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The role of remote sensing to enlarge knowledge on health state of a historical building hit by earthquake: the case of Garisenda leaning tower (Bologna)

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Abstract

An evaluation of the health state of a fragile historical building like a leaning tower, especially if it is located in an environment characterized by significant seismic risk, requires the integration of data obtained through various types of observation techniques. This is the case of the Garisenda Tower in Bologna, which is a 48 m high leaning tower, whose tilt angle reaches 4°, and for which some concerns about its stability recently grown. Historical sources, past and current monitoring of both structure and subsoil with several instruments, geological, geophysical and geotechnical surveying (in particular, continuous borehole coring) and experimental modal analysis provide a large amount of information on the tower and its environment. This study is aimed at pointing out how remote sensing can contribute to the achievement of a reliable picture of the current health state of the tower, considering that this picture could be useful for planning future reinforcement/restoration strategies. In particular, the results of the multitemporal morphological analysis of the tower façades, based on remote sensing data acquired in 2010, during the 2012 Emilia Romagna earthquake and in 2023, are shown and discussed on the basis of some available information. The morphological analysis can provide real and interesting information on geometric deformations, also highlighting their possible partial or total recovery when the stress ceases, in particular when a seismic sequence ends, although an almost total recovery of such deformations does not necessarily imply that the structure is not affected by permanent damage.

Keywords: Historical Masonry Building; Leaning Tower; Health State; Garisenda Tower; Data Integration

1. Introduction

A leaning tower located in a medieval town characterized by medium-level seismicity and further factors, e.g. differential subsidence, is a fragile building placed in a system that is fragile in itself. The study of such a structure requires a multidisciplinary approach, where structural monitoring, geometric survey, research of deformations and/or damages, but also a careful evaluation of the soil properties as well as of static and dynamic soil/structure interaction, are integrated to provide a reliable picture about its health state (Sánchez-Aparicio et al., 2020).

Experimental modal analysis (EMA), based on data provided by accelerometers appropriately distributed on the structure, is commonly used for describing, understanding and modeling its dynamic behavior, leading to natural frequencies, damping ratios and mode shape with the aim of detecting possible damage (Capecchi and D'Ambrogio, 1993). In particular, EMA performed after an earthquake can provide indications of possible seismic-induced damage (Kita et al., 2021). This technique also allows calibration and verification of a finite element model (FEM) of the structure, which is a not an elementary task if there are significant uncertainties concerning material heterogeneity and construction techniques (Sunara et al. 2023). Furthermore, if accompanied by a suitable analysis of the natural frequencies due to the soil stratigraphy (Castellaro and Mulargia, 2010), EMA allows an evaluation of the presence of a resonant soil-structure coupling, factor of capital importance if an earthquake occurs (Gangone et al., 2023). Such an evaluation is surely recommended if the natural frequencies of the building are near to the stratigraphic ones (Gosar, 2010). Operational Modal Analysis (OMA), where the vibration source is the ambient noise and, therefore, no systems to excite vibrations are used, is a development based on advanced data processing techniques. OMA can also be implemented with non-contact measurements (Camassa et al., 2023; Providakis et al., 2023). The state of a significant and vulnerable building can be monitored with continuously operating sensors, providing real-time data (Saisi et al., 2018).

The geometric modeling of a historical building can be implemented in a completely contactless and, therefore, non-invasive way by using Structure-from-Motion photogrammetry (SfM) and/or terrestrial laser scanning (TLS). The morphological analysis, where the point cloud is compared to a plane (Pesci et al., 2013) or to a more general primitive (Teza and Pesci, 2013; Teza et al., 2016), can highlight seismic-induced deformations. On the one hand, the morphological analysis can reveal features which could be related to possible damage (e.g. bulges, deformations of various type), as well as traces of possible restoration works carried out in the past. On the other hand, if repeated several times after an earthquake, it can highlight earthquake-induced changes in the state of the masonry and show the total or partial recovery of the conditions preceding the earthquake. The data obtained by morphological analysis can be integrated in Historical/Heritage Building Information Modeling (HBIM), also aiding planning and design of restoration works (Bruno and Roncella, 2018). Besides geometric data, some remote sensing techniques can provide radiometric information that, jointly used with the geometric one, can detect a wide range of pathological processes (Sánchez-Aparicio et al., 2018). Finally, thermal imaging can aid the recognition of possible damage (Duan et al., 2013), in particular when 3D geometric information is available (Teza and Pesci, 2019).

A historical masonry structure can be affected by damages of various type, e.g. fractures, brick exfoliation, mortar deterioration, due to various factors, including: load over time, e.g. stress even far from the ultimate compressive strength; vibrations of anthropic origin (e.g. car traffic) or natural origin (e.g. wind); pollutants and weathering; in some cases, seismicity induced by fluid extraction from or injection into the soil; earthquakes or shocks of other origin due to explosions and/or lightning; in the case of large buildings, stress due to differential subsidence. Furthermore, in the case of a leaning masonry structure, the effects of the slope on the static and dynamic behavior of the building should be considered (D'Altri et al., 2018). In some cases, modeling requires the discretization into masonry units whose boundaries represent discontinuities (e.g., mortar joints) (Sarhosis et al., 2021). Finally, the reinforcement aimed at enhancing the performance of a high value historical building should be aesthetically acceptable (Sisti et al., 2023).

Characterization of the soil properties, including both its dynamic behavior (which could lead to soil/structure coupling in case of earthquake) and its stratigraphy (with a complete characterization of the aquifers), as well as its slow motions such as subsidence, is necessary for the evaluation of any critical issues related to a historical building exposed to natural and/or anthropic hazards (Micle, 2014). It is important to note that subsidence can present strong spatial variations, i.e. adjacent places or places relatively near (~10 m) could be affected by different motions due to heterogeneity of the ground, water extraction or local perturbations due to large buildings (Pesci et al., 2011a). These differential motions could induce excessive static loads on the buildings. The importance of analysis of soil-structure interaction is highlighted by Lancellotta (2013) and Cadignani et al. (2019) in the case of Ghirlandina

Tower in Modena, which is an 89 m high leaning bell tower. In particular, these authors show that the hypothesis of rigid constraint at tower base, which is used by many people to carry out a structural identification analysis, is unrealistic and unsuitable in the case of a tower which interacts with a soil characterized by differential subsidence and whose properties could change with the time. In some cases, the differential foundation weakening is so high that adequate countermeasures are necessary to avoid the building collapse. It is the case of Pisa leaning bell tower (Burland et al., 2003; 2020). In general, the reckless water withdrawal in urban areas, which occurred until the 70s and 80s in many Italian cities, gave rise to a weakening of the soil characteristics in many old towns, with consequences on historical structures. This concerned, for example, the above-mentioned Ghirlandina tower, but also the bell tower of Caorle (Venice), located a few dozen meters from the sea, with consequent interaction of sea water with the ground as a consequence of the withdrawal of fresh water (Teza et al., 2019).

Finally, each measurement activity, to be repeated over time (in case of surveying) or carried out in continuous mode (in case of monitoring), should preferably be performed in a non-invasive way to avoid perturbations of a fragile system.

This article is devoted to Garisenda leaning tower in Bologna, which recently hit the headlines because, among other worrying effects, a continuously operating extensimeter detected anomalous movements. The research aim is to discuss what is currently known about the tower, from historical sources, information on its dynamic behavior, monitoring data, soil stratigraphy, to results of remote sensing surveys implemented before, during and after the 2012 Emilia Romagna earthquake. The focus is on the role of remote sensing as technique that can complete the knowledge framework about a fragile historical building.

2. The Garisenda leaning tower and its environment

2.1 Bologna's area: history, geology and some anthropic facts

Bologna is a medium-sized city (~400,000 inhabitants) in Northern Italy which is part of a conurbation with 1.5 million inhabitants. It is well known because of its university, founded in 1088, which is the oldest in the world, and because its urban fabric is very particular. Bologna is crossed underground by streams and canals and has several wells built since Roman times and essential for the population and the manufacturing department throughout the Middle Ages. In the Late Middle Ages, between the 11th and 13th centuries, the most important families built several towers for reasons of defense and prestige. Their number was so high, about 100 in the small old town, that Bologna was nicknamed the "selva turrita", i.e. forest of towers. Only 24 towers still exist today, 6 of which are higher than 40 m. There is copious historical documentation about the reasons for the reduction in the number of towers: sabotage, dismantling, demolitions for urban planning purposes or damage that could not be restored, as well as collapse (Barbacci, 1977). Among the surviving towers, there are the Two Towers, i.e. the 97 m, 1.3° tilted Asinelli e the 48 m, 4° tilted Garisenda, which are very near each other. Figure 1 shows artifacts with the medieval city skyline, derived by ancient documents and available as collectibles.

Figure 1. (a) A terracotta tile by the artist Tiziano Vincenzi which reproduces the Bolognese skyline in medieval times, looking east. On the right, there are the Two Towers and the course of the Aposa river, today covered by the road surface; (b) another tile with a view towards the north. For further details: www.tizianovincenzi.it.

Recently, the Garisenda tower caused a great concern to the city community because the data provided by a monitoring system detected an anomalous movement which would suggest the existence of a possible torsion phenomenon which could be a possible precursor of instability and collapse (Aiello et al., 2023). This tower is under observation and the Municipality is currently planning safety and restoration works.

The Two Towers lean because of the subsoil properties. Bologna lies on a border area between the Apennines and the Po Valley having a complex subsoil, with aquifers at various levels. Therefore, this environment is particularly sensitive to subsidence, sometimes differential on scale of ~10 m and often caused or at least amplified by anthropic interventions (Giacomelli et al., 2023; Pesci et al., 2012; Stramondo et al., 2007; Zuccarini et al., 2024). Bologna is a fragile city because of both geology and the richness in historical monuments and buildings, which are undoubtedly subjected by geophysical and atmospheric events. Earthquakes are unpredictable phenomena both in time and intensity. The macroseismic databases report the most important events that created panic and damage in the city, and historical documentation preserves their memory. Maps of the most important events occurred in Italy and, at higher level of detail, in Bologna and its surroundings, taken from the Strong Earthquake Catalog (https://storing.ingv.it/cfti), are shown in Fig. 2.

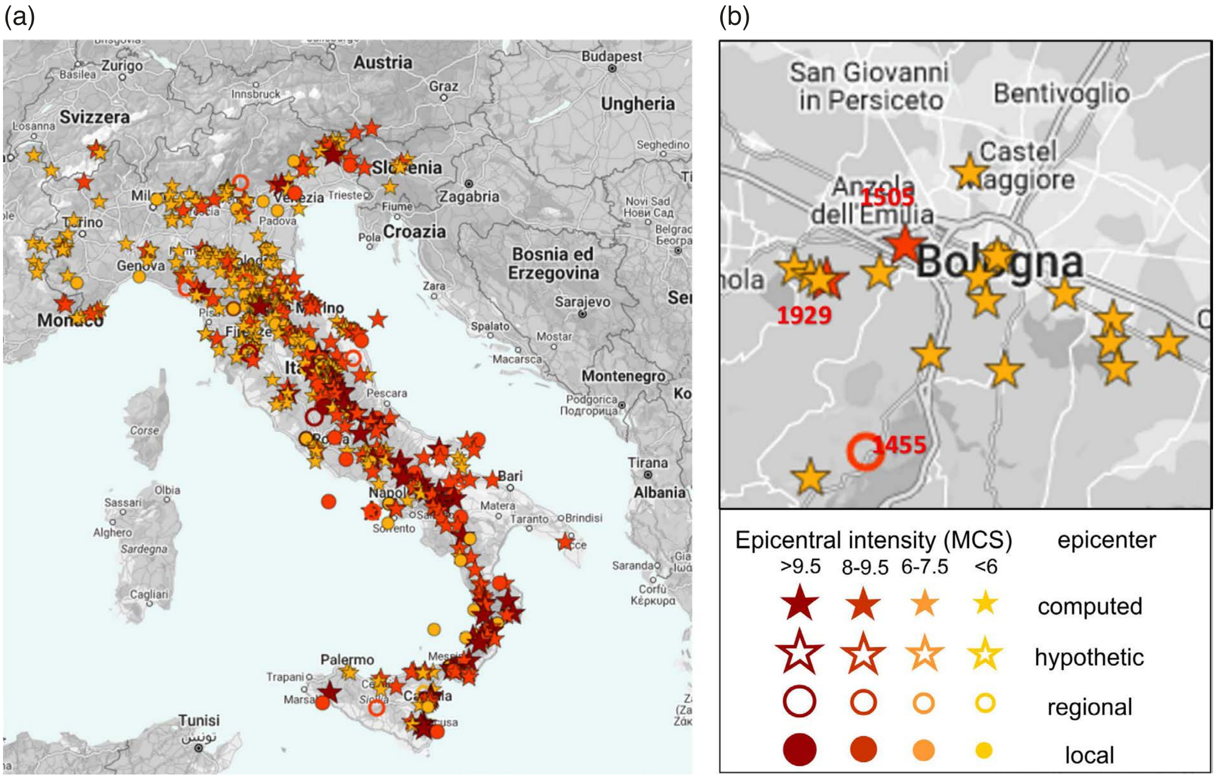

Figure 2. Maps of strong past earthquakes occurred from the ancient world to the end of the 20th century in Italy (a) and in Bologna area (b) from Strong Earthquake Catalog (CFTI), where positions and Mercalli-Conconi-Sieberg (MCS) intensities are shown.

