Garisenda Tower in Bologna (Italy): health monitoring by different non-destructive testing techniques

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Abstract: In the Garisenda Tower of Bologna, several non-destructive (NDT) techniques are being used to examine structural damage and cracking evolution. The acoustic emission (AE) activity emerging from the masonry structures is analysed and related to surrounding temperature and strain measurements by distributed fibre optic sensors (FOSs). A seismometer was used to monitor low-frequency vibrations propagating across the ground-building foundation interface in order to examine the impact of local seismic activity or heavy vehicle traffic on tower vibration. The obtained data has led to the identification of several sources of AE activity, which apparently indicates the existence of an evolving cracking pattern. A consistent increase in the cumulated function of AE signals suggests that tower damage is caused by more than temperature changes. As a result, the origin of damage can be identified as the material's time-dependent creep behaviour under dead load and its interaction with fatigue generated by thermal fluctuations.

Keywords: non-destructive techniques; acoustic emission; fibre optic sensors; FOSs; seismicity; medieval towers; Italy.

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1 Introduction

The Garisenda Tower in Bologna is a city symbol and one of the most valuable medieval heritages. It was named after the Garisendi family, who ordered its construction in the early 12th century at the same time as the Asinelli Tower. The towers, recognised as the 'Due Torri' of Bologna (Figure 1), were supposed to be the same height at first, but in 1351, the Garisenda began to tilt due to a foundation failure. Hence, for safety reasons, it was lowered by about 13 metres from its original height of 61 metres. More recently, the stability of the Garisenda Tower focused the interest of the scientific community (Baraccani et al., 2020; Pesci et al., 2011; Poluzzi et al., 2019; Dallavalle et al., 2022). The two towers are nowadays owned by the Municipality of Bologna, which is responsible for their maintenance.

Figure 1 The Asinelli (left) and Garisenda (right) Towers in Bologna (see online version for colours)

In particular, the Garisenda Tower is 48 metres high, has 7.5 m sides, and today leans about 3.22 m to the East side. This tower is currently undergoing different non-destructive testing (NDT) techniques to assess structural damage and cracking evolution. A piezoelectric (PZT) sensor network is used for acoustic emission (AE)-based local damage detection (Carpinteri and Lacidogna, 2007; Carpinteri et al., 2007). The AE activity emerging from the monitored masonry structures is analysed and related to surrounding temperature, and strain measurements by distributed fibre optic sensors (FOSs). The array of eight AE sensors (working in the frequency range 10–200 kHz) has been fixed at the cell level of the tower. Six of these sensors have been applied inside the tower cell on the surface of the selenite load-bearing walls, one embedded inside the 'a sacco' masonry fill, and the last one outside of the cell, just below the selenite ashlar. Six FOS distributed strain sensors have also been applied to the inner face of load-bearing walls along the vertical direction from the ground level.

Low-frequency vibrations propagating across the ground-building foundation interface have been detected by a seismometer in order to investigate potential effects of the local seismic activity and the heavy vehicle traffic on the tower vibration. As a tall building, the tower could be exposed to the impact of wind and, thus, such effects have been investigated as well, as was already done in Carpinteri et al. (2016), on the monitored system. The analysis of the experimental results has led to the identification of several sources of AE activity, which apparently indicates the existence of an evolving cracking pattern (Ohtsu, 1996; Pollock, 1973; Carpinteri et al., 2008). FOS and temperature measurements have revealed a quite good correlation between wall deformations and the internal temperature of the tower, with the largest contractions observed at about 6.0°C and the largest expansions observed at about 25.0°C. The correlation between AE activity and FOS strain measurements has revealed that the largest AE rate is observed during the wall contraction phases, in a strain interval between –0.15 mm/m and –0.20 mm/m detected in a local temperature range from 5.0 to 12.0°C. Finally, no apparent correlations of the AE activity with local environmental phenomena, e.g., peaks in the wind velocity past the tower and moderate seismic events in a radius of 30 km, have been observed on the mentioned system.

