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27 November 2026

Experimental and Numerical Damage Assessment of the Garisenda Tower: Investigation by AE, Thermal, Seismic, and Permanent Strain Analyses

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Abstract. Structural Health Monitoring (SHM) of historic masonry structures, a topic of notable economic and cultural importance, has been gaining momentum, made possible by the rapid development of monitoring technology and methodology, and motivated by factors such as seismic events and the ever-increasing number of extreme weather situations experienced all over the world. In this scenario, this work intends to contribute to the state-of-the-art by showcasing a combined numerical and experimental methodology to the structural assessment of historical masonry structures. Specifically, this work presents thermal, permanent strain, dynamic response spectrum and operational modal analyses performed to evaluate the damage evolution in the Garisenda tower of Bologna. The analyses were performed with the use of a commercial FEA software, moreover in situ Acoustic Emission (AE), Fiber Optic Sensor (FOS), were also investigated. The proposed methodology could be a tool of choice for the SHM of historical masonry structures alike — such as towers — or it could even be extended to other types of constructions.

Keywords: FEM analysis, Acoustic Emission Technique, Structural Health Monitoring, Historic Masonry Structures.

1 Introduction

The Garisenda Tower in Bologna, Italy, is a historic landmark and an important example of medieval architecture. It was built in the 12th century alongside the Asinelli Tower and was named after the Garisendi family who commissioned its construction. However, the tower began to lean due to a foundation failure in 1351 and was subsequently lowered by thirteen meters for safety reasons. Today, the tower stands at 48 meters tall and leans approximately 3.22 meters to the east.

In recent years, the tower's stability has been studied extensively using various non-destructive testing (NDT) techniques. These studies have included the use of piezoelectric sensors to detect acoustic emissions (AEs) within the tower, as well as fiber optic

sensors (FOSs) to measure strain and temperature changes, and the identification of the modal characteristics of the tower using seismometers [1–4].

In the present work, the aforementioned NDT tools are used to evaluate the structural integrity of the Garisenda and identify potential issues. In addition, three FE models were made to investigate the stress state due to different mechanical states. The first is a thermo–mechanical analysis that studies the effect of daily thermal variations, while the second is a mechanical analysis that investigates the relation between the permanent deformations read by the FOSs and the damage levels of the base of the tower. The third is a dynamic analysis performed to investigate the impact of the Marradi earthquake from September 18, 2023, to the damage state of the tower.

2 Materials and Methods

2.1 Experimental results

2.1.1 Pendulum

In February 2021, a long pendulum (around 30m tall) was installed inside the tower to measure the planar (horizontal) movement of its top. A representation of the pendulum inside the tower is shown in Fig. 1.

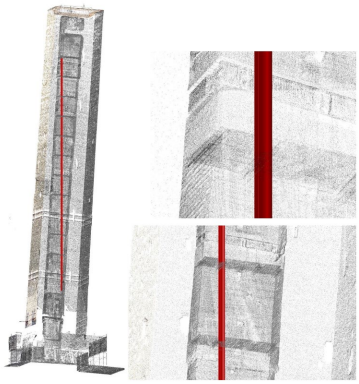


Fig. 1. A representation of the pendulum inside the tower. Courtesy of RTeknos.

The pendulum's acquisition system takes measurements automatically every six hours to send them to a data management program. Displacements up to 100 mm in the X direction, and up to 50 mm in the Y direction can be measured. The X direction of the pendulum points south-eastward, while the Y direction points north-eastward. The accuracy is up to 0.075% of the maximum readings, that is, 0.075 mm for the X direction and up to 0.0375 mm for the Y direction. An example of the pendulum displacement curves is shown in Fig. 2. The temperature on the inside of the tower base, "T1", is also reported.

