[Proceeding] AE monitoring and structural modelization of the Asinelli Tower in Bologna

AE monitoring and structural modelization of the Asinelli Tower in Bologna

Stefano Invernizzi[1], Giuseppe Lacidogna[1], Gianni Niccolini[1], Amedeo Manuello[1], Alberto Carpinteri[1]

[1]*Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Italy*
E-mail: *stefano.invernizzi@polito.it, giuseppe.lacidogna@polito.it, gianni_nicc@hotmail.com, amedeo.manuellobertetto@polito.it, alberto.carpinteri@polito.it*

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SUMMARY. The Acoustic Emission (AE) technique was used to assess the structural stability of the Asinelli Tower, the tallest building in the city of Bologna, which, together with the nearby tower, named Garisenda, is the renowned symbol of the city. AE is a passive, non-destructive structural evaluation technique based on the spontaneous emission of pressure waves by evolving fracture processes. The monitoring program was carried out with the aid of a USAM tool, which is part of the equipment used at the Fracture Mechanics Laboratory of the Department of Structural Engineering at the Politecnico di Torino. This tool makes it possible to conduct a complete analysis of AE signals, acquire a huge quantity of data from on site monitoring, and identify the microcracks triggering the damage processes in a structure.
In the second part of the paper, the results from a preliminary linear analysis are presented, in order to assess the structural behavior of the tower. The cracking and crushing strengths of the masonry have both been compared with the calculated stresses. The numerical analysis gives a valuable picture of the modal response of the tower, providing useful hints for the prosecution of structural monitoring.

1 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 (PZT) sensors, i.e., sensors calibrated for a frequency range of between 50 and 800 kHz. 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. 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. Using the AE technique, the authors have acquired considerable experience in the monitoring of medieval masonry towers and other significant historic buildings [1-5].

The AE technique is ideally suited to control the evolution of structural damage caused by pulse phenomena, such as wind and seismic actions. In this study − a significant zone of the masonry structure to be analyzed having been identified − the AE count obtained during the monitoring period was correlated with the frequency of seismic events in the areas around the city of Bologna. The data were used to assess the critical phenomena taking place in the structure with the aim to predict the evolution of damage over time.

2 STRUCTURAL DESCRIPTION OF THE TOWER

The authors of the various histories of the city of Bologna all agree in dating the Asinelli and Garisenda Towers to the early twelfth century, but with some minor discrepancies as to the year of construction, as pointed out by Ludovico Savioli in discussing the Asinelli Tower in his *Annali Bolognesi*, written around the end of the eighteenth century: *"Our chronicles do not converge around the time when it was perfected, some mentioning the year 1111, others the years 1117 and 1119; a majority of them indicate the year 1109"* [6,7].

The Asinelli Tower 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. From the structural standpoint, the tower can be subdivided into four segments, depending on type of masonry. The thickness of the walls varies from 3.00 m at the foundations to 1.00 m at the top. The first segment, at the base of the tower, is made entirely of selenite blocks. It starts at a depth of ca 1.70 m below ground level and rises to 3.00 m above ground. The substructure of the tower is nearly square, with sides approx. 10.50 m long. The second segment, with sides tapering from 8.15 m to 7.70 m, rises to a height of 34.20 m. The third segment, which constitutes the upper part of the tower and contains the merlons added in the fifteenth century, has sides that gradually decrease in size to ca 6.50m at a height of 81.25 m above ground level. The masonry of the second and third segments is a sacco, i.e., consists of an outer and an inner face, 90 cm and 45 cm thick respectively, enclosing a mixture of rubble, bricks and mortar – and is characterised by an overall thickness of 2.80 m. At the base, up to a height of 8.00 m, the tower is surrounded by an arcade built at the end of the fifteenth century.