In particular, in order to obtain a comprehensive evaluation of the structural conditions, the combined use of AE technique together with the data coming from other zones of the structure subjected to different stress-strain conditions or obtained using other techniques were used. In this paper, the AE signals distribution is related to the data measured by FOSs and a seismometer to obtain an objective correlation between the actions generated by the environment and the tower damage, as well as the evaluation of possible evolving cracking pattern and of structure deformation.

2 Experimental devices

2.1 AE monitoring

AE refers to the phenomenon of mechanical waves propagation in a material subject to an irreversible change in its structure due, for example, to the generation of fractures. Then, the AE consists in the rapid release of energy, in the form of mechanical waves, in a frequency range from tens of kHz to hundreds of MHz. The AE monitoring is a non-destructive control methodology based on the detection of pressure waves emitted by evolving defects.

During the experimentation at the Garisenda Tower, the AE monitoring is carried out by analysing the signals received from the piezoelectric transducers (PZT) using a threshold detection device (mod. AEmission) that counts AE events exceeding a certain voltage, and with a frequency ranging between 10 and 200 kHz. For each AE signal, this device provides the cumulative counting of mechanical waves, the acquisition time, the measured amplitude in volts, the duration, and the frequency. A high-performance field programmable gate array (FPGA) device performs real-time analysis of the data from

PZT sensors and extracts the parametric value. The data sampling rate is 5 MS/s at 16 bits.

It's worth noting that the perceived frequency level is determined by the attenuation with which the acoustic waves propagate through the damaged material. Only mechanical waves with a lower frequency, and thus a higher wavelength, can reach the sensors after having originated from a specific source when the material contains many inhomogeneities or defects.

2.2 Vibrometer/seismometer

In addition to the AEmission equipment, a vibrometer/seismometer (Istantel Micromate) with a special geophone was installed. The seismometer is equipped with three channels for the triaxial geophone connection and one channel for an air overpressure or sound level microphone. The device has a trigger threshold able of detecting movement speeds greater than or equal to 0.127 mm/s. The tool also has an internal clock that is synchronised with the UTC time reference.

2.3 FOSs system

In order to continuously measure the deformations of the cell as a result of the loads, a monitoring system using vertically positioned Osmos optical strands sensors was used. At the same time, the internal temperature was also measured. The data, collected at a frequency of 100 Hz and with a sensitivity of 1 με, were sent to an intelligent data acquisition unit (EDAS) which pre-processed them, stored them temporarily and sent them to a dedicated cloud. The data could be accessed and downloaded via a dedicated web platform.

