

# Structural Monitoring and Integrity Assessment of Medieval Towers

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**Abstract:** This investigation concerns the structural stability of two medieval buildings, "Torre Sineo" and "Torre Astesiano," rising in the center of Alba, a characteristic town in Piedmont, Italy. The geometrical and structural aspects of these masonry towers were analyzed and tests were performed to assess the evolution of damage phenomena. The slant of the towers was determined with the customary topographic survey methods. Nondestructive testing methods were used, instead, to determine the extent of damage and cracking and to assess the evolution of these phenomena over time. The damage processes underway in some portions of the masonry were monitored using the acoustic emission (AE) technique. The latter method makes it possible to estimate the amount of energy released during the fracture process and to obtain information on the criticality of ongoing processes. Finally, an ad hoc theory based on fractal concepts for assessing the stability of masonry structures from the data obtained with the AE technique is proposed.

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## Introduction

Nondestructive and instrumental investigation methods are currently employed to measure and check the evolution of adverse structural phenomena, such as damage and cracking, and to predict their subsequent developments. The choice of a technique for controlling and monitoring reinforced concrete and masonry structures is strictly correlated with the kind of structure to be analyzed and the data to be extracted (Carpinteri and Bocca 1991; Anzani et al. 2000). For historical buildings, nondestructive evaluation (NDE) techniques are used for several purposes: (1) detecting hidden structural elements, such as floor structures, arches, piers, etc.; (2) determining masonry characteristics, mapping the nonhomogeneity of the materials used in the walls (e.g., use of different bricks during the life of a building); (3) evaluating the extent of the mechanical damage in cracked structures; (4) detecting voids and flaws; (5) determining moisture content and rising by capillary action; (6) detecting surface decay phenomena; and (7) evaluating the mechanical and physical properties of mortar and brick, or stone.

This study addresses some of the aforementioned problems deemed of special significance. Tower geometry was defined

through the customary survey methods. Damage, cracking, and the evolution of these phenomena over time were assessed through a number of nondestructive techniques: thermographic exams were performed on the main sets of the towers subjected to cracking phenomena; tests with flat-jacks were conducted in order to evaluate the range of stresses affecting the structures; and at the same time, the cracking processes taking place in some portions of the masonry structures were monitored using the acoustic emission (AE) technique.

The AE technique has proved particularly effective (Carpinteri and Lacidogna 2002, 2003, 2006), in that it makes it possible to estimate the amount of energy released during the fracture process and to obtain information on the criticality of the process underway. Strictly connected to the energy detected by AE is the energy dissipated by the structure being monitored. The energy dissipated during crack formation in structures made of quasi-brittle materials plays a fundamental role in the behavior throughout their life. Strong size effects are clearly observed in the energy density dissipated during fragmentation. Recently, a multiscale energy dissipation process has been shown to take place in fragmentation, from a theoretical and fractal viewpoint (Carpinteri and Pugno 2002a,b, 2003). Based on Griffith's assumption of local energy dissipation being proportional to the newly created crack surface area, fractal theory shows that the energy will be globally dissipated in a fractal domain comprised between a surface and a volume in the Euclidean space. According to fractal concepts, an ad hoc theory is employed to monitor masonry structures by means of the AE technique. The fractal theory takes into account the multiscale character of energy dissipation and the strong size effects associated with it. With this energetic approach it becomes possible to introduce a useful damage parameter for structural assessment based on a correlation between AE activity in a structure and the corresponding activity recorded on masonry elements of different sizes, tested to failure by means of double flat-jacks.

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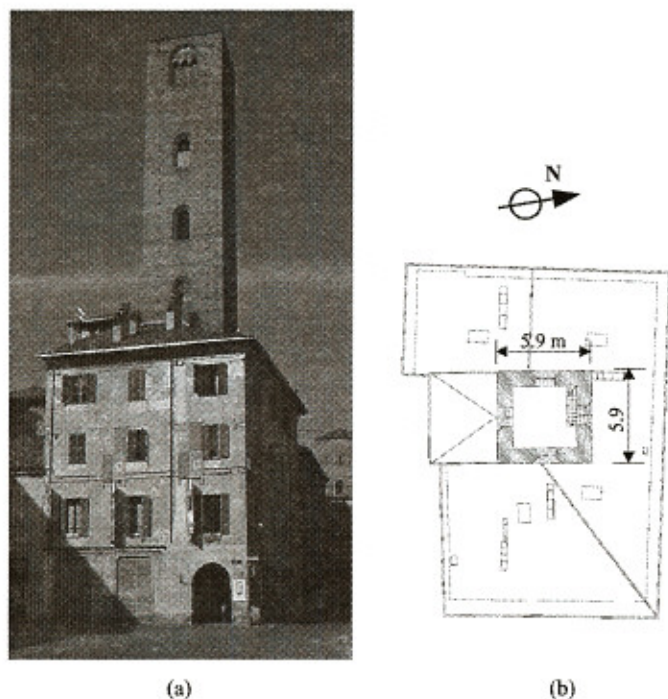


Fig. 1. Torre Sineo: (a) elevation of the tower; (b) plan of the tower and the building it is embedded in

### Description of the Two Towers

These masonry buildings from the thirteenth century are the tallest and mightiest medieval towers preserved in Alba. Torre Sineo (Fig. 1) has a square-shaped structure measuring  $5.9 \times 5.9 \text{ m}^2$ . It is 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, i.e., consist of brick faces enclosing a mixture of rubble and bricks bonded with lime and mortar. Over a height of 15 m, the tower was incorporated into a later building. Torre Astesiano (Fig. 2) has a similar structure, but has a rectangular base measuring  $5.0 \times 6.6 \text{ m}^2$ . The filling material is more organized, with brick courses arranged in an almost regular fashion, which, however, are not connected with the outer wall faces. In this case, too, the total thickness of the masonry ranges from 2 m at the bottom to 0.8 m at the top. Total height is  $\sim 36 \text{ m}$  and the tower does not lean on any side. It was also incorporated into a later building, approximately 15 m high, built when the tower had been completed.

