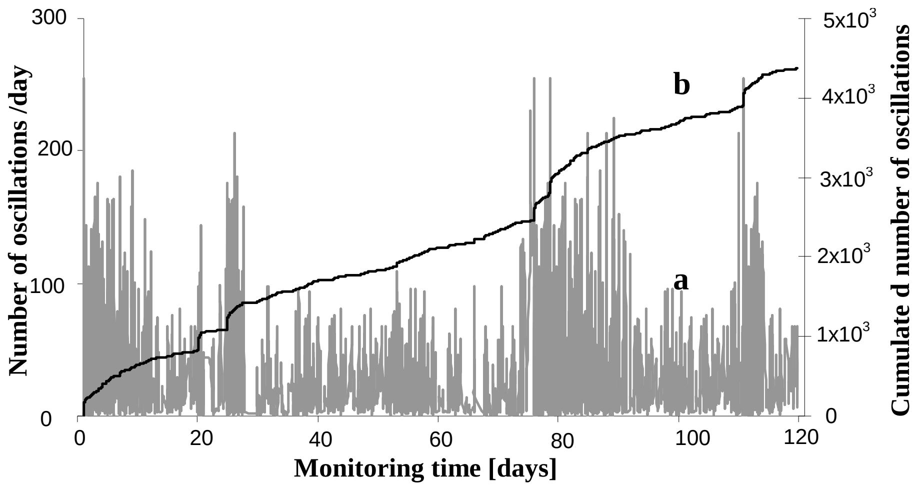


Figure 7. Differential (a) and cumulated (b) number of AE oscillations during the monitoring time on pillar 19.

DETECTION OF DAMAGE IN THE MONITORED PILLAR

Localisation of AE sources

The first stage of the localisation method consists in recognising the data needed to identify the AE sources, followed by the triangulation procedure. During the first stage, the groups of signals, recorded by the various sensors, that fall into time intervals compatible with the formation of microcracks in the volume analysed, are identified. These time intervals, of the order of micro-seconds, are defined on the basis of the presumed speed of transmission of the waves (*P*) and the mutual distance of the sensors applied to the surface of the material. It is usual to assume that the amplitude threshold of 100μV 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 value signals. In the second stage, when the formation of microcraks 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. Thus, with this procedure it is possible to define both the position of the microcracks in the volume and the speed of transmission of *P*-waves. The localisation procedure can also be performed through numerical techniques using optimisation methods such as the Least Squares Method (LSM) (Carpinteri et al. 2006a, Carpinteri et al. 2007a).

In the present work, applying the localisation procedure more than 50 AE sources have been localised with an high confidence level. Considering previous applications of the AE technique carried out by the authors, the approximation for elements with large size is about ± 10 mm (Carpinteri et al. 2006b). The localised sources and the cracking pattern for pillar 19 are represented in Figure 8. It can be noted that the localised sources are concentrated near the more visible crack paths. The localisation of these source concentration (Figure 8) and the oscillation counting (Figure 7) denounce that the pillar is subject to a damaging phenomenon in slow but progressive evolution.

