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ON-SITE INVESTIGATION AND MONITORING FOR THE ASSESSMENT OF A HISTORIC BRICK MASONRY TOWER

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ABSTRACT

An experimental investigation aimed to the evaluation of the state of damage of historic brick masonry structure, referred to as The Bellevue Tower, is presented. The tower was built at the beginning of the 16th century as part of the Ferrero Palace-Masserano-La Marmora, on the highest part of Biella, in the Italian region of Piedmont, and became the city landmark. The tower has a square plan for the first three lower floors from the ground level and an octagonal plan for the remaining four floors, ending with a stone-decorated cantilevered crowning.

The tower was a part of a public Palace from which it was separated, in terms of property, at the beginning of the 20th century. This separation altered the use and conservation path of the tower, that nowadays suffers from a severe state of damage and requires an immediate intervention and rehabilitation of the masonry structures and overhanging elements for safety reasons.

A methodology is put forward for combining laboratory and non-destructive testing methods with a monitoring system in order to evaluate the potential for conservation of this historic tower and its sustainability, in view of an effective intervention design.

KEYWORDS: brick masonry, flat jack test, monitoring, NDT, tower

INTRODUCTION

Masonry towers are largely diffused in Italy and Europe and constitute an important part of our heritage which requires suitable protection. The problem of their safety, which became particularly evident after the failure of monumental buildings including the recent collapses of the Meldert Bell-tower and the Maagdentoren Tower at Zichem, Belgium in 2006 has to be tackled by the owners and frequently local public institutions who cannot always afford very costly diagnostic techniques. On the other hand, before large investments are made for monitoring and/or repair interventions, preliminary screenings look very useful to qualify the buildings depending on the estimated degree of damage. For this purpose, some help might come if guidelines were provided by local authorities, so that a classification of the state of the towers based on direct observation could be routinely performed [1, 2].

The influence of time on the mechanical behaviour of masonry structures became evident after the collapse of the medieval Tower of Pavia, when the identification of a time-dependent behaviour, probably coupled in a synergetic way to cyclic loads, was identified as a possible explanation of the sudden collapse. Ancient buildings often show diffused crack patterns, which may be due to different causes in relation to original function, construction technique and loading history. In many cases it is the dead load, usually very high in massive monumental buildings, which plays a major role into the formation and propagation of the crack pattern [3, 4].

In the case of the Masserano Tower, the historic symbol of Biella city, in Piedmont region, Italy, large and long cracks are visible both on external and internal prospects. Single flat jack tests were carried out on the four sides of the tower, at the base of the octagonal part, in order to investigate the non-uniform vertical stress distribution and to compare it with the out-of-plumb survey of the same part. A detailed crack pattern survey was carried out with the aim of detecting whether the possible leaning and other movements, also related to the slope of the ground where the building rises, are still in progress or assessed. A simple but efficient system of static monitoring was applied on the major cracks [5].

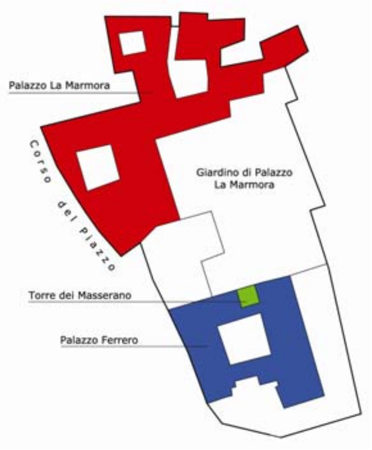


Figure 1: Plan of La Marmora Palace and Ferrero Palace.