Even if it was not the most devastating earthquake to hit Bologna, the "infinite swarm" is very well remembered in the chronicles of the time because the main shocks continued for a long time, from December 24, 1504 to May 19, 1505 (Guidoboni and Ciuccarelli, 2003), with Mercalli-Conconi-Sieberg (MCS) intensity VI-VII. A reasonable estimate of the median of the distribution of Peak Ground Acceleration (PGA) related to this seismic sequence is $PGA \sim 0{,}17g$ (Baraccani et al., 2017), where g indicate the gravitational acceleration ($g = 9.81$ m/s^2). For comparison, the median PGA reached in the case of the two most important phenomena that have affected Bologna in the last 1000 y, occurred in 1365 and 1433, was $PGA \sim 0{,}23g$. In any case, duration and damage inherent to the "infinite swarm" led Giovanni II Bentivoglio, lord of Bologna, to commission a fresco depicting the "Madonna del Terremoto" ("Mother Mary protecting the city from the earthquake") as a symbol of devotion and auspice of protection. This fresco highlights the steep slope of the Garisenda in 1505 (Fig. 3), whose severe inclination is cited in several

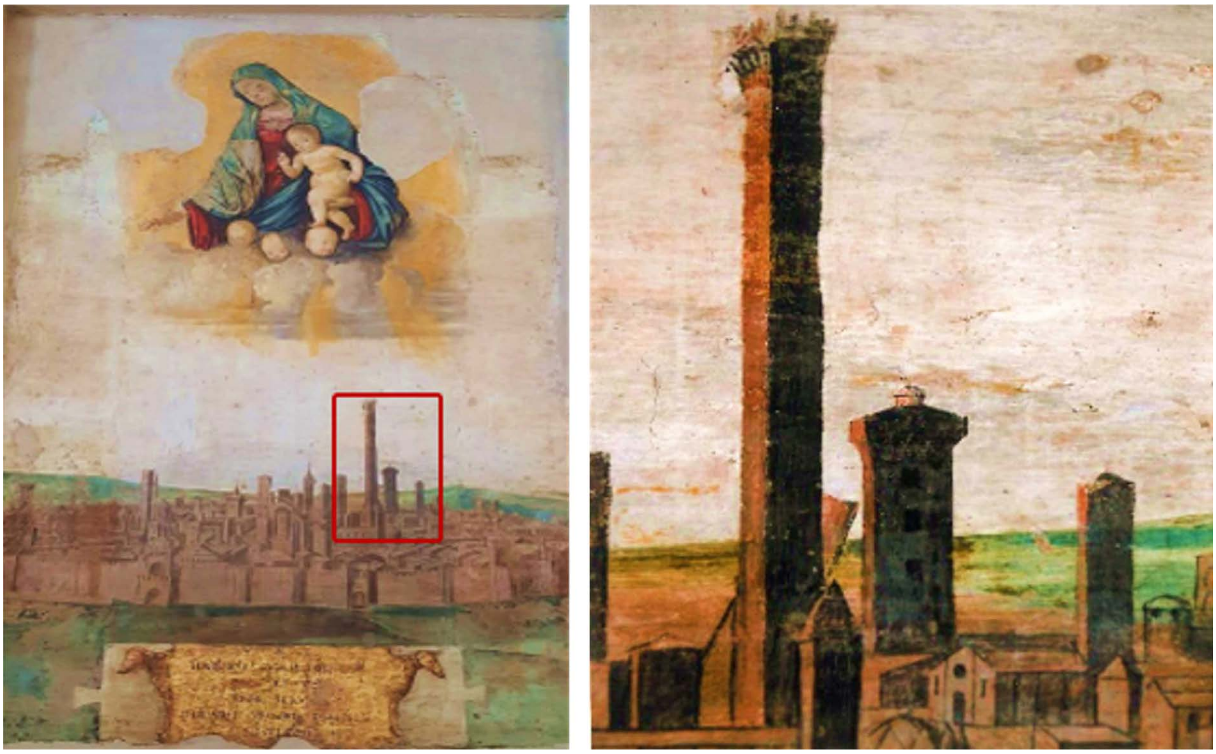

Figure 3. The fresco “Madonna del Terremoto”, commissioned to obtain pardon and stop earthquakes in 1505: (a) general view; (b) particular where the highest Asinelli tower and the very leaning Garisenda tower (partially hidden by the Asinelli one) can bee seen. The other towers shown here do not longer exist.

historical sources since the time of its construction. In 1929 an intensity MCS VI earthquake struck Bologna causing damage and some inhabitants had to shelter in tents.

The old town area is characterized by Quaternary deposits of continental origin referable to the Emilia-Romagna Supersyntem (Middle Pleistocene – Holocene), which consist of alluvial, deltaic, coastal and marine deposits, organized in cyclical successions of various hierarchical orders (Traversa, 2011). The subsoil of the Two Towers area was studied in detail by means of geotechnical campaigns carried out in 1973-75, 1995, 2000 and 2016, which made use of several continuous coring boreholes (generally vertical, in some cases inclined), collection of undisturbed samples and corresponding laboratory testing and installation, in 2016, of some monitoring instruments, i.e. piezometers (which measure groundwater pressure at various depths) and assestimeters (which measure the yield of the monitored elements); execution of some cone penetration tests; and a downhole geophysical test, also with a 100 m borehole, in 2016 (Marchi et al., 2019; 2022). Areas around the Two Towers were tested. In particular, the continuous coring boreholes performed in 2000 were drilled to investigate the geometry of the Garisenda foundation.

Four main separate units are identified (Marchi et al., 2022): Unit R, from the ground level to −5 m, which is an anthropic fill made of miscellaneous materials, including archaeological remains; Unit A, from −5 m to −16 m, which is a succession of silty-clays of variable thickness (from half a meter to some meters), characterized by a high variability in the shear strength and stiffness parameters. Between −9 m and −12 m depth there is a layer with lower mechanical characteristic which is involved by the pressure bulb of the towers foundations (the base of the conglomerate foundation block of Garisenda is located at −5.6 m from ground level); Unit B, from −16 m to −26.5 m, which is a close succession of clayey-silts and silty-clays having mechanical properties appear more homogeneous with respect to Unit A; and Unit C, below −26.5 m, which is a homogeneous normally-consolidated clayey material. From a hydrological point of view, there is a first superficial aquifer, whose top corresponds to the water table, from −5 m to about −20 m.

Subsoil management was and is always taken into consideration for the purposes of preserving the Two Towers. Cesare Salvanini (1891-1962), in the middle of the last century, warned the Municipality about the risk of tower collapse in the case of interventions on the subsoil for commercial purposes which could connect two underlying aquifers, thus undermining the state of imbibition and absence of water circulation. In his open letter, published in the March 1957 issue of the monthly journal "La Famèja Bulgnèisa" by the homonymous cultural society, he wrote: "The Two Towers are located on an island where aquifers are found, but without water currents"; "The exploitation of the highest aquifers would lead to effects certainly catastrophic, altering the state of imbibition of the clay and consequently its very variable volume"; "It is absolutely necessary to avoid the mistake of connecting, with the same pipe, the upper layers with the lower ones".

The Two Towers (and many others) resisted almost a thousand years to several potentially fatal events including earthquakes, strong adverse atmospheric events and lightning strikes, as well as bombings in very nearby areas during World War II. Moreover, the passage of heavy vehicles very close to a historical building for most of the day induces vibrations which cause fatigue in its masonry structure, in particular mortar degradation (Zini et al., 2022), and can also influence its seismic vulnerability (Haladin et al., 2023). Figure 4 shows the graph of the buses passage per minute within a few meters from the Two Towers. The data come from the official website of the Bolognese urban mobility company. The fact that for 14 hours per day 2 or more buses per minute pass at 2-4 m from Garisenda base should be noted. The same figure was shown in a meeting, organized by the University of Bologna, aimed at discussing the impact of traffic on fragile monuments in the city involving both citizens and scientific community (https://corsi.unibo.it/magistrale/IngegneriaSistemiProcessiEdilizi/bacheca/2011-05-la-citta-fragile-le-torri-e-il-patrimonio-della-citta-storica).

This issue was at the center of heated debates between those who believed it necessary to pedestrianize the area surrounding the towers, as well as other sensitive areas of the city, and those who, on the contrary, proposed the passage of even heavier and larger vehicles. According to some technicians, it was essential to eliminate the anthropic source of vibrations as much as possible to safeguard the health of the towers. According to others, vehicular vibrations did not represent any problem because they did not interfere with the natural vibration modes of towers and ground. An unambiguous interpretation of scientific data and observations is not an easy task because of complexity of soil and historical buildings. However, a prudential-conservative approach is advisable.

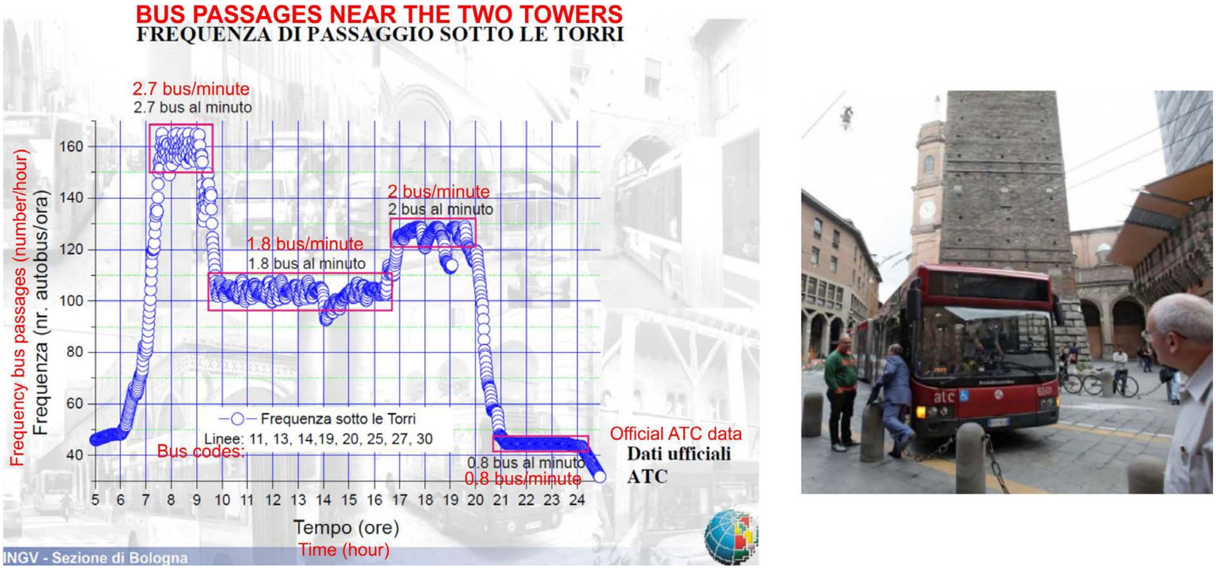

Figure 4. Frequency of buses passage close to Two Towers in 2011 (data from the official timetable of the Bolognese urban mobility company). Until the autumn of 2023, the road traffic, including trucks and buses, passed within a few meters from the towers. Today, because of concerns on Garisenda safety, road traffic passes near to Asinelli tower, but not close to Garisenda.