3 Experimental setup

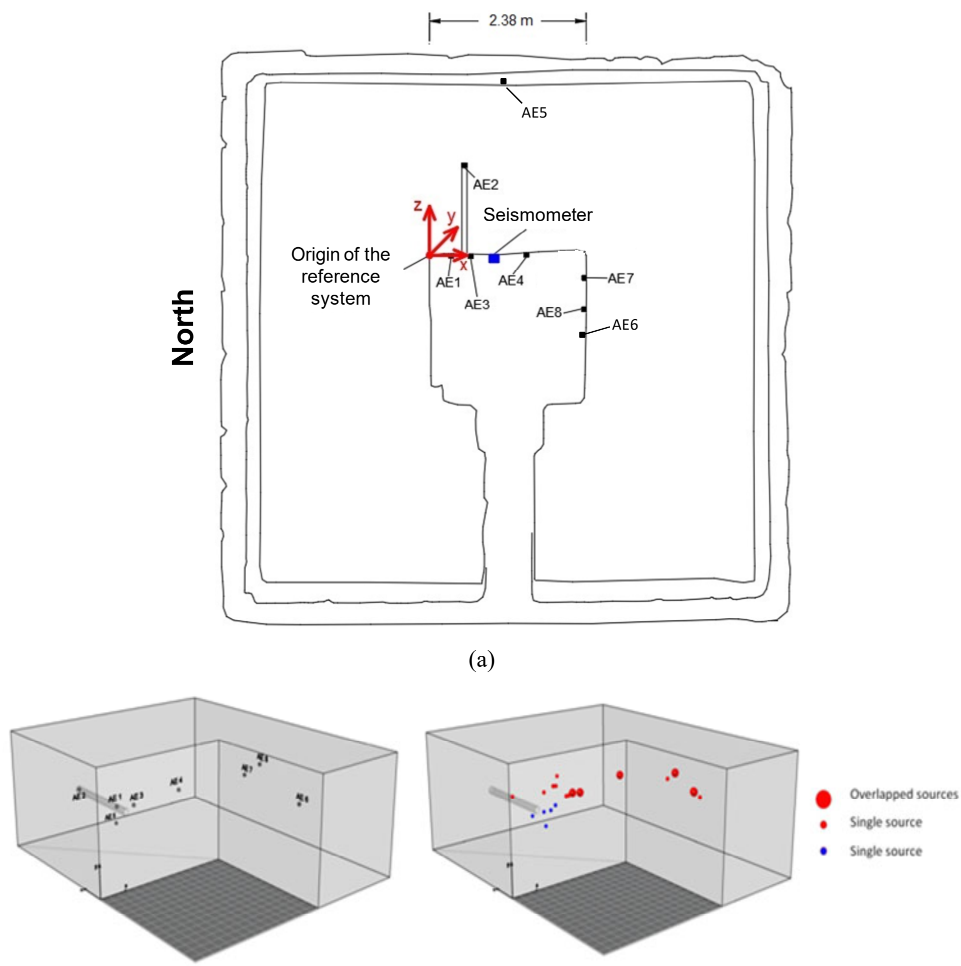
The acoustic piezoelectric sensors were fixed to the inner wall of the tower using a high-strength glue which guarantees an excellent grip even in particularly critical environmental conditions. Before placing the PZT, along one of the walls of the tower cell a core hole, with a diameter of 10 cm, a depth of 140 cm and at a height of about 120 cm from the floor, has been practiced in order to obtain selenite specimens to be tested in the laboratory. A total of eight sensors have been installed in the tower cell: six on the selenite load-bearing walls, one in the 'a sacco' masonry fill, and the eight outside the cell, below the selenite ashlars. As for the seismometer, it was positioned at a height of about 150 cm from the floor on the front wall.

The optical strands in number of 6 were fixed solidly according to the vertical. Four of them were 2.0 m long and positioned at the four internal corners of the tower cell, while two other ones of 1.0 m length were fixed on the East and South internal faces respectively. This arrangement made it possible, on the one hand, to monitor at greater distances from the neutral axis and, on the other, to measure directly on the most stressed faces.

4 Experimental results

The structural investigation of the Garisenda Tower by means of the AE technique, together with the experimental evidence acquired by the FOS system and the seismometer, began on May 31st, 2019 and is currently ongoing. The latest data was downloaded on September 18th, 2021, for a total of almost 30 months of monitoring to date.

Figure 2 (a) Plan of the tower with the origin of the Cartesian reference, for the arrangement of the AE sensors and the seismometer (b) Representation of the AE sensors positions in axonometry (c) AE sources distribution along the South-East walls of the tower* (see online version for colours)



(a)

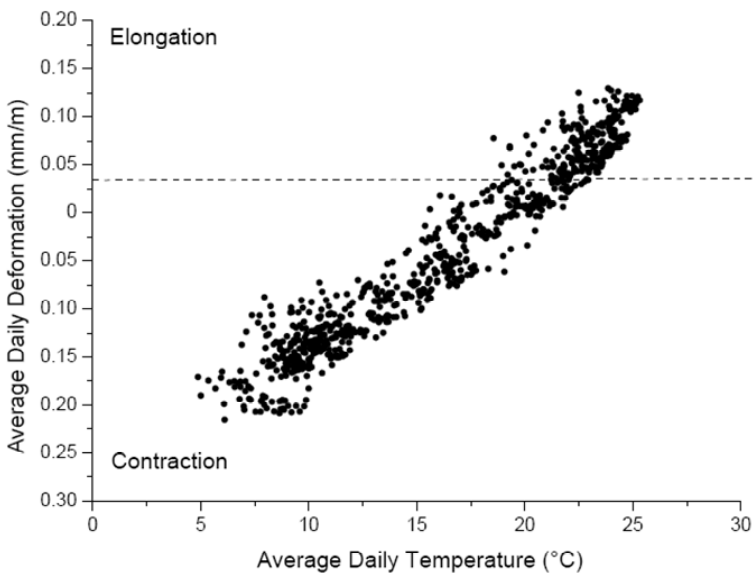
(b) (c)