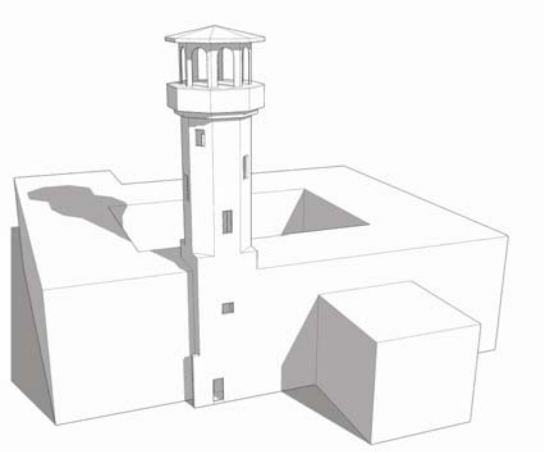


Figure 2: North front of Ferrero Palace and the Masserano Tower.

HISTORICAL INVESTIGATION

The tower called “dei Masserano” is part of a building complex formed by La Marmora Palace and Ferrero Palace, medieval dwellings rising in the “Piazzo”, the upper ancient village which still constitutes the historic city centre of Biella. The official date of the birth of Piazzo on the hill is 1160 but only in 1450 the presence of a building in the area of Ferrero Palace is documented. The present aspect of the complex, organized around five courts (Figures 1 and 2), did not result from a unitary project but from a series of annexations and transformations deriving from purchases carried out between the 15th and 18th centuries.

The construction of the tower, despite a precise date is not known, seems to go back to 15th and 16th centuries. The first view of the tower, very similar to its present aspect, is shown on a fresco of 1612 (Figures 3 and 4). Various events characterized the lives of the La Marmora family, who in 17th century splitted and built a different palace, and of Ferrero family, Princes of Masserano, who kept the tower until 1833, when the Ferrero eventually rejoined with the La Marmora family. Later, the Ferrero Palace and the tower were subjected to various different uses from dyeing place in 1854, to Spa in 1865. Being the tower dedicated to host a staircase, it was opened by inner doors, to connect it with the different levels of the palace. In 1912 the Ferrero Palace was sold by the La Marmora family to the Town Council that transformed it in a military convalescent home, but the tower remained until nowadays of the La Marmora family, who closed subsequently all the doors in connection with the rest of the Palace.

According to the Italian seismic code [6, 7], Biella is classified in 4th category (the lowest intensity one) and it is not at a particular risk, nor notice of historic earthquake has been registered. No effects of the earthquake of December 23rd 2009 in the province of Reggio Emilia were observed on the readings of the geometry static monitoring in progress on the tower.

Figure 3: View of Biella "Piazzo" from the town, fresco at La Marmora Palace, 1612.

Figure 4: View of the Tower Masserano from the courtyard.

DAMAGE DESCRIPTION

The Masserano Tower, built in solid brickwork masonry, has a square plan for the first three lower floors, inserted in the Ferrero Palace, and an octagonal plan for the remaining four floors, ending with a crowning supported by stone cantilevers and is characterized by a central pillar having a squared base 1.56 m wide and an octagonal upper part of about 1.21 m radius (Figure 9).

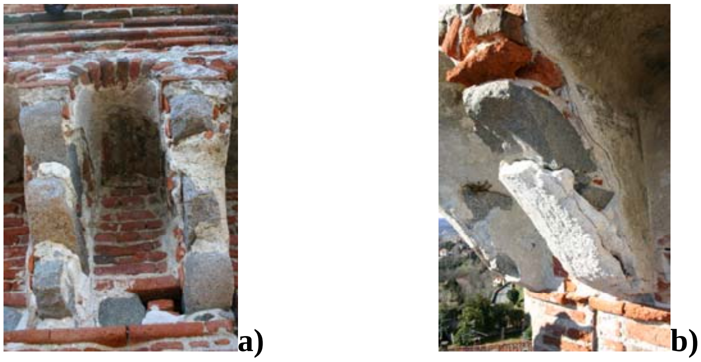


Figure 5: Crowning of the Tower La Marmora Masserano: details of the damage phenomena.

Figure 6: Bolt of a tie rod on the crowning.

