STRUCTURAL CONTROL AND HEALTH MONITORING
Struct. Control Health Monit. 2016; **23**:659–667
Published online 28 September 2015 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/stc.1804

A study on the structural stability of the Asinelli Tower in Bologna

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SUMMARY

This study concerns the structural stability of the Asinelli Tower in Bologna. This building is the tallest and, with the Garisenda Tower, the most undisputed symbol of the City of Bologna. The stability conditions of the tower were analyzed by means of the Acoustic Emission technique. Specifically, this approach was used to analyze the influence of repetitive and impulsive events of natural or anthropic origin, such as earthquakes, wind, or vehicle traffic on the damage evolution of the tower. Copyright © 2015 John Wiley & Sons, Ltd.

Received 14 April 2015; Revised 8 July 2015; Accepted 7 September 2015

KEY WORDS: acoustic emission; damage evolution; seismic effects; masonry structures; non-destructive monitoring

1. INTRODUCTION

Early detection of fracture precursors is a critical issue because of the treacherous nature of damage phenomena, which may suddenly degenerate into catastrophic failures. The application of non-destructive investigation techniques, based on detection of various forms of energy spontaneously released during damage growth, can be extremely helpful for the conservation of monuments of the past centuries. Well-reasoned maintenance and intervention programs first require the use of non-destructive investigation techniques to assess the integrity of art works without altering their state of conservation.

With the Acoustic Emission (AE) monitoring technique, the spontaneous release of stored strain energy by evolving defects in the form of transient elastic waves (known as acoustic emissions) is detected by means of wide-band piezoelectric sensors, sensitive in the ultrasonic range, typically between 50 kHz and 1 MHz.

Thus, as it provides information on the internal state of a material, the AE technique is well suited for the structural integrity assessment of materials and also large-sized structures (buildings, bridges, etc.) before they become safety hazards [1,2]. The observed proportionality between the rates of recorded AE activity from visible cracks and the measured crack growth rates confirmed the effectiveness of the AE technique for damage evolution assessment in structural elements [3]. Recently, an improved approach, which considers the refraction of AE waves because of the layers in masonry material, has been proposed to provide more reliable crack locations in masonry structures [4]. Furthermore, the AE technique can be used to predict the time to failure [5], as performed for walls made with historical brickwork [6]; such predictive power and the non-invasivity of this technique can be exploited to protect the Italian cultural heritage, as historic buildings and monuments are exposed to

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seismic risk and, in general, to severe, long-term, cyclic loading conditions or harsh environmental conditions.

Many structures may undergo accelerated aging and deterioration because of the action of small and intermediate earthquakes, rather frequent in Central and Southern Italy. The triggered damage, often inaccessible for visual inspection, eventually results in increased vulnerability to strong earthquakes [7].

Herein, the results of AE monitoring of the Asinelli Tower are presented. We analyze the time correlation of the AE activity in the tower with the occurrence of nearby earthquakes as well as with the intensity of the vehicle traffic in the roads around the tower.

2. STRUCTURAL DESCRIPTION OF THE ASINELLI TOWER

The authors of the various histories of the city of Bologna all agree in dating the Asinelli and Garisenda Towers to the early 12th century; there are some minor discrepancies as to the year of construction, as pointed out by Ludovico Savioli in discussing the Asinelli Tower in his Annali Bolognesi: "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" [8,9].

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 ~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 ~1.70 m below ground level and rises to 3.00 m above ground. The substructure of the tower is nearly square, with sides approximately 10.50 m long. The second segment, with sides tapering from 8.15 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 15th century, has sides that gradually decrease in size to ~6.50 m 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 and 45 cm thick respectively, enclosing a mixture of rubble, bricks, and mortar—and is characterized 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 15th century.

The studies conducted in the early 20th century by F. Cavani [10] 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° and a deviation from verticality of 2.38 m. Thus, we find that the deviation increased by 13 cm in the course of approximately 1 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 plain view indicating the zone of application of the AE sensors.

3. MONITORING BY MEANS OF THE AE TECHNIQUE

The AE activity was monitored in a zone significant for monitoring purposes and easy to reach, by attaching six piezoelectric sensors (working in the range of 50–500 kHz) to the north-east corner of the tower at an average height of ~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 ~2.45 m (Figures 2 and 3).