Notes: *The larger dots indicate overlapping acoustic sources. The points represented in blue were located from the 290th to the 450th day of monitoring in the masonry depth of the tower. The localisation of other points from 450th day onwards is still in progress.

The experimental result analysis revealed several sources of AE activity, identified by a dedicated program of AE sources localisation (Carpinteri et al., 2006), implying the existence of an evolving cracking pattern. Figure 2 shows the plan of the tower cell at a height of 2 metres from the ground, with the AE sensors and the seismometer arrangement. In the same figure, an axonometry with the representation of the AE sensors positions and the distribution of the AE sources localised along the walls in the South-East corner of cell are reported.

During the monitoring time FOS and temperature measurements revealed a fairly good correlation between wall deformations and tower internal temperature, with the largest contractions occurring at about 6.0°C and the largest expansions occurring at 25.0°C. See Figure 3 in which a graph showing the daily deformations, obtained by averaging the data recorded on the six optical strands, is reported as a function of the average daily temperature measured inside the tower cell.

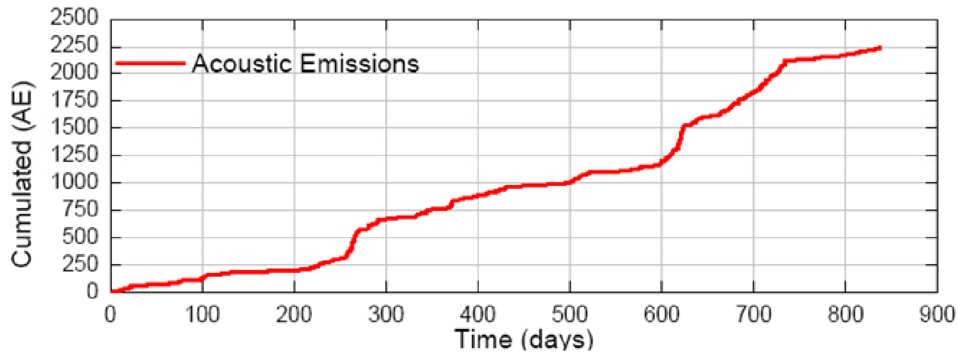
Figure 3 Correlation between walls average vertical deformations measured by FOS and tower internal temperature



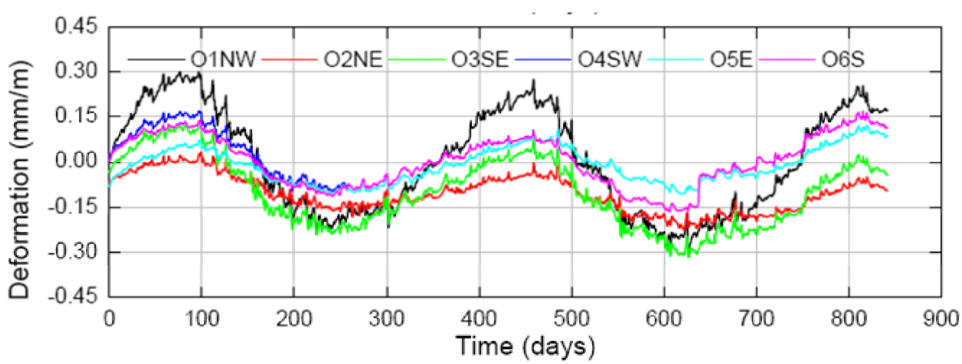
In addition, Figure 4 shows the growth of the AE signals cumulated function, obtained from all the transducers during the monitoring time, with the trend of the daily strains measured by means of the six optical strands. Observing the chart of the deformations trend, it can be seen that the minimum values of the contraction deformations are attributable to the optical strand O5E which is arranged in the South-East corner of the tower cell, while the maximum values of the expansion deformations are attributable to the optical strand O1NW arranged in the North-West corner. By relating the AE signals cumulative chart to that of the deformation trend, it can be seen that the maximum increases of the AE signals are obtained in relation to the minimum values of the masonry walls contractions, i.e., around 240 days (January 25th, 2020) and 607 days (January 26th, 2021) from the start of monitoring.

