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Preserving the heritage of world's monuments through Structural Health Monitoring – A case study: the Garisenda Tower

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ABSTRACT

The Italian peninsula has numerous heritage structures, including fifty-five sites registered under the UNESCO World Heritage Convention, living testimonies of the passage of man through times. Heritage structures are subject to aging and impact from the climate, resulting in deterioration of the structural behaviour. These phenomena can significantly reduce their usability, or even undermine the stability, and eventually induce safety, and rehabilitation issues. For those primary reasons, increasing attention is given by local authorities to understand the behaviour of structures and take the right action at the right time. To preserve the cultural heritage, Structural Health Monitoring (SHM) is becoming more important, as it allows to follow the evolution of structural behaviour. The study of meaningful variables allows to identify the activated structural mechanisms and, consequently, implement timely actions against ongoing degradation phenomena. A notable example is represented by the activities undertaken by the Municipality of Bologna on the Torre della Garisenda. The structure is monitored since 2019 to study the behaviour of its basement through measurements collected by deformation and temperature sensors. The installed monitoring system allows to carry out numerous analyses: evaluation of the structural response under dynamic actions, study of the evolution of the static behaviour of the tower and analysis of the effects induced by seasonal thermal variations. Advanced algorithms for data analysis allow to develop critical analysis and interpretation on the obtained results, providing information to support decision making process. Indications on the functionality of the system and typical examples of the collected results are provided.

I. INTRODUCTION

An historic or heritage site is an official location where elements of political, military, artistic, cultural, or architectural, social history have been preserved due to their cultural heritage value. Historic sites are usually protected by law, and many have been recognized with the official national historic site status.

The status of historical monument marks, for an object or a building, the recognition of its heritage value in terms of history and art. As such, the owner of a historic monument is invested with an important responsibility for the preservation of this legacy of history and its transmission to future generations (Ministère de la Culture website, République Française).

UNESCO World Heritage Convention in an international treaty called the Convention concerning the Protection of the World Cultural and Natural Heritage, adopted by UNESCO in 1972. The world heritage list is impressive and includes 897 cultural sites. As of 2021, Italy has a total of 58 inscribed properties, including 53 cultural sites, making it the state party with the most World Heritage Sites just above China (56) (Unesco website, World Heritage List).

To take the case of a particular country, France has hundreds of thousands of heritage buildings, of which 45,600 are registered as Historic Monuments.

Heritage sites present a wide variety of structural cases. One common point though is the usual lack of knowledge regarding the construction and maintenance methods, which are by definition very different from the current ones, and by consequence the difficulty to conduct studies to check their structural safety.

Structural Health Monitoring (SHM) has been used as an effective solution for preserving the integrity of the Heritage sites, ensuring the safety to users, and assisting owners in developing real-time diagnostic for maintenance, repair or rehabilitation works.

OSMOS has a vast reference of sites it has monitored or is monitoring over the last 20 years including: the Tour Eiffel and Notre-Dame cathedral in Paris, France; the Sagrada Familia in Barcelona, Spain; the Propylaea of the Acropolis of Athens, Greece; and the 11th century Torre della Garisenda, in Bologna, Italy.

II. ISSUES AND MONITORING SOLUTIONS FOR HERITAGE

Heritage buildings and assets appear as very challenging objects in the field of Structural Health Monitoring (SHM). Indeed, they are built with complex materials in terms of mechanical behaviour, including, for example, strong non-linearities in the case of masonry, and both anisotropy and high sensitivity to the environmental conditions in the case of timber.

Several methods for the SHM of heritage structures have been documented in the literature. The most common approach is vibration-based monitoring, especially in regions with both numerous historical constructions and high seismic activity, like the Mediterranean area. Features resulting from an Operational Modal Analysis (OMA) can be used to detect damages by the mean of various data science tools: a recent example is the assessment of the Torre Gabbia in Mantua by Marrongelli *et al.* (2021). Another iconic building monitored with high sensitivity seismometers for vibration analysis is the main spire of the Duomo di Milano, with more than one full year of feedback as documented by Gentile and Ruccolo (2021). Apart of the vibration-based monitoring, other SHM techniques are used, which do not require the high sampling rate and massive data quantity required for OMA. Among them, an interesting combination of satellite and in-situ monitoring of cracks on the Palazzo dei Consoli of Gubbio has been presented by Cavalagli *et al.* (2021).