2.2 Main geometric data on Garisenda tower

The Garisenda tower is more than 900 y old (here and below y denotes the non-SI time unit year), having been built between 1109 and 1119, and one of the most tilted towers in the world. Since the tower is approximately aligned with the four cardinal directions, each of its walls will be indicated in the following according to its orthogonal direction, i.e. east (E), north (N), west (W) and south (S) respectively. According to Fabbi (2011) and Bertolini (2023), the main characteristics of the Garisenda tower are (Fig. 5): 1) since 1890, after the demolition of the buildings around the base (shops and chapel), it is an isolated structure on all sides; 2) the height of the tower is 53.5 m above the foundation level and 48.2 m above ground; 3) its center of gravity is approximately 25 m above the foundation plane; 4) the tower weighs approximately 42 MN and has a square plan, with a side of 7.4 m at the base; 5) the current inclination angles of the straight tower axis are 3.91° towards E and 0.67° towards S. For comparison, the mean leaning angle of Torre di Pisa after the 1993 and 2001 remediation works is 3.97° (Burland et al., 2020); 6) the tower basement and foundation have an 8.75 m wide squared base. The external walls of the basement, which are made of selenite blocks, reach 2.3 m below ground level whereas the foundation block is a 3.3 m high massive conglomerate parallelepiped (the space between the basement external walls is filled with the same material). The foundation footing, which is orthogonal to the tower straight axis, reaches ~5.6 m below the surface level and, therefore, is lapped by the mean water table. The structure of basement and foundation was obtained by means of coring and ground penetrating radar inspections.

The original tower height was 60 m. In 1293, the impressive inclination towards E led the Municipality to decide for its demolition, that did not occur for economic and political reasons. However, in order to prevent possible collapses, the tower height was reduced to the current 48 m in 1353 (Giordano, 2000). Many leaning or unsafe towers of Bologna were cut off or demolished during the 14th century, and others collapsed. The last demolitions took place in the 20th century.

The tower was built of bricks with the rubble masonry technique, "muratura a sacco" in Italian, similarly to the Asinelli Tower. Its cross-section is squared and tapered from bottom to top, from 7.4 m side at the base to about 6.9 m. The base of the Garisenda, restored at the end of the 19th century, is made up of squared blocks of selenite, superimposed on each other. Between 1998 and 2000 the body of the tower was renovated and consolidated using internally metal frames at various levels (up to the top) anchored to the walls with joints designed for a strong hold. Subsequently, three external bands, steel belts with sealing angles on the corners of the tower, were also installed up to a height of 25 m (Giordano, 2000; Giordano and Nanelli, 1999).

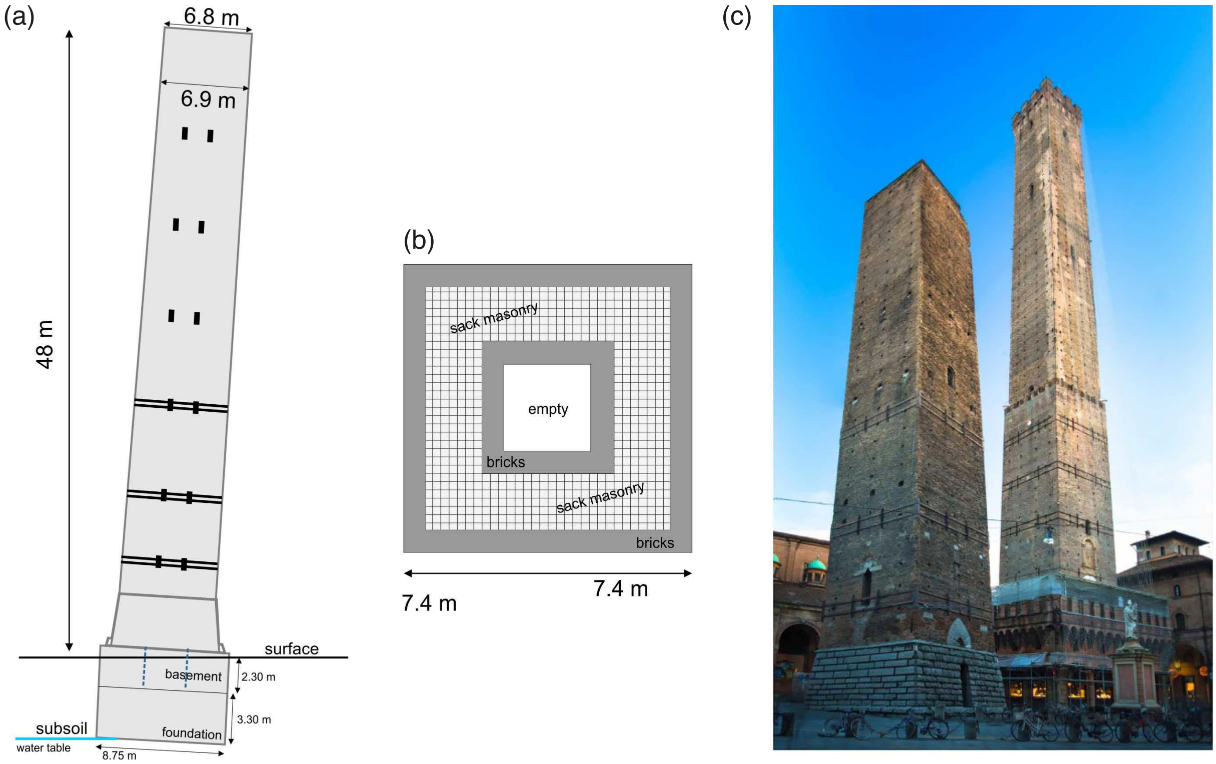

Figure 5. (a) Scheme of Garisenda and its basement/foundation, where main tower geometry, tapering, chains and tie rods at various levels are shown; (b) typical horizontal cross-section with rubble masonry; (c) image of Garisenda (left) and Asinelli tower (right).

2.3 Description of some technical measurements

At the beginning of the 20th century, professor Francesco Cavani (1853-1923) carried out a study aimed at monitoring the movements of the tower top with respect to the base and evaluating the effects due to heating daily cycles and winds. He used a system of plumb lines and optical sights and also provided basic geometric information, in particular the 3.22 m overhang of the E side (Cavani, 1903; 1917; 1919). The annual time series of movements towards N and W directions and some positions of the plumb are shown in Fig. 6. Cavani interpreted the detected movements as mainly due to solar radiation and, only in extreme and exceptional cases, to very strong winds. During 1904, the tower was affected by a weak drift in N direction with superimposed NS oscillations, whereas in EW direction it mainly oscillated. The main sun-induced oscillation was ~1.5 mm with ~9 s period, while the typical values for strong wind were 4.5 mm and 22 s. The extreme effect observed in that year was ~7 mm with 39 s period. Since the observed behavior seemed to be consistent with that of similar buildings, Cavani attributed the good health state of the tower to the excellent quality of the underlying soil. According to that author, the significant leaning angle was caused by a differential subsidence of the ground, which is the only cause of the highly inclined structure. Such a failure already occurred during the construction phase. Moreover, Cavani described the tower body as twisted, with slopes and changes in slope along its entire masonry which occurred over the years as a result of different compressions and settling of the constituent materials. He also noticed anomalous bulges in the SE parts and cracked bricks both here and in the SE corner.

On the one hand, these results were quite reassuring because the materials were in good conditions and capable of withstanding even greater stress. On the other hand, these results supported the hypothesis that a very strong

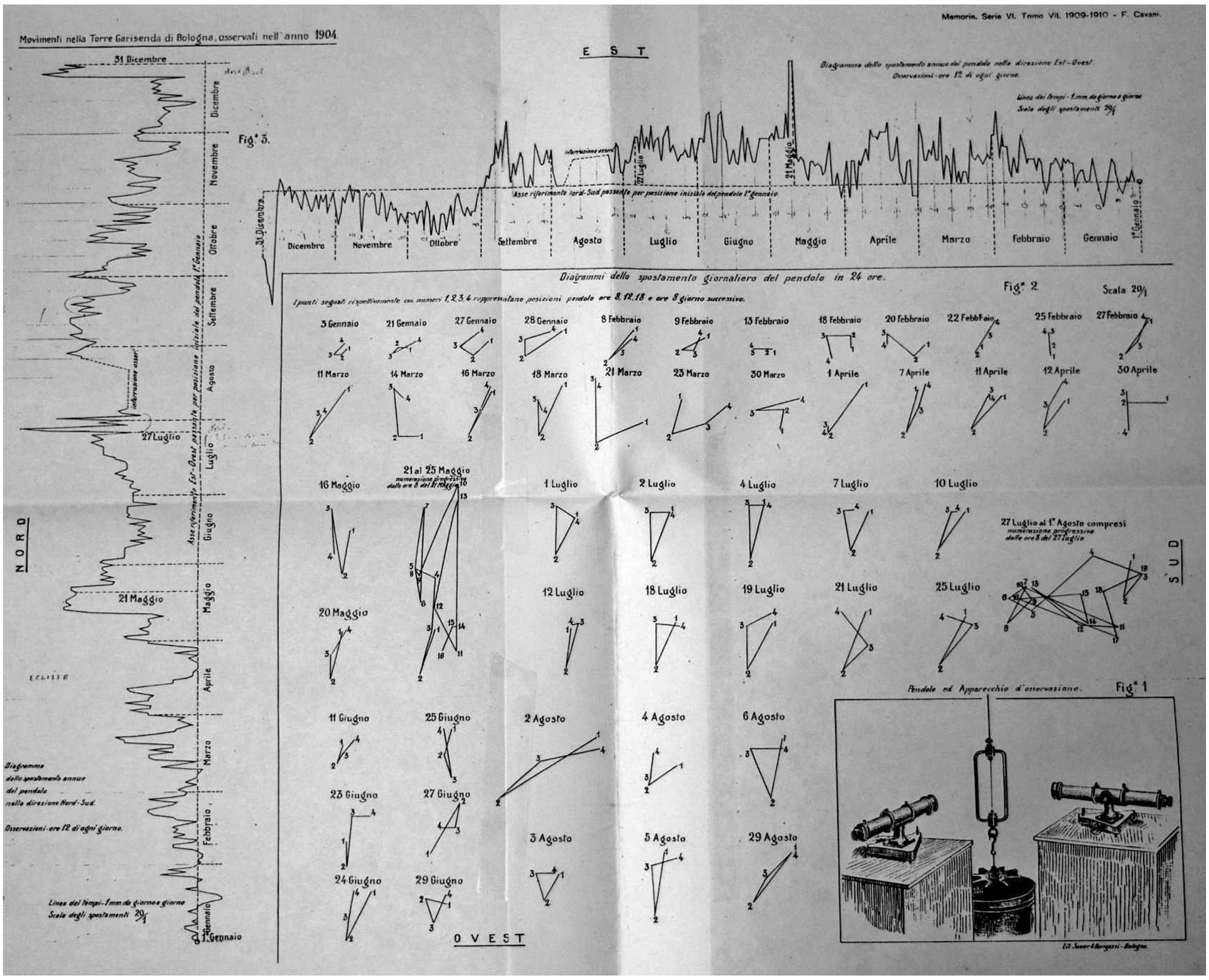

Figure 6. Time series taken in 1904 (left: N; top: E) and movements of the tower top detected using a plumb line and the optical system implemented by Cavani (for each day, 1, 2, 3 and 4 indicate the position of the plumb at 8:00, 12:00, 18:00 and 8:00 of the next day respectively).

pressure acts on the ground, hence the need to avoid variations that could compromise its characteristics. Cavani also recommended constant care and checks. The comparison of the slope measurements carried out in 1902 and 1999 highlights a ~70 cm subsidence at the E side of the tower base, which corresponds to a mean increase in leaning angle of $\sim 2 \sim 10^{-3}$ degrees per year and an additional overhang of ~20 cm.