AE monitoring began on 23 September 2010 at 5:40 PM and ended on 28 January 2011 at 1:00 PM, thus covering a 4-month period. The array of six AE sensors applied to the wall is shown in Figures 4 and 5, while Table I lists the coordinates of the sensor positions.

After setting a detection threshold of 100 mV (appropriate for masonry according to the authors' experience [3,4,7,11,12]) to filter out environmental background noise, we started data acquisition storing two quantities for each AE signal: the arrival time, determined by using the first threshold crossing of the signal, and the peak amplitude V_{max} (expressed in μV), which defines the magnitude of the AE event as $M = \log(V_{max}/1\ \mu V)$ [7,13,14].

DOI: 10.1002/stc

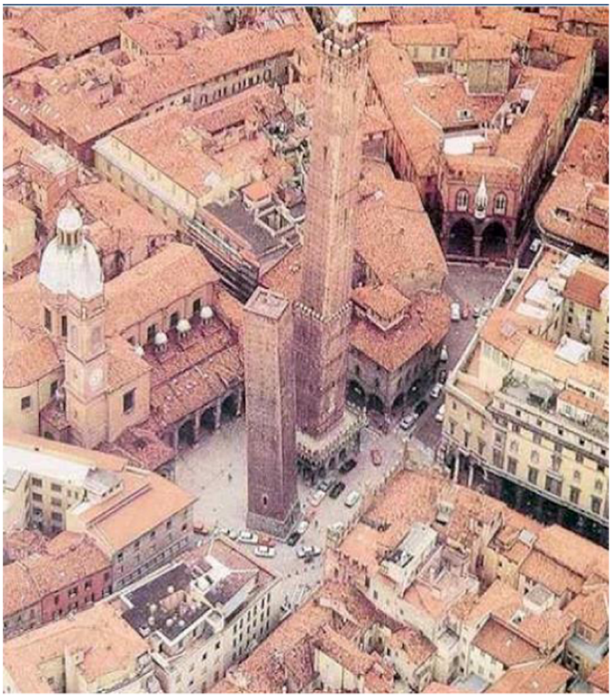

Figure 1. The Asinelli Tower and the Garisenda Tower in the city center of Bologna.

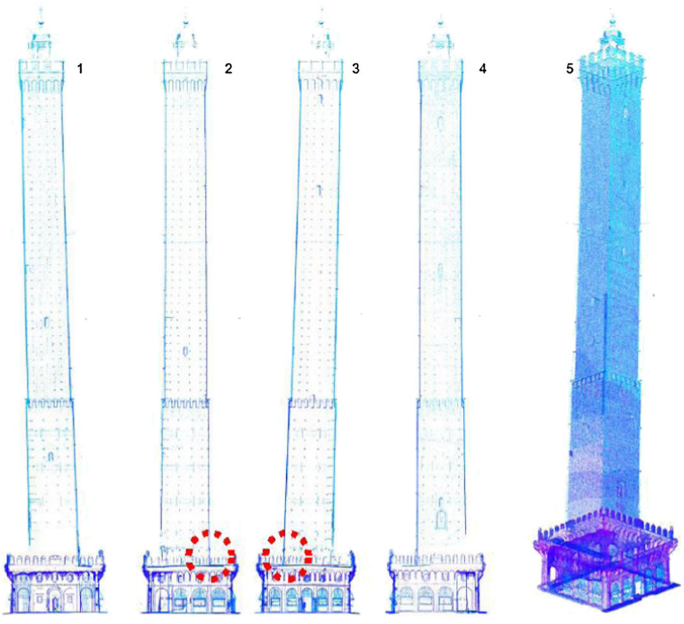

Figure 2. Front views and axonometric view of the Torre degli Asinelli. These views, supplied by the Municipality of Bologna, are taken from the measurements of the exterior of the structure made by Prof. Alessandro Capra by laser scanning. Faces (1) south, (2) east, (3) north, (4) west, and (5) axonometric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

The damage process zone was identified through Zonal Location Technique, tracing the AE signals to the zone around the array of sensors. This method was used because high material attenuation affected the quality of signals at multiple sensors and, consequently, the use of triangulation techniques.