### Nondestructive Evaluation Tests

#### Geometrical Survey and Cracking Network

The geometry of the towers and the buildings they are embedded in was fully acquired and organized within a CAD system. The positions of the openings and the variations in the thickness of the tower walls were carefully recorded, together with the positions of the main cracks observed in the two structures. From the architectural standpoint, Torre Sineo is characterized by Roman arch windows on all sides, at each floor. The loggia has elegant triple arch windows. The deviation from verticality of the Sineo Tower was evaluated with an optical instrument (Sokkia SEF 4110R). One side of the tower leans to the north. Maximum eccentricity,

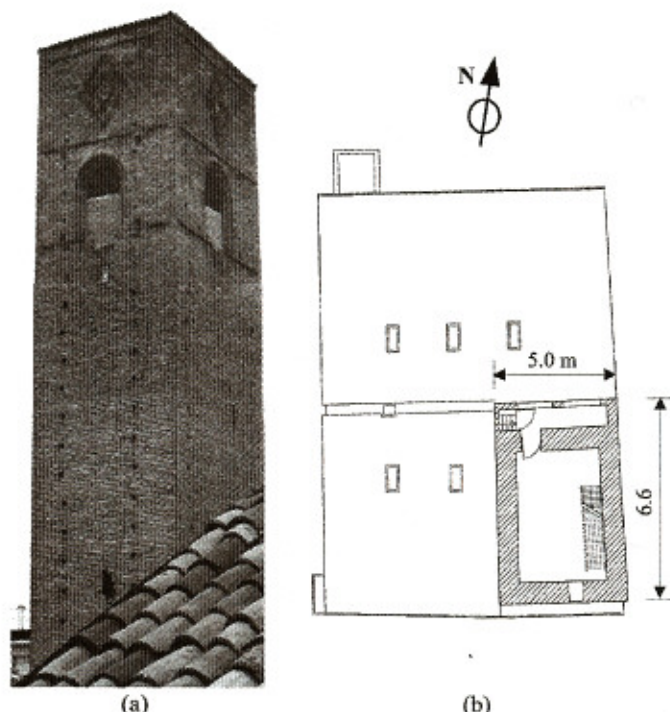


Fig. 2. Torre Astesiano: (a) elevation of the tower; (b) plan of the tower and the building it is embedded in

of 39 cm to the north and 3 cm to the west, was measured at the top. Measurements performed at different heights suggest that the tower experienced a rigid body tilting, i.e., no sensible deviation from straightness was recorded (Carpinteri et al. 2005). A cracking network can be observed on both the internal and the external views. The most significant cracks are located inside the tower, mainly between the sixth and the eighth floor. On the outer surfaces, minor cracks are observed, mostly near the windows, and in particular, between the sixth and the seventh floor. The cracking pattern and the slant of the tower are schematically summarized in Fig. 3.

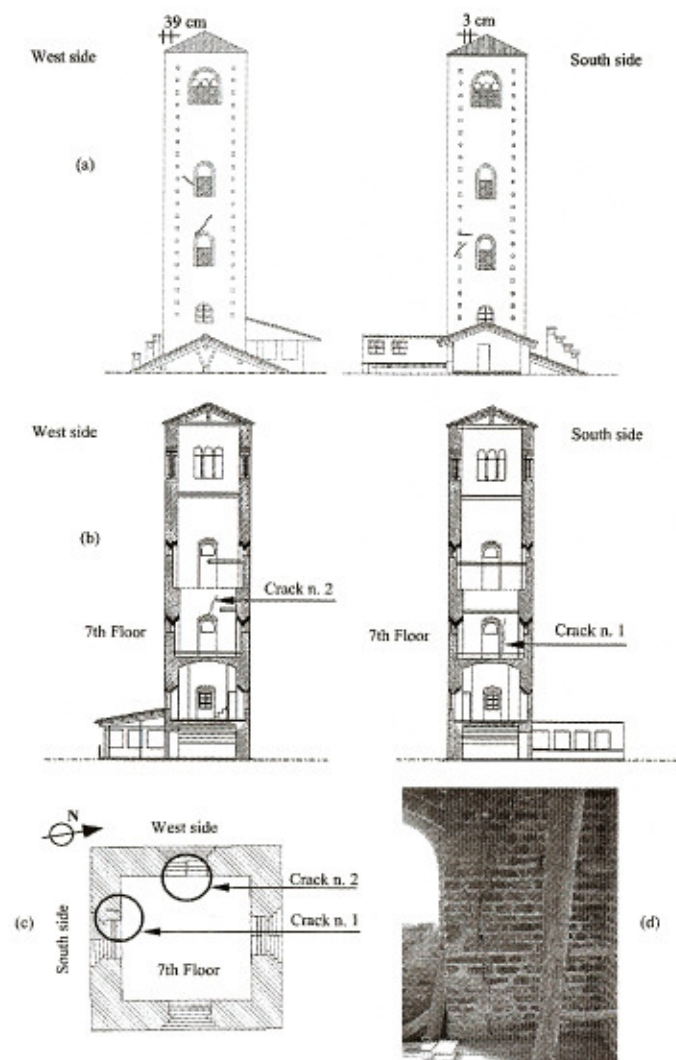
Torre Astesiano has large windows only in the upper part. The intermediate floors, in fact, are illuminated by narrow slits. Architectural ornamentations at the loggia level are defined by three brick cornices in relief and two concentric rhombi, on all four sides. The cracking configuration is not characterized by cracks distributed over the entire surface of the masonry, but rather by a long vertical crack in the upper part of the southern façade (Fig. 4).

#### Flat-Jack Tests

Tests with single and double flat-jacks were performed on the masonry walls of both towers. These tests were designed to estimate stress values in the masonry at different levels and to assess the elastic modulus and failure strength in situ.

Compressive stresses in existing masonry structures are measured on site by inserting a thin, single flat-jack in a slot sawn into a mortar joint (ASTM 1991a). This method is relatively nondestructive. When a slot has been formed in the masonry, the compressive stresses present at that point cause the masonry above and below the slot to get closer. Accordingly, the compressive state of stress in the masonry can be measured by introducing a flat-jack into the slot and increasing the pressure applied until the original distance between the points above and below the slot has



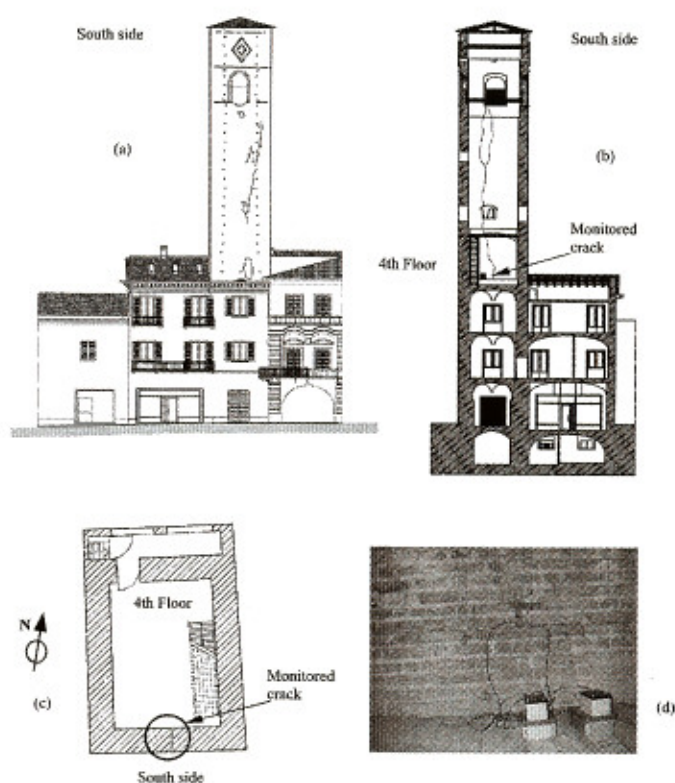


**Fig. 3.** Torre Sineo: (a) elevations of two sides of the tower, notice the presence of cracks near the openings and the deviation from verticality of the tower; (b) cross sections of the tower; (c) plan of the zone monitored; and (d) photograph taken during the monitoring of Crack No. 1