To better highlight this phenomenon, the correlation chart between the cumulated AE activity and FOS average daily deformations, as well as that between the cumulated AE activity and average daily temperature, are shown in Figure 5.

Figure 4 Trend of the (a) cumulate function of the AE signals recorded by the eight sensors and (b) daily deformations measured by means of the six optical strands (see online version for colours)



(a)

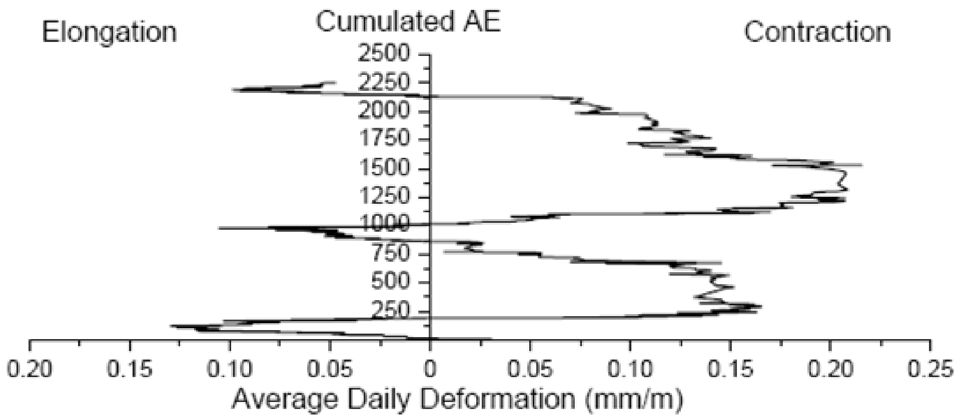


(b)

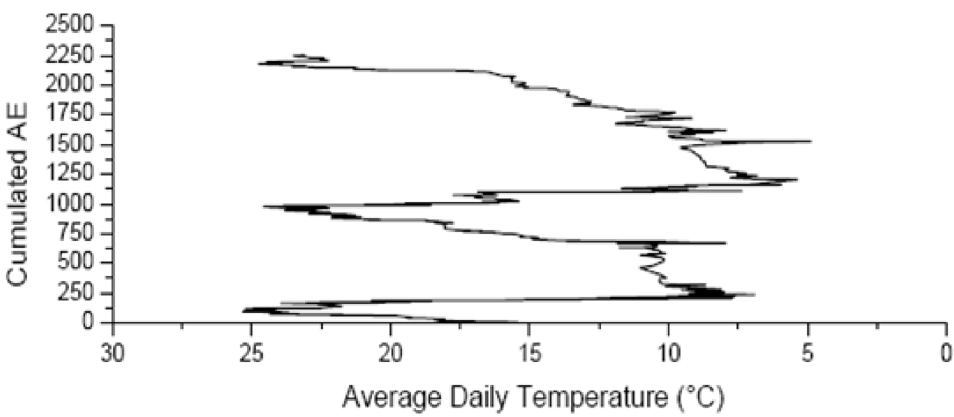
They reveal that the largest increases in AE signals is observed during wall contraction phases, in a strain interval near –0.15 mm/m or near –0.20 mm/m. This phenomenon is observed in a temperature range between 5.0 and 12.0°C. This means that the tower at the cell level is damaged mainly in the winter season when the temperatures inside the cell are minimal and the masonry contracts after expanding in the hottest season, while in the other phases there is a trend characterised by a steady growth of AE signals but without apparent discontinuities or sudden jumps.