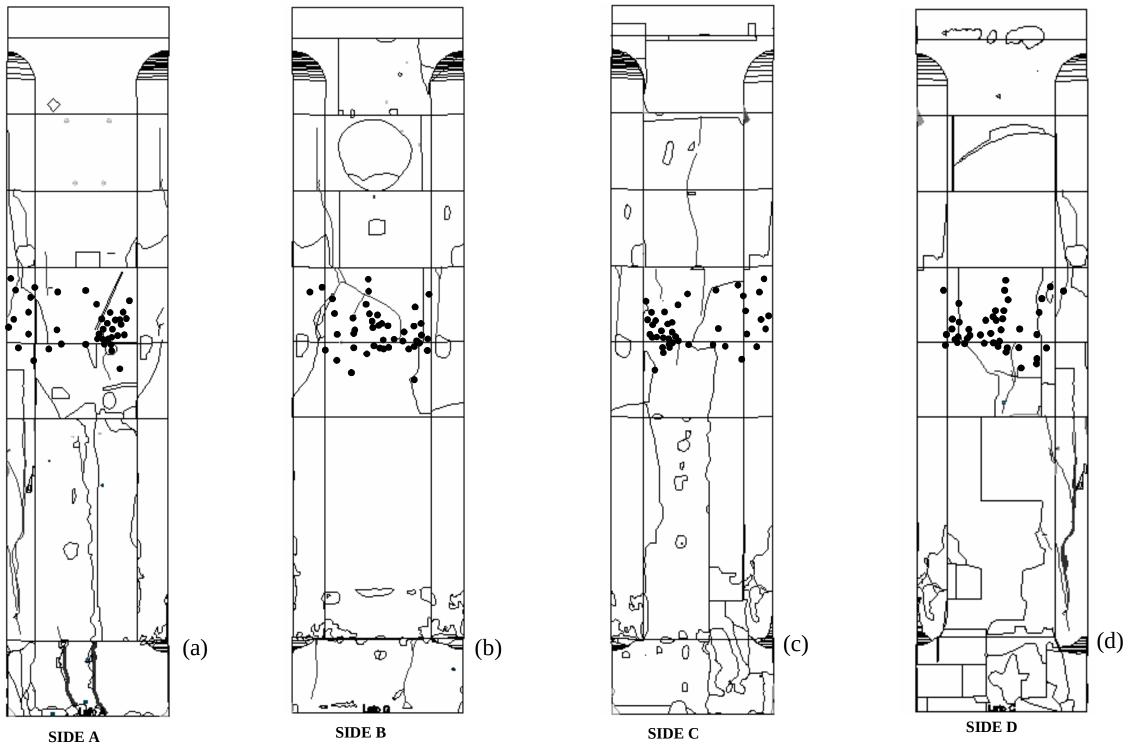


Figure 8. Cracking pattern and localisation of AE sources for pillar 19.

Time dependence of damage

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:

$$\eta = \frac{E}{E_d} = \frac{N}{N_d} = \left(\frac{t}{t_d}\right)^{\beta_t} . \quad (1)$$

In equation (1), 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, i.e., though it evolves linearly over time, it can reach indifferently either stability or instability conditions (Carpinteri and Lacidogna 2007b, Carpinteri and Lacidogna 2006a).

During the observation period, which lasted 121 days for the pillar 19 in the Syracuse Cathedral, the number of AE counts was $\cong$ 4300 (Figure 7). In order to obtain indications on the rate of the damage process in the pillar, as given in equation (1), 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 9. The result confirm that the damage process in the pillar is in metastable conditions according to a quasi-linear progression over time.

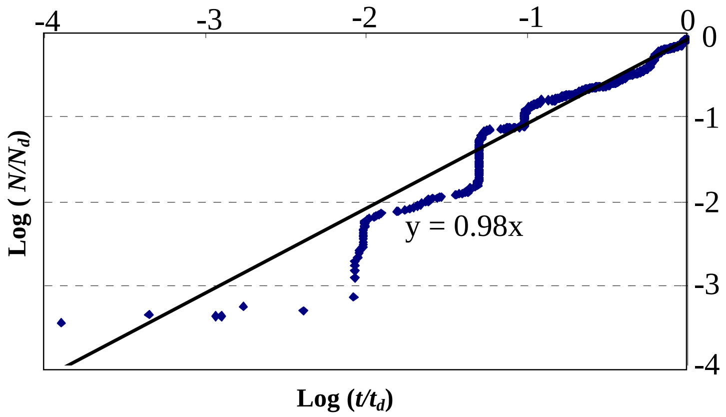


Figure 9. Evaluation of damage, β_t exponent for pillar 19.

CONCLUSIONS

The evolution of damage in a pillar made of calcareous stone blocks that is part of the vertical bearing structure of the Syracuse Cathedral was evaluated using the acoustic emission technique. The monitoring process was performed by means of the USAM® equipment available at the Fracture Mechanics Laboratory of the Structural Engineering Department of the Politecnico of Turin. With this equipment it proved possible to acquire a great quantity of data during the monitoring process and subsequently perform a full analysis of the AE signals.

The monitoring period 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 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 localisation procedure it was possible to identify ca 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. These results confirm much more in detail what was found by crack survey and monitoring and convinced the Superintendent to carry out for the moment a provisional confinement for pillars 18, 19, 29 and 30.