Damage assessment in the wall is performed considering the statistical distribution of the AE signal magnitudes fitted by the Gutenberg–Richter law, $\log N\,(\geq M) = a - bM$, where N is the number of AE

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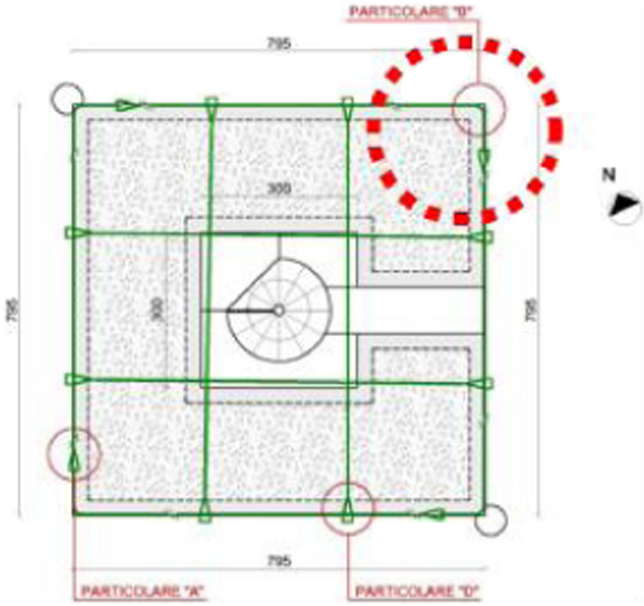

Figure 3. Cross section of the tower at a height of ~10 m above ground. Drawing supplied by the Municipality of Bologna. The corner where the sensors were applied is marked with a circle.

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

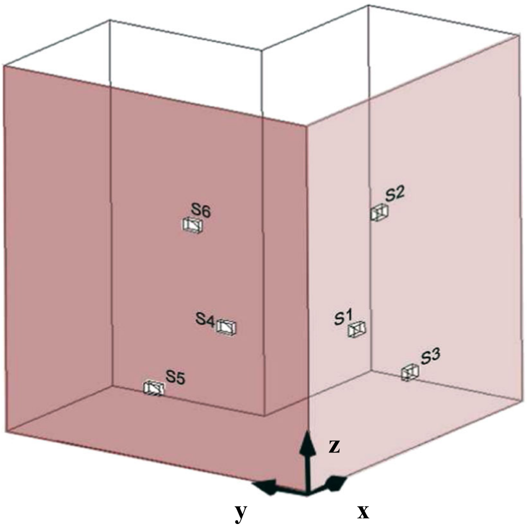

Figure 5. Axonometric scheme of the points of application of the AE sensors at the north-east corner of the tower.

Table I. 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.

events with magnitude greater than M and a and b (or b-value) are fitting parameters. The b-value is an important parameter for damage assessment of structures as it decreases in case of damage evolution [13].

The time evolution of damage is captured as well by a time-scaling approach, $N(t) \sim t^{\beta t}$, where $N(t)$ is the accumulated number of AE events up until the time t and β_t is a fitting parameter, which characterizes the damage evolution ($\beta_t > 1$ describes accelerated damage) [6].

The steady trend of b-value over time, plotted in Figure 6(c), suggests that the wall experiences damage but is still far from unstable conditions.

Several studies established that the total rate of damage, as measured, for instance, by the accumulated AE released energy, increases as a power law of the time to failure on the approach to the structural collapse [15,16]. Here, the lack of a power-law acceleration of the accumulated number of AE events in time (Figures 6(a) and 7) suggests that the monitored structure is mainly stable. However, the abrupt increments in the AE activity, related to the highest β_t-values in Figure 6(b), reveal temporary instability.

4. INFLUENCE OF ENVIRONMENTAL PHENOMENA ON THE AE ACTIVITY OF THE ASINELLI TOWER

An investigation of causal relationships between AE bursts and environmental local phenomena such as earthquakes, wind and vehicle traffic intensity is attempted.

Figure 8 displays the AE instantaneous rate (averaged over 1 h), and the sequence of nearby earthquakes as functions of time.[‡] Among all regional seismic events that occurred during the monitoring period, we considered only local earthquakes (with Richter magnitude ≥0.5 and epicenter within a radius of 20 km from Bologna) and the two strongest regional ones, as the most likely to affect the tower stability.

