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The Garisenda Tower in Bologna: Effects of degradation of selenite basement on its static behaviour.

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ABSTRACT: The Garisenda tower in Bologna, a 48 m tall structure with a square base of 7.45 meters per side, is characterized by an overall out of plumb of 3.32 m in the South-East direction. Its construction dates back to the XI century and, due to its impressive leaning, in 1350–1353 the original height of 60 m was reduced to the 48 m of the present day (Cavani 1903; Giordano 2000). The tower can be seen as partitioned in a lower portion, with walls composed by two external leaves of selenite stones filled with rubble conglomerate, and an upper portion where the external leaves are made of masonry bricks. Recent investigations have proved that selenite blocks of the basement have been altered as a result of (a) exposition to high temperatures during important fires, that took place at the end of XIV and XVII centuries, and possibly because of the presence of forges (that were demolished at the end of the XIX centuries) and (b) high level of humidity in the inner lower part of the tower. This process has produced a gradual local disintegration of the selenite stones, leading in some case to a reduction of the original 50 to 60 cm thickness by an amount of about 20 cm. The contribution submitted to this conference is aimed at clarifying this important aspect, linked to the ageing and damage of structural stones and the related consequences in terms of stress distribution and concentrations that could induce fracture propagation and sudden collapse of the tower basement.

1 INTRODUCTION

Bologna, in the Middle Ages had well over 100 tall towers (Roversi 2011), although today fewer than 24 remain. Among the survivors are the so-called Two Towers: the 98 meter tall Asinelli and the Garisenda, which today stands 48 m tall, lesser than the original 60 m, and leans noticeably.

The preservation of historic towers requires a deep understanding of their structural response and the reasons that allowed them to survive over the centuries. It seems in fact evident that the remaining towers survived the initial period in which they were near foundation *bearing capacity collapse*, due to *lack of strength* of the soil. Delay or interruption of the building process enabled the foundation soil to improve its strength and the tower to be successfully finished. Due to uneven

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settlements, some towers appear today to be affected by an alarming angle of inclination. This highlights the danger of a *leaning instability*, which may increase if there is *lack of stiffness* of the soil, as it was the case of the leaning tower of Pisa.

In some cases the demolition of the upper part of a leaning tower allowed to avoid this problem and to preserve the building but not its historic integrity (examples may include the civic tower of Ravenna and the present case of the Garisenda Tower).

In addition, problems of structural nature may interact with the geotechnical aspects above highlighted. Indeed the inclination of the towers often due to differential settlements of the foundation may induce dangerous levels of stresses upon the structure of towers and deserves special attention, as proved by the collapse of the Campanile (Bell Tower) in Venice in 1902 and of the Civic Tower in Pavia in 1989 (Anzani et al. 2000; Binda et al. 1992; Macchi 1993;.

The noticeable and paradigmatic example of the eight-centuries-old Civic Tower in Pavia, that collapsed unexpectedly and spontaneously, attracted the attention of many researchers, in order to capture in other similar cases signs of deterioration, including cracks propagating through the bricks and the mortar, and to try to clarify the reasons of collapses which occur after so many years after the construction.

In medieval towers the support walls are usually categorized as single or multiple-leaf. Towers supported by multi-leaf walls typically have inner and outer leaves of brick or stone, within which a mixture (hereafter referred to as "conglomerate") of lime mortar, river gravel and shards of bricks was dumped. By considering that the multi-leaf walls technique dates back from the Roman times, it seems reasonable to assume that this method was well mastered by the 11th century masons, when the construction of the Pavia or the Garisenda towers began. However, an "induced vulnerability" may appear due to the decay over time of the mechanical properties of materials, masonry apparatus and mortar.

Therefore, the stress distribution caused by creep, shrinkage and long-term gradual drying of the wall (which can be also affected by carbonation of the lime mortar) could explain unexpected collapses, as the one occurred in Pavia (Ferretti & Bažant 2006).

In this context, a peculiar and rather unique case is represented by the Garisenda tower in Bologna, a 48 m tall structure with a square base of 7.45 meters per side, characterized by an overall out of plumb of 3.32 m in the South-East direction. Its construction dates back to the XI century and, due to its impressive leaning, in 1350–1353 the original height of 60 m was reduced to the 48 m of the present day (Cavani 1903; Giordano 2000).

The structure of the tower is made of a:

lower portion composed by two external leaves of a common type of gypsum rock stones (found in historic constructions in Bologna and called "selenite") filled with rubble conglomerate, and an upper portion with rubble conglomerate bounded by two masonry brick wall leaves.

It is to be noted that the in the lower portion an additional leave of selenite stones which encases the base of the tower (and hereafter referred to as "*bugnato*") was put in place at the end of the 19th century, mainly for aesthetical reasons.

Recent investigations have proved that selenite blocks of the basement have been altered as a result of (a) exposition to high temperatures during important fires, that took place at the end of XIV and XVII centuries, and possibly because of the presence of forges (that were demolished at the end of the XIX centuries) and (b) high level of humidity in the inner lower part of the tower.