In 1993, Municipality and University of Bologna, in collaboration with the Superintendence of Cultural Heritage, stipulated an agreement aimed at studying the structural health of the tower (Giordano, 2000). Among these studies, the following ones are particularly important: 1) numerical analysis of the stress state and expected deformations due to static weight, wind action, thermal variations, cracking, low intensity earthquakes; 2) investigations on the foundation by means of continuous core sampling and static penetrometric tests, already mentioned in Subsection 2.1; 3) inspections with ground penetrating radar on the ground and on the checkered walls with annotation of great heterogeneity, humidity of the wall structures, tests with jacks to observe the tension state, mechanical core drilling and endoscopic investigations; 4) chemical-physical investigations on the constituent elements and mortar evaluation. After a very long investigation phase, some consolidation works were carried out: metal belts were placed on the tower body and on its base (a system adapts the external belts to daily and seasonal temperature changes); degraded masonry was replaced; the façades were cleaned; fractures and interstices between the bricks were filled with suitable mortar.

Seismometric/accelerometric monitoring is carried out since 2012. Baraccani et al. (2020) identified the main modes of the Two Towers (in particular, recognized the first three flexural modes of each tower) and evaluated the effects of traffic-induced vibrations. Variations of the average values of the fundamental frequencies within the different seasons and over the years were lower than 1%. Experiments carried out on Asinelli tower with heavy trucks passing at 30 km/h speed showed that peak accelerations and peak horizontal displacements at the tower top can reach values of $3 \times 10^{-3} g$ and 0.4 mm respectively, whereas the corresponding values at 35 m height are $1.5 \times 10^{-3} g$ and 0.1 mm.

Several monitoring instruments were installed on the tower to provide real-time information on the structural health of the tower (https://www.geopop.it/torre-garisenda-di-bologna-a-rischio-quali-sono-le-possibili-cause-dellallarme): 9 strain transducers with invar wire placed on the masonry; 4 strain gauges placed on the supporting belts; 6 biaxial inclinometers; 3 laser distance meters placed on Prendiparte tower, cupola of S. Maria della Vita, and via S. Stefano 16; 8 biaxial inclinometers; 1 goniometric station; 1 meteo station; 2 temperature sensors. Some data (temperature of the Two Towers; wind velocity and direction of Garisenda tower from gonioanemometric transducers) are freely available on a web page of Municipality of Bologna (http://www.tecnoinmonitoraggi.it/cms_dati.htm). The

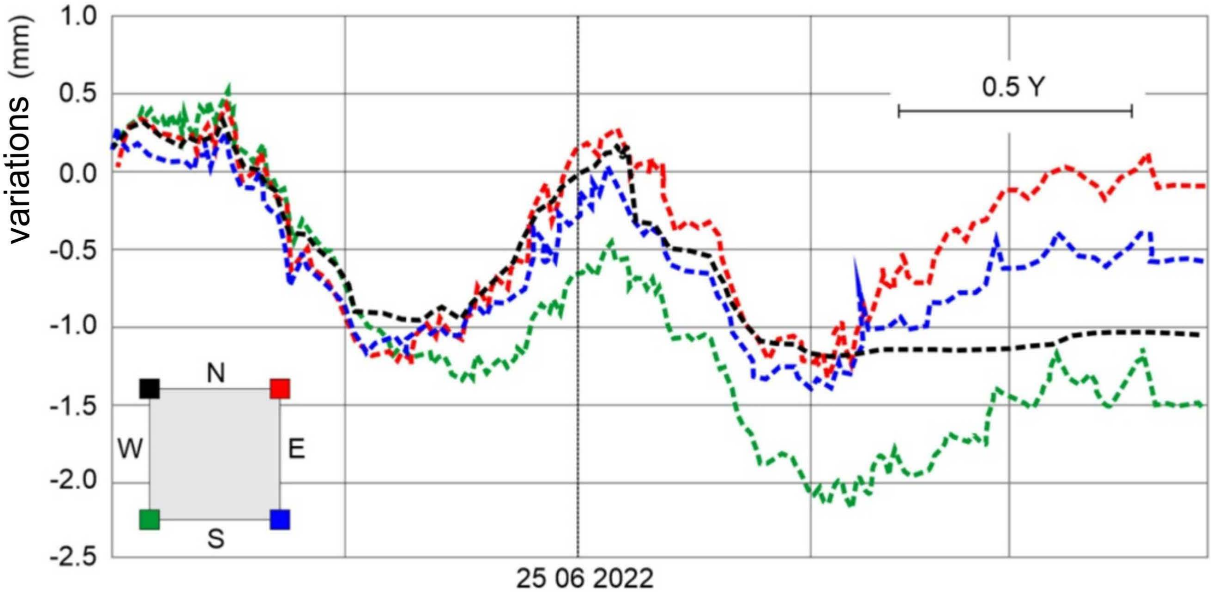

Figure 7. Time series related to strain gauges placed in the corners of Garisenda base. The green line (SW corner) shows, besides oscillations, a ~1 mm/y drift. The image results from a digitalization of the original graph shown in Aiello et al. (2023).

monitoring system runs simultaneously for the Two Towers. Since the distance between the gravity centers of the Two Towers is 20.8 m and the minimum distance between the structures is ~5 m, their foundations are mutually interacting and, probably, the towers' fates are closely linked.

Recently, since the end of 2021, the monitoring data led to some concerns regarding the health state of Garisenda tower. Figure 7 shows some time series provided by strain gauges and published by the scientific commission in charge of the study of the tower, where a worrying trend of ~1 mm/y of shortening emerges (Aiello et al., 2023). This phenomenon appeared to be subsequently attenuated and a possible outcome could be a return to the previous situation. The alarm, however, was not dismissed and some precautions were taken because it is necessary to understand what happened, given the fact that no seismic tremors or other shocks occurred after 2012. The municipality promptly activated a plan to secure the area. A containment and protection belt was placed around the Garisenda tower to ensure safe isolation of streets and nearby buildings, to prevent tragedies and damage in the event of a collapse pending appropriate consolidation interventions.

3. Morphological analysis based on remote sensing data

The main objective of this article is to understand what contribution remote sensing can make to improving the knowledge framework on the structural health status of a historic building, in particular in case of earthquake. is TLS. The result of a TLS survey, which is the technique used in the case of the Garisenda tower, is a dense point cloud, i.e. a set of coordinates of measured points and related radiometric information, from which information useful for the purposes of assessing the health state of a historical building can be extracted. An example of use of TLS (or SfM) data is the morphological analysis of the walls of the building, i.e. the comparison between the point cloud and a theoretical reference surface (plane in the case of the Two Towers), especially when this analysis is repeated over time leading to multitemporal deformation maps (Pesci et al., 2013). A morphological map enables the detection of everything that deviates from a condition of regularity. In particular, patterns recognized in a morphological map can provide information about the processes that acted on the observed historical building leading to its current state, including earthquakes or other strong phenomena (Pesci et al., 2013; Bonali et al., 2014; Pesci et al., 2024).

Some experiments carried out in recent years led to these statements:

(i) the used instrument (Optech ILRIS-3D) provides point clouds whose spatial resolution, for an appropriate sampling rate, is approximately 1/3 of the footprint (Pesci et al., 2011c);

(ii) it is possible to model possible distortions due to the spot spreading phenomenon thanks to stringent constraints on the position of the instrument when a tall building is observed. However, these distortions have a negligible impact on the morphological analysis (Pesci et al., 2013);

(iii) the error due to alignment (i.e. co-registration) of partial point clouds of a same wall, under the condition that there is an appropriate overlap (at least 40-50%), is negligible with respect to the measurement noise (Pesci et al., 2011a);

(iv) multitemporal morphological deformation maps are significantly more reliable than the results of direct comparison between point clouds because the effect of noise is minimized, leading to more stable results (Pesci et al., 2013);

(v) the convolution between the laser beam function and a model of the observed surface allows the reconstruction of a synthetic point cloud with noise and resolution properties very similar to those of real measurements, fact that can be useful in survey planning with a defined instrument, or also for the choice of the instrument (Pesci et al., 2011c).

The Two Towers were the subject of various TLS surveys, initially carried out in 2010 to evaluate the performance of this technique in the case of leaning buildings and with stringent constraints on possible station points from some directions (Pesci et al., 2011a; 2011b). Other surveys were carried out (however focusing mainly on the Asinelli tower, observed after each major shock) during and after the period of the Emilia Romagna earthquake to search the areas of the towers characterized by higher sensitivity to seismic-induced deformations (Pesci et al., 2013). Finally, a survey of the Garisenda was carried out in 2023, at the time of the above-described alarm. A SfM survey of the Garisenda tower was also carried out (Teza et al., 2016).

3.1 Garisenda tower

The first complete TLS survey of Garisenda tower was carried out in 2010 in order to characterize its external walls. The survey was carried out by means of a long-range instrument Optech ILRIS 3D, which can acquire data also at several hundred meters from the target and therefore ensures high quality data also at the building top since the Garisenda tower can be observed from sufficiently long streets to reduce the effects of the point spread (Pesci et al., 2013). Moreover, the relatively small observed areas require not more than the motion of lightweight mirrors, therefore preventing calibration errors. It should be noted that the type of analysis performed here does not require the use of technologically state-of-the-art instruments conceived for the architectural surveying. On the contrary, an instrument conceived for environmental surveying, if its calibration certificate is valid, is particularly suitable for the morphological analysis of a tall tower.

The data processing provided the wall morphologies and a general layout of the tower (Pesci et al., 2011a). In order to obtain a digital model defined in a convenient Cartesian space, the vertical direction was defined, in the absence of electronic devices, from an initial leveling with a standard spirit level and carrying out a least square adjustment on the basis of the vertical elements of some buildings surrounding the Two Towers. After this operation, the found overhangs resulted to be consistent with the known results. Finally, it should be underlined that the morphological analysis does not depend on the used reference system, used here only for completeness of the result.

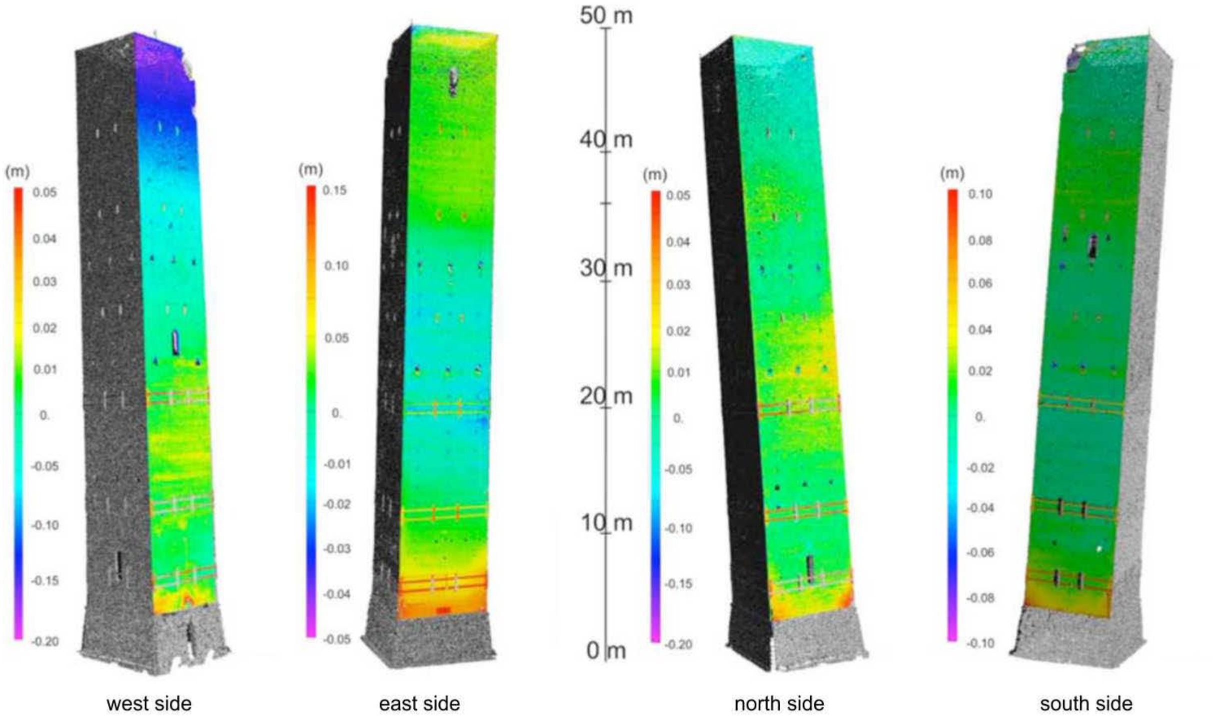

Figure 8. Garisenda tower morphological maps from data taken in 2010, for each side (W, E, N, S) (modified from Pesci et al., 2011a). The color bars are in the interval from −20 cm to +25 cm for a complete representation.