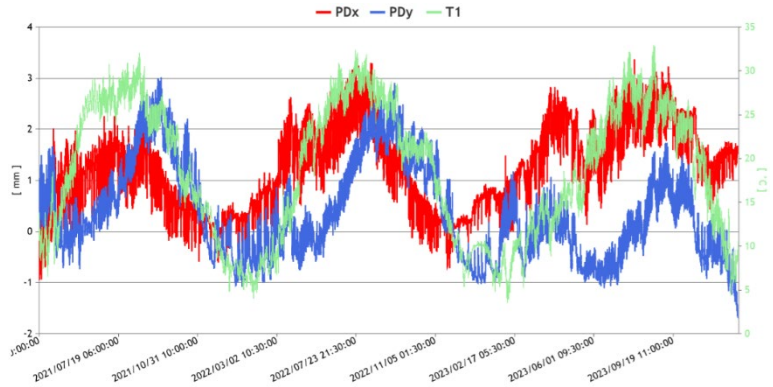
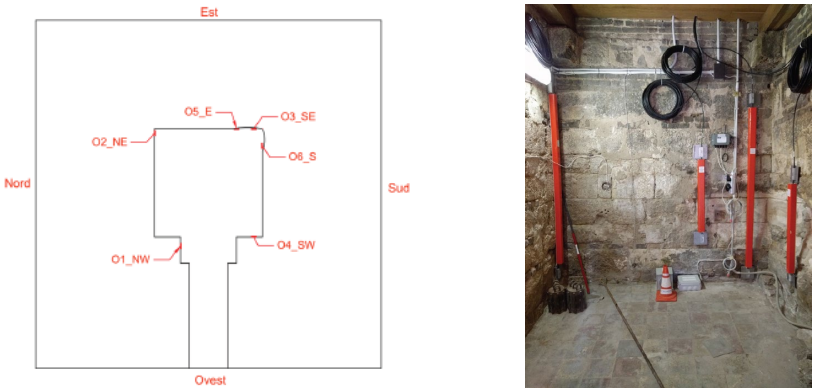


Fig. 2. The displacements "PDx" and "PDy" of the pendulum, viewed on the RTeknos website.

2.1.2 Optical strings

To continuously measure the deformations of the tower base, 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 one με, was sent to an intelligent data acquisition unit (EDAS) which performed pre-processing, temporary data storage, and the transmission to a dedicated cloud. The data could be accessed and downloaded via a dedicated web platform [5].

Fig. 3 reports a scheme of the disposition of the optical strings inside the tower (a), the optical strings inside in the East wall of the tower base (b).



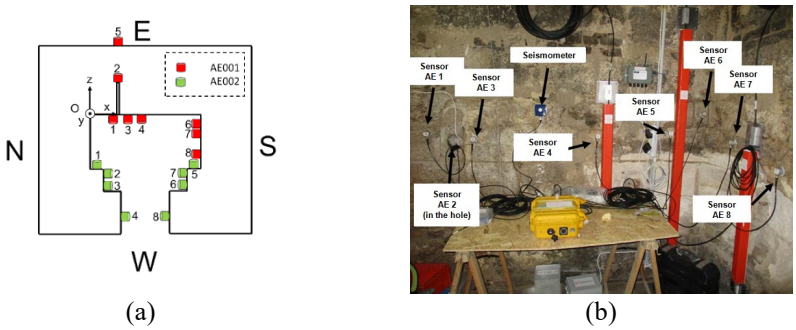
(a) (b)

Fig. 3. the disposition of the optical strings inside the tower (a), the optical strings inside in the East wall of the tower base (b).

2.1.3 Acoustic Emission

Regarding AE monitoring, the equipment installed in the Garisenda Tower base consists of two AE devices AE001 and AE002 each provided of eight channels, connected to eight piezoelectric sensors. The AE001 device was installed on May 31, 2019, while the AE002 was installed on March 14, 2023. A piezoelectric (PZT) sensor network is used for Acoustic Emission (AE) local damage detection. The sensors are Lunitek AEmission, model LT18 -003-PRD00-R0, with a frequency range of 15-625 kHz.

With this system it is possible to perform a real-time analysis of the signals coming from the PZT sensors and extract the parametric data. The sampling rate is fixed in 5 MS/s at 16 bits. The PZT sensors have been fixed to the inner wall of the tower by means of a high-strength glue, which ensures excellent grip even in particularly critical environmental conditions. Fig. 4 (a) shows a schematic of the arrangement of the PZT sensors on the tower base, while the sensors themselves are shown in (b).



(a) (b)

Fig. 4. A schematic of the arrangement of the PZT sensors on the tower base (a), the sensors installed in the East wall of the tower base (b).