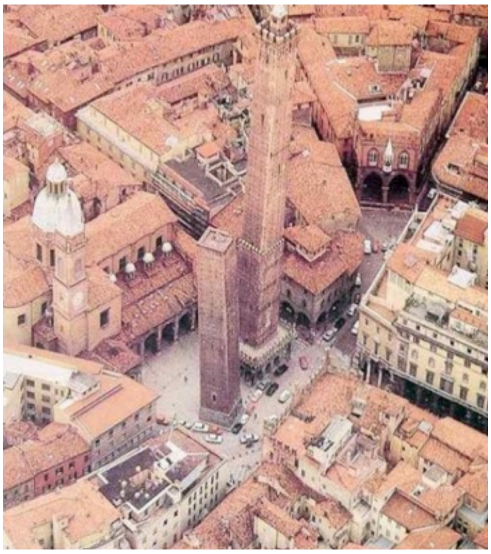

Figure 1. The Asinelli Tower and the Garisenda Tower in the city center of Bologna.

The studies conducted in the early twentieth century by F. Cavani [8] revealed that the Asinelli Tower leaned westward by 2.25 m; this is the reason why it is known as the tallest leaning tower in Italy. The latest measurements, made in 2009 by Prof. A. Capra by laser scanning, on behalf of the municipality, showed an overall inclination of 1.51 degrees and a deviation from verticality of 2.38 m. Thus we find that the deviation increased by 13 cm in the course of approx. one century, that is to say at an average rate of 1.30 mm/year. Figure 1 shows the Asinelli Tower and the adjacent Garisenda Tower in the city center of Bologna. Figures 2 and 3 show the front elevations and the cross-section of the Asinelli Tower and a plan view indicating the zone of application of the AE sensors.

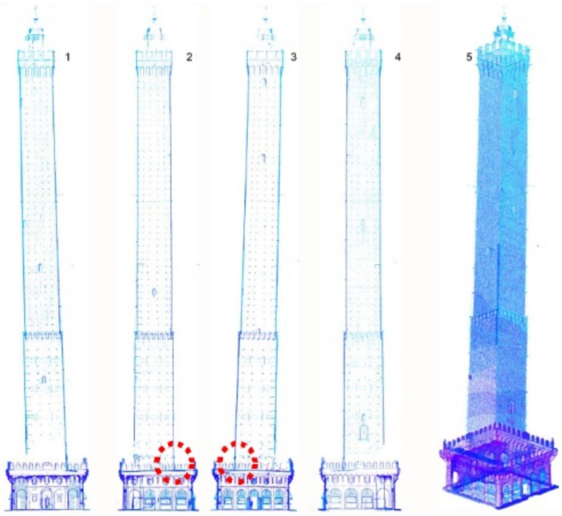

Figure 2. Front views and axonometric view of the Torre degli Asinelli. These views, supplied by the Municipality of Bologna, are taken from the measurements of the exterior of the structure made by Prof. Alessandro Capra by laser scanning. Faces (1) South; (2) East; (3) North; (4) West; (5) Axonometric view. The transducers were applied to the north-east corner of the tower, in the zones marked with a circle.

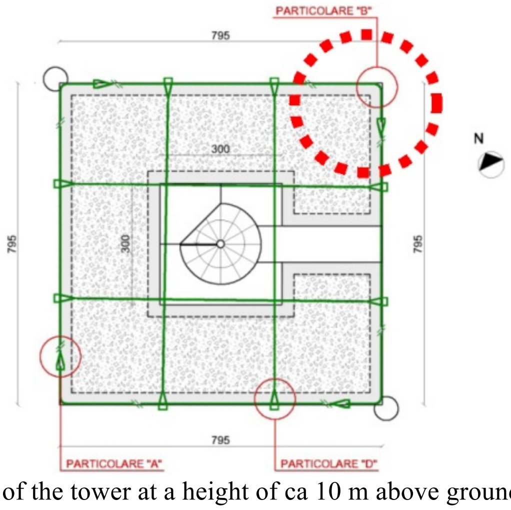

Figure 3. Cross-section of the tower at a height of ca 10 m above ground. Drawing supplied by the Municipality of Bologna. The corner where the sensors were applied is marked with a circle.