This process has produced a gradual local disintegration of the stones, leading in some case to a reduction of the original 50 to 60 cm thickness to about 30 to 40 cm.

Further alteration phenomena have also been observed on the selenite blocks of the "*bugnato*" (exposed to open air), such as surface dissolution, granular disaggregation of macro-crystals, bacterial actions, all aspects not properly addressed in the scientific literature when dealing with selenite rocks, also due to the peculiarity of the selenite stone mainly used in the area around Bologna only.

All these phenomena claimed for a program of structural monitoring, careful inspection and preservation measures to be implemented, such as: (a) replacement of weathered or fissured key stones, (b) mortar injections to both enable the filling of possible cavities and cracks in the rubble conglomerate core, (c) confinement of the lower portion of the structure. It is to be noted that the mortar injections are also useful to enhance the bonding between the "*bugnato*" (external selenite cladding) to inner structure (selenite leaves and rubble conglomerate), and improve the stress redistribution altered by creep.

2 BRIEF NOTES ON PREVIOUS RESTORATION WORKS

As it is the case for most of historic towers, is not an easy task to summarize in few notes the complex history of the Garisenda tower; therefore in the following only those aspects strictly relevant to its preservation are recalled and the reader should refer for more insight to the book of Giordano (2000).

The Garisenda was built in the XII century, at the same time as the Asinelli tower, both in front of Porta Ravegnana and just outside of the so-called "selenite" walls, a place strategically important for the defense of Bologna.

Since early times, the Garisenda tower should have appeared perilously leaning, if in 1293 a decision was already taken of its demolition and the tower survived to this decision just for economic constraints. It was in 1350-1353, at the time when Giovanni da Oleggio was sent as Governor of Bologna by Giovanni Visconti of Milan, that the original height of 60 m was reduced to the 48 m of the present day. Furthermore, it must be mentioned, for reasons that will be presented in the next point, that the image of the tower as it stands today dates back to 1890, because before that time craftsmen and commercial activities attached huts all around its perimeter. A small church (of the B.V. delle Grazie) was also present until 1871, when it was dismantled.

A direct inspection showed at that time severe alterations of the leaves of selenite, with some blocks reduced on its original thickness. Therefore, a first restoration work took place, with a complete substitution of the selenite blocks of the exterior face. Incidentally, these blocks were caved in the style of "*bugnato*", i.e. with rounded edges and not with sharped edges as in the local tradition.

At 9.52 a.m. on the 14th July 1902 the bell tower of San Marco in Venice collapsed, leaving a pile of debris more than 20 m high, and this tragic event claimed for an analysis of the stability of the Garisenda.

In 1903, Francesco Cavani, of the "*Alma Mater Studiorum*", University of Bologna, published his report referring the inclination of the mean axis with respect to the gravity vector equal to 7% with a corresponding overhanging of 3.22 m (Cavani 1903, 1917, 1919).

By considering that the tower has a base area of 55,5 m^2 and that the foundation area is equal to 76,56 m^2, and by considering two extreme assumptions: a density of the masonry equal to 2000 kg/m^3 (which gives an upper bound weight of 41200 kN) and a density of 1600 kg/m^3 (which gives a lower bound weight of 32960 kN), Cavani (1903) reached the conclusion that the maximum compression stress, due to the upper bound value of the dead weight, was equal to 1.96 MPa on the masonry, and 1.1 MPa was the contact stress at the foundation level.

If wind effects are taken into account, the values grow respectively to 2.43 MPa and 1.26 MPa. These rather high stress levels were later on recognized as being the cause of a diffuse state of damage, with cracks not only along the mortar but also into the bricks.

In recent years the Municipality of Bologna appointed in 1986 a first Commission, composed by R. Alessi, G. Folloni and F. Bergonzoni. Unfortunately, Alessi and Folloni passed away and in 1996 the composition of the commission was updated with the appointment of P. Pozzati and M. Unguendoli. In 1998, a third commission was appointed, composed by C. Ceccoli, P. Pozzati, P. Diotallevi, L. Sanpaolesi and G. Dallavalle (Ceccoli 1998, 1999, 2001; Pozzati & Unguendoli, 1997).

As a results of the investigations performed in those years, some remedial measures were made in 1998: a masonry consolidation trough substitution of the weathered bricks and injections of mortar; installation of steel frame to improve the connection of the two leaves of bricks.

Thereafter, in 2008, external steel ties were installed to provide a confinement of the masonry, but no provisions concerning the selenite basement were made at that time.

Finally, with reference to the photogrammetric survey performed in 1997, it is of interest to outline that the Northern and the Western faces do not show evidence that the masons corrected the verticality of the tower, as it would have been the case if the tower began to tilt during the construction. This was the cases of the leaning tower of Pisa and the Ghirlandina tower in Modena. Therefore, it could be argued that uneven settlements occurred when the tower reached its original height of 60 m, as it is discussed in section 4.