The approach proposed by OSMOS for the SHM of heritage buildings is an in-situ monitoring system which usually combines the measurement of strain variations, crack openings and tilts at a low sampling rate ("static" monitoring) with threshold-triggered records at a high sampling rate up to 100 Hz for alerts in case of rapid evolutions ("dynamic" monitoring), and eventually for dynamic assessment through OMA, using additional accelerometers. As an example, the evolution of vertical strain and the tilt of the main pillars of the Cathédrale Saint-Pierre in Beauvais, France (highest stone nave in the world), have been monitored since 2014.

Ancient masonry bridges are also of great interest, especially when they are both of historical value and important traffic infrastructures. For example, a permanent SHM system has been set up since 2017 on the Pont de Pierre in Libourne, France, combining strain measurements under one of the arches and on the spandrel walls, with settlement and water level measurements (OSMOS Group SA, 2018). This system allows to assess the correlations between surface strain of the masonry and both settlements and water level, including a strong effect of the tides on the compression of the arches. Moreover, the threshold-triggered dynamic strain records are sensitive enough to assess the effect of heavy traffic on the keystone of the arch, and the continuous monitoring of strain on the spandrel walls gave anticipated signs of a potential crack opening, which eventually appeared visually on the wall. In this case, it is worth to notice that the Optical Strand strain sensors were integrated inside the cladding during rehabilitation works and are totally invisible, preserving the visual appearance of the construction (Figure 1).

Figure 1. Optical Strand Strain sensor and temperature gauge integrated inside the cladding of the Pont de Pierre in Libourne, France. The picture is taken before completion of the cladding. ©OSMOS Group SA.

More recently, the continuous SHM of heritage buildings answered to a stringent necessity in the case of the fire which ravaged the Notre-Dame de Paris Cathedral on April 15, 2019 (Figure 2). Immediately after the disaster, the most critical parts of the damaged vaults have been instrumented with high-precision lasers to detect and anticipate any further movement. Then, up to more than 140 sensors have been in operation through the whole duration of the securing works, and furthermore for the assessment in view of the reconstruction. This complex system involves several different types of sensors, measurements and data analysis tools, including an immediate alert feature based on tilt and strain measurements on the damaged scaffolding of the spire during its dismantling until November 2020, a static monitoring of the deflection of the vaults with rows of tiltmeters, and OMA performed from numerous accelerometers on both the timber structures inside the two belfries and on the vaults and pillars of the nave (OSMOS Group SA, 2020).

These many examples show that the SHM of heritage buildings involves a wide discrepancy of different tools, from sensor types to data analysis methods. This is due to the extended complexity of this kind of structures, with uncertainties concerning the mechanical behaviour of the materials, difficulties to build relevant modelling near to reality, and variety of the structure types from massive walls to light vaults. Thus, gathering relevant information through SHM on these structures requires to combine different approaches.

In this paper, we will focus on one part of the SHM system of the Torre della Garisenda located in Bologna, Italy, dedicated to the assessment of the strain at the basement of the tower. Other types of measurements have been taken on the tower in parallel for various purposes as described by Di Tommaso *et al.* (2021). Among them, studies have been carried out from GNSS measurements (Poluzzi *et al.*, 2019) and terrestrial laser scanning (Capra, 2015). The Torre Asinelli located nearby is also an interesting subject for scientific investigation (Invernizzi *et al.*, 2019).

Figure 2. Set-up of the monitoring system of Notre-Dame Cathedral in Paris. ©OSMOS Group SA.

The strain monitoring at the base of the tower is performed both in static mode for long-term and seasonal evolutions, and in triggered dynamic mode in the case of vibrations induced by the wind or by an earthquake. Such combined static and dynamic monitoring with a single system performing strain measurements has proven its efficiency in numerous contexts, including a study on one pier of the Viaduc de Millau in France as reported by Cartiaux *et al.* (2021).

III. A CASE STUDY: THE TORRE DELLA GARISENDA

Bologna's towers, structures with both military and noble functions of medieval origin, are one of the city's characteristic features. Their number was very high, about 90 constructions, including real towers and tower-houses.

In general construction terms, the towers were square, with foundations a few metres deep in soils that were not always adequately performing. The base of the tower was built with large blocks of selenite and the rest of the construction was built with thinner and lighter walls as it rose, made of "sack" masonry, *i.e.* with a thicker inner wall and a thinner outer wall: the cavity was then filled with stones and mortar.

Today there are about twenty of them left, the best known of which are the so-called "two towers", known as Asinelli and Garisenda respectively, located in the historic centre of the ancient university city. The two towers are commonly recognised as a symbol of Bologna and stand in the heart of the city at the entry point of the ancient Via Emilia.

Probably built around 1109, they had a military function (signalling and defence) and represented the social prestige of the family responsible for their construction.