In addition to a superficial decay at the crowning (Figures 5 and 6), that mostly worried the owners initially, the tower shows a diffuse damage that induced to carry out a detailed crack pattern survey in order to understand the movements and prevent possible collapse mechanisms. The tower is affected by a major crack pattern, both on the lower square portion and on the upper octagonal one, including the central pillar. Cracks are particularly visible on the South and North-East octagonal fronts and on the corresponding lower portion of the square fronts. On the North-East front an out-of-plane relative displacement can be observed which exhibits a long vertical crack (Figure 7), also continuing on the squared lower portion of the tower.

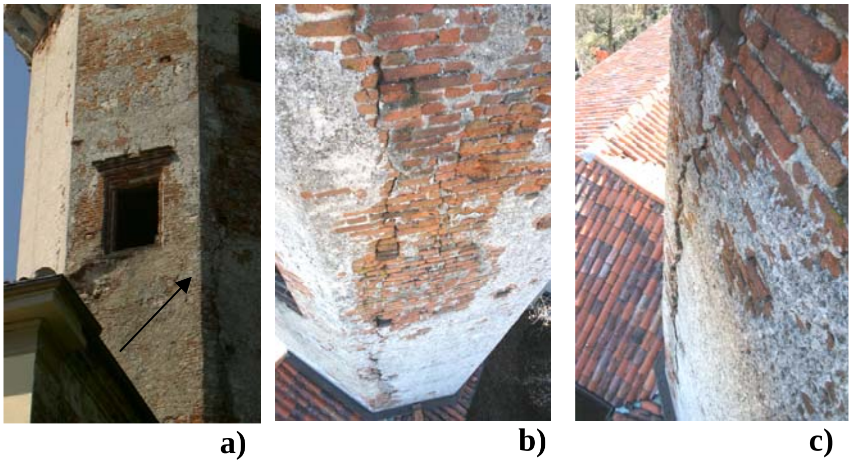


Figure 7: Cracks on the North-East wall of the tower.

Figure 8: Crack on the North wall of the tower.

Many of the cracks cut the whole wall thickness, in other cases they only run on the surface. Sometimes the cracks can be interpreted as the results of compression, like for instance those on the central pillar at the ground level (Figures 9 and 10) and those on the South side at ground level (Figures 11 and 12) where very low sonic velocity was also recorded.

The state of damage of the central pillar at the underground level appeared immediately particularly serious due to the presence of diffused vertical cracks, taking also into account the presence of two recesses on opposite sides of the basement that abundantly reduces the solid cross section. On the contrary, the upper part of the central pillar till the crowning presents no cracks.

East and West fronts present diagonal cracks due to shear. This resulted, as shown in Figure 17, from the effects of a soil settlement towards South East and therefore indicating the need of measuring a possible tower tilting [5,8]. This movement could justify the presence, on the front North wall of the palace, of two bending vertical cracks having maximum aperture on the upper end (Figure 8). The crack pattern seems to be also influenced by the inclusion of the tower within the Ferrero Palace: above the level where the tower becomes octagonal and stands out the building, it is no more restrained by the Palace. Here its walls are cut by a thick network of cracks, particularly evident on the Eastern side, presumably due to compression (Figure 7).