3 THE SELENITE: ALTERATION BY EXPOSURE AND THERMAL DEHYDRATION

The selenite is a common type of gypsum rock that belong to the *Messinian Gessoso-Solfifera Formation*, extensively quarried since Roman time in the Bologna hills and used in various historic constructions in Bologna (Del Monte 2005), because of its sparkling attractive appearance and because the rock is light, soft, easy to cut, shape and carve (Lugli 2019).

The selenite rock used in the tower consists of large twinned crystals of gypsum, with a “swallow tail” or “arrow-head” shape, all pointing in the same direction. Two main varieties were used, the massive facies, with crystals up to 30 cm across, and the banded facies with smaller crystals, 1 to 5 cm across, organized in parallel layers (Lugli et al. 2010).

There are two main degradation features as far as the blocks used in the construction of the tower are concerned, one related to the natural alteration at outside exposure conditions and the other due to the action of heat because of fires occurred inside the tower and the presence in the past of forges.

The selenite cladding the external part of the tower (the so called “*bugnato*”) is subjected to dissolution by rainwater forming karren, grooves separated by sharp ridges, as large as 14 mm and as deep as 7 mm. In some areas of concentrated rainwater flow, the selenite rock are cut by vertical grooves up to 70 mm across and 100 mm deep (Del Monte et al. 1999). The most common alteration features on the “bugnato” are gypsum efflorescence crusts partially detached, granular disaggregation of the crystals, black crusts and biological attack by lichens and endolithic cyanobacteria. These alteration features are typical of selenite rocks exposed at Mediterranean and other climate conditions (Artieda 2013; Rhind et al. 2014).

The selenite leaves in the inner part of the tower (which contain the rubble conglomerate) display the typical signature of thermal alteration. The gray and sparkling appearance of the original rocks was turned into white by dehydration of the gypsum crystals, which may start at relatively low temperatures, as low as about 100° C. The whitening of the gypsum crystals is one of the distinctive geological feature for the recognition of ancient fires in historical sites (Lugli 2002), such as the Palace of Knossos in the Minoan Crete (from the middle Bronze Age), Eraclea Minoa in Sicily (6th-1st BCE) and the medieval Abbey church in Nonantola, Modena (Lugli 1995, 2019). The change in colour from gray to white is due the formation of a mosaic of bassanite (emihydrate, $CaSO4 \cdot {}^{1}/_{2}H2O$) and soluble anhydrite ($CaSO4 \cdot \varepsilon H2O$) microcrystals. These sulfate crystals are unstable and rapidly rehydrate back to gypsum ($CaSO4 \cdot 2H2O$) capturing moisture and capillary water to form an alabastrine rock. These mineral transitions are accompanied by significant volume changes. Although the initial dehydration induces the presence of secondary porosity by volume decrease, the voids are rapidly closed by the growth and volume expansion of the late gypsum crystals. The resulting white rock shows pseudomorphs of the original selenite crystals, but consist of new microcrystalline interlocking gypsum crystals. Because the rehydration phenomena occur soon after the fire, the mechanical properties of the resulting alabastrine rock was actually improved by the textural rock changes connected to the dehydration-rehydration transitions compared to the original rock. A core drilled on the northern wall of the tower showed that the thermal alteration of the selenite rock reached the depth of 15 cm from the slab surface.

At the south-eastern corner of the tower the thermal alteration process was much stronger. Here the rock has been deeply pulverized at the scale of the single micro-crystal components, with loss of material and a regression of the original slab surface of 20 cm (Figure 1). As revealed by SEM-EDS analyses, the disaggregated material consists of anhydrite that was not rehydrated back to gypsum (Figure 2). These characteristics demonstrate that the south-eastern corner of the tower was heated at temperatures above 500°C, which is the transition point for the formation of insoluble anhydrite. This calcium sulfate form is much slower in rehydrating back to gypsum compared to soluble anhydrite formed at the expenses of gypsum at lower temperatures. The hydration process in this case may even occur at geological time scale. The formation of insoluble anhydrite also induces the most extreme net volume decrease (up to 38.6 %), which contributed to disrupt the original texture of the rock.

The described dehydration phenomena are possibly the consequence of one of the blazes known to have affected the tower in the XIV and XVII centuries. The stronger alteration and the higher temperature reached in the south-eastern side of the tower may be related to the presence of flammable material during the blaze or by the activity of a forge installed in the corner of the room. The presence of active forges has been documented around the tower until the XIX century.

Figure 1. Different degrees of thermal alteration of the selenite rock in the southwestern corner of the Garisenda tower entrance room. Note the recession of the slab surface affected by higher temperature.

4 SOIL PROFILE, SUBSIDENCE AND MONITORING

The need to provide a reliable soil-foundation model suggested geotechnical campaigns at different times: 1973–75, 1995 and 2000. More recently, between May and August 2016, a new site investigation was carried out with the aim of complementing the previous ones and enabling a geotechnical model to be defined in some detail. Furthermore, four piezometers were installed at the depth of 10, 20, 30 and 100 m from the ground level, to monitor of water table, providing evidence of a limited downward seepage.