3 MONITORING WITH THE ACOUSTIC EMISSION TECHNIQUE

Only a limited number of sensors were available and hence the AE devices were positioned in a zone that would be both significant for monitoring purposes and easy to reach. In particular, six AE sensors were applied to the northeast angle of the tower at an average height of ca 9.00 m above ground level, immediately above the terrace atop the arcade. In this area, the double-wall masonry has an average thickness of ca 2.45 m (see Figs. 2 and 3). AE monitoring began on 23 September 2010 at 5:40 PM, and ended on 28 January 2011 at 1:00 PM. It was carried on for ca 2915 hours, corresponding to 122 consecutive days. The arrangement of the AE sensors, shown in the photos in Fig. 4, corresponds to the scheme illustrated in Fig. 5. The sensors were glued to the outer surface of the masonry with cold set silicone based adhesives, selected on account of their good ultrasound signal transmission capacity, resulting in reduced damping at the interface between the masonry and the sensors.

The coordinates of the sensor application points are given in Table 1. The origin of the coordinate system of reference, as can be seen in Fig. 5, is at the bottom corner of the masonry at the intersection with the outer surface of the terrace surrounding the tower.

Figure 4. Photos of the AE data acquisition system on the monitoring site.

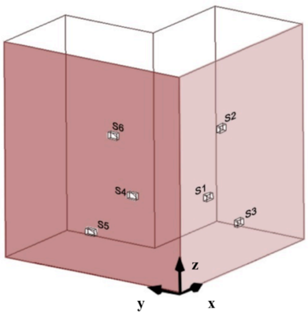

Figure 5. Axonometric scheme of the points of application of the AE sensors at the north-east corner of the tower.

Table 1: Coordinates (in cm) of the points of application of the sensors

Sensors	x	y	z
S1	51.50	0.00	98.00
S2	78.00	0.00	171.0
S3	110.00	0.00	53.00
S4	0.00	63.50	102.00
S5	0.00	121.06	50.00
S6	0.00	89.00	167.00

measurements in cm

4 RESULTS OF THE MONITORING

The data collected during the monitoring period were analyzed to evaluate crack growth and correlate it with the other phenomena considered, e.g., earthquake frequency in the areas around the city, and wind effects on the tower.

In AE analysis, the signals received by the transducers are analyzed by means of a threshold detection device that counts the signal bursts exceeding a certain electric tension (measured in volts (V)). Then, cumulative curves are plotted reflecting the number of bursts recorded in a continuous manner during the testing period. This method of analysis, known as Ring-Down Counting, is widely used for defect detection purposes. As a first approximation, in fact, the total count number, N, can be compared with the amount of energy released during a monitoring period based on the assumption that N grows proportionally to the growth of the damage zone. Needless to say, this assumption will apply only to a slowly progressing damage process. [9].

Figure 6 shows a plot of the cumulative AE count obtained on the basis of the number of events detected per monitoring day. The curve was plotted starting from the date of application of the sensors to the time the sensors were permanently removed. Throughout the monitoring period, the threshold level for the detection of the input signals coming from the PZT transducers was kept at 100 mV. Based on the authors' experience, in fact, this level is the most significant for the detection of AE signals from damage processes in non-metallic materials such as concrete and masonry [1,2,5,9].

From the curve in Fig. 6 it can be seen that the masonry is actually undergoing a damage process. The plot of the cumulative AE count, in fact, is characterized by jumps reflecting sudden increases in N that are seen to occur at certain time intervals. The discontinuities in the cumulative AE count curve denote the critical moments during which the release of energy from the microcrack formation process is greatest.

The AE count hourly distribution chart over a 24 hour time span, as determined for the entire monitoring period, is shown in Fig. 7.

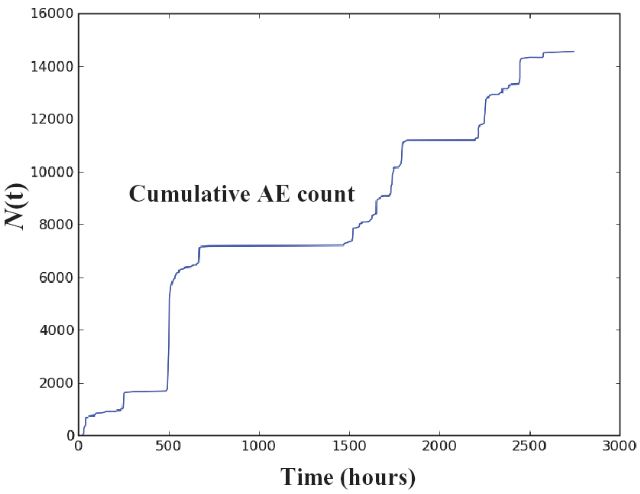

Figure 6. Cumulative AE count based on the data collected at the northeast corner of the tower, from 5:40 PM of 23 September 2010, to 1:00 PM of 28 January 2011.