The morphological map of the W façade (Fig. 8) clearly show areas of swelling (positive values) in the lowest band of the tower body and between the two metal belts installed in 2000 for consolidation purposes (given the shape of the building, which has a square cross-section, the terms façade, elevation and side are used here as synonyms). Furthermore, a sudden change in the inclination of the tower in the upper part (~40 m height) is evident. A clear bulge in the lower part of the tower and a slope change in the upper part are observed also in the case of E side, i.e. the opposite façade. The N elevation is characterized by a clear bulge at the tower base and bulges also appear in the area above the third metal belt and in the upper band (~35 m). The opposite side, i.e. the S one, once again shows a bulge at the base and a sequence of positive and negative deviations along the entire body of the tower. The high resolution of the model and the completeness of the acquired data therefore enable to discover that all the anomalies observed are distributed in the areas characterized by: maximum variation in leaning angle; application of metal straps; in general, where the load on the structure is considered to be maximum. It is ultimately interesting to observe that proceeding upwards, changes in regime are observed on the tower walls, with alternating compression and expansion zones. However, it should be remembered that this kind of observation does not allow discrimination between a case where the observed geometry comes from a slow deformation taking place centuries and a case where it is due to construction defects and/or restoration interventions of which memory was lost over time. Ultimately, the morphological and geometric evidences detected in 2010, in particular the presence of bulges or recessed areas as well as twisted structures agree with the above described Cavani's diagnoses dating back to early 20th century and describe a structure whose state is due to several centuries of resilience. Similar patters can also be recognized in the Asinelli tower (Pesci et al., 2011a).

A seismic sequence struck the Emilia Romagna region in May-June 2012. The moment magnitude (M_W) of the main shock and the three strongest aftershocks were between 4.9 and 5.9, and hundreds of smaller shocks also occurred (https://terremoti.ingv.it/iside). Unfortunately, this sequence caused the death of 17 people, the forced temporary eviction of thousands of people, and the temporary closure of many commercial activities. Although Bologna is at ~50 km from the epicenters, the three main shocks were clearly felt by the Bolognese population.

A TLS survey of the Garisenda tower was carried out in June 2012 in order to evaluate possible morphological variations of the tower's façades due do the mentioned seismic sequence by comparing the results with the October 2010 ones. Similarly, possible morphological variations due to the presumed phenomenon that should have caused the anomalies found in the strain gauge monitoring were searched on the basis of a new TLS survey carried out in November 2023. The tower was entirely surveyed in 2010 (Fig. 8), while in 2012 and, mostly, in 2023 some parts in the lower part of the tower were not acquired because of scaffolding and panels.

The procedure aimed at comparing the morphological maps, developed in 2010 (Pesci et al., 2011a) and optimized in 2012 (Pesci et al., 2013), consists of these steps:

1) for each measurement session, registration of the partial point clouds using an Iterative Closest Point (ICP) algorithm to provide a complete point cloud of the tower;
2) creation of a point cloud for each façade;
3) point clouds regularization with a 5 mm sampling step;
4) for each façade, alignment of the corresponding 2012 and 2023 point clouds to the reference one (2010);
5) for each façade, creation of a reference primitive, i.e. a plane, from 2010 point clouds by means of a least square approach. Each primitive has a physical meaning; it represents the corresponding regular and non-deformed theoretical façade of the tower in 2010.
6) for each façade and each epoch, computation of point-to-plane distance (along the normal of the plane) from the reference primitive, leading to the color scaled morphological map;
7) for each façade, comparison of multitemporal morphological maps. In this way, the temporal sequence of variations (deformations) with respect to of the 2010 primitive is obtained and, in particular, the differences between the recognized patterns, and their distribution along the tower body, are shown.

This kind of analysis highlights the deformation changes of the façades. Each façade was processed and studied independently. Each survey was carried out with high overlap (50%) to warrant the correctness of the final alignment and the precise reconstruction of the façade. However, the used method is completely unsuitable for the observation of any rigid body movement (roto-translation) of the whole tower. In reality, as described in Discussion, any effects of rotation or variation of the edges between the façades could give visible signals in the morphological maps, but these would still be patterns to be interpreted on the basis of a global model of the tower, not examined here.

Figure 9 shows the complete sequence of morphologies of the tower façades, where the effects of the above-mentioned occlusions which prevented the complete surveys in 2012 and 2023 can be seen. In first analysis, in 2012 the morphology of the tower changed with respect to the initial condition. It should be noted that the survey was carried out after the first earthquake and the last one ten years later, when the seismic sequence was extinct since a long time. The N and S sides are characterized by areas of discontinuity in the distribution of differences which can be seen with the used range of differences (±5 cm, i.e. 10 cm range). Changes which are evident in the 2012 map completely disappear in the 2023 ne (see e.g. N façade at ~35 m height). The E and W sides are the leaning ones; for this reason, morphological maps with 25 cm range are used. However, probably due to a conformation already more altered in 2010 compared to a regular plane, no significant changes are observed in these two façades (except for a bulge area between 10 and 20 m elevation in W side).

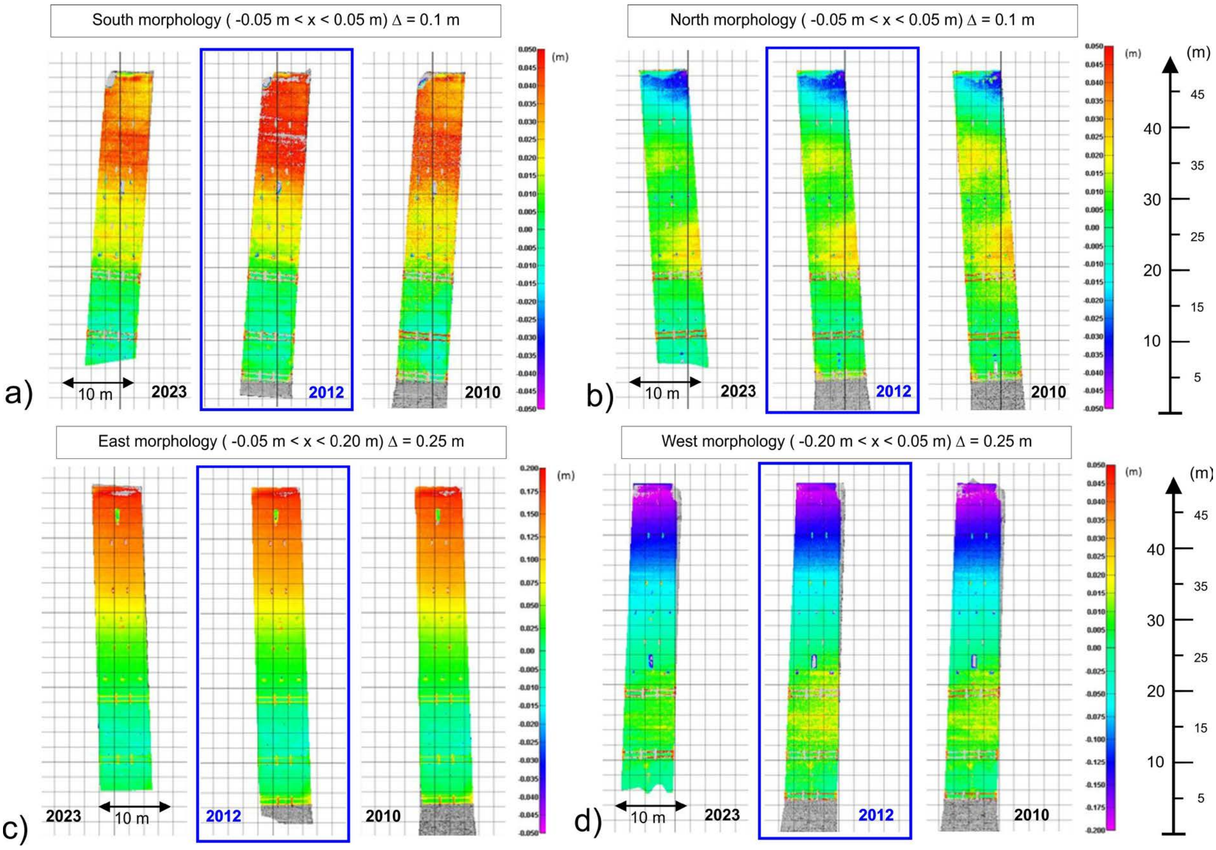

Figure 9. Morphologies from point to plane distances. (a) S side; (b) N side; (c) E side; (d) W side. The ranges of variations are within 10 cm for N and S façades and within 25 cm for the others, which are the leaning sides.

In order to better focus on the differences between the three quartets of multitemporal morphological maps and therefore better detect the occurred changes, these maps are represented with narrowed difference ranges in Figs. 10-12. The price to pay is the presence of areas of off-scale values.

As for the S side, the 2010 morphology changed after the first shock of the 2012 earthquake with a positive deformation in a band at heights from 30 m to 35 m above the ground (Fig. 10a for the whole façade and Fig. 11 for the part from 25 m to 48 m height). The values represent an accentuation towards the south of some millimeters. The changes are well visible above 32 m altitude. In 2023 the conformation was very similar to the initial one (2010) but with a more localized distribution of positives, in a height band approximately 10 m wide, compared to the initial band approximately 15 m high. The resulting conformation is set back (towards the elevation plane) with geometry suggesting a twisted (counterclockwise) conformation. Furthermore, it should be noted that even in the lowest sector of the tower (12-20 m elevation range) the temporary effects of the 2012 earthquake produced less negative values.

The N side (Figs. 10b and 12) was affected by significant deformations after the 2012 shock. The positive pattern of 2010 was reduced both in the 15-25 m band and in the upper 30-40 m band. Furthermore, a negative widening of the apical band can be observed above 40 m, with a more accentuated twisted shape that suggests a twist. The 2023 measurements showed attenuated variation compared to 2012, confirming the morphology although highlighting a slight decrease in values, continuous compared to the previous phenomenon. In this case, the values suggest that the structure of the elevation was slightly more recessed than in 2010. It seems that deformations affected the façade portion above 30 m.

The E side (Figs. 10c and 13, left panel) seems to be much more stable, even if a positive accentuation of the apical band can be observed in an extremely contained area. Above 45 m, an advance on the normal of the plane is clearly visible but the line marking the change in behavior is ~42 m high.

Finally, the W side (Figs. 10d and 13, right panel), in analogy with the E one, shows small differences observed at the limit of the resolution, with zero-positive values in the 12-22 m range and a slight indentation in the apical area above 40 m elevation.