The soil profile consists of an alternation of silty-clays and clayey-silts, down to the investigated depth of 100 m. The soil samples extracted during borings and the geotechnical interpretation of the CPTU (piezocone penetration tests) profiles suggest that the deposits can be divided in:

anthropic fill, between the ground level and 4.5 ÷ 5 m of depth (anthropogenic deposits) and a variable succession of lenses of silty clays and clayey silts (floodplain deposits).

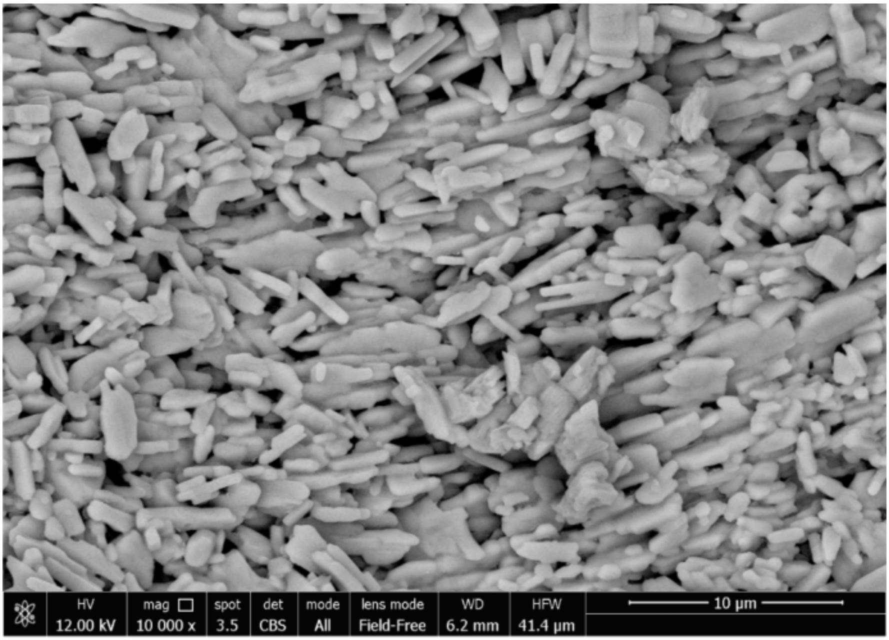

Figure 2. SEM image of the disaggregated material collected from the high temperature alteration zone of Figure 1. Note the high porosity and disruption of the former selenite macrocrystal now consisting of insoluble anhydrite microcrystals.

Despite the lithological uniformity of the deposits (e.g. grain size distributions and Atterberg limits in Figure 3), their mechanical properties appear heterogeneous both laterally and vertically. As an example, Figure 3 shows the scatter of the undrained strength (su) profiles, deduced from CPTU tests carried out in proximity of the north-east corner of the Garisenda tower.

The geological setting with the identification of the sedimentary facies of the area can provide a significant interpretative key of such alluvial deposits, showing typical lenticular geometries with poor lateral extent. This feature can explain the lack of uniformity found in a small area like the size of the Garisenda base. In addition, the floodplain successions are locally interrupted by paleosols, identified by a typical dark colour (photo of a portion of SPZ100 borehole coring in the left side of Figure 3) and followed by lighter horizons with carbonate nodules. They are characterized by higher shear strength, probably due to their over-consolidation state, while the non-paedogenized horizons, not involved in the carbonatation or desiccation processes, show a poorer mechanical response.

The geological history, with the described post-depositional phenomena, had profound implications on the soil response to loading and, in particular, the lack of uniformity in the subsoil conditions could be one of the main initial reasons of the severe inclination of Garisenda Tower towards the east side (Bertolini et al. 2022).

In addition to the above referred investigation a great effort was also devoted to monitor the effects of the subsidence.

As it was the case of many other cities, after the Second World War the city of Bologna experienced a significant demographic growth and an industrial development, so that an intensive groundwater extraction occurred to satisfy the increased demand of water. This water exploitation induced a marked increase of subsidence in urban areas and induced local institutions to undertake investigations and to quantify these movements (Darini et al. 2018).