been restored: it corresponds approximately to the pressure applied by the flat-jack multiplied by factors accounting for the ratio,  $k_a$ , between the bearing area of the jack in contact with the masonry and the bearing area of the slot, and for the physical characteristic of the jack,  $k_m$ . The average compressive stress in the masonry,  $\sigma_m$ , can be calculated as

$$\sigma_m = k_m k_a p \quad (1)$$

where  $p$  = pressure required to restore the gauge points to their original distance. The double flat-jack test provides a relatively nondestructive method for determining the deformation properties of existing nonreinforced solid-unit masonry (ASTM 1991b). The test is carried out by inserting two flat-jacks into parallel slots, one above the other, in a solid unit masonry wall. By gradually increasing the flat-jack pressure, a compressive stress is induced in the masonry comprised in between. The stress-strain relation can thus be obtained by measuring the deformation of the masonry. If the test is continued to local failure, it is also possible to determine the compressive strength, but this may damage the masonry area adjacent to the flat-jacks.

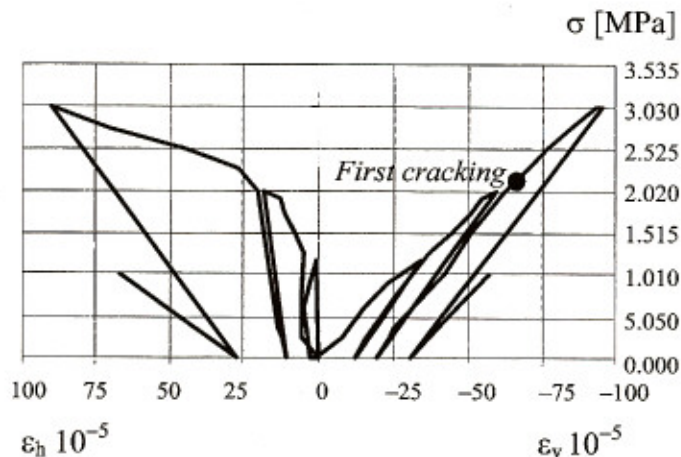


**Fig. 4.** Torre Astesiano: (a) elevation of the tower, notice the presence of the main crack in the upper part of the tower; (b) cross section of the tower; (c) plan of the zone monitored; and (d) photograph taken during the monitoring of the tip of the main crack

For Torre Sineo, vertical stress and the elastic modulus ( $E$ ) were determined on site at two different height levels, according to the scheme shown in Fig. 5. The results are summarized in Fig. 6 and Table 1. Vertical stress and elastic modulus were also measured for the Torre Astesiano at different levels, according to the scheme shown in Fig. 7. The results are summarized in Table 2.

### Thermography

Thermovision is a nondestructive testing (NDT) method that has been applied for several years to artwork and monumental build-



**Fig. 5.** Outcome from the double flat-jack test; vertical and horizontal strains are plotted as functions of the stress in the wall



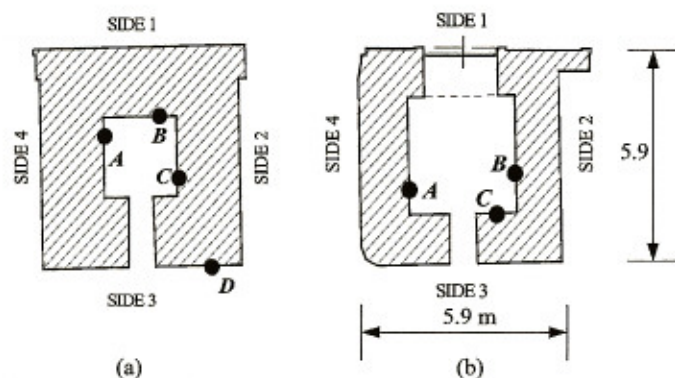


Fig. 6. Torre Sineo: plan of the single and double flat-jack testing points at (a) foundation; (b) ground floor level

Table 1. Torre Sineo Results from Single and Double Flat-Jack Tests

Points	Foundation floor		Ground floor	
	$\sigma_z$	$Y$	$\sigma_z$	$Y$
A	2.455	—	0.871	—
B	0.297	—	0.746	—
C	1.059	—	—	—
D	0.502	—	—	5,000

Note: Average compressive stress and Young's Modulus values are in MPa.

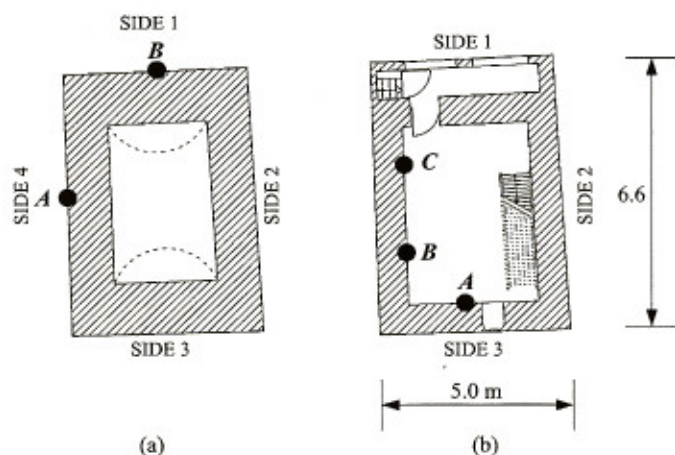


Fig. 7. Torre Astesiano: plan of the single and double flat-jack testing points at (a) foundation; (b) third floor level

Table 2. Torre Astesiano Results from Single and Double Flat-Jack Tests

Points	Foundation floor		Third floor	
	$\sigma_z$	$Y$	$\sigma_z$	$Y$
A	0.480	—	0.780	3,300
B	0.400	—	0.660	2,500
C	—	—	0.660	6,000

Note: Average compressive stress and Young's Modulus values are in MPa.