The Torre della Garisenda (Figure 3), with a square base structure of 7 m on each side and built in the same way as abovementioned, stands out for its lower height of only 47 m. It is known for its steep slope, with an angle of 4° (3.22 m overhang). Originally about 60 m high, it was lowered by about 12 m due to the dangerous inclination caused by the poor mechanical and load-bearing capacity of the foundation soil in the mid-14th century.

Figure 3. The two Towers: Garisenda (left) and Asinelli (right). The external side of the selenite basement of the Torre della Garisenda is clearly visible, as well as the entrance door.

The Municipality of Bologna, the current owner of the Torre della Garisenda, has long launched investigations, observations and even interventions with a view to its conservation, a priority for the entire community. To this end, through the Public Works Department-Maintenance Sector, the structural monitoring in place has been intensified, implementing from 2019 a system able to continuously follow the behaviour of the selenite base of the tower by detecting the vertical deformations of the same as well as the temperature values.

This monitoring system consists of 6 sensors based on optical fibres (called Optical Strand, hereinafter OS), installed inside the basement, 4 of which are 2 m long at the corners and 2 are 1 m long at a concavity of the basement straddling the SE corner. Table 1 summarises the installed sensors. The monitored parameter concerns the vertical strain on the inner face of the walls, as the sensors were installed inside the tower only, with an expected accuracy of 30 με. In addition to the deformation measurement sensors, a temperature sensor and an expert unit were installed which allows data acquisition at a frequency of 100 Hz. In addition, an earthquake early warning system has been recently installed at the base of the tower.

Table 1. Summary of installed OS sensors. *Sensor removed on 2020/02/11

Sensor ID	Position
O1_NW	North-West corner
O2_NE	North-East corner
O3_SE	South-East corner
O4_SW*	South-West corner
O5_E	East wall
O6_S	South wall

The installed monitoring system allows to carry out a significant number of analyses: evaluation of the structural response under dynamic actions (wind, seismic), study of the evolution of the static behaviour of the tower and analysis of the effects induced by seasonal thermal variations on deformations. Advanced algorithms for data analysis allow to develop critical analysis and interpretation on the obtained results, providing useful information to support decision making process.

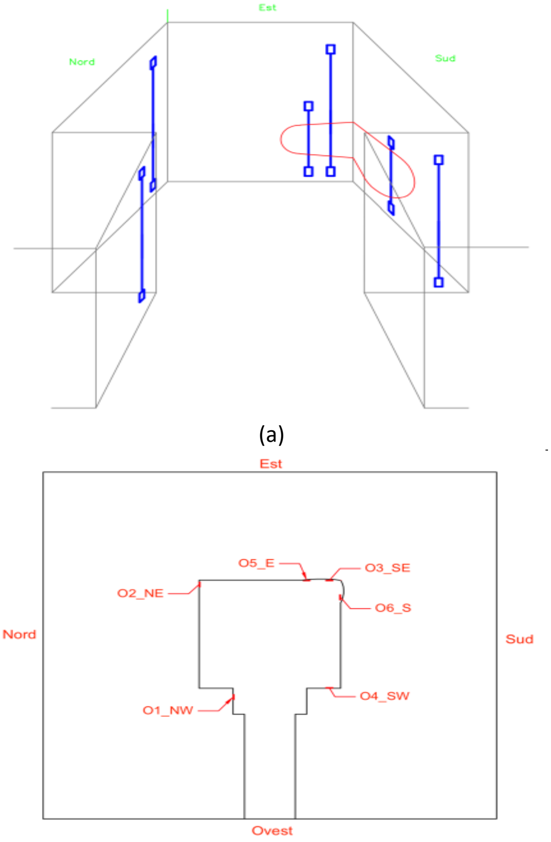
A possible extension of the presented monitoring system can be represented by the installation of additional 4 Optical Strands at the outer corners of the basement of the tower. In this way, it would be possible to quantify the difference in the movements of the sack masonry and the selenite external cover.

Figure 4 shows the positioning of the sensors inside the base.

The trend in static measurements from March 2019 to December 2021, for each sensor, is given below (Figure 5).

To perform the correction of the effects of the temperature from static measurements, a methodology consisting of two steps has been carried out:

- Quantify a linear law which links the temperature with the strain per each sensor, based on the 15-days long learning period showing the best correlation between the two considered parameters.
- After this first correction, large yearly cycles that seem to be also correlated with the temperature still appear. Thus, we propose a second correction, with a smoothing time window of 10 days (instead of 24 hours) and a learning period of 180 days (6 months instead of 2 weeks).