2.2 Numerical FEM analyses

To assess the state of stress in the tower regarding thermal, permanent strain, and seismic effects, three Finite Element (FE) models were built using the DIANA program. The model setup was similar to the one presented in [6] was built with pyramidal and prismatic elements of 2nd order, for a total of 21603 elements and 71193 nodes. Snapshots of the model can be seen in Fig. 5, where the inner structure of the tower, as well as the materials used in the model, are evidenced.

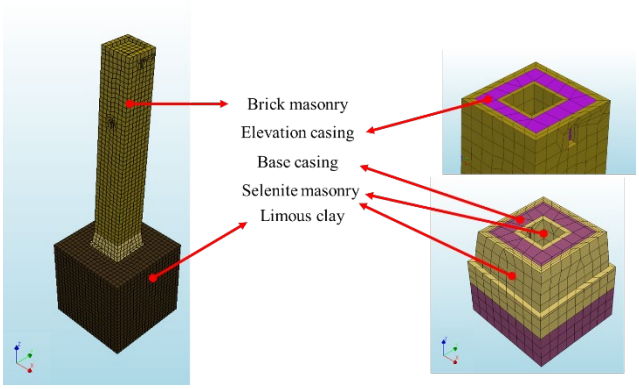


Fig 5: Snapshots of the FE model in DIANA with the materials and sections evidenced.

2.2.1 Thermo–mechanical analysis

The thermo–mechanical model was built to evaluate the stress created due to the daily thermal variation experienced by the tower. The model assumed that temperature variations outside the tower's walls were the sole cause of the observed movement at the top, which are resultant from environmental conditions (such as sun irradiation, wind, shadow from nearby buildings, etc.). The effects of the temperature difference on the inner part of the walls, as well as on the interior of the tower, were not considered.

2.2.2 Permanent deformation analysis

From the behavior of the FOSs strains, a cyclic component and a “drift” component can be evidenced. The first could be related to recoverable seasonal effects – for example, to the thermal strains experienced in summer and in winter – while the second could be related to irreversible effects. Fig. 6 presents the FOSs strains plotted together with the accumulated number of AE signals in the tower base.

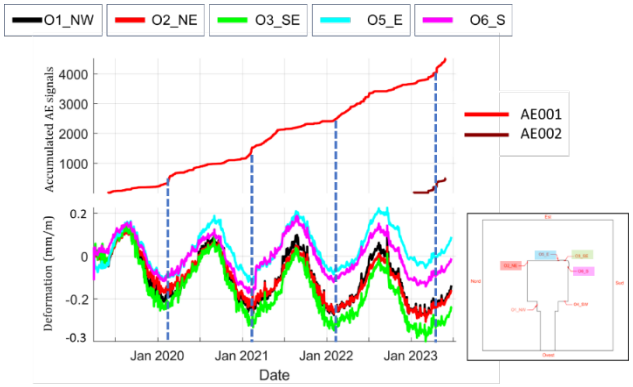


Fig. 6. The accumulated number of AE signals vs the optical strings deformation trend.

From these graphs it can be noted that the surges in the number of AE signals occur when these strains are at or close to a minimum. To investigate if this aspect could be related to the non-recoverable part of the strains, a numerical FE model was also built.

The model setup is analogous to the one utilized for the thermo–mechanical analysis; however thermal effects were neglected in this case. A prescribed vertical strain condition was applied to all the elements of the base of the tower. Four case studies were conducted, where the local minima of the strains reported in Fig. 6 were used as the prescribed strain. The self-weight of the tower was also considered.

Although the behavior observed in the deformation of the optical strings could be considered creep, the material formulation used in this study does not consider viscoelasticity, which could be important [7–9]. That will be investigated in future works.

2.2.3 Modal identification with FOSs data

The FOSs data was also used to identify the 1st vibrational mode of the tower. The variation of the vibration frequency could be used as an indicator of structural damage.

The data corresponding to dynamic events of the FOSs was analyzed for the whole monitoring period – from 2019 to 2023. The FOSs consider an event to be dynamic if the frequency of the recorded data is higher than 0.1 Hz.

This data is composed mainly of ambient noise in the operating conditions of the tower – which could be related to anthropic effects (e.g. traffic), weather, etc. In this sense, the analysis is output-only, as the input signal characteristics are not well known, a common situation in operational modal analysis.