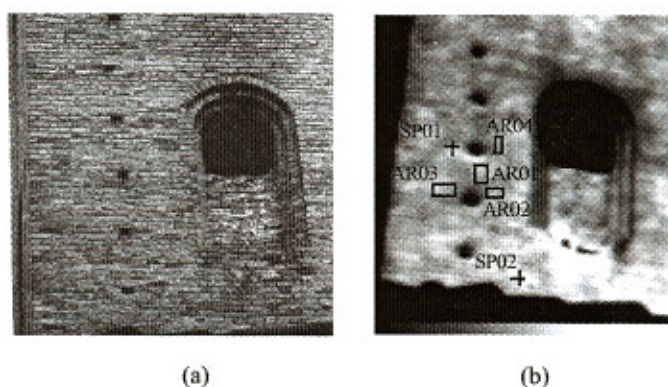


Fig. 8. Torre Sineo thermography: (a) view of portion analyzed; (b) temperature diagram in the 28.6–32.9°C range

ings (Carpinteri and Bocca 1991). It is a telemetric method ensuring high thermal and spatial resolution, and can be applied to large areas of a wall.

Thermographic analysis is based on the thermal conductivity of a material and it may be either passive or active. In its passive form, it analyzes the radiation from a surface during thermal cycles due to natural phenomena (e.g., exposure to sun light and consequent cooling). In its active form, the surface to be analyzed is subjected to forced heating. The total flux of energy emitted,  $F$ , by a surface is the sum of the energy,  $F_c$ , emitted by the surface by thermal excitation and the flux,  $F_r$ , emitted by the surface around each point

$$F = F_c + F_r \quad (2)$$

The infrared camera measures the energy flux  $F$ . The test is carried out by placing the camera at a certain distance from the surface.

Thermovision can be very useful for diagnostic purposes and it is often used to identify areas where construction anomalies can be hidden by renderings and plaster. It should be noted that in the diagnosis of old masonry structures, in the absence of thermal irradiation, thermovision analyses are limited to the superficial layers. Thermographic data were interpreted with the aid of a specific software, IRWIN Report 5.21. Fig. 8 shows a photograph of a badly damaged portion of the Sineo Tower [Fig. 8(a)] and compares it with the relative thermographic image [Fig. 8(b)]. Some of the temperatures obtained are listed in Table 3: the coldest masonry points might reflect the presence of a crack.

Fig. 9 compares a thermographic image and a photograph of a damaged portion of the Torre Astesiano. From the thermographic image it can be seen that the average temperatures of the masonry zones in the proximity of the vertical crack are higher than the

Table 3. Surface Temperatures Acquired through Thermography

Points	Temperature (°C)
Spot 1	30.2
Spot 2	32.7
AR 01 mean	31.6
AR 02 mean	30.8
AR 03 mean	31.6
AR 04 mean	30.8

Note: Points refer to Fig. 8(b).





Fig. 9. Torre Astesiano thermography: (a) view of portion analyzed; (b) temperature diagram in the 28.6–32.9°C range

temperatures recorded at the crack. The reduction in temperature, in fact, reflects the gaps in the bricks along the crack (see Table 4).

### Acoustic Emission Monitoring

Monitoring a structure by means of the AE technique makes it possible to detect the onset and evolution of stress-induced cracks. Crack opening, in fact, is accompanied by the emission of elastic waves that propagate within the bulk of the material. These waves can be captured and recorded by transducers applied to the surface of the structural elements (Fig. 10). The signal identified by the transducer (Fig. 11) is preamplified and transformed into electric voltage; it is then filtered to eliminate unwanted frequencies, such as the vibrations caused by the mechanical instrumentation, which are generally lower than 100 kHz. The signal is then analyzed by a threshold measuring unit which counts the oscillations exceeding a certain voltage value. This method of analysis is called ring-down counting (Pollock 1973; Brindley et al. 1973). As a first approximation, the counting number,  $N$ , can be corre-

Table 4. Surface Temperatures Acquired through Thermography

Points	Temperature (°C)
Spot 1	30.2
Spot 2	30.5
AR 01 mean	31.6
AR 02 mean	31.8

Note: Points refer to Fig. 9(b).

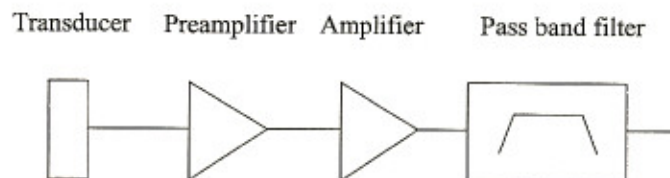


Fig. 10. Acoustic emission measurement system

lated to the quantity of energy released during the loading process. This technique also considers other procedures. For instance, by keeping track of the characteristics of the transducer and, in particular, of its damping, it is possible to consider all the oscillations produced by a single AE signal as unique events and to replace ring-down counting with the counting of events (Fig. 12).

### AE Data Acquisition System

The AE monitoring equipment adopted by the writers consists of piezoelectric transducers fitted with a preamplifier and calibrated on inclusive frequencies between 100 and 400 kHz. The threshold level of the signal recorded by the system, fixed at 100  $\mu$ V, is amplified up to 100 mV. The oscillation counting capacity is limited to 255 every 120 s of signal recording. In this way a single event is the result of two recorded minutes.

As specified in the literature (Ohtsu 1996), the maximum amplitude of direct nonamplified signals is about 100  $\mu$ V, hence, neglecting the attenuation by reducing to a few cm the distance of the transducer from the signal generation point, it can be assumed that the measuring system is able to detect the most meaningful AE events reflecting cracking phenomena in the masonry. Attenuation properties, in fact, depend on the frequency range: higher frequency components propagate in masonry with greater attenuation. Based on experimental results, for a measuring area at a distance of 10 m only AE waves with frequency components lower than 100 kHz are detectable (Carpinteri and Lacidogna 2006). With this system, the intensity of a single event is by definition proportional to the number  $N$  recorded in the time interval (event counting). Clearly, this hypothesis is fully justified in the case of slow-crack growth (Holroyd 2000).

### AE Damage Detection of the Towers

AE sensors were applied to the zones where damage had been determined to be most severe through the determination of crack-