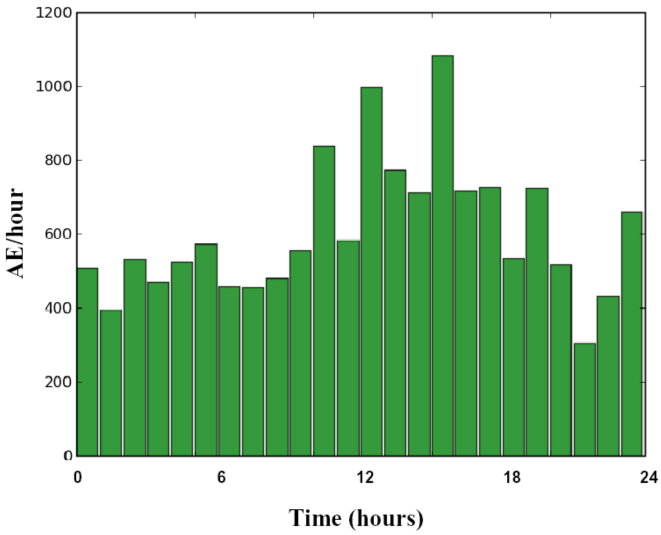

Figure 7. AE count hourly distribution chart over a 24 hour time span, as determined for the entire monitoring period.

4.1 *AE and earthquakes*

During the monitoring period, frequent seismic activities were recorded in the area around the city of Bologna. Earthquake data were taken from the website of the Istituto Nazionale di Geofisica e Vulcanologia (INGV). From among all the seismic events, only those that might have affected the stability of the tower were taken into account. In particular, the following seismic events were considered: the two strongest quakes –i.e., the one that hit the Rimini area on 13 October at 11:43 PM (4.1 Richter magnitude), and the one recorded in the Modena Apennines on 21 November at 4:10 PM (3.4 Richter magnitude)– and the earthquakes with a magnitude of over 0.5 that occurred within a radius of about 20 km from the center of the city.

The chart in Fig. 8 shows the AE count rate per hour, the earthquakes recorded within a 20-km radius from the city center, and the two strongest quakes that hit the region. All the quakes, the two most important ones (denoted with red dots) and the weaker ones (blue dots), are shown as a function of time of occurrence and magnitude.

Fig. 8 reveals a *correlation between the AE events recorded experimentally and the seismic events*. As can be seen, in fact, the energy peaks measured through the AE count rate almost invariably occurred during a seismic event. In particular, the highest AE count peak (ca 500) was detected on 13 October, at 11:43 PM, when the Rimini area was hit by the 4.1 magnitude quake. Hence, this seismic event is the pulse phenomenon that resulted in the highest damage effect on the tower.

The second strongest earthquake, i.e., the 3.4 magnitude quake that hit the Modena Apennines on 21 November at 4:10 PM, does not introduce any significant change to the chart shown in Fig. 8, since the AE activity detected during this event was rather limited.