First, a Power Spectral Density (PSD) estimate of each dynamic event was performed [10]. Then, using the Peak-Picking Method, the 1st vibrational mode was identified as the frequency with the highest energy content [11]. The results were compared to previous measurements found in the literature, that were used as a reference [1, 6].

3 Results and Discussion

3.1 Relation between thermo–mechanical analysis and pendulum displacement

For the thermo–mechanical analysis, four calculations were performed to evaluate the thermal displacements and stresses in the tower: two in the summer period (August 21, 2021, and August 13, 2022) and two others in the winter period (January 29, 2022, and March 03, 2023).

These days were chosen because they coincide with the maximums (in the summer periods), or with the minimums (in the winter periods) of the trend of the deformations recorded by the five optical strings inside the tower base, as can be seen in Fig. 7.

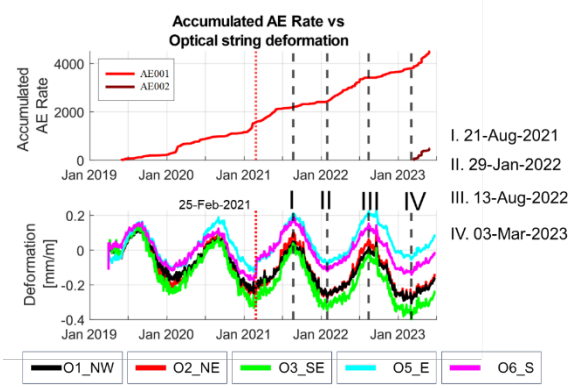


Fig. 7. The days chosen to perform the numerical thermal analysis.

An example of such analysis is shown in Fig. 8, which depicts the displacements measured by the pendulum (in dark blue), and those retrieved by the thermo–mechanical simulation (in magenta).

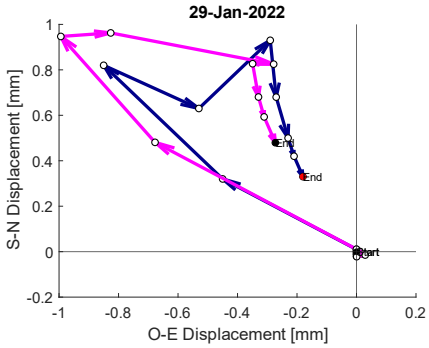


Fig. 8. The experimental and the numerical displacements on January 29, 2022.

Numerical and experimental results seem to present good agreement. The maximum Von Mises stress was then calculated in the surrounding region of the East wall of the inside of the tower, which is within range of most part of the AE sensors installed in 2019. Table 1 summarizes the results.

Table 1. The maximum Von Mises stresses resultant from the thermo–mechanical analysis.

Date	Maximum Von Mises Stress [MPa]
21/Aug/2021	6.44 E-3
29/Jan/2022	1.39 E-2
13/Aug/2022	1.44 E-2
03/Mar/2023	4.99 E-5

For comparison, the maximum stress in the same region due to the self-weight is around 1.21 MPa. It can be inferred that the stresses verified in this case are then negligible.

3.2 Relation between permanent deformation and Acoustic Emission

The stresses resultant from the permanent deformation were evaluated in the same way as the ones from the thermo–mechanical analysis. Table 2 summarizes the results.

Table 2. The maximum Von Mises stresses resultant from the permanent deformation analysis

Date	Maximum Von Mises Stress [MPa]
10/Feb/2020	1.79
18/Jan/2021	1.96
29/Jan/2022	2.22
03/Mar/2023	2.56

In this case, the order of magnitude of the stresses due to permanent strain is comparable to that generated by the self-weight, which is 1.21 MPa. It is also worth noting from Table 2 that by increasing the level of shortening applied to the tower base, the maximum stress increases steadily.

3.3 Damage evolution assessment via modal analysis

Following the procedure described in Section 2.2.3, dynamic events recorded by the FOSs were analyzed to retrieve the 1st vibrational mode of the tower. An example of a dynamic, recorded by the string "O1_NW", is shown in Fig. 9.