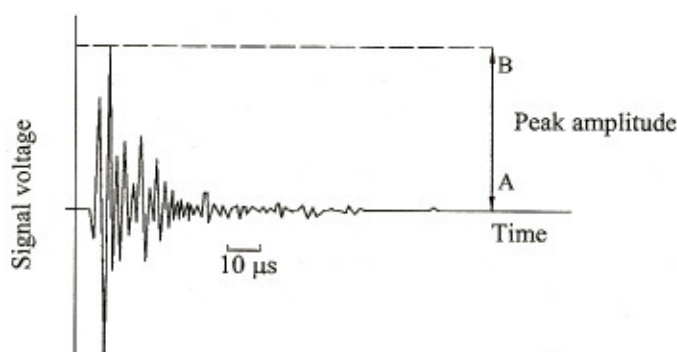


Fig. 11. AE signal identified by the transducer



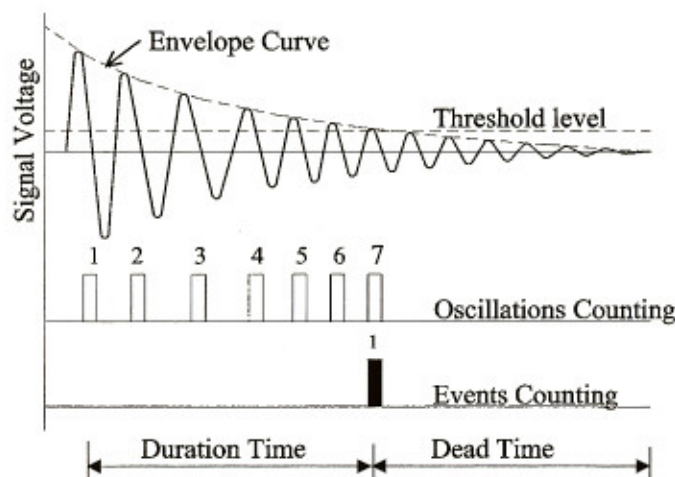


Fig. 12. Counting methods in AE technique

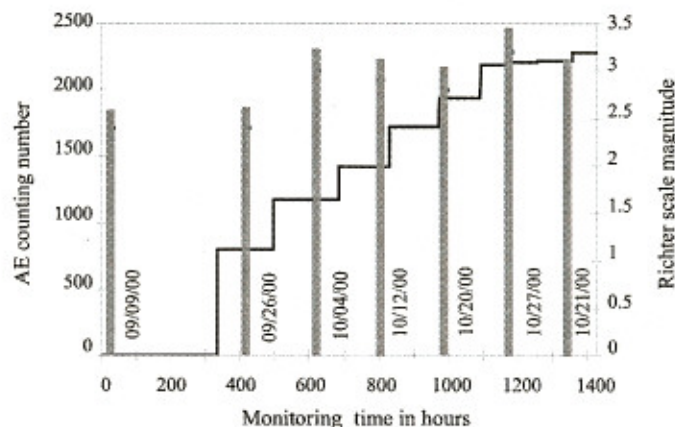


Fig. 13. Torre Sineo AE and seismic events

ing conditions. Obviously, in order to obtain a full description of the conditions of the masonry during the monitoring period, it would be advisable to install several sensors at different levels, with their centers of gravity spaced no more than 20 m apart (Carpinteri and Lacidogna Italian Patent No. To 2002 A000924, 2002). In this manner, AE signals would be picked up over a frequency band not lower than 100 kHz. Accordingly, when dealing with structures such as the towers in question, the sensors should be applied to all four walls. The costs incurred to fit this many sensors, however, would be very high, and this is why it is deemed preferable to limit the intervention to a number of zones showing signs of damage.

In this case, since the towers are not very tall (<40 m) and their interior surface is quite regular, by fitting the sensors in the zones displaying the most conspicuous cracks, i.e., at about mid-height, it proves possible to achieve good overall control. Needless to say, the foundations were excluded, since, on account of their thickness ( $\approx 2$  m), they posed no risk of instability. Obviously, there was a possibility of some damaged zones being obscured to the perception of the sensors due to discontinuities in the masonry that escaped notice or due to preexisting cracks. These uncertainties could be reduced by performing ultrasound tests at a preliminary stage, wherever possible, in order to detect the masonry areas containing discontinuities (Carpinteri and Bocca 1991).

For the Sineo Tower, through AE monitoring, two cracks were detected in the inner masonry layer at the seventh floor level (Fig. 3): one next to a window on the southern façade (Crack No. 1), and another above a window on the west façade (Crack No. 2).

To collect the AE signals, transducers were applied, one per crack, with their centers of gravity at a distance of  $\sim 3$  cm from the crack tip. In this manner, as described in the previous section, the attenuation due to the distance between the sensor and the signal source can be reduced. The monitoring process revealed an on-going damaging process, characterized by slow crack propagation inside the brick walls. In the two damaged zones, crack spreading had come to a halt, the cracks having achieved a new condition of stability, leading towards compressed zones of the masonry. The evolution of the two cracks was monitored over a total of about 1,400 h (Fig. 13).

In this particular case it can be seen that in the zone monitored each appreciable crack advance is often correlated to a seismic event. In the diagram shown in Fig. 13, the cumulative AE func-

tion relating to the area monitored in the proximity of Crack No. 1 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. A similar diagram was produced for Crack No. 2. Seismic event data were provided by the National Institute for Geophysics and Volcanology in Rome. It can be seen that the behavior of the zones monitored of the tower is stable when the structure is subjected to vertical loads alone, whereas the structure is unable to respond elastically to shaking or horizontal actions.

A similar behavior was observed for the Torre Astesiano. 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 the large vertical crack (Fig. 4). The results obtained during the monitoring period are summarized in the diagram in Fig. 14. In this case, too, it can be seen how the damage to the masonry and the propagation of the crack, as reflected by the cumulative number of AE events, evolved progressively over time. A seismic event of 4.7° on the Richter scale occurred during the monitoring period: from the diagram we can see how the cumulative function of AE events grew rapidly immediately after the earthquake.

During the observation period, the towers behaved as sensitive earthquake receptors. Thus, as can be seen, the AE technique is able to analyze state variations in a certain physical system and can be used as a tool for predicting the occurrence of "catastrophic" events. In many physics problems—e.g., when studying test specimen failure in a laboratory, the modalities of collapse of

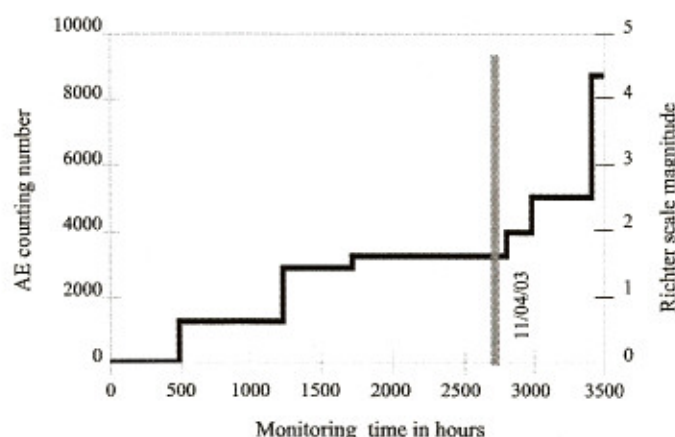


Fig. 14. Torre Astesiano AE and seismic events



a civil structure, the natural seismic activity of a volcano, or the localization of the epicentral volume of an earthquake—the zone and the modalities of a collapsed structure are generally analyzed “after” the event. This technique can be used instead to identify the premonitory signals that “precede” a catastrophic event, as, in most cases, these warning signs (i.e., the ultrasonic waves) can be captured well in advance (Kapiris et al. 2004).