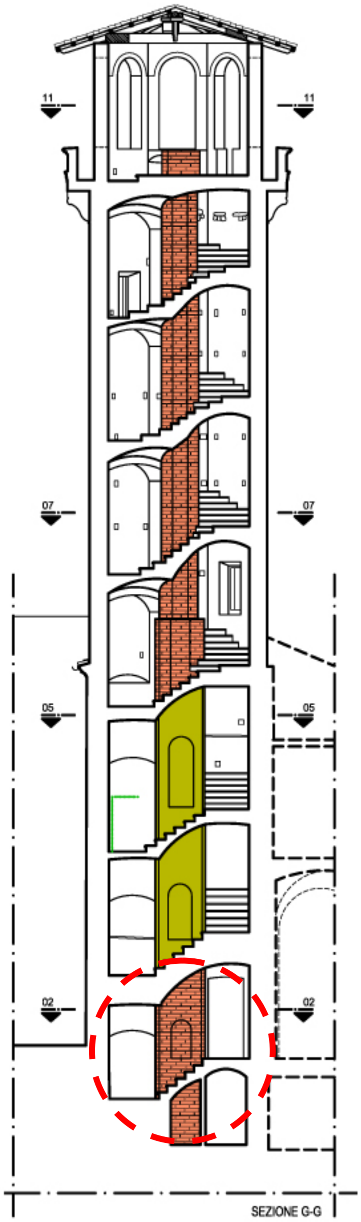
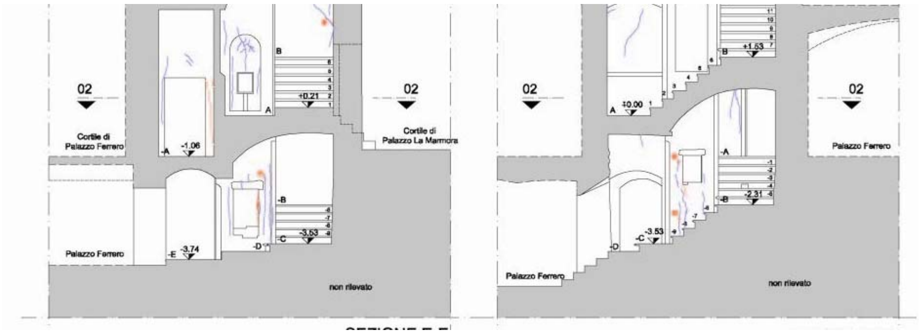
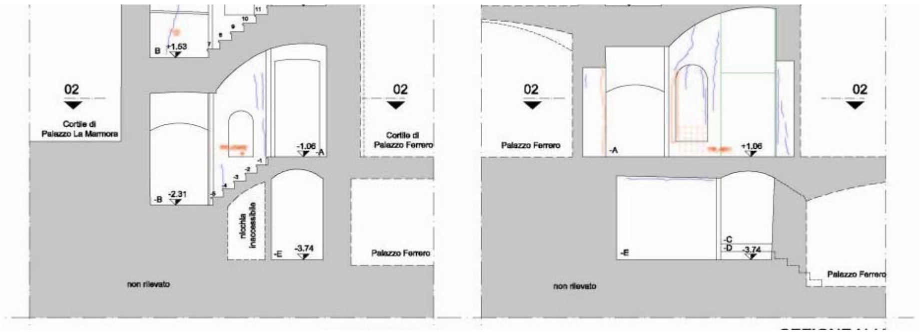


Figure 9: Vertical section showing the central pillar.



East **North**



West **South**

North-East corner **South-West corner**

Figure 10: Crack pattern on the central pillar at ground level.

ON-SITE NDT INVESTIGATION

After a visual inspection by means of a mobile platform, pulse sonic carried out by direct transmission on a grid of 750x750 mm and flat jack tests have been carried out to mechanically characterize the masonry and identify the vertical stress distribution [8, 9]. The results of sonic tests (Figures 13 and 14) indicate a particularly low value corresponding to a testing point on the South side at ground level [10]. Differently from the testing point at the underground level, where the masonry can benefit from the confining effect given by the foundations, here, where the wall is laterally free, its masonry quality is worse and shows thin cracks presumably due to compression (Figure 12).