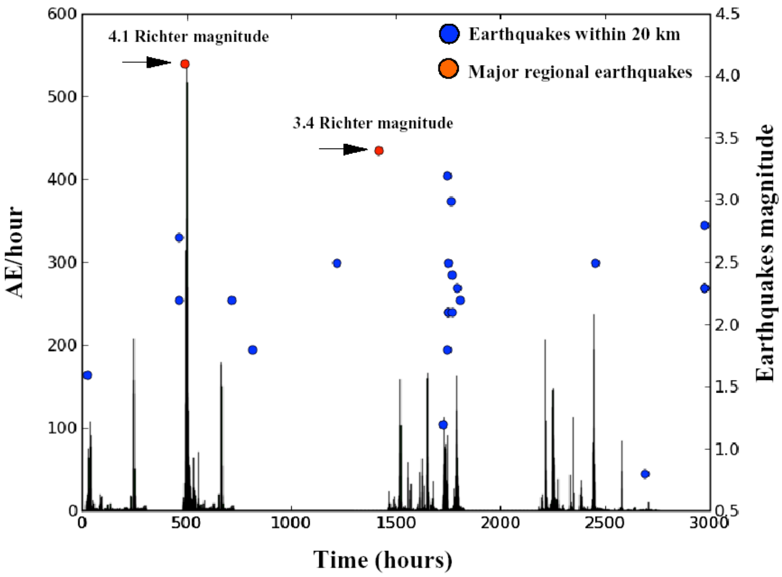

Figure 8. Historic series of the AE differential count and the earthquakes detected within a 20-km radius from the Bologna city center. The chart also shows the two strongest regional earthquakes, which occurred in Rimini area and in the Modena Apennines. This chart refers to the entire monitoring period.

4.2 *AE and wind*

Further analyses were also conducted with a view to correlating the intensity of the wind acting on the tower with the AE data recorded during the monitoring period, but no clear correlation has been identified as yet. The measurements of wind velocity were obtained from data acquired by wind velocity sensors applied at the height of 78 m on the monitored tower, and averaged for each hour. The wind velocity intensities measured during the monitoring period were comprised between 1 and 7 m/s. These velocities were unable to generate sensible aerodynamic loads on the structure.

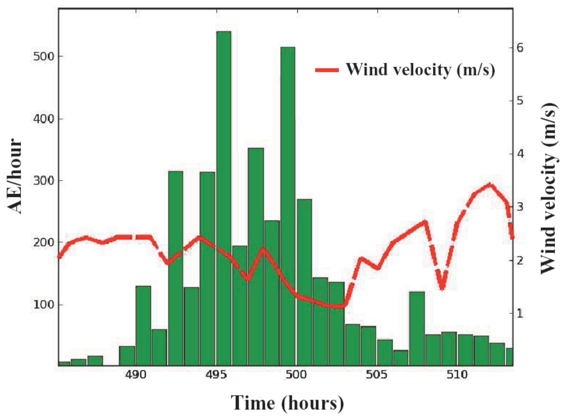

Figure 9: AE rate and wind velocity measurements during the monitoring period in a time window of 30 hours just after the earthquake of 13 October 2010.

In the chart of Fig. 9 are represented in detail the AE count rate and the wind velocity in a time window of 30 hours just after the earthquake that hit the Rimini area on 13 October 2010. The graph shows that the peaks in the AE count rate do not correspond with those of the wind velocity.

Moreover, the chart of Fig 10 relates the wind velocities and the AE count rate obtained during all the monitoring period (2915 hours). This graph makes clearer that the two phenomena are completely statistically unrelated.

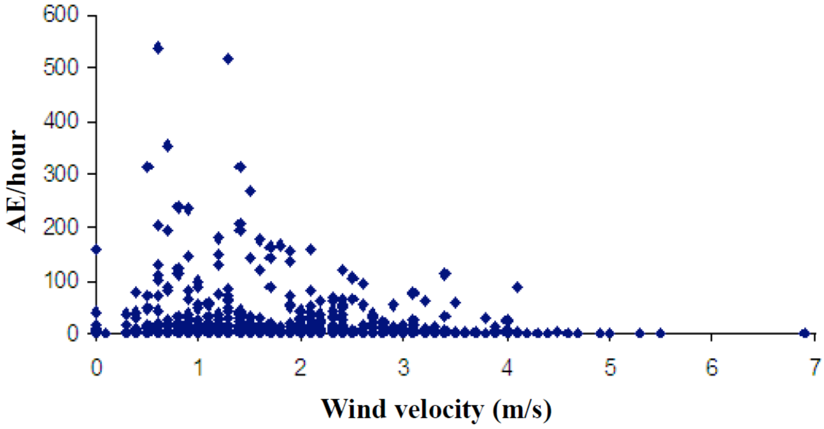

Figure 10: Chart relating the wind velocity and the AE count rate during all the monitoring time, the two time series seem to be statistically unrelated.