### Critical Behavior Interpreted by AE

All NDT methods work by introducing some type of energy into the system to be analyzed. While thermography uses heat, in AE tests the energy input is the mechanical stresses produced through the application of loads. External forces or internal pressures are used to generate discontinuities or cracks that emit energy waves. By analogy with seismic events, acoustic emissions can be likened to miniature earthquakes. Under the assumption of a certain state of stress being present, the intensity and frequency of the AE waves emitted by a body originate from structural disorder, i.e., from the concentration of local stresses as determined by the distribution of defects (Richter 1958; Pollock 1973).

A very important aspect of this is that in many kinds of structures, especially very complex or highly redundant ones, there are places where stresses are low, or even approach zero. These low stress areas do not emit, and therefore, will not interfere with AE monitoring results; however, this does not rule out the possibility that stresses in others areas can be high enough to undermine the bearing capacity of a building. In this manner, once the damaged or cracked parts of a structure—which generally correspond to the zones where stresses are highest—have been identified, the AE method makes it possible to assess the evolution of damage and predict whether it will gradually come to a halt or will propagate faster and faster.

With this criterion, by distributing several sensors covering adjacent areas, it proves possible to take into account stress redistribution capacities even in a complex structure. This approach was used in monitoring Torre Sineo, by arranging the sensors in the zones subject to the highest stresses in two contiguous walls. The sensors, in fact, are able to perceive the energy released by the cracks monitored and also the AE signals coming from distances of up to 10 m from their points of application, covering a wide area of the masonry walls.

By adopting more advanced AE monitoring devices, it is also possible to classify crack modes into tensile and shear types, and to determine crack orientation. This procedure, referred to as moment tensor analysis, is based on the theoretical treatment of AE waves according to the principles of elastodynamics, and makes it possible to locate the tips of the cracks during the propagation process by fitting at least six sensors, distributed throughout the area of the structural element analyzed (Ohtsu 1996; Shah and Li 1994). Analyses of this type, requiring the elaboration of a huge quantity of data, are better suited for monitoring structural elements of limited size, in which the intensity of the loads and stress distribution are known. They are hardly suitable for the interpretation of data obtained from a prolonged monitoring period, as is necessary to characterize the long-term behavior of a structure.

In this study, the AE technique has not been used so much, with the purpose of performing a structural analysis of the masonry buildings and interpreting the local nature of fracture phenomena in the structural elements monitored. The development of stress paths during damage evolution of the Sineo Tower has been performed by the writers by means of powerful finite-element

methods (Carpinteri et al. 2005). It appears, nevertheless, that these complex analyses are useful in the context of a deterministic analysis, which is not always in tune with the stochastic evolution of the defect patterns.

Rather, the goal was to highlight the critical phenomena and the scale effects of fracture mechanics in the masonry by analyzing, through a statistical and fractal approach, the microscopic and mesoscopic phenomena interacting, with a view to defining the behavior on the structural scale. This approach does not require a detailed characterization of the local states of stress and cracking conditions of the elements monitored, and it amounts instead to a summary analysis geared to the identification of instability conditions. These instability, or critical, conditions are reached in relation to a certain distribution of the defects, which is deemed independent of the state of stress and crack orientation (Shcherbakov and Turcotte 2003). Accordingly, the monitoring method proposed, taking its cue from fragmentation theory, is designed to quantify the energy dissipated during the damaging process by counting the AE events. The identification of critical conditions is not entrusted to an analysis of the loading process, rather, it depends primarily on the distribution and evolution of the crack patterns.

### Fractal Criterion for AE Monitoring

A statistical and fractal analysis of data from laboratory experiments was performed, considering the multiscale aspect of cracking phenomena. The fractal criterion takes into account the multiscale character of energy dissipation and the strong size effects associated with it. This makes it possible to introduce a useful energy-related parameter for the determination of structural damage (as used by Carpinteri et al. 2003, 2004, for reinforced concrete structures) by comparing the AE monitoring results with the values obtained on masonry elements of different sizes tested until failure by means of double jacks.

Fragmentation theories have shown that during microcrack propagation energy dissipation occurs in a fractal domain comprised between a surface and the specimen volume  $V$  (Carpinteri and Pugno 2002a, b, 2003).

This implies that fractal energy density (having anomalous physical dimension)

$$\Gamma = \frac{W_{\max}}{V^{D/3}} \quad (3)$$

can be considered as a size-independent parameter. In the fractal criterion [Eq. (3)],  $W_{\max}$ =total dissipated energy;  $\Gamma$ =fractal energy density; and  $D$ =so-called fractal exponent, comprised between 2 and 3.

On the other hand, during microcrack propagation, acoustic emission events can be clearly detected. Since the energy dissipated,  $W$ , is proportional to the number of AE events,  $N$ , the critical density of acoustic emission events,  $\Gamma_{AE}$ , can be considered as a size-independent parameter

$$\Gamma_{AE} = \frac{N_{\max}}{V^{D/3}} \quad (4)$$

where  $\Gamma_{AE}$ =fractal acoustic emission energy density; and  $N_{\max}$  is evaluated at the peak stress,  $\sigma_u$ . Eq. (4) predicts a volume effect on the maximum number of AE events for a specimen tested to failure.

The extent of structural damage can be worked out from the AE data recorded on a reference specimen (subscript  $r$ ) obtained



from the structure and tested to failure. Naturally, the fundamental assumption is that the damage level observed in the reference specimen is proportional to the level reached in the entire structure before monitoring is started.

From Eq. (4) we get

$$N_{max} = N_{max,r} \left( \frac{V}{V_r} \right)^{D/3} \quad (5)$$

from which we can obtain the structure critical number of AE events  $N_{max}$ . An energy parameter describing the damage level of the structure can be defined as the following ratio:

$$\eta = \frac{W}{W_{max}} = \frac{N}{N_{max}} \quad (6)$$

$N$  being the number of AE events recorded by the monitoring apparatus.

### Time Dependence of AE

The extent of structural damage observed during the monitoring period can also be correlated to the rate of propagation of the microcracks.

If we express the ratio between the cumulative number of AE events 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:

$$\eta = \frac{W}{W_d} = \frac{N}{N_d} = \left( \frac{t}{t_d} \right)^{\beta_1} \quad (7)$$

In Eq. (7), the values of  $W_d$  and  $N_d$  do not necessarily correspond to peak stress conditions ( $W_d \leq W_{max}$ ;  $N_d \leq N_{max}$ ) and the  $t_d$  parameter must be construed as the time during which the structure has been monitored. By working out the  $\beta_1$  exponent from the data obtained during the observation period, we can make a prediction as to the structure's stability conditions. If  $\beta_1 < 1$ , the damaging process slows down and the structure evolves towards stability conditions in as much as energy dissipation tends to decrease; if  $\beta_1 > 1$  the process becomes unstable, and if  $\beta_1 \approx 1$  the process is metastable, i.e., though it evolves linearly over time, it can reach indifferently either stability or instability conditions.