The cell masonry of the tower has an overall thickness of about 275 cm (see Figure 2) and, starting from the inside of the cell, is composed of a depth of about 40 cm of selenite (a particular variety of crystalline gypsum) block masonry, a filling of heterogeneous ‘a sacco’ masonry of about 150 cm, and about 80 cm of selenite blocks on the outside, including the ashlar coating. Therefore, the damage detected in the periods of contraction may be due to a phenomenon of differential deformation between the elements of selenite which are placed towards the cell compared to those of ‘a sacco’ masonry. The latter, due to the thermal inertia of the materials, are subjected to less thermal oscillations and therefore undergo less marked deformations. This temperature gradient could induce shear stresses between the selenite blocks and the chaotic ‘a sacco’ masonry capable of generating AE signals. As a result, a fatigue phenomenon caused by seasonal temperature changes would occur, slowly damaging the tower.

Figure 5 Correlation between (a) cumulated AE activity vs. FOS average daily deformations and (b) cumulated AE activity vs. average daily temperature



(a)

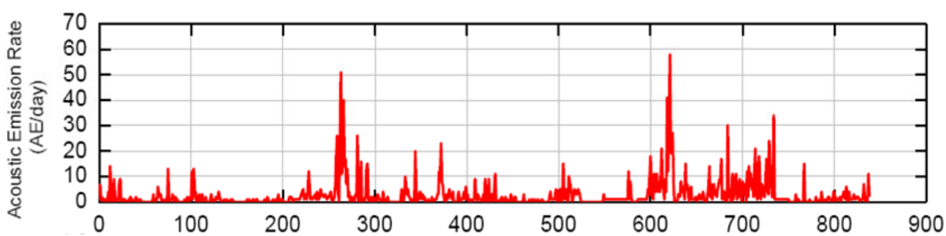


(b)

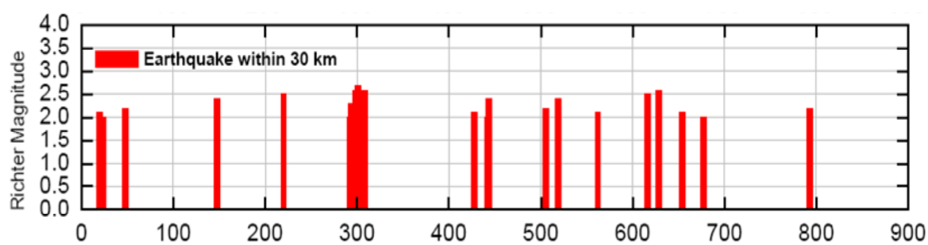
As regards the other environmental actions on the tower, in the graphs of Figure 6 are compared the trend in the rate of the AE signals received by all the sensors during the entire monitoring period, the number of earthquakes, represented by their magnitude on the Richter scale, having their epicentres detected within a radius of 30 km from the city centre of Bologna, as well as the speed of the transversal oscillations of the tower obtained by the seismometer. The earthquakes have been obtained from the website of the Italian National Institute of Geophysics and Volcanology (INGV).

The graph shows how there may be a correlation between the rate of the AE signals, which shows a significant increase in the initial days of monitoring, and the occurrence of two earthquakes with a magnitude close to 2.0 on the Richter scale. This correlation is also proven by the rather high values of the transverse displacement speed of the tower cell measured by the seismometer in the same period. On the other hand, around 250 days from the start of monitoring, although the rate of the AE signals presents a clear peak, no concomitant earthquakes appear. Unfortunately, in this case, the effects on the tower of the seismic action cannot be proven by the measurement of the displacement speed obtained by the seismometer, as the data in this period are not available due to system maintenance. The last peak of the AE signals occurs around 610 days from the monitoring start. Although in this case there are two concomitant earthquakes with a magnitude close to 2.5 on the Richter scale, but their effects on the tower are not proven by the increase in displacement speeds, which are almost null.