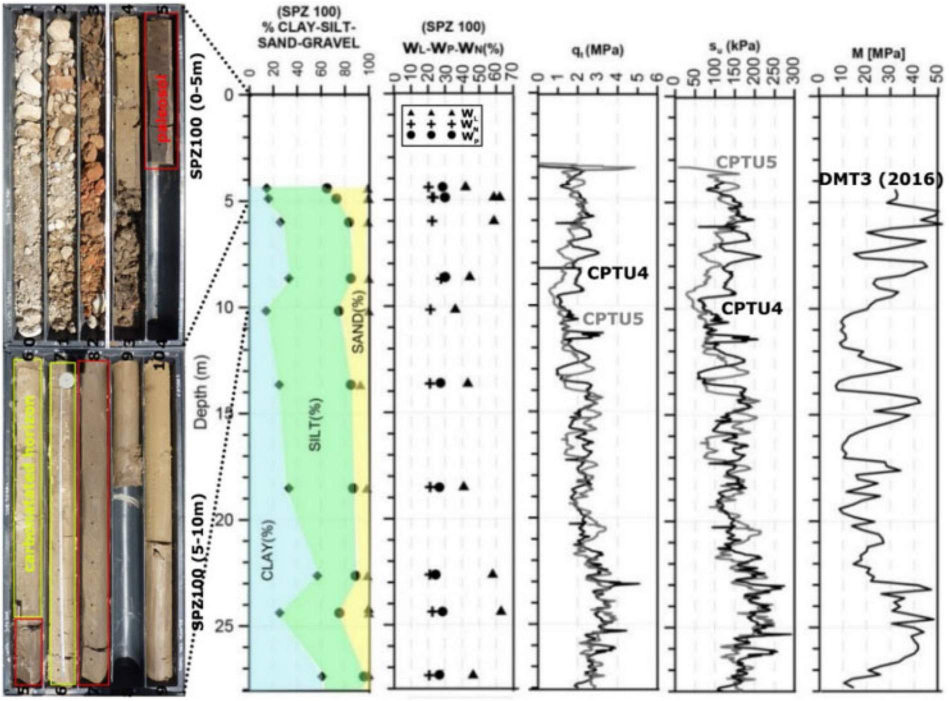

Figure 3. From the left: photo of soil samples extracted from the continuous coring borehole SPZ100 (2016 campaign); soil profile of the investigated site, showing the grain size distribution, Atterberg limits, cone tip resistance (q_t) and shear strength (s_u) as deduced from the CPTU 4 and CPTU 5 (2016) profiles and the constrained modulus as deduced from the dilatometer test DMT3 (modified from Marchi et al. 2019).

A first levelling network of 200 benchmarks was installed along the “via Emilia” between 1950 and 1980 by the Management district of the Reno River Basin. Thereafter, the Municipality of Bologna promoted an extended network of 500 benchmarks, that included the previous ones, with measurements campaigns in 1983, 1987, 1992, 1999 (Darini et al. 2018).

A more detailed and effective campaign of levelling started in November 1972 for the Asinelli tower and in April 1990 for the Garisenda tower, in the context of a research programme promoted by the Municipality with the “*Alma Mater Studiorum*”, University of Bologna (Bitelli 2018).

It is apparent from measured data that, in the time interval 1990–2019, the benchmarks 12 (on the North-East corner of the basement) and 13 (South-East) suffered settlements of about 4.92 mm and 5.64 mm, with an average annual rate of 0.18 mm/year.

The benchmarks 10 (South-West) and 11 (North-West) settled 1.63 mm and 1.24 mm respectively, with an average rate of 0.05 mm/year.

At first glance, these results could not appear as alarming in itself, but it must be recalled that they contribute to increase the already alarming out of plumb of 3.40 m and that the rate of differential settlements continue to increase in time, adding further negative effects on the state of stress of the selenite blocks.

Due to these alarming phenomena, an experimental programme was set up on May 31st 2019 to also monitor the evolution of the structural health of the tower. Due to lack of space and the short period of time elapsed since that time, there is not possibility to consider in this paper the obtained data, but is worth to mention at least the installed system.

Six optic-fiber sensors have been applied to the inner face of the load-bearing walls in the vertical direction: 4 of them, 2.0 m length, have been fixed at the internal corners, and 2 other ones, of 1.0 m length, on the East and South internal faces.

In addition, 8 acoustic emission sensors have also been placed at the basement level: 6 of them fixed on the inner surface of selenite, 1 embedded inside the masonry fill, and 1 outside of the basement, just below the selenite ashlar.

More recently, on February 25th 2021, a pendulum was installed at the elevation of 39.30 m, and on June 3rd 2021 4 wire strain gauges at the outside corners of the basement.

Note that all the above mentioned sensors were also intended to complement the system installed in March 2011 (see Andreon et al. 2011), comprehensive of extensometers, short and long base deformeters, laser displacement sensors, inclinometers, gonioanemometer and temperature sensors to monitor the upper portion of the tower.

5 INSTABILITY OF SELENITE BLOCKS AND REMEDIAL MEASURES

As mentioned in the brief historic notes of section 2, old documents give a ‘800 picture of several huts around the base of tower with artisans works. Following a refurbishment of the whole area of the city where the towers are located, the huts were demolished and direct inspection showed that the outer selenite leaves of the base of the tower were severely damaged (most likely due to an improper use in the huts). The damaged outer selenite leaves were then repaired with various materials and covered with the vestment made with ashlar of selenite stones in form of rusticated stonework, called “*bugnato*”.

The peculiar shape of the “*bugnato*” results in a reduced contact surface between the stones in comparison to the volume of blocks and it is worth to mention that the basements of coeval towers in the town are made by solid parallelepipedon stones of selenite with very small thickness mortar joints being load-bearing system and a complete surface of contact.