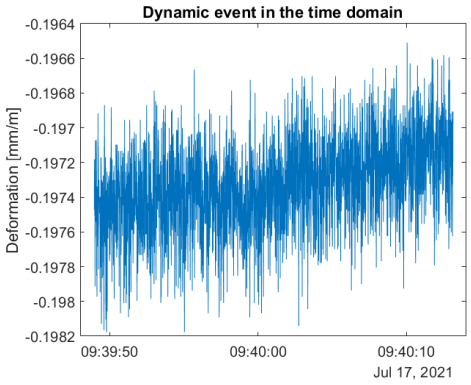


Fig 9. A dynamic event recorded by the FOS "O1_NW" on July 17, 2021.

The PSD estimate of this event was performed to obtain the signal in the frequency domain, presented in Fig. 10, which also highlights the frequency recovered with the Peak Picking technique to identify the 1st vibrational mode of the tower.

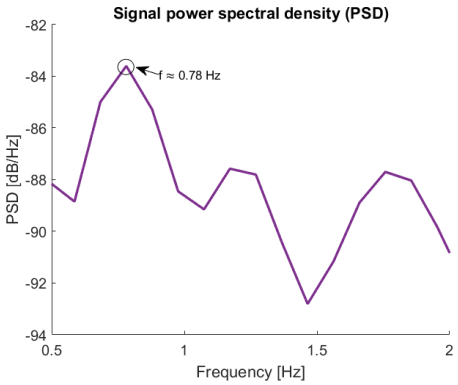


Fig 10. The PSD estimate of the signal presented in Fig. 9.

The same procedure was repeated for every dynamic signal of every optical string. In total, 231 dynamic events were analyzed. The evolution of the peak frequency with time was then investigated, presented in Fig. 11.

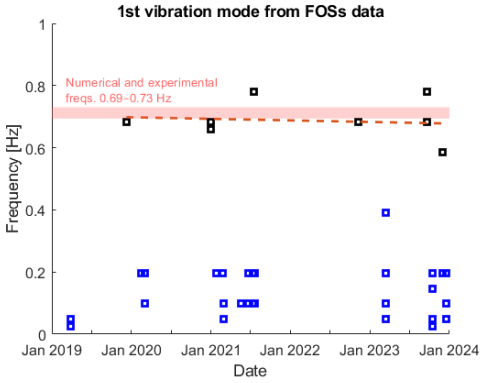


Fig 11. The evolution of the peak frequency with time. The values in black were considered significant, while the values in blue were discarded.

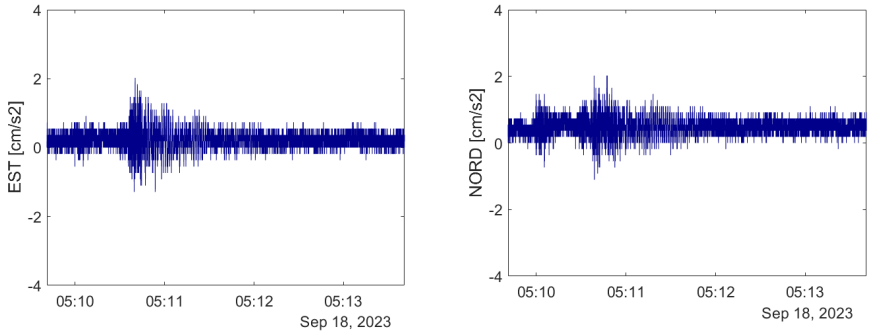
A set of dynamic events (represented in black) can closely retrieve the 1st vibrational mode of the tower, while others (represented in blue) were not deemed relevant and were discarded.

It is important to note that this kind of analysis was possible because other numerical and experimental measures performed *a priori* could be used as a reference, otherwise, it would be difficult to assess precisely which values were or were not related to this vibrational mode.

Lastly, the trend line (in dashed red) of the peak frequency with time was constructed, which suggests an increase of damage in time. As its slope is negative, the peak frequency tends to diminish. This could be related to a loss of stiffness of the tower, caused, for example, by material degradation.