### Flat-Jack and AE Tests

As previously described, nondestructive tests were performed by means of flat-jacks to determine the stress level in different masonry sections of the towers. Furthermore, in order to assess the extent of damage in the zone monitored using the AE technique, a compressive test was conducted on the masonry through the combined use of double jacks and AE sensors (Fig. 15).

In particular, for the Astesiano Tower, compressive tests were performed with double flat-jack tests on three different masonry sections, at the third level, at Points A, B, and C, identified in Fig. 7. The prismatic masonry volumes tested in compression were delimited crosswise by vertical cuts (Fig. 16).

The dimensions of the cross section of the elements shown in Fig. 16 correspond to the effective area of the masonry to which the pressure of the flat-jacks is applied. The tests are in keeping with the procedures specified in ASTM (1991b), other than for the vertical cuts produced in order to eliminate in the element damaged the influence of the adjacent masonry portions. Fig. 17 shows the results obtained from these tests for the intermediate element (Volume 2). Similar results were obtained for the other

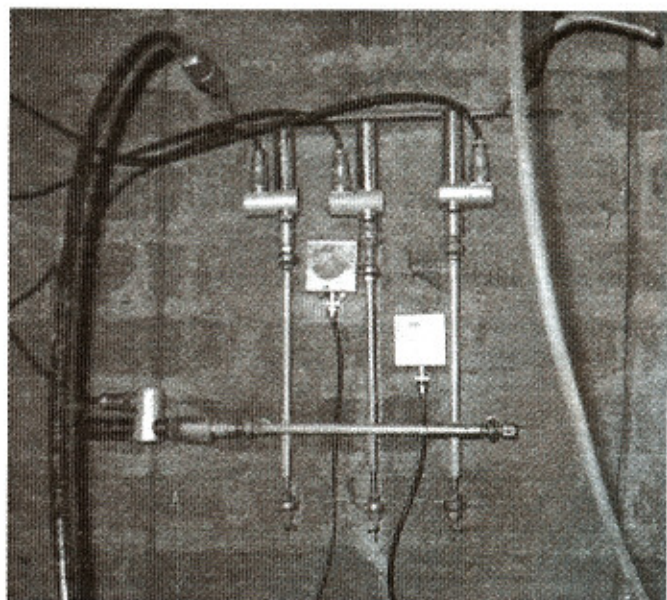


Fig. 15. Combined flat-jack test and AE monitoring

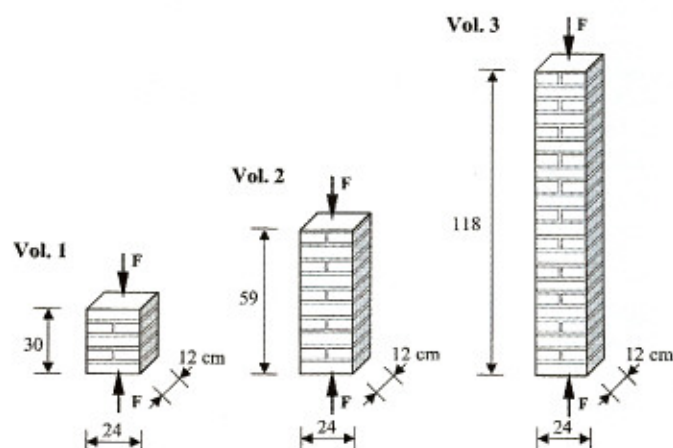


Fig. 16. Masonry elements tested in compression by means of double flat-jacks

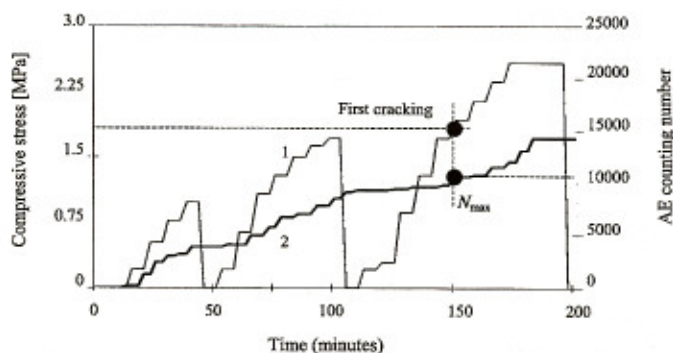


Fig. 17. Double flat-jack test on Volume 2: cumulative number of AE events (2) versus cyclic loading (1)



**Table 5.** Experimental Values Obtained from Flat-Jack Tests and AE Measurements

Specimen	Volume (cm <sup>3</sup> )	Peak stress (MPa)	$N_{\max}$ at $\sigma_u$
Volume 1	8,640	2.07	~6,500
Volume 2	16,992	1.61	~12,000
Volume 3	33,984	1.59	~18,000

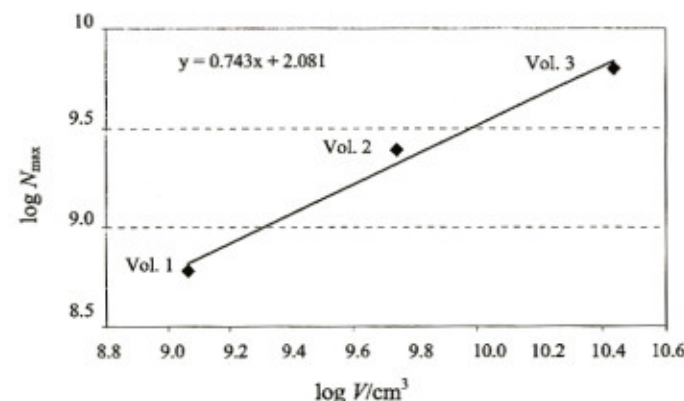
two elements. Fig. 17 illustrates the three loading cycles performed as a function of time and the diagram of the cumulative number of AE events. From the AE diagram it can be clearly seen that the material releases energy when the stress level reached previously is exceeded (Kaiser 1950). Moreover, from the diagram, we find that the cumulative number of AE events at failure stress is  $N_{\max} \approx 12,000$ . The experimental results obtained on the three masonry elements are summarized in Table 5.

Table 5 shows that in compressive tests the cumulative number of AE events increased with increasing specimen volume. From a statistical analysis of the experimental data, parameters  $D$  and  $\Gamma_{AE}$  [Eq. (4)] can be quantified. Parameter  $D$  represents the slope, in the bilogarithmic diagram, of the curve correlating  $N_{\max}$  to specimen volume. By best fitting, we obtain  $D/3 \approx 0.743$  (Fig. 18), so that the fractal exponent, as predicted by fragmentation theories, turns out to be of between 2 and 3 ( $D \approx 2.23$ ). Moreover, the critical value of fractal AE density turns out to be  $\Gamma_{AE} \approx 8.00 \text{ cm}^{-2.23}$ .