During recent controls with laser-scanner the “*bugnato*” was evaluated not to be any more in planar condition, with pick swelling of 25 mm observed in the last ten years. An alarming hypothesis was that the cladding had started to contribute to the tower statics, and it was prone to local instability. A geometrical model of this swelling phenomenon showed that the observed swelling is coherent with a shortening of the height of the “*bugnato*” of about 1.10 mm. This phenomenon could be a consequence of the creep in the inner structure (the material filling multi-leaf stonework) and/or deterioration of the inner selenite leaves.

In addition to the criticalities of the “bugnato” represented above, the investigations developed in 2018–2020, as well as the results of the monitoring system, confirmed the existence of problems related to the alteration of the inner selenite leaves of the tower basement.

It is worth to point out that only the surface of the interior selenite leaf can be inspected, while all other faces are not directedly visible being either in contact with the inner conglomerate or encased by the “bugnato”. As shown in Figure 1 this surface is highly altered and it can be expected that also the other surfaces (inner toward the conglomerate and external toward the “bugnato”) can be subjected to the same severe alterations observed inside with and significant reduction in the original thickness of the blocks.

In order to assess the effects of the wall deterioration (both in the selenite leaves and in the inner conglomerate) a specific finite element model was developed (see Figure 4), which makes use of solid elements. The model comprised the selenite leaves and the inner conglomerate, as well as the upper portion of the tower made of conglomerate and masonry; “the bugnato” was not considered in model, being a superficial covering not completely connected to the inner structure.

A number of numerical simulations were then developed. By assuming a modulus of elasticity for both the selenite leaves and the inner conglomerate equal to $E = 40.000$ daN/cm^2, the maximum stress level in the selenite was found to be about 40 daN/cm^2, and in the conglomerate of about 20 daN/cm^2.

Thereafter, to simulate the deterioration of the selenite in the area around the corner where the most severe deterioration was observed (orange portions represented in Figure 4). the modulus of elasticity was progressively reduced at 75%, 50%, 25%, 10% and 2% of its original value, down to a minimum value of $E = 800\,\text{daN/cm}^2$.

All simulations were developed considering only the dead load (wind and seismic actions were not considered in these preliminary analysis). Furthermore, to take into account the reduced strength in traction of the selenite leaves and of the conglomerate, the models were progressively adapted so that any finite element block which deployed a stress in tension higher than $1\,\text{daN/cm}^2$ was decoupled from the others nearby blocks.

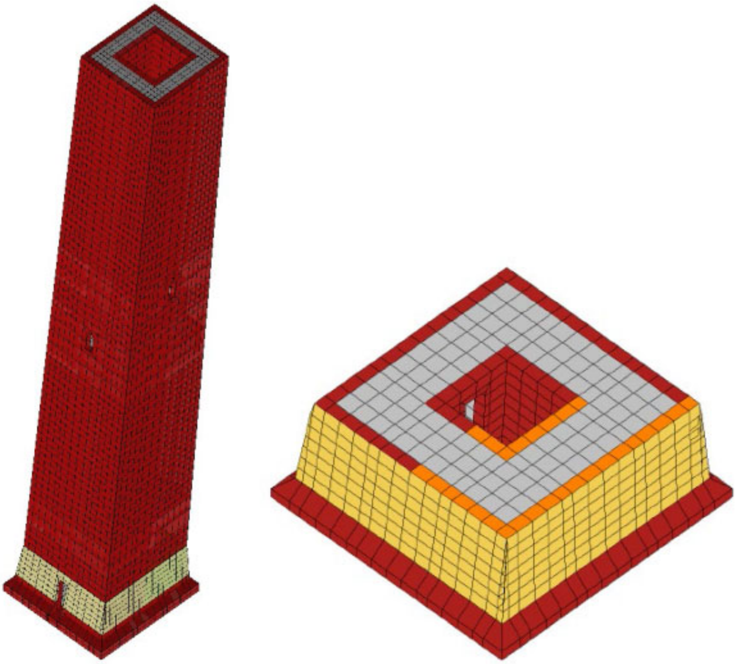

Figure 4. Schematic representation of the finite Element Model of the tower: unaltered selenite leaves (dark red), inner conglomerate (grey), altered selenite leaves (orange).

The obtained results have shown that the "deterioration" of just a small portion of the selenite leaves leads to a significant increase in the stress condition of the inner conglomerate with a consistent reduction in the level of safety of the structure. More specifically:

(a) the maximum level of stress in the selenite blocks remains almost unaltered, even though an "arching effect" can be detected, with transfer of load into the selenite blocks surrounding the altered ones;

(b) the maximum level of compressive stress in the inner conglomerate reaches average level of stresses of about $30\,\text{daN/cm}^2$ along the entire Est wall (Figure 5), significantly greater than the value of the "undamaged condition" and alarmingly close to the crushing stress of the conglomerate (found through experimental tests on samples extracted from the tower inner conglomerate and ranging from 25 to $35\,\text{daN/cm}^2$).