3.4 Dynamic analysis of the tower to investigate an earthquake impact

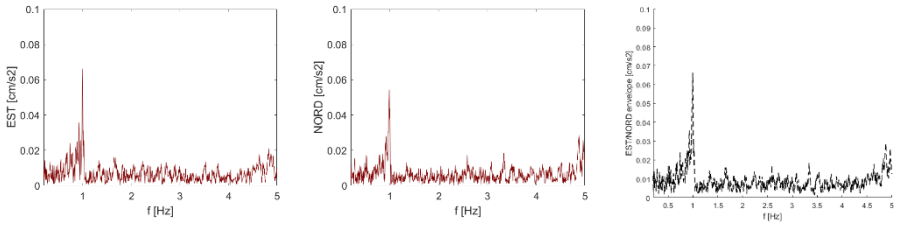
On September 18, 2023 the effects of an earthquake registered in the Marradi region (Mw 4.9, around 52 km from Bologna) were captured by the accelerometers installed in the tower base, as can be seen in Fig. 12.



(a) (b)

Fig 12. The time-domain acceleration of the tower base in the East-West direction (a) and in the North-South direction (b).

To quantify potential damage effects of this event, a Response Spectrum FEA study was built. A Fourier analysis of the signals was first performed to obtain the acceleration spectra in the frequency domain. Only the plane acceleration components were considered, the vertical component being neglected. The envelope of both signals was built, considering for each frequency the maximum acceleration value. This envelope was used as an excitation of the tower base (Fig. 13).



(a) (b) (c)

Fig 13. The frequency-domain acceleration of the tower base in the East-West direction (a), in the North-South direction (b), and the envelope of both signals (c).

The maximum Von Mises stress was again calculated in the surrounding region of the East wall of the inside of the tower. It was seen that, in comparison with the stress due to self-weight, there was a maximum increase in stress of 1 E-3 MPa, which indicates that there was no effect of the earthquake on the tower. This can be confirmed by the fact that there was little to no AE activity on the tower base in the same period, as shown in Fig. 14, depicting the AE rate and the accumulated number of AE events.

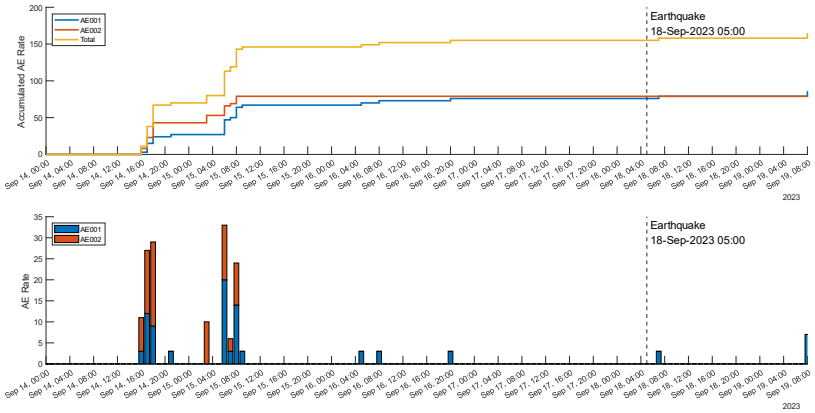


Fig 14. The AE rate and accumulated number of AE events from September 14, 2023, to September 18, 2023 (the day of the Marradi earthquake).

4 Conclusions

In this work, NDT monitoring techniques in the Garisenda tower of Bologna – piezoelectric (PZT) sensors to detect acoustic emission (AE), fiber optic sensors (FOS) to measure strains, and a pendulum to measure the planar movement of the tower top – were considered to investigate the damage in the base of the tower.

A first thermo–mechanical FE study was conducted to evaluate the stress state of the tower base regarding the temperature changes that generate the daily motion of the pendulum. The study showed that these temperature variations induce displacements that do not induce high stress levels.

A second FE study considered the effects of permanent strains in the base of the tower, which are read by the FOS. The study showed that the stresses in the tower associated with these strain levels are higher than the ones observed in the thermo–mechanical study.

An analysis of the dynamic events recorded by the FOSs, due to ambient noise in operational conditions of the tower, was used to identify the 1st vibrational mode of the tower using the Peak Picking Method. The mode frequency was in agreement with the ones obtained from experimental and numerical results found in the literature. The results showed a trend of the frequency to lower with time, which could be an indicator of damage – for example, due to material degradation.

Lastly, a third FE study, this time a Response Spectrum analysis, was conducted to evaluate the impact of the Marradi earthquake, from September 18, 2023, on the tower. It was shown that the stress increase generated by the earthquake was practically negligible, which is in agreement with the little to none AE activity registered during the same monitoring period.

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