Figure 6 (a) Rate trend of the AE signals during the entire monitoring period (b) Number of earthquakes, represented by their magnitude on the Richter scale, having their epicentres detected within a radius of 30 km from the city centre of Bologna (c) Speed of the transversal oscillations of the tower obtained by the seismometer (see online version for colours)



(a)



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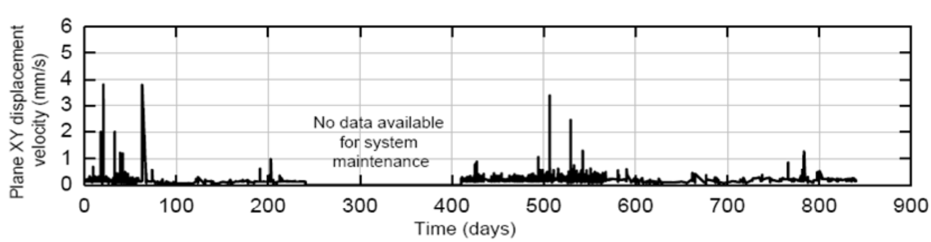
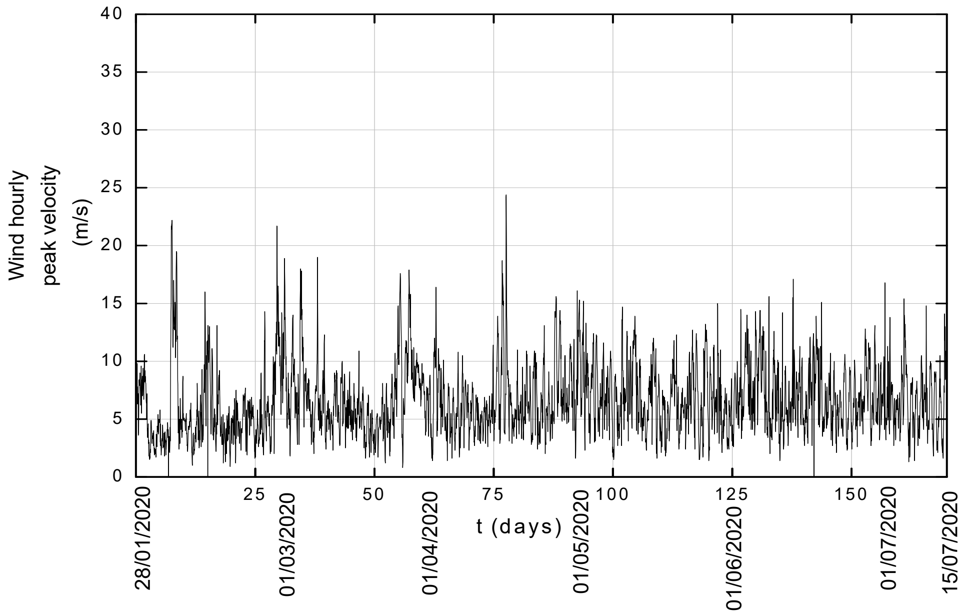


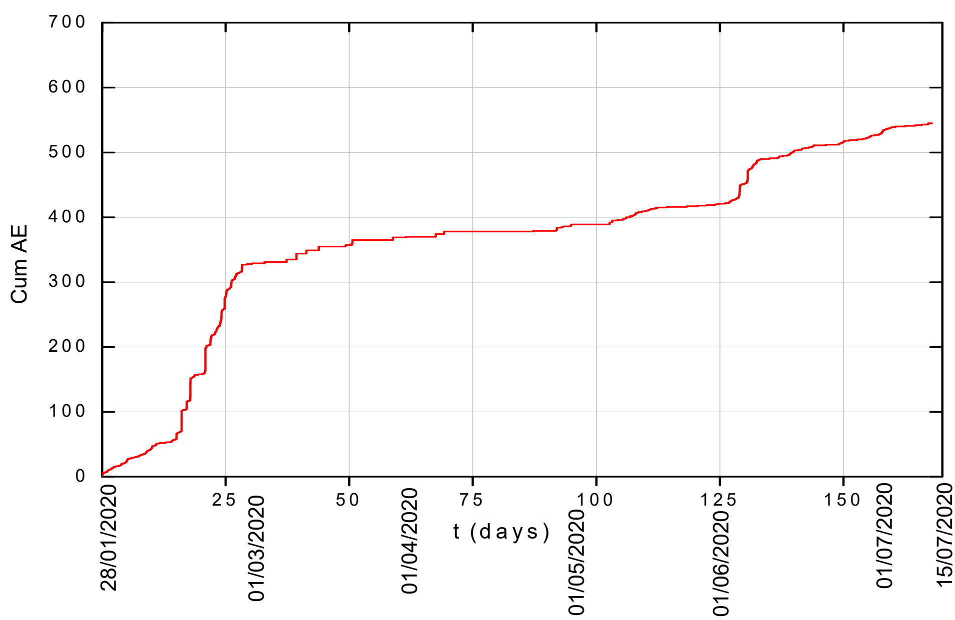
(c)