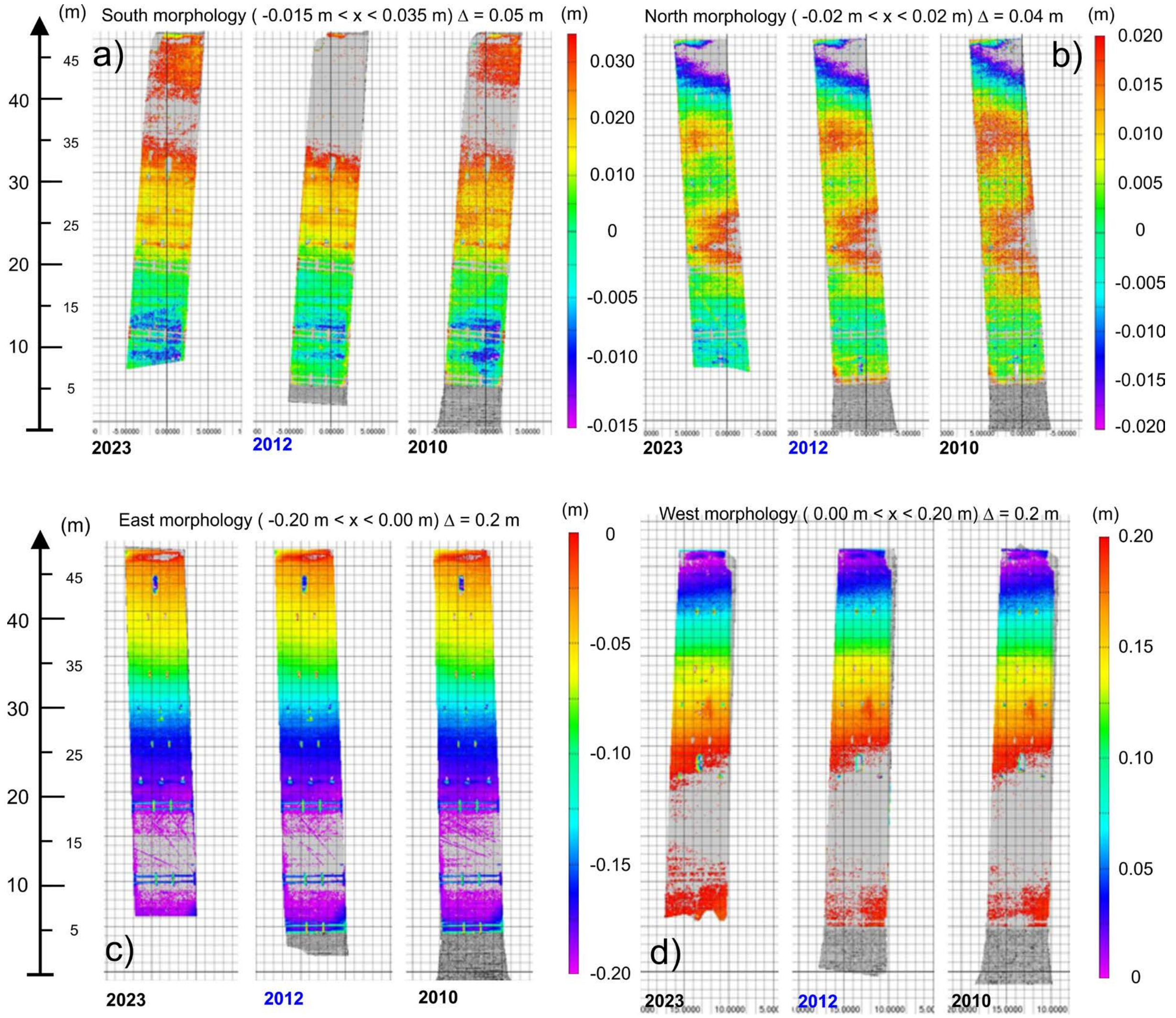

Figure 10. Morphological maps from point to plane distances. (a) S side (5 cm range of variation); (b) N side (4 cm); (c) E side (20 cm); (d) W side (20 cm).

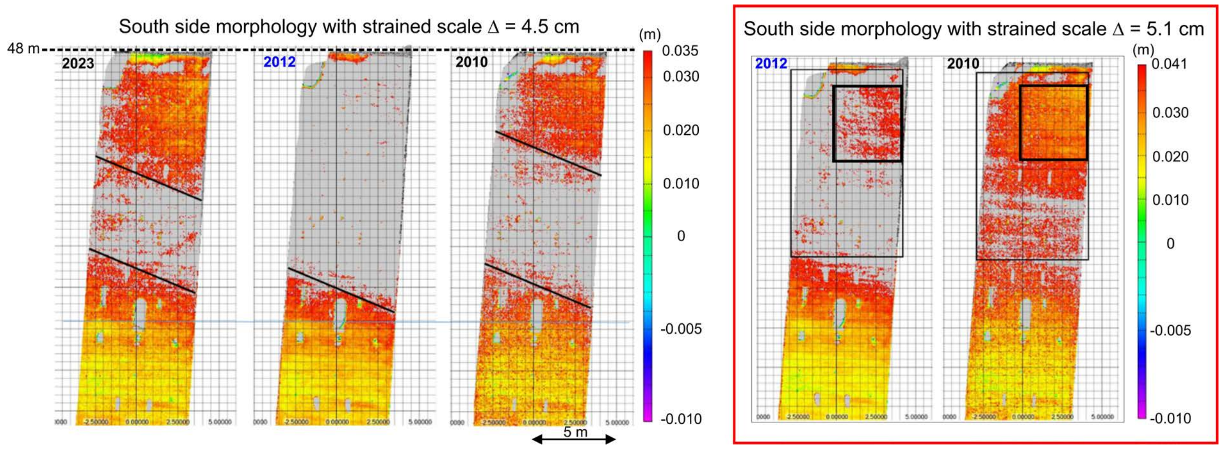

Figure 11. S side. More maps with 4.5 cm and 5.1 cm difference ranges to visualize the distributions of differences for tower elevation higher than 25 m.

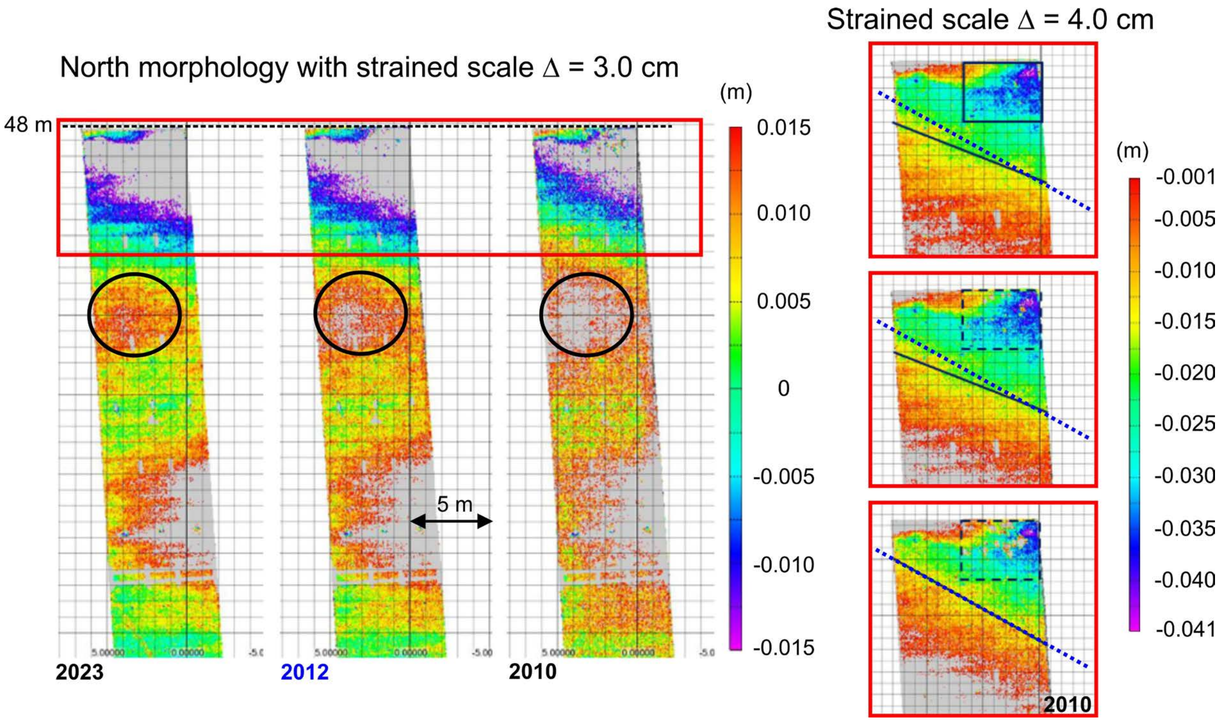

Figure 12. N side. More maps (4.0 cm and 3.0 cm ranges) to visualize the distributions of differences in the body and in the upper part of the tower (elevation higher than 15 m).

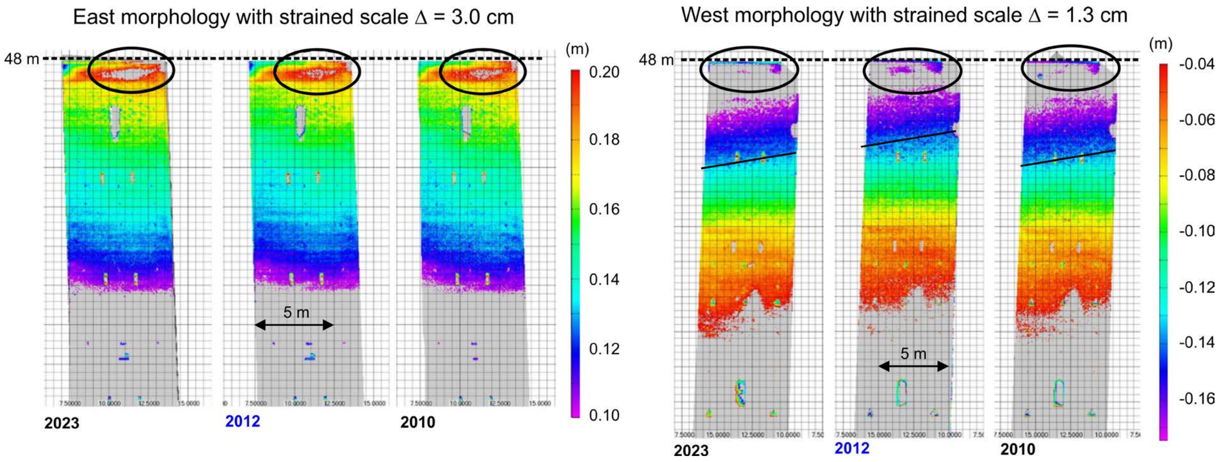

Figure 13. More maps to observe minor variations on façades E (left panel, difference range: 3.0 cm) and W (right panel, difference range 1.3 cm) above 20 m elevation.

The direct comparisons between the multitemporal point clouds of the upper parts of the tower are shown in Fig. 14. Since all TLS surveys were carried out in order to have two façades in a same partial point cloud, pairs of adjacent façades were considered; in this way, each alignment and comparison process was carried out on two multitemporal point clouds, without possible systematic errors related to co-registration of partial point clouds. The results show the differences (except for general rigid body movements), whose distributions not only confirm the already shown deformations, but also suggest the hypothesis of seismic-induced torsion of the tower, as described in the preliminary FEM analysis provided by Casolino (2024).