5 PRELIMINARY FINITE ELEMENT ANALYSIS

A preliminary linear elastic finite element analysis has been carried out in order to assess the stress level in the tower, together with the main dynamic characteristics. The finite element model accounts for the three-dimensional geometry of the tower, and is composed of nearly 15300 wedge and pyramid elements connecting almost 9000 nodes. The mass of the masonry and of the stone in the foundation has been assumed equal to 1800 kg/m^3. A mean value for the young modulus, accounting for the fact that up to a certain height the tower presents three leafs walls with internal filling, has been assumed equal to 5 MPa.

The preliminary linear elastic analysis considered only the self-weight of the tower (Fig. 11a). It was possible to assess that the elastic deformation of the tower is about 8 cm, which is about 1/30 of the present total deviation from verticality.

The level of stress in the masonry of the tower (Fig. 11b) is generally low, although in proximity of the monitored area, the level of vertical stress approach 2.1 Mpa, which can be critical in case of very poor masonry.

The preliminary modal analysis showed that the first mode is bending in the west-east plane, with a resonance frequency of 0.357 Hz (Fig. 11c). The second mode is bending in the orthogonal plane, with an eigen-frequency equal to 0.365 Hz (Fig 11d). The third eigen-frequency is 1.75 Hz, and the fourth is 1.78 Hz. The fifth mode is torsional (Fig. 11e) with an eigen-frequency of 3,07 Hz. Those results agree quite well with more detailed dynamic analyses carried out by other Authors [11].

The maximum vertical stress in the tower is compatible with the acquire rate of acoustic emissions from the monitored region. The fact that the first modal shape tends to increase the stress in the same area agrees well with the increase of acoustic emissions connected with seismic events.

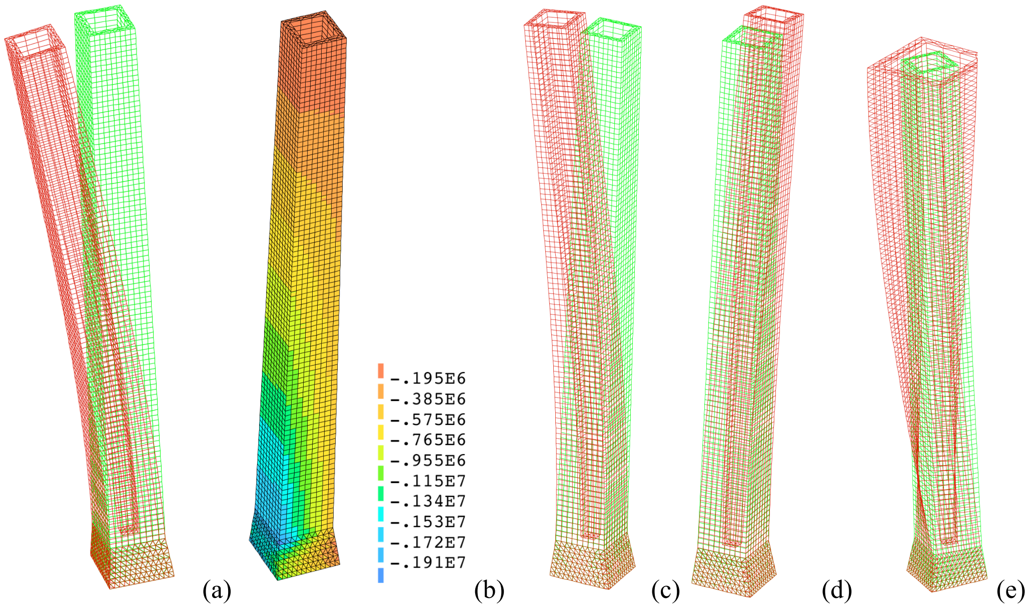

Figure 11. Deformation due to the effect of gravity (a); vertical stress expressed in MPa (b); first modal shape (c); second modal shape (d); fifth modal shape (e).

6 CONCLUSIONS

From the monitoring process carried out on a significant part of the *Torre degli Asinelli* it was possible to evaluate the incidence of seismic activity and wind action on the progress of fracture and damage phenomena within the structure.

During the monitoring period a correlation between peaks of AE activity in the structure and regional seismicity is found. The tower, in fact, as in the case of other monitored historical structures built in seismic territory [1,2,5,10], behaved as sensitive earthquake receptor.