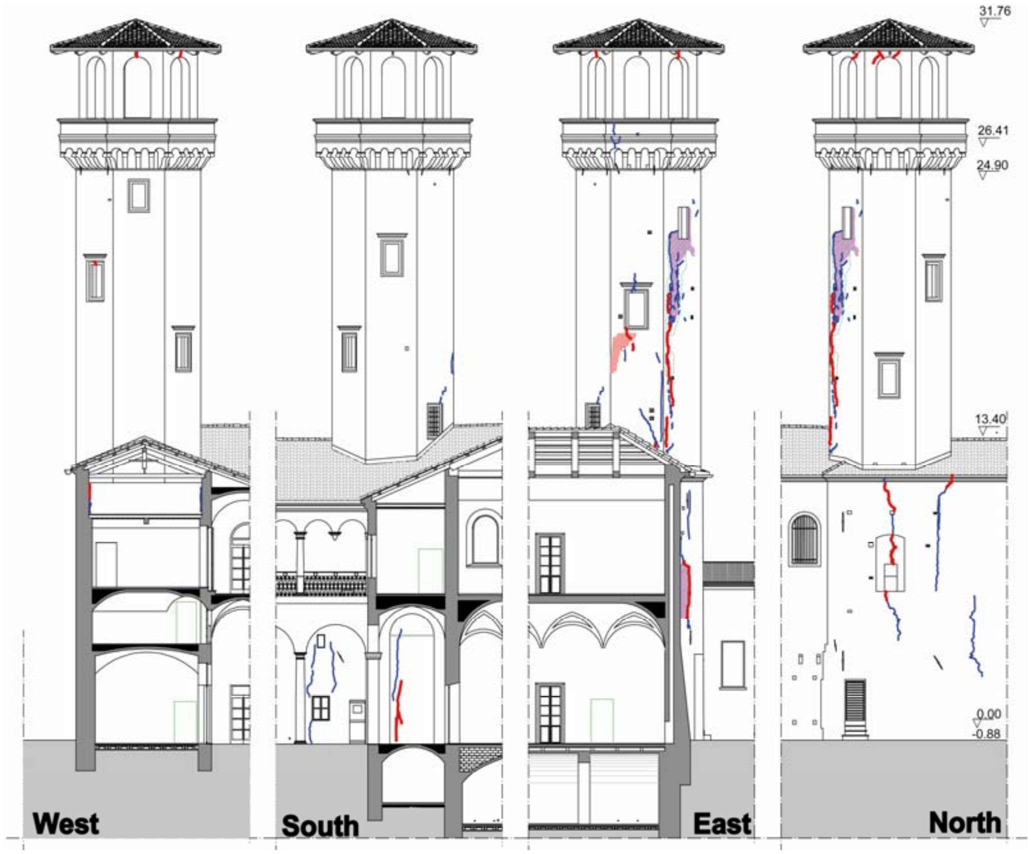


Figure 11: Survey of the crack pattern on the outer walls (courtesy of Studio L. Malavolta).

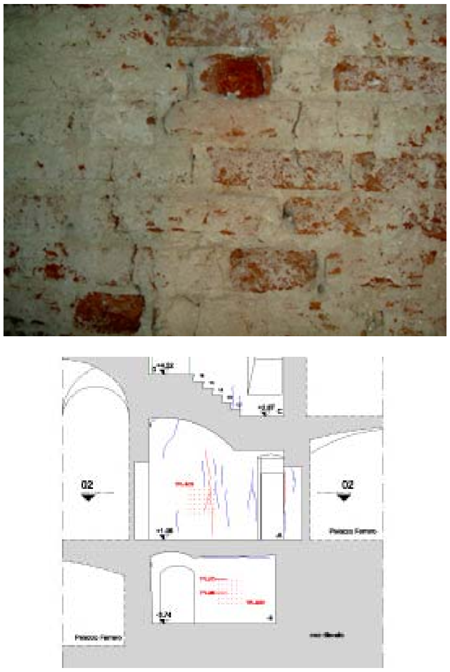


Figure 12: Crack pattern of the South wall at the ground level.