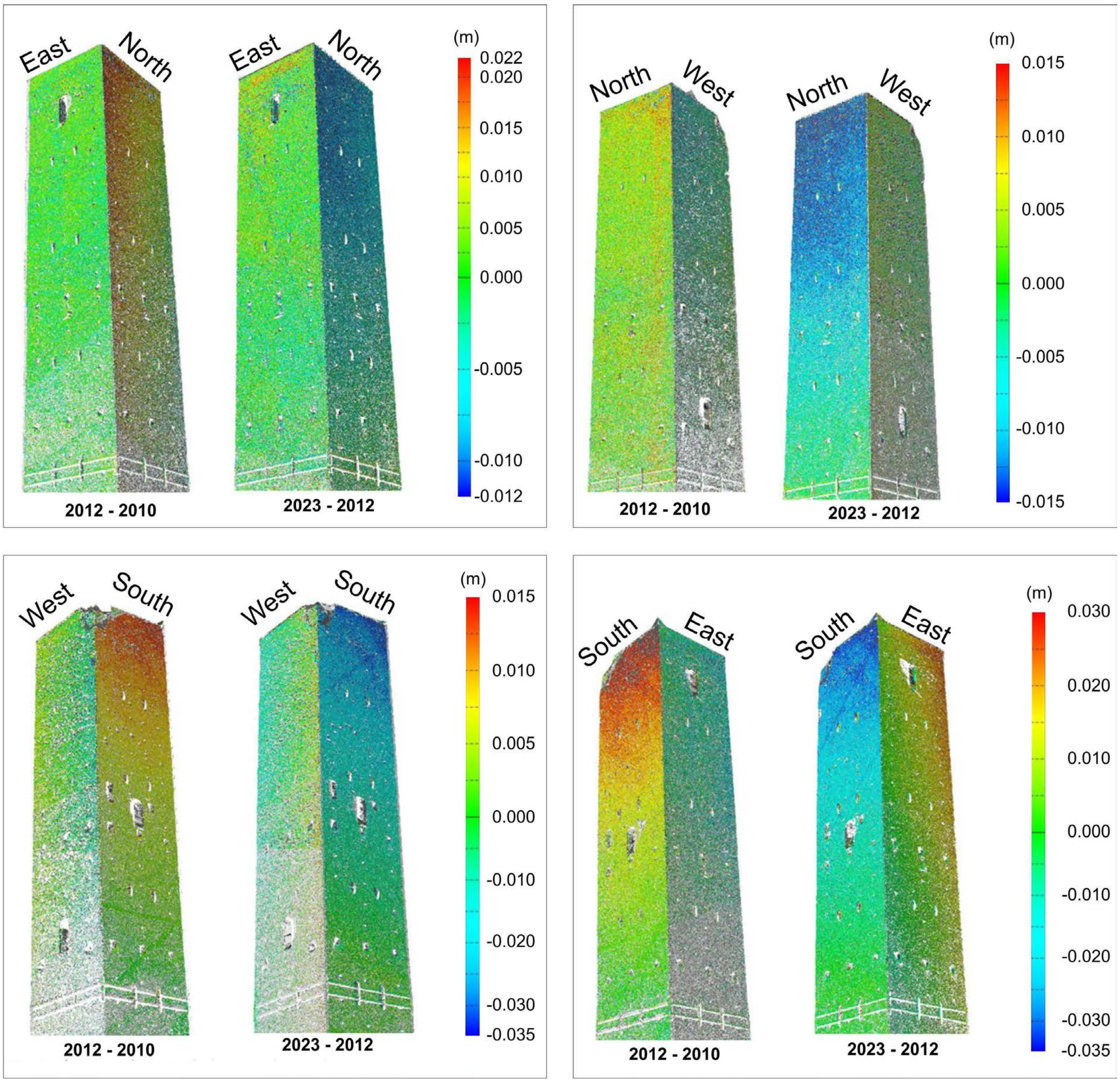

Figure 14. Direct comparison between multitemporal point clouds related to pairs of adjacent façades. Note that for each station point, the two surfaces are simultaneously acquired.

3.2 Asinelli tower and 2012 earthquake

The Asinelli tower was also surveyed in 2010, to evaluate its geometry and morphology (Pesci et al., 2011a), and in 2012, focusing on the upper part (above 40 m elevation) because the lower part was hidden by scaffoldings (Pesci et al., 2013). For reasons of comparison with Garisenda, those results are briefly summarized here (Fig. 15). Three surveys of the Asinelli tower were carried in 2012 to observe its conditions after some seismic shocks. The multitemporal morphological maps showed that the tower reacted to the seismic stress by deforming, in particular the main effects appeared after the first shock occurred on 20 May 2012, and then slowly returning, on a time scale of some days or some weeks, to its initial equilibrium condition (the 2010 one), even if some morphological features were slightly accentuated.

Since the Asinelli tower height is about twice the Garisenda one and it is slimmer, only a survey of the lowest tower was carried out after the first seismic shock. Therefore, it is not known how long it took the Garisenda to return to its initial state. In particular, this may not have happened on all sides since, as can be seen from Figs. 9-12, both the N and S façades of the Garisenda show patterns in 2023 consistent with those of 2012. As there is a lack of data acquired in the intermediate period, it is not possible to discriminate whether the 2023-2010 variations are also connected to the earthquake or just are due to static effects (weight), subsidence, variations in the subsoil or atmospheric, climatic and anthropic phenomena. However, these morphologies indicate the bands and levels of the tower body which are particularly affected by the effects of stress and undergo deformation.

The morphological analysis, although limited to each façade and without considering the tower as a single object, still allows a direct understanding of the typology of movements occurred in the last 13 years and an observation of what had accumulated over the centuries, of course provided that information from different sources is also considered.

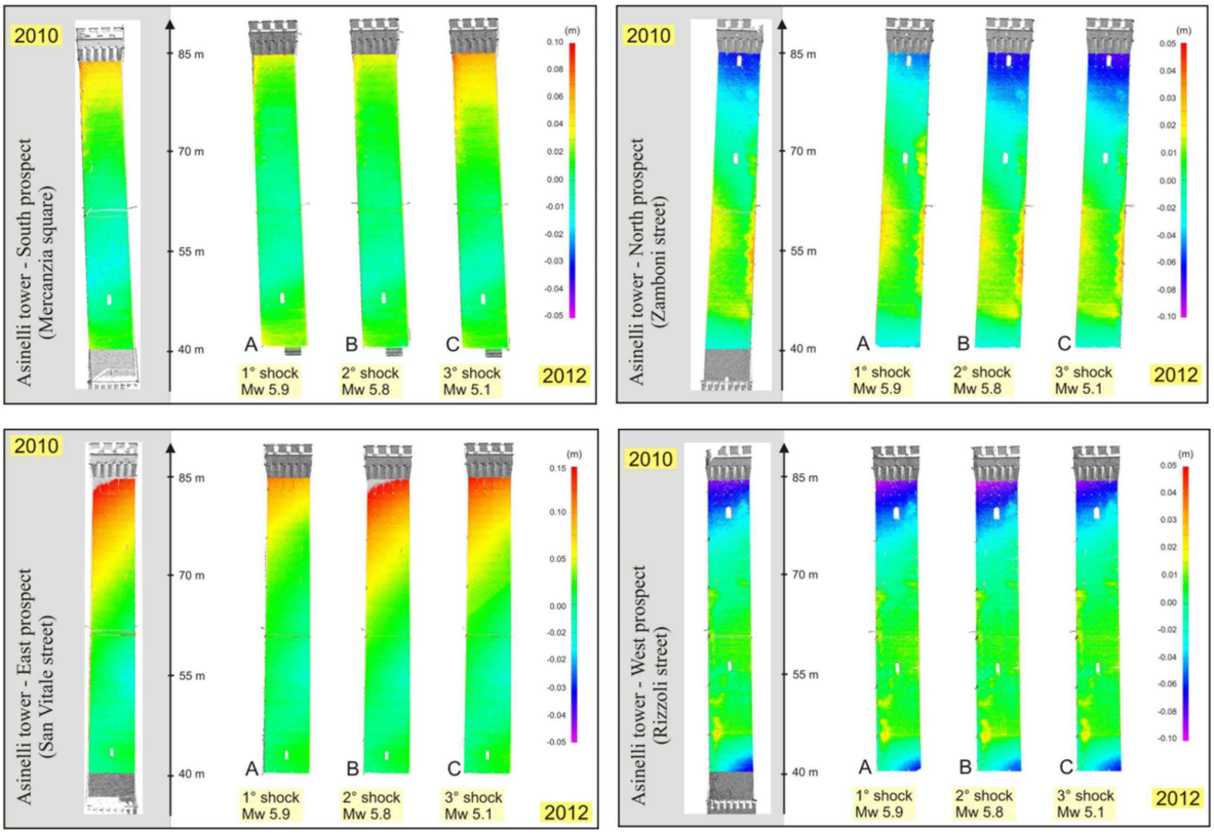

Figure 15. The Asinelli tower during the seismic sequence after the three main shocks. The survey A (first shock) was carried out at the same time of the above described 2012 survey of the Garisenda tower. Modified from Pesci et al. (2013).

4. Discussion

In this section, the results of the TLS surveys of the Garisenda tower are discussed on the basis of the available data obtained with other techniques, including numerical modeling, taking also into account what was observed in the case of the very near Asinelli tower. The objective is on the one hand to understand how these surveys can broaden the framework of knowledge relating to the state of health of the Garisenda, and on the other hand to provide the reader with useful methodological guidance, given that many cities around the world are characterized by potentially fragile historical buildings located in fragile ancient urban areas.

The study of the multitemporal morphological maps shows that, as expected, the façades of a tower hit by an earthquake were affected by some deformations. It was equally expected that, after other shocks, the morphology changed again. It was less expected that, at the end of the seismic sequence, the morphology returned, barring minimal residual variations, the initial one, i.e. before the earthquake. Finally, it was even less expected that the initial morphology would quickly recover after a new shock. These results highlighted the need to interpret the fact that some deformations, although subsequently disappeared, really occurred and were detected. The previous section recalls the results obtained in the case of the Asinelli because it was surveyed three times during and after the seismic sequence, while the Garisenda was surveyed only after the first shock. The multitemporal morphological maps (Fig. 15) show that deformations appeared and subsequently disappeared as effect to a slow return to the 2010 equilibrium conditions. No more than very limited portions of the surface are characterized by not completely recovered slight deformations. Similarly, the morphological maps of the Garisenda tower obtained in 2010 and 2023 (Figs. 9-13) show no more than residual differences.

The search for an interpretation of the results observed through multi-temporal morphological maps requires some considerations regarding what the current morphology expresses. The results highlight that there are two contributions to the observed morphology: (i) geometrically reversible (or at least almost completely reversible) changes after each seismic shock, which could be indicative of apparently reversible conditions; (ii) a cumulative contribution which remains. This second contribution is probably due to ancient strong shocks (earthquakes, lightings, and so on) which produced permanent effects, but also continuous heavy load over centuries, material deterioration or other factors which can act on the façade shape as time passes.

It is necessary to state that if a stress causes the modification of the state of the external surface of a building and the cessation of this stress leads to a more or less rapid almost complete recovery of the previous state, this does not necessarily mean that there is not a permanent effect. The geometry is restored, any brick dislocations are recovered, but the state of the masonry may be changed. Namely, the masonry could be prone to different, and potentially dangerous, responses in the event of future stresses similar to those which, occurring now, have provoked an apparently elastic response. For this reason, we spoke above of “apparently reversible conditions” and not simply of “reversible conditions”. Therefore, in the case of temporary effects it is perhaps not legitimate to speak of elastic deformations. but it is reasonable to hypothesize that these variations are linked to the response of a mortar-brick system.

Before proposing an attempt to interpret the morphological maps, the EMA/OMA results for both the Two Towers are shown. It is appropriate to point out that the behavior of a building depends both on the characteristics of the materials that compose it, as well as on their interaction, and on its geometric composition. These considerations are particularly important in the case of a historical building, as construction methods and materials can be multiple and stratified, leading to discontinuities in the materials and to possible localized critical issues due to the interaction between them or due to different levels of degradation and aging. This can also give rise to variations in the mass and stiffness characteristics of the building as a whole, leading to changes of eigenfrequencies.