The strongest earthquakes were the 4.1 magnitude event occurred on 13 October 2010 at 11:43 PM in the Rimini area (epicenter about 100 km far from Bologna) and the 3.4 magnitude event on 21 November 2010 at 4:10 PM in the Modena Apennines.

There appears to be a significant correlation in time between AE activity in the tower and local seismicity, as the Rimini earthquake apparently triggered the largest AE burst, thus resulting in the highest damage effect on the tower; the about 3000 AE events detected in the first 12 h after the earthquake account for the 25% of 14 400 events collected during the entire monitoring period.

On the other hand, there is an evidence of seismic events which followed AE bursts and, therefore, did not trigger acoustic emissions from the tower. In particular, the seismic sequence between 1700 and 1800 h apparently occurred as the culmination of a 10-day period of intense AE activity.

Such AE bursts may indicate crustal stress releases affecting large areas during the preparation of a seismic event, as supported by several case histories from Italy, where an increased AE activity was observed before strong earthquakes.

However, a rigorous investigation on causal relationships between AE bursts and earthquakes would require a simultaneous operation of suitable arrays of AE monitoring sites, adequately placed in the territory, e.g., over a large regional area.

[‡]Earthquake data were taken from the website of the Istituto Nazionale di Geofisica e Vulcanologia-INGV, http://www.ingv.it/it/.

DOI: 10.1002/stc

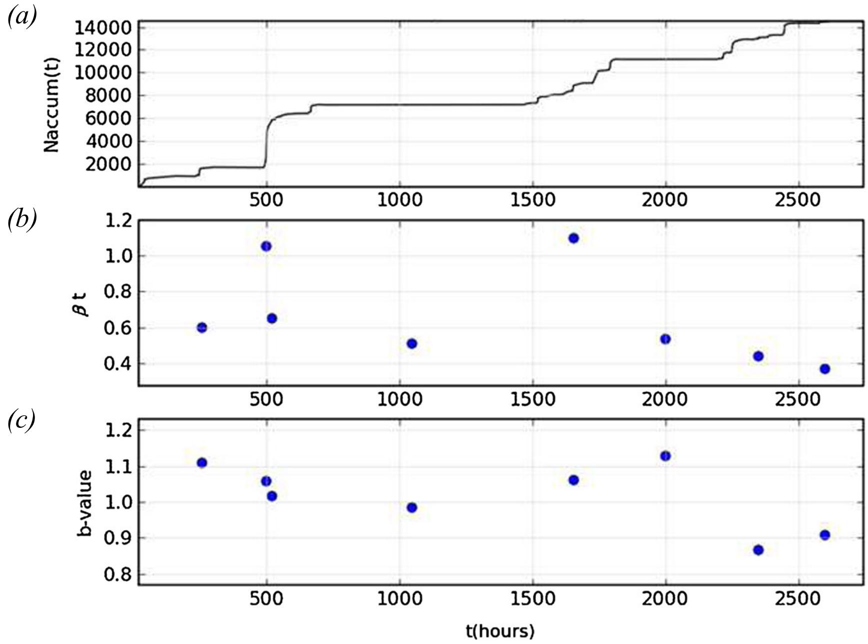

Figure 6. Damage assessment of the Asinelli Tower: accumulated number of AE events as a function of time (*a*); β_t and *b*-value trends over time during the entire monitoring period: β_t and *b*-values are calculated with using groups of 2000 AE events (*b* and *c*).

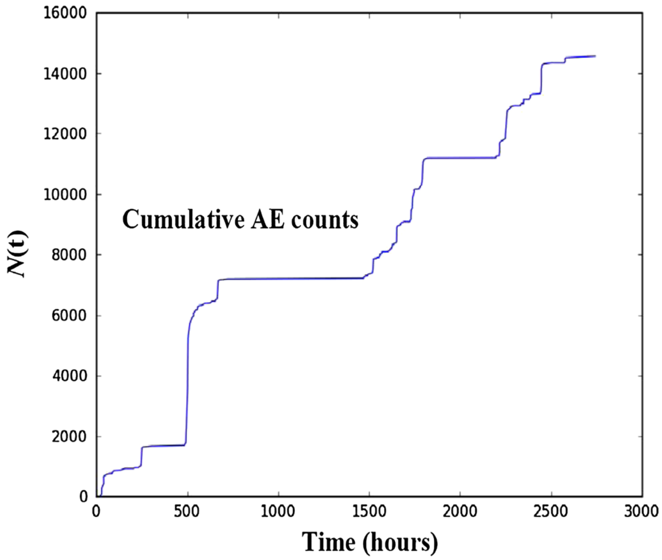

Figure 7. Accumulated number of AE events based on the monitoring of the north-east corner of the tower, from 5:40 PM of 23 September 2010 to 1:00 PM of 28 January 2011.