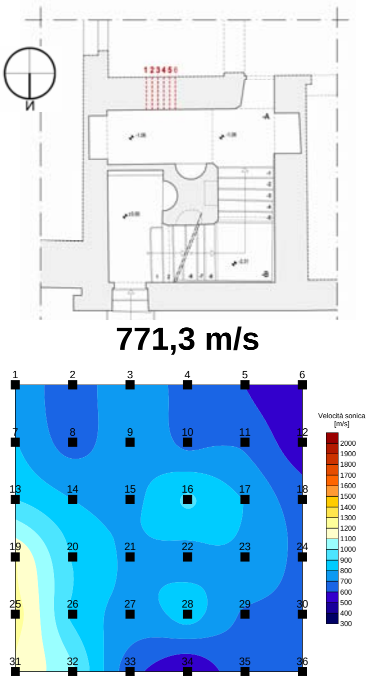


Figure 13: South wall, ground level: sonic velocity

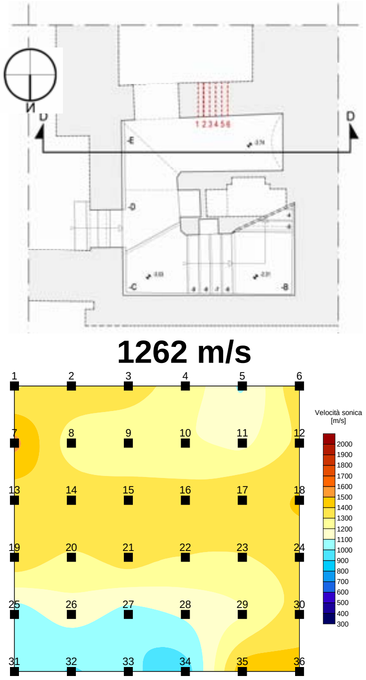
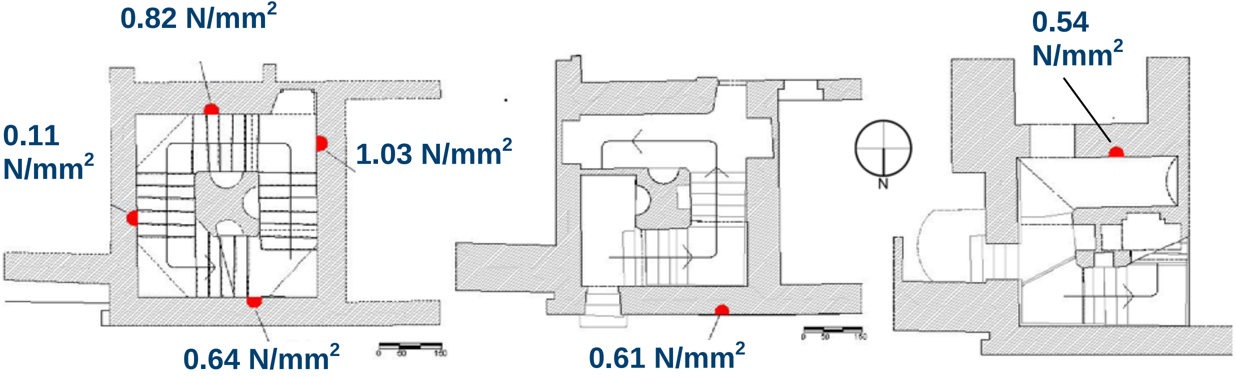


Figure 14: South wall, underground level: sonic

velocity.



a) b) c)

Figure 15: Results of single flat jack tests: a) at a height of 12 m b) at ground level, c) at underground level.

The results of flat jack tests indicate a variation of the vertical stress with height which is reasonably influenced by a complex of factors including the tower geometry, the presence of apertures, the possibility of stress diffusion at lower levels allowed by the continuity with the palace walls, the presence of cracks, etc.

A simple calculation based on the effect of the dead load gives at the base of the tower a uniformly distributed stress in compression of about 0.8 N/mm^2 assuming perfect verticality of the tower. The vertical stress values measured on each of the four walls at a height of 12 m, just below the level where the tower shape turns into an octagon (Figure 15), show a non uniform stress distribution.

Though the highest and lowest recorded vertical stresses are apparently difficult to interpret, nevertheless the presence of bending can certainly be assumed. In particular, it has to be considered that single flat jacks are able to locally measure the vertical stress component only on one face of a wall. In this respect, since all single flat jack tests could only be carried out on the inner part of the walls for accessibility reasons, no information are available on the stress distribution across single walls. However considering on the one hand the extremely low value on the West face of East wall as well as the high value on the East face of the West wall and on the other hand the higher stress value on the South wall than on the North wall, an overall bending toward South East can be assumed, probably due to the tower tilting. This is also responsible of the crack pattern described above and is plausibly due to soil settlement. The hypothesis is confirmed by the results of the geometrical survey subsequently commented.