Concerning the actions of the wind on the tower, by way of example, in the graph of Figure 7 the hourly peak wind speed in m/s, recorded in the city of Bologna, is related to the cumulative function of the AE signals in the period from January 28th, 2020 to July 15th, 2020, i.e., from 242 to 411 days from the start of monitoring. From the graph, it can be seen that wind and AE signals are not correlated, as the peaks in wind speeds do not correspond to simultaneous increases in the AE signals cumulated function.

Figure 7 (a) Hourly peak wind speed in m/s, recorded in the city of Bologna and (b) cumulative function of the AE signals in the period of 242 to 411 days from the start of monitoring (see online version for colours)



(a)



(b)

The data represented in Figures 4–7 confirms that the major effects of damage on the tower cell are mainly due to thermal variations and the seasonal temperature gradient, rather than to other environmental actions such as the action of earthquakes and wind.

However, the continued growth of the cumulated function of AE signals during the monitoring period (Figure 4), demonstrates that there are other effects besides those of thermal variations that produce damage to the tower. In many circumstances, the dead load, which could be very large in massive monumental buildings, is a major factor in the formation of the fracture patterns (Binda et al., 2006). In this case, the inclination of the tower towards the side where the AE sensors have been applied can generate high stresses near the limit of the crack formation in the masonry. Therefore, the time-dependent creep behaviour of the material under dead load and its interaction with fatigue due to thermal variations can be identified as the cause of damage.

5 Conclusions

The AEs technique, combined with experimental evidence obtained by an optical fibre system (FOS) and a seismometer, was used to investigate the integrity of the Garisenda Tower during a long period of structural monitoring. The tower survey started on May 31st, 2019 and is currently ongoing. The latest data was downloaded on September 18th, 2021, for a total of almost 30 months of monitoring to date. During the period of observation the existence of an evolving cracking pattern was detected by means of the AE activity analysis.

The correlation between AE activity and FOS strain measurements has revealed that the largest AE rate is observed during the wall contraction phases of the tower cell, in a strain interval between –0.15 mm/m and –0.20 mm/m and in a temperature range from 5.0 to 12.0°C.

In the described monitoring phases, however, no clear relationships between AE activity and local environmental phenomena, such as peaks in wind velocity that hit the tower and modest seismic events within a 30 km radius, have been detected on the stated system.

The constant rise in the cumulated function of AE signals, on the other hand, suggests that tower damage is also caused by further factors other than temperature variations. Based on the available data, therefore, the source of damage can be recognised as the material's time-dependent creep behaviour under dead load and its interaction with fatigue caused by temperature fluctuations.

A possible approach of the structure to a hypothetical critical state could be investigated in the future by *b*-value (Carpinteri et al., 2008) and natural time analyses from the AE data time series (Lacidogna et al., 2019; Varotsos et al., 2011). Further studies can be also conducted by modelling the time-dependent creep behaviour under dead load of the material that makes up the walls of the tower cell (Binda et al., 2006).

Moreover, it should be noted that, starting from February 25th, 2021, a pendulum is active inside the tower, anchored at an altitude of 39.30 m and equipped with a telecoordinometer (for reading the horizontal displacements of the tower). From June 3rd, 2021, the data from four wire strain gauges installed at the corners of the tower base is also available. As a result, future research will be able to compare the data obtained by the AE with that obtained by these new devices to have an even more complete picture of the stability conditions of the tower.

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