The presented monitoring campaign was motivated by the debate about the incompatibility between heavy vehicle traffic and Bologna's historic center.

In general, traffic-induced vibrations in buildings are mainly because of heavy vehicles that pass at relatively high speed on a road with an uneven surface profile. Interaction between the wheels and the road surface causes a dynamic excitation generating waves that propagate in the soil and impinge on the foundations of nearby structures.

Therefore, we used AE data to investigate the correlation between high-frequency vibrations of the tower and possible anthropogenic sources, specifically vehicle traffic, in view of their possible mitigation.

DOI: 10.1002/stc

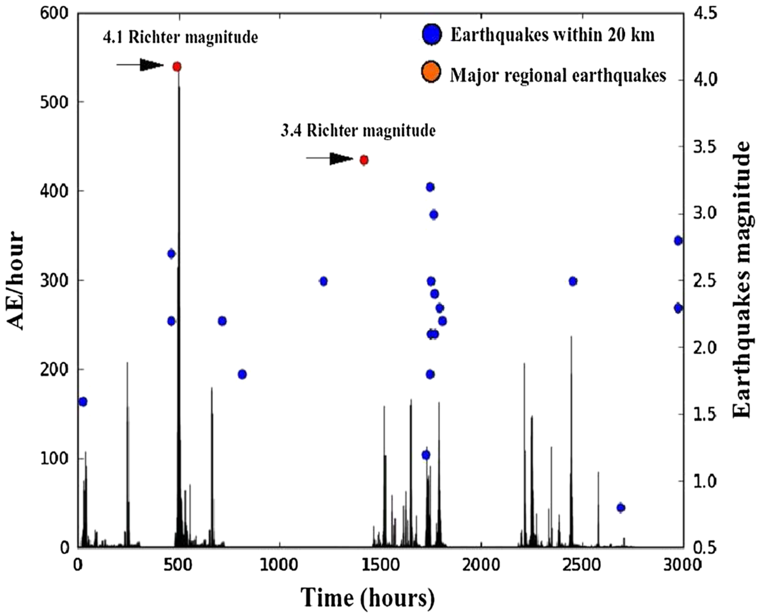

Figure 8. Instantaneous AE rate averaged over 1 h and nearby earthquake occurrence as functions of time.

The vehicle volume hourly distribution shown in Figure 9 was originated from data collected for one week, including mass transit, private, and heavy vehicles, from 8 PM to 6 PM in the areas surrounding the tower.

However, the lack of correlation between a repetitive phenomenon, such as the vehicle city traffic, and the AE data series, characterized by well spaced bursts with often long silent periods, clearly emerged.

We investigated possible effects of the wind action on the tower analyzing wind speed data acquired by sensors applied at the height of 78 m on the ground. However, the measured wind speed, between 1 and 7 m/s, was unable to generate sensible aerodynamic loads on the structure, as confirmed by the lack of causal relationship between wind intensity and AE activity in the tower: the AE count rate and the wind speed in the 30-h time window just after the strong Rimini earthquake shows that the peaks in the AE activity did not correspond to peaks of wind speed (Figure 10). The diagram in Figure 11, which correlates wind speed and AE count rate during the whole monitoring period, confirms that the two phenomena are statistically unrelated.