In the case of the Asinelli tower, the modal analysis carried out in various years did not highlight any significant variation in the frequencies of the explored modes. In particular, the lower flexural eigenmode (split into two eigenmodes with very near frequencies, one in the direction of maximum inclination and the other at orthogonal direction) always has frequency between 0.32 Hz and 0.33 Hz, even before, during and after the 2012 seismic sequence (Riva et al., 1998; Castellaro and Mulargia, 2010; Azzara et al., 2014; Baraccani et al., 2020). This suggests the absence of significant permanent damage, which would have caused a significant frequency reduction. A building of only two floors damaged by an earthquake can suffer a 20% reduction in frequency of the lower mode (Sivori et al., 2022). Moreover, a detailed study of the point cloud highlighted three changes in leaning angle of the Asinelli’s axis at 45 m, 60 m and 75 m elevation respectively (Pesci et al., 2011a). A theoretical, FEM-based profile of Peak Floor Acceleration $PFA(z/H)$ in the direction of maximum slope, i.e. the peak acceleration at the normalized height z/H, where z is the elevation and H the tower height, was obtained by using realistic synthetic seismic signals expected to occur in Emilia Romagna and able to excite the fundamental vibration eigenmodes of the tower (Riva et al., 2003). There are PFA peaks for $z = 35$ m ($z/H = 0.36$) and $z = 65$ m ($z/H = 0.67$); moreover, PFA linearly increases for $z > 80$ m ($z/H = 0.82$). The obtained values are therefore similar to the leaning change elevations. It should however be noted that, although a detailed study of the trend of the leaning angle with height requires a purely 3D approach, the effects of slope variations can also be observed in the morphological maps (Fig. 15). For comparison, the main construction changes of the Asinelli tower occur at 11.5 m (change of cross-section of rubble masonry), 34 m (transition from rubble masonry to solid brick masonry) and 56 m (cross-section change in solid brick masonry).

Concerning the eigenmodes of the Garisenda tower, the available results show that the long-term acceleration monitoring based on ambient vibration, carried out since 2012, did not highlight significant variations; they were contained within 1% as the seasons changed (the climatic conditions act of the eigenfrequencies) and the year passed. The lower flexural eigenmode splits into an eigenmode in the direction of inclination and the orthogonal one, has frequencies of 0.72-0.73 Hz (Baraccani et al., 2020). Unfortunately, to the best knowledge of the authors, no EMA/OMA data prior to 2012 seem to be available. However, it is reasonable to conclude that, even in the case of Garisenda, the OMA seems to validate what obtained with the morphological analysis, i.e. the absence of signs of degradation progressed in recent years, always keeping in mind that the absence of signs of deterioration does not certify that this is absent. However, the difference between a study carried out to understand the ways in which the tower vibrates and other studies aimed at evaluating the deformations induced by seismic stresses of a certain importance must be considered. Since the natural frequencies of fundamental modes of Garisenda tower and soil are $f_T = 0.73$ Hz and $f_S = 0.8$ Hz respectively (Baraccani et al., 2020; Castellaro and Mulargia, 2010), it is $|f_T - f_S|/f_S = 0.09$. Therefore, soil-structure interaction can occur (Gosar, 2010). However, the condition $f_T < f_S$ implies that, in the event of earthquake-induced damage, this coupling should tend to decrease. It should be noted that, during their almost thousand-year existence, the Two Towers were hit by two earthquakes with median $PGA{\sim}0.23g$, occurred in 1365 and 1433, and five earthquakes with median $PGA{\sim}0.15g$ – $0.19g$ (Baraccani et al., 2017). These phenomena should have caused no more than moderate damage to the Garisenda because strong damage would have probably caused the collapse because of the aforementioned soil-structure interaction. It is unlikely that more important phenomena could affect the city of Bologna in the future, although this cannot be ruled out. Regarding the 2012 earthquake, from the macroseismic intensity map it is reasonable to assume $PGA{\sim}0.03g$ for the main shock, occurred on 20 May 2012.

Regarding the morphological analysis in the case of the Asinelli tower, both the morphological maps and the profile of acceleration in the direction of maximum slope were available and it was possible to relate them. The Two Towers are empty buildings and, in particular, the Garisenda tower is a hollow parallelepiped in rubble masonry. In the case of Garisenda tower, the *PFA* profile is unavailable. In the design phase, if a reliable numerical model of the system is not available, in accordance with Eurocode 8 a linear trend $PFA(z/H) = PGA[1 + \alpha(z/H)]$, where α depends on the fundamental period of the building, can be considered with a conservative approach (CEN, 2010). More accurate and complex formulas are available, see e.g. Huang and Lu (2021) and references therein. In this case the objective is not to design, but to interpret. For this reason, it is possible to take note of the following facts about tall buildings (Pinkawa et al., 2014): (i) the real profile of $PFA(z/H)$ is generally less onerous than the linear one; (ii) for low z/H the effects due to higher modes are relevant; (iii) the $PFA(z/H)$ can show various peaks (Riva et al., 2003).

Since the behavior of a portion of rubble masonry of a historical building depends on several variables, an examination of the real causes of this behavior would be extremely complex and characterized by significant uncertainties. For this reason, no more than some intuitive aspects are discussed here. The Garisenda tower consists of walls perpendicular to each other and well connected to each other thanks to a crossed texture along the edges. Consequently, the structure resists earthquakes because the horizontal stresses break down into components belonging to the planes in which the walls are textured.

The façade variations recognized in the multi-temporal morphological maps and partly recovered over time are due to, with good approximation, the stress orthogonal to the texture plane of the masonry affected by the seismic-induced deformation. This type of dislocation is possible because masonry is a composite construction material, where the mortar acts as a means of transmitting stress from brick to brick and its conditions are crucial for the cohesion of the masonry and consequently for the masonry's ability to respond to external actions such as those caused by the earthquake. It is important to reiterate that, even in the event of total recovery of the deformations, the masonry has still partially suffered them. A reasonable hypothesis is that the mortar, over the centuries, take a certain shape around the bricks becoming, in part, a sort of housing for these bricks. It is therefore reasonable to hypothesize that, also depending on the force exerted by the mass above, a shaking can produce a dislocation of the brick, visible in the morphological map, but not significant due to friction and the "memory effect" due to the adapted reciprocal shapes over the centuries. However, the friction that binds the components of the masonry is insufficient to give rise to a permanent effect, also because the displaced bricks are not geometrically well adapted to the new condition. Therefore, in absence of further shaking, they should tend to slowly return to the initial condition; furthermore, a subsequent shaking could also promote the return to the initial and natural position. Figure 16 shows a simplified scheme of the hypothesized process. It is important to note that this is no more than a hypothesis proposed in order to provide a preliminary interpretation of the comparisons between multitemporal morphological maps. It is important to underline that the recovery of the initial condition after a shock (slow recovery in the absence of other shocks, or even fast recovery in the event of a further shock) is based on the fact that the mortar is not subjected to degradation on a scale of a few years or a few decades. Intense traffic near to a historical masonry building can induce fatigue phenomena, in particular mortar degradation (Zini et al., 2022). The mortar degradation can attenuate or even eliminate the effect of mutual adaptation of the masonry elements.

This would lead to both a friction reduction, resulting in larger deformations, and an attenuation of the forces bringing the system back to the initial condition, resulting in a permanent deformation. In addition, the new state would be prone to further deformations in case of other shocks. Small but continuous vibrations can therefore cause a significant reduction in the performance of the structure in dealing with large vibrations such as those of an earthquake.

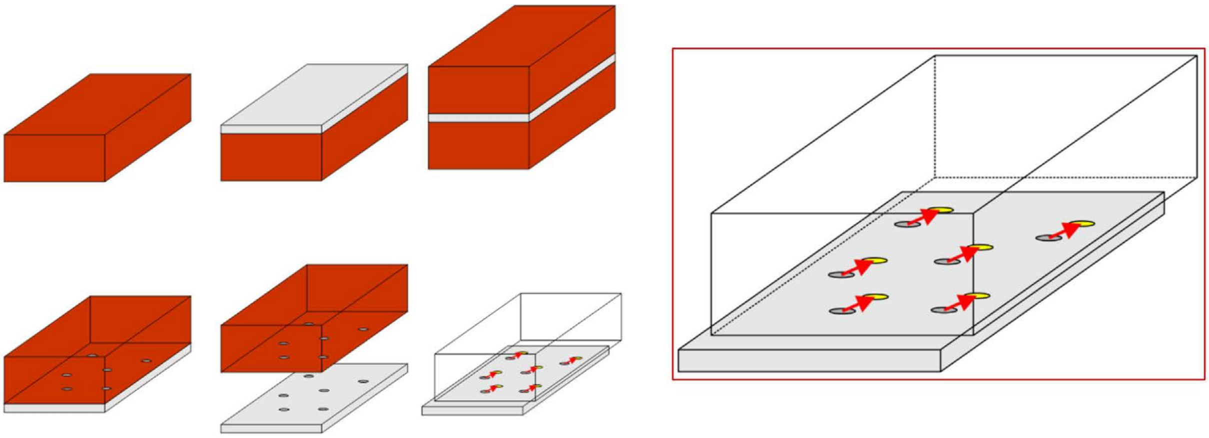

Figure 16. Simple scheme of the hypothesized phenomenon. The mortar, on which the brick rests, altered and deformed, maintains an imprint (schematic-elements). In the presence of an earthquake and acceleration, the brick can move due to insufficient friction. The plastic housing of the mortar will then host the brick in the spaces adapted to it over the centuries.

The direct comparison between the point clouds shown in Fig. 14, interpreted also on the basis of the multitemporal morphological maps, show results in agreement with the hypothesis of existence of a seismic-induced torsion. Since the factor which recently led to new concerns about the tower stability was a torsion locally detected by means of monitoring instruments, this result requires further detailed analyses.

Very recent results (Casolino et al., 2024) show the Garisenda tower reaction to an earthquake modeled considering a realistic soil-structure coupling. The static and dynamical analyses show displacement and deformation patterns compatible with the above described results from multitemporal morphological maps and direct point clouds comparisons, in terms of compression, traction and torsion effects distribution. Moreover, this FEM analysis provides high stress values, near to the structural materials limit.

From a methodological point of view, it is important to underline that the study of the conditions of a building in seismic areas cannot ignore the evaluation of the site effects. For example, the PGA values normally available nationally refer to hard ground. In different conditions, it is necessary to evaluate any seismic amplification linked to the depth of the bedrock, as well as any topographic effects, and therefore obtain the site-specific PGA. Moreover, the analysis of the soil-structure interaction is necessary because the displacement amplitude can be enhanced by factor of some ten percent if a resonance occur (Gosar, 2010; Castellaro et al., 2013).

The case of a well-known seismic series is considered here. However, the tower exists since ~900 years and has had to withstand countless shocks of various types, from earthquakes (albeit non-destructive in Bologna) to extreme weather events such as strong winds and lightning. The morphological map in conditions far from an earthquake can therefore be considered as a representation of the cumulative effect of all such events even if, in the absence of adequate data (e.g. a historical document which associate a given feature of a façade with a given event), it is not possible to characterize them individually. The morphological map can therefore be seen as a representation of the resilience of the tower.

Remote sensing techniques can therefore be very useful in assessing the conditions of a historical building. Obviously, they cannot be used alone except for an absolutely preliminary evaluation (for example, after a seismic shock). They do not replace diagnostic and monitoring techniques, but are added to complete the picture of the health state of the studied building.

5. Conclusions and future works

This study aims to describe what remote sensing can add to the knowledge framework of a historic building already obtained through other monitoring and surveying techniques, also providing useful methodological guidance in the field of architectural heritage preservation.

As regards the Garisenda tower, this study shows the deformation pattern due to the 2012 earthquake, which subsequently subsided. This result, apparently unexpected, does not indicate an absence of damage but suggests the existence of a reactive behavior to the shocks. A first purely qualitative attempt to understand the phenomenon was proposed by considering the brick-mortar interaction. This hypothesis will be the subject of a future study aimed at providing quantitative results. In general, the observed deformation pattern allows the recognition of areas mainly sensitive to the seismic shocks allowing the characterization of phenomena acting on the tower. Another future study is based on the idea to implement the achieved information in a FEM analysis.

The used low-cost approach, albeit with all the limitations of the case, is suitable for the study of numerous medieval masonry buildings lying in an old town.

Data and Sharing Resources. The laser scanning surveys were carried out by the authors. These data may be shared upon reasonable requests. All other data and information were taken from the sources reported in the References.

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In memory of Enzo Boschi and his great love for Bologna.

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