Finally, during the monitoring, no statistical correlation was found between wind and acoustic emission.

The presented study suggests that the AE structural monitoring coupled with local earthquake activity can be a tool of crucial importance in damage mitigation of the structure.

In order to arrive at a more comprehensive and objective evaluation of the structural conditions of the tower, the results obtained with the AE technique −that analyses the ultrasound signals coming from microcracks in the masonry− should be supplemented with data obtained on other zones of the structure subject to different stress-strain conditions.

Moreover, earlier studies conducted by the authors with the AE technique on the stability of historic buildings made of stone or brick masonry have shown that the damage process is characterized by appreciable size effects on dissipated energy density. The multiscale aspect of energy dissipation can be addressed with statistical and fractal criteria in order to predict the onset of critical conditions in an actual structure [1,2].

By adopting these methods it becomes possible to introduce an appropriate energy parameter for the assessment of damage propagation in structural elements. This parameter is based on the correlation between the cumulative AE count in an actual structure and the corresponding AE activity measured on different size specimens obtained from the structure and tested up to failure

[1,2]. Accordingly, if an opportunity arose to take test specimens from the tower (small cores, 2.5 to 10 cm in diameter, according to a minimally invasive approach), or if it were possible to carry out on-site double-jack tests while acquiring the AE signals, the safety and residual life of the structural parts monitored could be evaluated more effectively.

Additional significant data −as was done in [12] for the Medieval Towers of Alba− are obtained with a FEM numerical modeling of the structure that is able to capture the static effects on damage phenomena of permanent loads and the dynamic effects of seismic events and wind-structure interaction.

References

[1] Carpinteri, A. and Lacidogna, G., “Structural monitoring and integrity assessment of medieval towers”, *Journal of Structural Engineering, ASCE*, **132,** 1681–1690, (2006).

[2] Carpinteri, A. and Lacidogna, G., “Damage evaluation of three masonry towers by acoustic emission”, Engineering Structures, **29**, 1569–1579, (2007).

[3] Carpinteri, A. and Lacidogna, G. (Eds), *Earthquakes and Acoustic Emission*, Taylor & Francis, London (2007).

[4] Carpinteri, A., and Lacidogna, G. (Eds), *Acoustic Emission and Critical Phenomena: From Structural Mechanics to Geophysics*, CRC Press, Boca Raton (2008).

[5] Niccolini, G., Carpinteri, A., Lacidogna, G. and Manuello, A., ”Acoustic emission monitoring of the syracuse athena temple: Scale invariance in the timing of ruptures”, *Physical Review Letters*, **106**, 108503/1–4, (2011).

[6] Savioli, L. V., *Annali Bolognesi*, Vol. 3, Bassano, Remondini e figli, Bologna (1784–1795).

[7] Bertocchi, E. and Trussardi, D.C., *Studio delle vicende storiche e dei quadri fessurativi di torri in muratura per la valutazione della loro sicurezza sotto carichi ciclici e di lunga durata*, Degree Thesis, Politecnico di Milano, Supervisors Binda, L. and Anzani, A. (1996).

[8] Cavani, F., *Sulla pendenza e sulla stabilità della Torre degli Asinelli di Bologna*, Accademia delle Scienze, Bologna (1912).

[9] Carpinteri, A. and Lacidogna, G., “Damage monitoring of an historical masonry building by the acoustic emission technique”, *Materials and Structures*, **39,** 161–167, (2006).

[10] Carpinteri, A., Lacidogna, G. and Niccolini, G., “Acoustic emission monitoring of medieval towers considered as sensitive earthquake receptors”, *Natural Hazards and Earth System* Sciences, **7**, 1–11, (2007).

[11] Riva P., Perotti F., Guidoboni E. & Boschi E., “Seismic analysis of the Asinelli Tower and earthquakes in Bologna”, *Soil Dynamics and Earthquake Engineering* **17**, 525–550, (1998).

[12] Carpinteri, A., Invernizzi S. and Lacidogna, G., “In situ damage assessment and nonlinear modelling of a historical masonry tower”, *Engineering Structures*, **27**, 387–395, (2005).