These studies proved that it was necessary to take immediate action in order to reduce the risks of collapse of the basement of the tower, and the following interventions were implemented (see Figures 6, 7 and 8):

(a) passive confinement of the tower base obtained through FRCM belting along horizontal joints of stonework, with the voids between the "bugnato" and the selenite leaves filled using ad hoc elements that can be easily removed in the future;

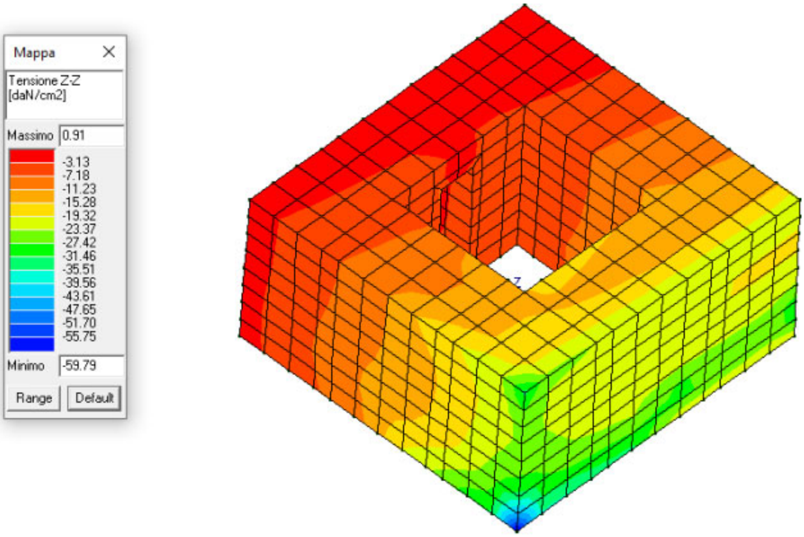

Figure 5. Analysis of the base of the tower in its "deteriorated" condition ($E = 800\ \mathrm{daN/cm^2}$, for the altered selenite leaves represented in orange in Figure 4).

Figure 6. FRCM belting (A).

Figure 7. Post tensioned steel bars (B).

(b) active confinement of the tower corner by insertion of post tensioned stainless steel bars 24 mm in diameter (stainless steel AISI 304) and corner stainless-steel plates;

(c) active confinement of the "bugnato" through a funicular belting of the tower base. This was obtained by a monitored post tensioning of steel-cables with the insertion of wood blocks (of different thickness) between the "bugnato" and the cables.

Figure 6. Confinement of the bugnato (C).

Even though these interventions have produced positive effects on the structural safety of the tower, it is of uppermost importance to continue to strengthen the tower base through: (a) injection in the inner conglomerate, (b) substitution of the deteriorated selenite blocks, and (c) to improve the connection between the leaves and the infill.

The implementation of these further interventions without compromising the structural safety of the tower is difficult to achieve and may require in the future the provision of an "ad hoc" structure to safeguard the tower against adverse conditions that could happen during the work.

6 CONCLUSIONS

Surveys performed in recent years with laser-scanner proved that the "bugnato" was not to be any more in planar condition, with pick swelling of 25 mm observed in the last ten years. An alarming hypothesis was that the cladding had started to contribute to the tower statics, and it was prone to local instability. Therefore the Municipality of Bologna promoted additional and more specific investigations on the tower basement.

These investigations have shown that selenite blocks have been subjected to a process of gradual disintegration, leading in some case to a reduction of the original 50 to 60 cm thickness by an amount of about 20 cm.

Numerical simulations have also shown that the detected deterioration of the selenite stones lead to substantial increase in the stress levels of the rubble conglomerate that makes up the structural bearing walls, reaching values of stress near to its ultimate strength.

These dangerously high level of stress occur on the leaning side (East face) of the tower which, due to the high level of inclination (about 7 %) is under substantial static effort.

It was thus deemed necessary to provide the basement of tower with conservation measures, such as passive confinement obtained through FRCM belting along horizontal joints of stonework, active confinement of corners by insertion of post tensioned stainless steel bars 24 mm in diameter (stainless steel AISI 304) and stainless-steel plates, active confinement of the "bugnato" through a funicular belting of the tower base.

These remedial measures were successfully implemented and removed the risk of local instability, but additional conservation measures are also taken into consideration to improve the strength of the infill conglomerate, to substitute the deteriorated selenite stones and to improve the connection between the leaves and the infill.

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REFERENCES

Andreon F., Dallavalle G., Gasparini G., Trombetti T.(2011). Le Torri Asinelli e Garisenda : le indagini e gli interventi di consolidamento. Inarcos n 719 Maggio.

Anzani A., Binda L., Mirabella Roberti G. (2000). The effect of heavy persistent actions into the behaviour of ancient masonry, Mat. Struct., RILEM 33, 228, 251–261.

Artieda O., 2013. Morphology and micro-fabrics of weathering features on gyprock exposures in a semiarid environment (Ebro Tertiary Basin, NE Spain). Geomorphology 196 (2013) 198–210.

Bertolini I., Marchi M., Gottardi G., Amorosi A., Bruno L. (2022). Investigating a geotechnical 'cold case': the Two Towers of Bologna (Italy). In Proceedings of the III International Symposium On Geotechnical Engineering For The Preservation Of Monuments And Historic Sites, Naples, Italy, 22–24 June 2022. Submitted for publication.