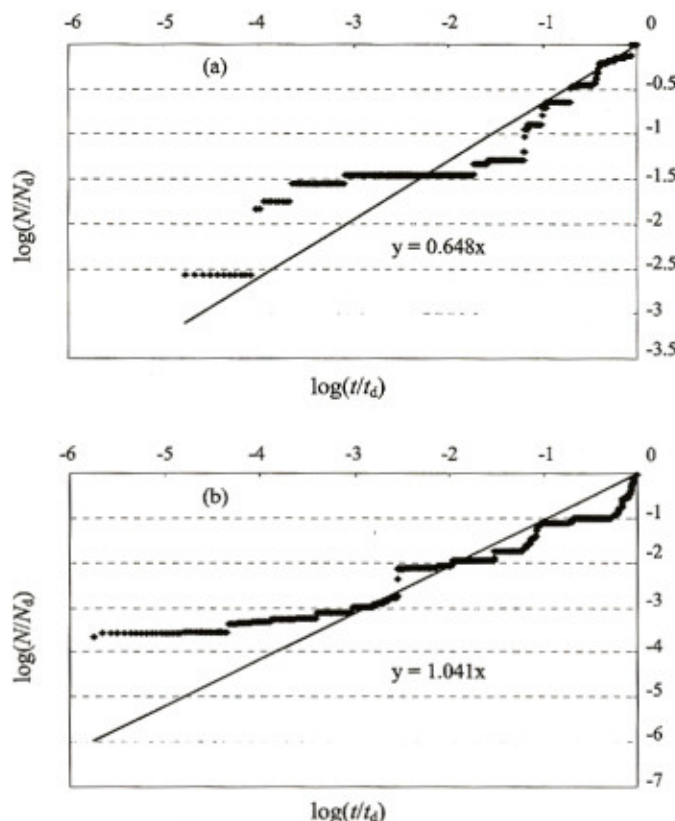
#### Damage Level of the Monitored Volumes

During the observation period, which lasted 60 days for the Sineo Tower and 146 days for the Astesiano Tower, the number of AE events recorded for the former was  $N \approx 2,250$  (Fig. 13), and for the latter it was  $N \approx 9,000$  (Fig. 14). Through earlier tests performed on rubble filled masonry, 80 cm thick, and hence characterized by appreciable discontinuities, it was ascertained that the transducers were able to pick up the AE signals from a distance of up to 10 m from their points of application (Carpinteri and Lacidogna Italian Patent No. To 2002 A000924, 2002) and to a depth of 12 cm, i.e., over a length corresponding to the thickness of the outer layer of bricks.

Since the average width of the sides of the towers is about 500 cm, the total volume monitored by the transducers will be  $V \approx 500 \times 2,000 \times 12 = 1.2 \times 10^7 \text{ cm}^3$ . From Eq. (4), using fractal exponent  $D \approx 2.23$  and the critical value of fractal acoustic emis-



**Fig. 18.** Volume effect on  $N_{\max}$



**Fig. 19.** Evolution of damage: (a) Torre Sineo; (b) Torre Astesiano

sion density,  $\Gamma_{AE} \approx 8.00 \text{ cm}^{-2.23}$ , we obtain a critical AE number of  $N_{\max} \approx 1.46 \times 10^6$ . Introducing the values of  $N$  and  $N_{\max}$  into Eq. (6), we get  $\eta \approx 0.154\%$  for Torre Sineo and  $\eta \approx 0.616\%$  for Torre Astesiano. These values represent, in percentage terms, the amount of energy released with respect to the energy that would cause the ultimate damage of the monitored volumes.

Finally, in order to obtain indications on the rate of growth of the damage process in the towers, as given in Eq. (7), the data obtained with the AE technique were subjected to best fitting in the bilogarithmic plane. For the Sineo Tower, this yielded a slant  $\beta_i \approx 0.648$ , for the Astesiano Tower  $\beta_i \approx 1.041$  (see Fig. 19).

These results confirm how the damage process stabilized in the Sineo Tower during the monitoring period, whereas for the Astesiano Tower it evolved towards a condition of instability according to a quasilinear progression over time. In fact, if we introduce the values of  $N$  and  $N_{\max}$  obtained for Torre Astesiano into Eq. (7), with  $\beta_i = 1.041$ , we get  $t/t_{\max} \approx 7.532 \times 10^{-3}$ . Thus, for this tower, the lifetime of the monitored zone (i.e., time before the maximum number of AE events corresponding to the peak stress is reached) is estimated to be  $\sim 53$  years. During this time period, in view of the stress redistribution capacity in the masonry, the structure will not necessarily reach ultimate failure conditions, but should undergo a progressive global weakening.

#### Conclusions

In view of the appreciable number of old structures still in use today, more attention should be paid to preservation and rehabilitation issues. A sound safety assessment cannot be based solely on the visual observation of cracks and signs of damage in structural elements. The evolution and interaction of different damage phe-



nomena should be considered instead. This is why structural monitoring is taking on ever greater importance in the whole process of reliability assessment: in this connection, the AE technique can be highly effective.

This technique makes it possible to introduce a useful energy-based damage parameter for structural assessment, which establishes a correlation between AE activity in a structure and the corresponding activity recorded on specimens taken from the structure and tested to failure.

Moreover, by applying compressive tests through the combined use of double flat jacks and AE sensors, the safety of structures undergoing damage and degradation processes can be efficiently evaluated in situ.

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## Notation

The following symbols are used in this paper:

- $D$  = fractal volume exponent;
- $F$  = total energy flux measured by infrared camera during the thermographic analysis;
- $F_c$  = energy flux emitted by a material surface;
- $F_r$  = energy flux emitted around each point of a material surface;
- $k_a$  = flat-jack test factor accounting for the geometry of the cut in the masonry wall;
- $k_m$  = flat-jack test factor accounting for the physical characteristic of the jack;
- $N$  = number of AE events;
- $N_d$  = AE events at the end of a monitoring period;
- $N_{max}$  = AE events at the peak stress;
- $p$  = flat-jack pressure;
- $t$  = monitoring time;
- $t_d$  = duration of the monitoring time;
- $V$  = specimen volume;
- $W$  = dissipated energy during microcrack propagation;
- $W_d$  = dissipated energy at the end of monitoring period;
- $W_{max}$  = dissipated energy at the peak stress;
- $Y$  = masonry stiffness modulus;
- $\beta_r$  = monitoring parameter describing the structural stability;
- $\Gamma$  = fractal energy density;
- $\Gamma_{AE}$  = fractal acoustic emission energy density;
- $\eta$  = energy parameter describing the damage level of a structure;
- $\sigma_m$  = average compressive stress in the masonry; and
- $\sigma_u$  = material peak stress.

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