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Experimental and numerical analysis for the strengthening intervention of the bell-tower of St. Sisto’s Church in Bergamo

Bortolo Balduzzi, Dario Mazza
Municipality of Bergamo, Italy

Diego Papis, Christian Rossi, Pier Paolo Rossi
R.teknos s.r.l., Bergamo, Italy

ABSTRACT: The bell-tower of St. Sisto’s church in Bergamo is a slender structure about 40 m high. Over a pre-existing stone masonry belonging to XVI century, a structurally complex bells-cell made with sandstone blocks and concrete precasting elements, was built in 1903 by the architect Muzio. In order to analyse the static and dynamic behaviour of the structure, a wide experimental investigation, including in situ and laboratory tests, was carried out. The vibration modal shapes of the bell-tower were then determined by in situ dynamic test. On the basis of the photogrammetric survey and of the mechanical parameters of the materials determined by in situ and laboratory tests, a detailed finite element mathematical model was carried out. The reliability of the model was checked by a validation process using the results of flat-jack tests (for the analysis of the static behaviour) and the results of the vibration test (for the analysis of the dynamic one).The model clearly shows that the capacity of the tower to support dynamic horizontal loads (earthquake) is not satisfactory. For this reason, a strengthening intervention was designed in order to decrease the seismic vulnerability of the bell-tower without inducing heavy visual impact. The choice of the most suitable steel strengthening structure was defined by using the finite element model as a design tool.

1 INTRODUCTION

The first church of St. Sisto was built in the middle of XV century along one of the main roads leading to the centre of Bergamo. The actual church was built between the years 1726 and 1754 by the architect Gian Battista Caniana. The old bell-tower of the church was built in 1596 by using a stone masonry made with regular sandstone blocks in the external layer and a mixed brick and stone masonry in the inner layer.

The old bell-tower was strongly modified in 1903 when the architect Virginio Muzio built over the lower part of the pre-existing tower, a new complex structure including a bells-cell and an additional smaller cell on the top; for this construction he used sandstone squared blocks and concrete precast elements assembled on site, with some additional brick masonry elements to support the higher cell. The new structure is divided into different layers. A lower bells-cell with four sandstone pillars at the corners was built just over the pre-existing tower; over the pillars, a frame with decorated precast concrete elements is layed. This frame is supporting a second smaller cell with four pillars made with brick masonry. The upper cell supports a small dome, made with precast concrete elements, with the copper statue of St. Sisto at the top.

A view of the upper part of the bell-tower is shown in figure 1.

Figure 1 : View of the St. Sisto’s bell-tower and particular of the damages induced by the impact of lightnings against the walls.

The total height of this slender bell-tower is about 40 m and, owing to its geometrical and structural characteristics, the upper part of the tower seems to be not too able to support heavy horizontal actions.

In the last few years, the bell-tower was seriously damaged by several impacts of lightnings against the walls and some decorative elements collapsed. In figure 1, some particulars of these damages are shown. After the last impact of a lightning in July 2002, which caused the falling of a concrete decorative globe from the top of the upper cell, the Municipality of Bergamo realized that the structural conditions of the bell-tower were unable to guarantee a satisfactory safety level of the whole structure. For this reason they decided to confine the bell-tower with a strong structural scaffolding and to start a wide program of diagnostic analysis with the aim of obtaining all the information required for a correct definition of the restoration and strengthening design of the whole tower.

2 DIAGNOSTIC INVESTIGATION

In July 2004, the Company R.teknos was encharged by the Municipality of Bergamo to carry out an experimental investigation in order to determine the structural and mechanical parameters necessary to develop the design of strengthening intervention as well as that of the restoration of the damages induced by the impact of lightnings and by the injury of time.

At first, a geometric survey was carried out, by using photogrammetric technique, together with a detailed crack-pattern survey of the external and internal walls. The main cracks were described as well as the damaged zones with special attention to the effect of the impact of lightnings against the walls. The surface decay of stones, concrete and mortars was analysed, as well as the oxidation processes of the steel structures and those of the copper statue of St. Sisto.

The composition and the structural characteristics of the masonry were investigated by means of small diameter corings and video-camera survey. Special attention was devoted to the stone masonry of the lower part of the bell-tower (built in the year 1596); it was observed that the outer leaf is made with regular blocks of sandstone, the inner one is a masonry made with some bricks and irregular stones and between the two leaves a filling masonry with irregular stones was found, with composition similar to that of the inner leaf but with a greater porosity.

The state of stress of the masonries was measured at different levels by using flat-jack testing technique. Special attention was devoted to the four sandstone pillars at the corners of the lower bells-cell, where an average stress value of about 0.65 MPa was measured, and to the masonry of the old tower where an average state of stress of about 0.97 MPa was measured in the outer leaf and about 0.42 MPa in the inner one. The values of the state of stress measured at the different sections are shown in figure 2a. [1] [2]