Binda L., Gatti G., Mangano G., Poggi C., Sacchi Landriani G. (1992). The collapse of the Civic Tower of Pavia: a survey of the materials and structure, Masonry International 6 (1) (1992) 11–20.

Bitelli G. (2018). Convenzione tra il comune di Bologna e Università di Bologna (Dipartimento DICAM) sull'organizzazione dei dati storici relativi ai rilievi di livellazione geometrica effettuati sulle due torri.

Ceccoli C. (1998). (coordinator of the Commission). Relazione programmatica-descrizione dei metodi di indagine e del sistema di monitoraggio. Novembre.

Ceccoli C. (1999). (coordinator of the commission) Il consolidamento della Torre Garisenda. Relazione illustrativa. Ottobre.

Ceccoli C. (2001) (coordinator of the commission). Relazione tecnica sul progetto complessivo di consolidamento e sugli interventi di prima fase. Marzo.

Capra A., Bertacchini E., Castagnetti C.,Dubbini M.,Rivola R.,Toschi I. (2011). Rilievi laserscanner per l'analisi geometrica delle Torri degli Asinelli e della Garisenda. Inarcos n 719 Maggio.

Cavani F. (1903). Pendenza, stabilità e movimento delle torri. La Garisenda di Bologna e la Ghirlandina di Modena. Atti del Collegio degli Ingegneri e degli Architetti in Bologna.

Cavani F. (1917). Sulla pendenza delle principali torri di Bologna, Modena e Pisa. Atti del Collegio degli Ingegneri e degli Architetti di Bologna.

Cavani F. (1919). Su alcune questioni relative alla pendenza delle torri Atti del Collegio degli Ingegneri e degli Architetti di Bologna.

Darini G., Modoni G., Saroli M., Croce P. (2008). Land subsidence induced by groundwater extraction: the case of Bologna. Int. Congress on Environmental Modelling and Software Integrating Sciences and Information Technology for Environmental Assessment and Decision Making, 1386–1393.

Del Monte M., 2005. L'epoca d'oro della selenite a Bologna. Il Geologo dell'Emilia-Romagna, 20, p. 5–24.

Del Monte M., Forti P. and Tolomelli M., 1999. Degradazione meteorica dei gessi: nuovi dati dalle torri medioevali di Bologna (Italia)". Atti e Memorie della Commissione Grotte "E. Boegan", Trieste 2000, 37, 77–91.

Ferretti, D., and Z. P. Bažant (2006). Stability of ancient masonry towers: Stress redistribution due to drying, carbonation, and creep. Cement and Concrete Research 36:1389–1398.

Giordano F. (2000). La torre Garisenda. Costa Editore, 208 pp.

Lugli S. 1995. Blocchi di roccia gessosa nella chiesa abbaziale di S. Silvestro a Nonantola (Modena): caratteristiche geologico-petrografiche e ipotesi di provenienza. Atti della Società dei Naturalisti e Matematici di Modena, 124 (1993), 137–160.

Lugli S., 2002. Recognition of ancient fires in archaeological sites containing gypsum rocks. Proceedings of the VI International Conference of the Association for the Study of Marble and Other Stones in Antiquity (ASMOSIA), Venice, 15-18 June 2000, 545–548.

Lugli S., 2019, Il gesso in natura e nell'arte. GeoArcheoGypsum2019, Geologia e archeologia del gesso: dal lapis specularis alla scagliola, (a cura di) D. Gulli S. Lugli, R. Ruggieri, R. Ferlisi. Palermo, Regione siciliana, 17–31.

Lugli S., Manzi V., Roveri M. & Schreiber B.C., 2010. The Primary Lower Gypsum in the Mediterranean: A new facies interpretation for the first stage of the Messinian salinity crisis. Palaeogeography, Palaeoclimatology, Palaeoecology, 297, 83–99.

Macchi G. (1993). Monitoring medieval structures in Pavia. Structural Engineering International, 1, 9–9.

Marchi M., Bertolini I., Gottardi G., Amorosi A., Bruno L. (2019). From geological and historical data to the geotechnical model of the Two Towers in Bologna (Italy). In Proceedings of the XVII ECSMGE, Reykjavik, 1–6 September.

Pozzati P.,Unguendoli M. (1997). Situazione statico strutturale delle due torri di Bologna. Convenzione fra Comune di Bologna ed Università degli studi di Bologna . Relazione conclusiva dei responsabili scientifici.

Rhind T., Ronholm J., Berg B., Mann P., Applin D., Stromberg J., Sharma R., Whyte L.G. and Cloutis E.A., 2014. Gypsum-hosted endolithic communities of the Lake St. Martin impact structure, Manitoba, Canada: spectroscopic detectability and implications for Mars. International Journal of Astrobiology 13 (4): 366–377.

Roversi G. (2011). Le torri di Bologna-quando,come e perché. Grafis.