(a)

(b)

Figure 4. Torre della Garisenda – Configuration of Optical Strands inside the base: a) axonometric view; b) plan view.

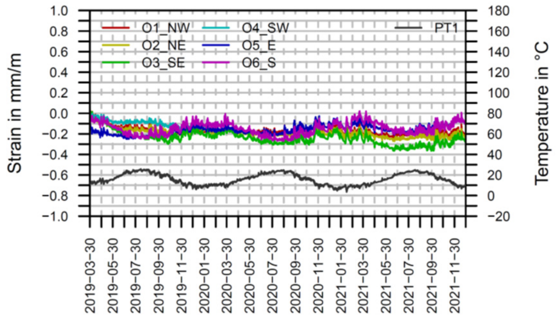


Figure 5. Recorded static measurements from March 2019 to December 2021.

The very good correlation between temperature and strain is confirmed, so the effect of the temperature follows different laws depending on the time scale: at a middle-term (1st correction) the masonry appears to be slightly blocked and is compressed by the heat, which is a typical behaviour for locally hyperstatic structures like a massive masonry wall is. At long-term scale (2nd correction) we have a normal dilatation factor with expansion in the case of heat.

Another conclusion is that we have no uniform trend in compression: on the results of the 2nd correction for the SE sensor given as an example, we first see a quick compression to -0.1 mm/m during the first 3 months, which is due to the adaptation of the sensors to the masonry (we have Optical Strands in tension fixed on a material which is not perfectly rigid). So, the first 3 months may be omitted if we want to check actual trends over the long-term.

The results of this second correction on a “long-term” scale of 6 months are shown in Figure 6.

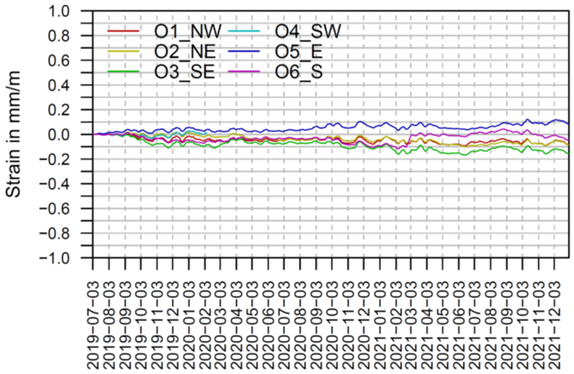


Figure 6. Corrected static measurements from temperature effects.

After two years and a half, the long-term evolution without effects of the temperature is as follows (Table 2).

Table 2. Final deformation values. *Final value for the O4 SW sensor is on 2020/02/11, when this sensor was removed

Sensor ID	Final value [mm/m]
O1_NW	-0.082
O2_NE	-0.086
O3_SE	-0.157
O4_SW*	+0.012
O5_E	+0.086
O6_S	-0.047

The mean value of the trend is -0.045 mm/m, with more compression on the South-East corner and on the North side. We have less compression and even decompression on the South-West corner and on the East side.

These values have a significant order of magnitude compared to the dynamic effects also recorded: wind with 0.005 mm/m strain amplitude and earthquake with 0.010 mm/m strain amplitude.

However, considering that the static values are strongly influenced by the temperature, which we tried to correct through a purely empirical method, but also by other environmental conditions like humidity and whatever may have an incidence on the masonry blocks and mortar, it is too early to conclude about a real long-term trend.

For what concerns dynamic measurements, in what follows two noticeable events captured by the considered monitoring system are presented. For both events, the time series of the deformations and the Fourier transform of the recorded signals are shown, in order to allow the identification of the frequencies peculiar to the structure during each of the events considered.

August 2nd, 2019, at 15:13 UTC: Strong wind inducing vibrations with a frequency of 0.68 Hz. No remaining strain is noticed after these vibrations, from which we conclude they did not have any harmful consequence on the monitored parts of the structure. The amplitude of the strain at the base of the tower reaches 0.005 mm/m (Figure 7).