SURVEY OF THE TOWER VERTICALITY

Following all previous considerations, measurements of the tower verticality were carried out both through the plumb and through a topographic survey with a laser integrated theodolite (GEOTOP). The use of two methods was required because of the difficulty to establish a closed polygonal: the “forward intersection” was adopted, keeping the fixed points on the tower, and surveying them from several station points. The survey was carried out only from outside; due to the low visibility of some sides, that were hidden by the roof, the loss of verticality was calculated by using two different zero levels: one at 14.40 m and the other at 18 m. A loss of verticality was detected mainly in the South-East direction, towards the center of the hall (Figure 13). In fact, this is the direction where the ground slopes and buttresses built on the eastern front of the palace testify that the phenomenon presumably initiated in the past. To better understand the effects of this movement on the tower, also considering the influence of its inclusion in the Ferrero Palace and its interaction with the ground slope, a 3D representation is shown in Figure 16.

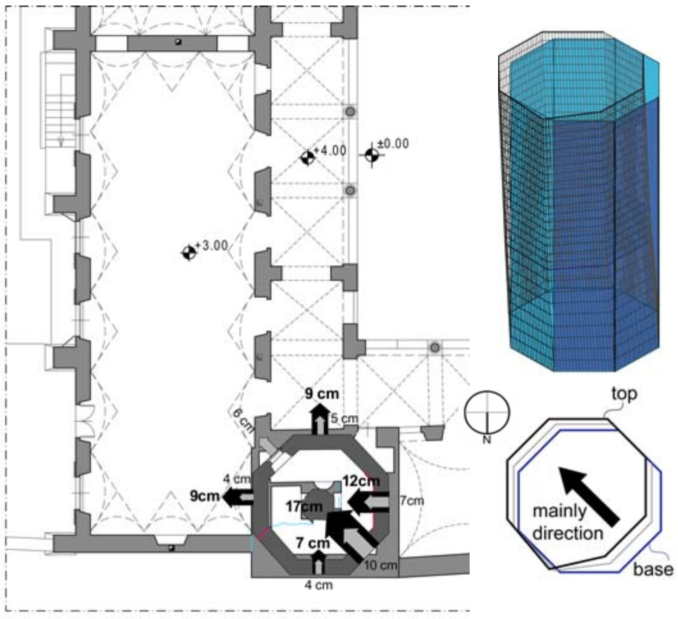


Figure 16: Survey of the tower verticality.

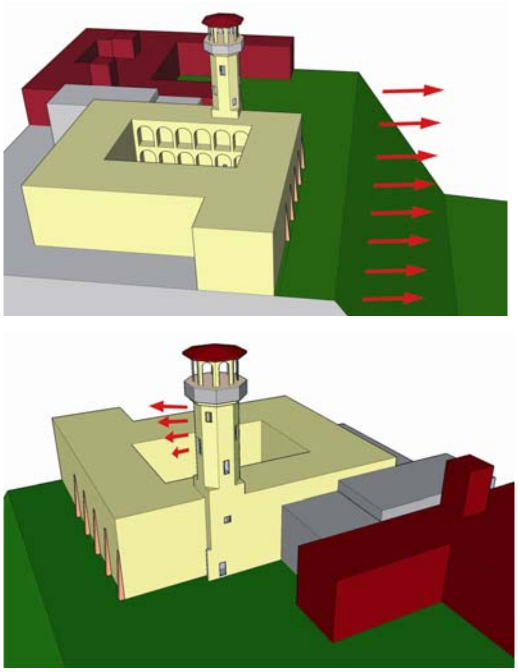


Figure 17: Direction of ground slope and tilting of the tower.