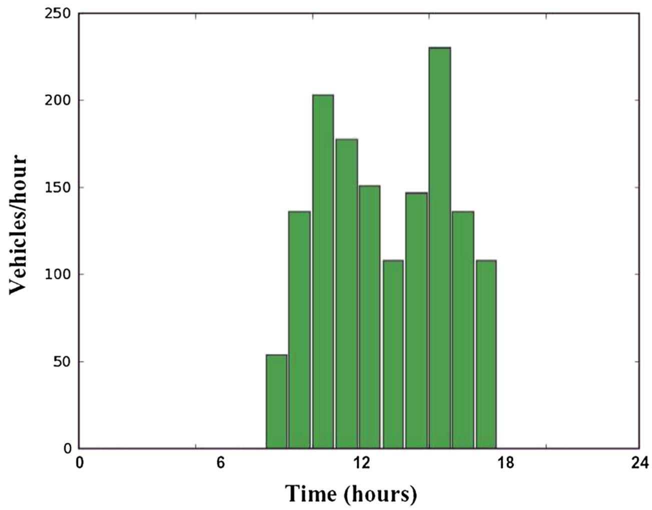

Figure 9. Vehicle volume week distributions in the areas surrounding the Asinelli Tower from 8:00 AM to 6:00 PM.

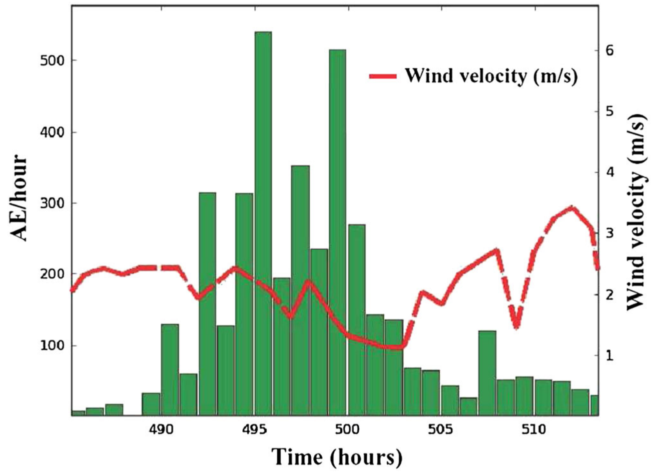

Figure 10. Instantaneous AE rate and wind speed in a time window of 30 hours just after the earthquake of 13 October 2010.

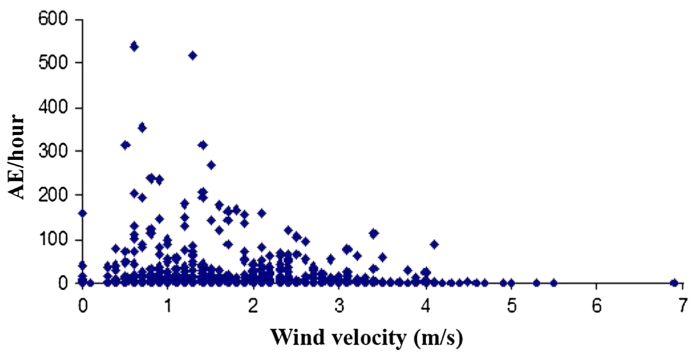

Figure 11. Diagram relating wind speed and AE rate during the entire monitoring period.

5. CONCLUSIONS

The integrity of the Asinelli Tower was evaluated by means of the AE technique, applied to a significant part of the structure. The AE data analysis suggests that the monitored wall experiences damage but is still far from unstable conditions.

We have also analyzed the relative influence of vehicle traffic, seismic activity, and wind action on the progress of damage in the monitored portion. During the monitoring period a correlation between peaks of AE activity in the tower and regional seismicity is found. The tower, in fact, as in the case of other monitored historical structures built in seismic areas [7,11,12,17], seems to be particularly sensitive to the action of nearby earthquakes, behaving as a sensitive earthquake receptor.

Actually, no statistical correlation was found between AE activity and other potential AE sources (wind and vehicle traffic) considered.

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 should be supplemented with data obtained from other zones of the structure subject to different stress–strain conditions or by means of other techniques [18]. The presented study suggests that the AE structural monitoring, coupled with the analysis of environmental actions, can be a tool of crucial importance in structural damage mitigation.

Additional significant data—as was performed in [19] for the Medieval Towers of Alba—could be obtained with a FEM numerical modeling of the structure that is able to capture the static effects of permanent loading and the dynamic effects of vehicle movements, seismic events, and wind–structure interaction.

ACKNOWLEDGMENTS

The authors wish to thank the Municipality of Bologna and Eng. R. Pisani for allowing this study on the Asinelli Tower.

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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