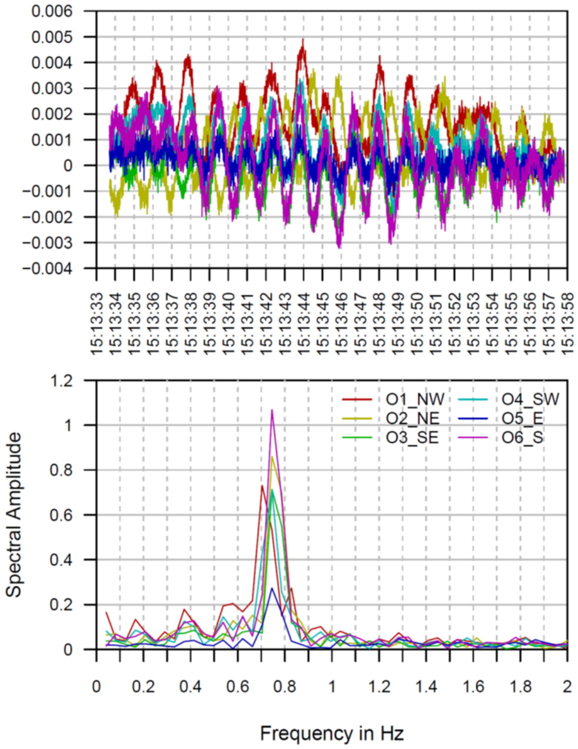


Figure 7. Deformation recording during 8/2/2019 wind event and corresponding frequency analysis.

December 9th, 2019, at 03:37 UTC: earthquake with a magnitude of 4.8, which epicenter was 75 km south to Bologna. This is by far the most important event on terms of bending vibrations of the tower with a maximal amplitude of 0.010 mm/m in the masonry. This however remains a low order of magnitude for a masonry wall. Vibrations are recorded with a main frequency of 0.68 Hz, mainly in the East−West direction. Additional vibrations in the North−South direction are also recorded with a frequency of 0.72 Hz. At the end of the event the tower recovers its initial state in terms of strain which means there have not been significant plastic effects due to the earthquake (Figure 8).

IV. CONCLUSIONS

The two years of vertical strain monitoring at the base of the Torre della Garisenda show a light global trend in compression, with an average of -0.045 mm/m and a maximal value for the South-East corner at -0.157 mm/m. At the opposite, the South and East sides appear to have a light trend in decompression, with a maximum value of +0.086 mm/m for the East side.

However, these values remain inside the uncertainty margins due to the difficulty of assessing the exact effect of the environmental condition, including the temperature.

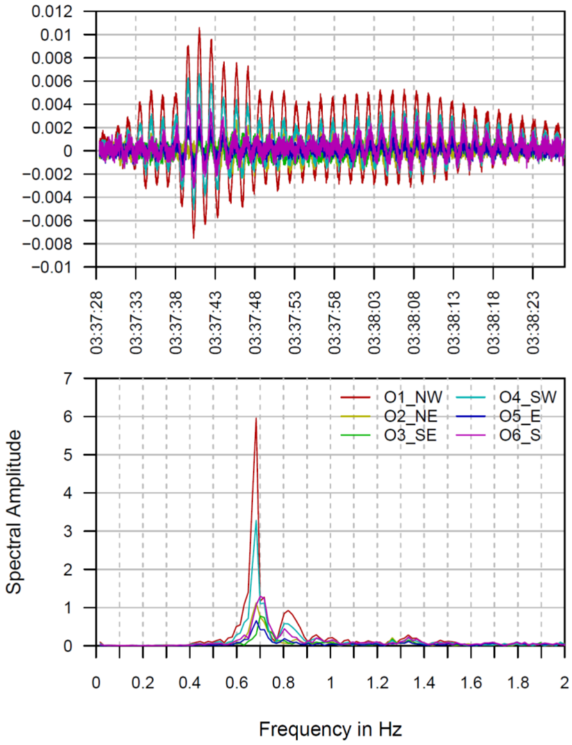


Figure 8. Deformation recording during 12/9/2019 earthquake event and corresponding frequency analysis.

The monitoring system has also proven its ability to release relevant insights both at long-term and dynamic time scales with the same Optical Strand strain sensors: threshold triggered records at a high sampling rate allow the assessment of the effects of wind and earthquakes, as well as the identification of the first vibration modes of the tower through a spectral analysis of the strain signal, which reflects the curvature of the tower at its basement.

The strain monitoring system of the Torre della Garisenda is still operational without maintenance operation since more than two years, which shows that the type of sensors chosen is both rugged and well adapted to the case of historical monuments built with old and heterogeneous masonry.

Structural Health Monitoring (SHM) has been demonstrated as an effective solution for heritage site preservation in terms of their legacy of history and their transmission to future generations by ensuring the safety to users, and assisting owners in developing real-time diagnostic for maintenance, repair or rehabilitation works.

Possible future developments of the presented activities may involve a deeper investigation of algorithms for temperature compensation, thanks to a longer observation period of the tower thermal response. Moreover, it would be very interesting to monitor strains on the external selenite coating to quantify the sliding between the two components of the basement.

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