MONITORING

A monitoring program has been designed to record the possible evolution of the movements of the main cracks over a first period of 18 months to achieve an accurate evaluation of the state of damage and a safety assessment of the building. In addition to temperature data, manual readings are taken on three metal plates at each position, so to know two relative displacement components: a “dilation” one, orthogonal to the crack direction and a “shear” one, parallel to it. The locations of the main cracks subjected to the monitoring scheme are indicated in Figure 18.

Despite the interpretation of some readings cannot be yet univocally given, some interesting overall considerations may be drawn. Some cracks exhibit significant displacements both in the dilation and in the shear direction, generally following a cyclic trend strongly influenced by temperature variations. Considering shear displacement (Figure 19), it is interesting to notice that some cracks are not significantly involved by this component, like cracks 9, 10 and 11 on the central pillar and cracks 12, 1, 2, and 5, where dilation is prevalent. Differently, shear displacement components look particularly evident on cracks 7 and 8 on East wall where it shows a comparable amount but an opposite sense with respect of cracks 5 and 6 on West wall. For East and West wall are parallel, these readings indicate an overall shear displacement of the tower which has to be related to the ground settlement also influencing the tower tilting. The meaning of shear of cracks 3, and 4, which is opposite to that of cracks of the same side, remains more difficult to understand.

East **North** **West** **South** **East** **North**

Figure 18: Position of the main cracks subjected to the monitoring campaign.

Cracks 3, 7 on the East wall and 6 on the West wall are affected by significant dilation with the same trend of temperature (Figure 20), whereas cracks 9, 10 and 11 on the pillar are affected by counter-cyclic dilation with respect to temperature (Figure 21). In particular, because since June the pillar has been exhibiting a continuous dilation, and considering the significant vulnerability of slender elements toward sustained compression, a retrofit intervention is in progress to guarantee the pillar safety.

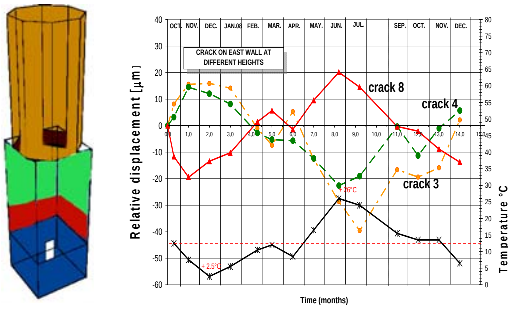


Figure 19: Shear on the main wall (cracks n. 3,4, 8).

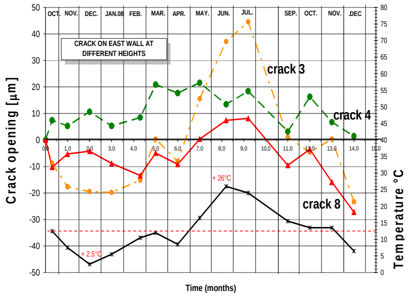


Figure 20: Dilation on the main wall (cracks n. 3,4, 8).

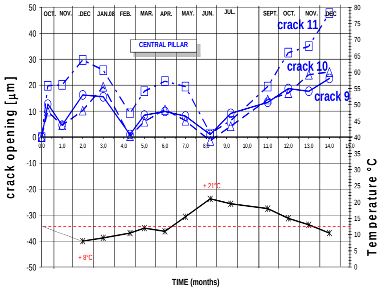


Figure 21: Dilation on the pillar (cracks n. 9, 10, 11).

CONCLUSIONS

A global approach for the safety assessment of historic towers has been applied to the study of the Masserano Tower in Biella, which included the following aspects: geometrical survey highlighting the irregular features like the lack of verticality; survey of the crack pattern and of the damage phenomena visually detected; interpretation of the crack patterns and recognition of its causes; on site characterisation of the masonry walls through sonic and flat-jack tests; monitoring of the damage evolution in time still in progress. The detailed knowledge of the building allowed to recognise dangerous elements and to design initial retrofitting interventions. The calibration of theoretical models and further investigation are still on-going, to collect other information on the general behaviour of the structures. Future interventions will be finalized both to directly repair the occurred damage and to remove the vulnerability sources.

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