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REFERENCES

Agnello, G., "*Il Duomo di Siracusa e i Suoi Restauri*", a cura di S. L. Agnello, Ediprint, Siracusa, (in Italian), 1996.

Agnello, S.L., "La Rinascita Edilizia a Siracusa Dopo il Terremoto del 1693", *Archivio Storico Siciliano*, serie III, vol. IV, 1950-51, Palermo, 1950. (in Italian).

Binda, L., Saisi, A., **"**Compatibility Between Safety and Authenticity: the Experience of Noto Cathedral, Authenticity in the Restoration of Monuments", *WTA*, "*Wetenschappelijk- Technische Groep Voor Aanbevelingen*, ISSN 0947-4498, Leuven, Keynote Lecture, 2003a, pp. 1-11.

Binda, L., Cantini, L., Condoleo, P., Saisi, A., Zanzi, L., "Investigation on the Pillars of the Syracuse Cathedral in Sicily", 3-Day Int. Conf. Structural Faults & Repair, M.C. Forde (Ed.), Engineering Technics Press, Edinburgh, ISBN 0-947644-59-8, CD-ROM, 2006, pp. 1-12.

Binda, L., Saisi, A., Tiraboschi, C., "Investigation Procedures for the Diagnosis of Historic Masonries", *Construction and Building Materials*, ed. Elsevier-Norwich, Vol. 14, N. 4, 2000, pp. 199-233.

Binda, L., Lualdi, M., Saisi, A., Zanzi, L., "The Complementary Use of on Site Non Destructive Tests for the Investigation of Historic Masonry Structures", Proc. 9th North American Masonry Conference, (9NAMC), 2003b, pp. 978-989.

Brindley, B.J., Holt, J., Palmer, I.G., "Acoustic Emission-3: The Use of Ring-Down Counting", *Non-Destructive Testing*, Vol. 6, 1973, pp. 299-306.

Carpinteri, A., Lacidogna, G., "Damage Monitoring of an Historical Masonry Building by the Acoustic Emission Technique", *Materials and Structures*, Vol. 39, 2006a, pp. 161-167.

Carpinteri, A., Lacidogna, G., "Structural Monitoring and Integrity Assessment of Medieval Towers", *Journal of Structural Engineering (ASCE)*, Vol.132, 2006b, pp. 1681-1690.

Carpinteri, A., Lacidogna, G., "Damage Evaluation of Three Masonry Towers by Acoustic Emission", *Engineering Structures*, Vol. 29, 2007, pp.1569-1579.

Carpinteri, A., Lacidogna, G., Manuello, A., "Damage Mechanisms Interpreted by Acoustic Emission Signal Analysis", *Key Engineering Materials*, Vol. 347, 2007a, pp. 577-582

Carpinteri A., Lacidogna G., Niccolini G., "Critical Behaviour in Concrete Structures and Damage Localization by Acoustic Emission", *Key Engineering Materials*, Vol. 312, 2006a, pp. 305-310.

Carpinteri, A., Lacidogna, G., Paggi, M., "Acoustic Emission Monitoring and Numerical Modelling of FRP Delamination in RC Beams With Non-Rectangular Cross-Section", *Materials and Structures (RILEM)*, Vol. 40, 2006b, pp. 553-566.

Carpinteri, A., Lacidogna, G., Pugno, N., "Structural Damage Diagnosis and Life-Time Assessment by Acoustic Emission Monitoring", *Engineering Fracture Mechanics*, Vol. 74, 2007b, 273-289.

Pollock A.A.,"Acoustic Emission-2: Acoustic Emission Amplitudes", *Non-Destructive Testing*, Vol. 6, 1973, pp. 264-269.

Privitera, S., (1863), "*Illustrazioni sull'Antico Tempio di Minerva Oggi il Duomo di Siracusa, Memoria del Parroco Serafino Privitera*", Catania, Tipografia La Fenice Musumeci, (in Italian).

Russo, S., (1991), "La Cattedrale di Siracusa", *Archivio Storico Siracusano*, III V, (in Italian).

Russo, S., (1992), "*Siracusa Medievale e Moderna*", Arnaldo Lombardi, Palermo, (in Italian).

Swindlehurst W., "Acoustic Emission-1: Introduction", *Non-Destructive Testing*, v.6, 1973, pp.152-158.