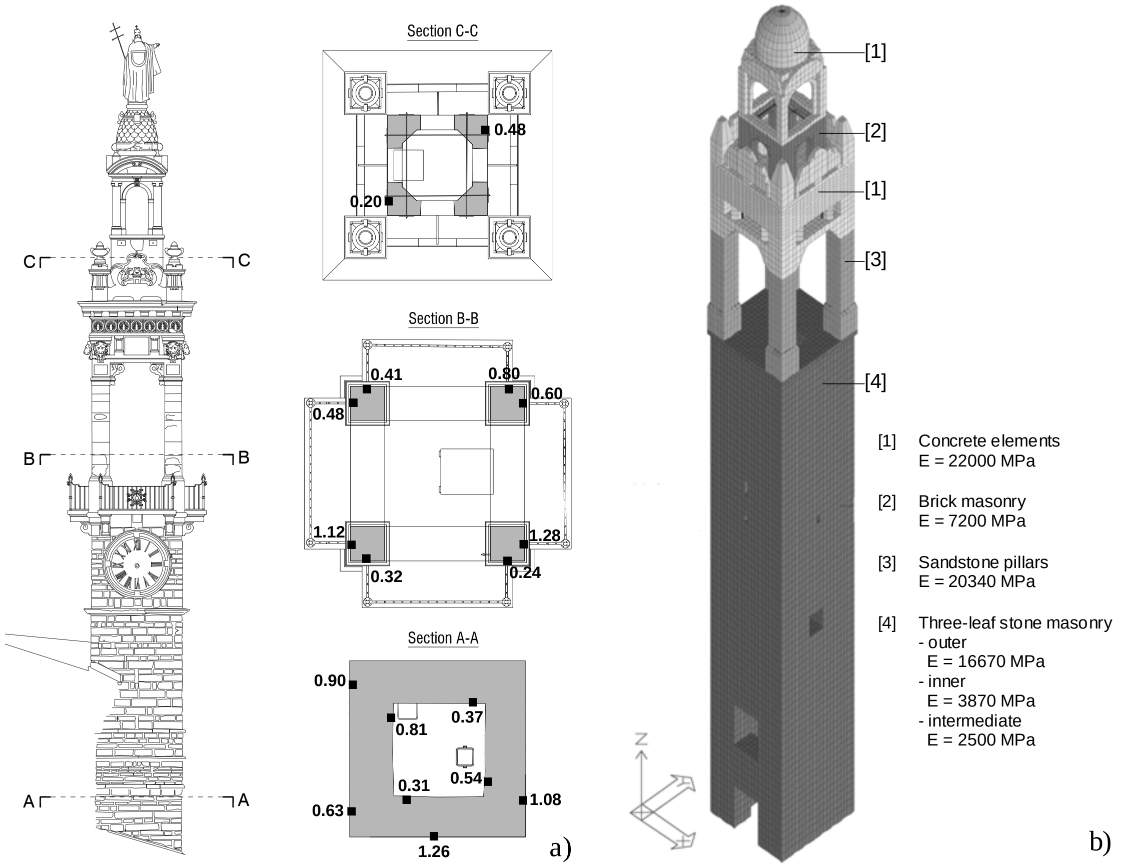

Figure 2 : a) Values of the state of stress in MPa measured by flat-jack tests;
b) Deformability characteristics of the different materials which compose the tower.

By using two parallel flat-jacks, the deformability characteristics of the masonries were determined. The masonry of the lower part of the tower (built at the end of XVI century) shows a mean deformability modulus of about 16670 MPa in the outer leaf made with regular stone blocks, and 3870 MPa in the inner one where the masonry is made with bricks and irregular stones; for the filling masonry between the two leaves, a Young modulus of 2500 MPa was estimated. The deformability modulus of the sandstone pillars at the corners of the bells-cell was estimated on the basis of the results of single flat-jack tests; an average value of about 20340 MPa was estimated. The deformability characteristics of the precast concrete elements were determined by means of laboratory compression tests on samples cored by small diamond drilling machine; a mean value of 22000 MPa was estimated. The analysis of the deformability characteristics of the brick masonry pillars which support the upper cell was determined by using flat-jack test; a mean value of 7200 MPa was determined. The schematic view of the materials which compose the tower is shown in figure 2b) with the indication of the corresponding deformability moduli. [3]

The detailed analysis of the state of stress and of the deformability characteristics of the different materials which compose the tower, was used for constructing a 3D finite element model of the structure.

Several chemical-physical and mineralogical tests were carried out on samples of the different materials (sandstone, bricks, concrete and mortars) in order to analyse the decay characteristics of the materials for the choice of the most appropriate restoration solutions.

In consideration of the slenderness characteristic of the bell-tower, it seemed advisable to analyse in detail the dynamic characteristics of the structure and the vibrating modes. An experimental investigation based on the analysis of the vibrations induced to the tower by environmental effect was carried out by using several accelerometers installed at different levels. The first five vibrating modes were checked and the type and frequency of each mode are summarized in the following table 1.

Table 1 First five vibrating modes of the bell-tower measured by dynamic vibration tests.

Mode	Frequency Hz	Type
1	1.36	First bending mode (x)
2	1.47	First bending mode (y)
3	4.25	Torsional mode
4	5.36	Second bending mode (x)
5	5.69	Second bending mode (y)

For each vibration mode, the deformation induced to the structure was analysed and it was observed that the two flexional vibration modes induce high horizontal deformation in the two cells located in the upper part of the tower.

3 NUMERICAL MODEL

3.1 Description of the model

A 3D finite element model was chosen to evaluate the structural behaviour of the bell tower under the effect of static loads and dynamic actions.

The mechanical properties chosen to describe the materials follow the results of the diagnostic investigations described in paragraph 2. The values of the Young modulus chosen for the construction of the numerical model are summarized in figure 2b). The finite element model, including 28980 solid elements, was validated both in static and dynamic field by the comparison between the results of the model and those obtained by the experimental investigation (flat-jack and vibration tests).

3.2 Result of static analysis

Linear elastic analysis was carried out assuming as load conditions only the dead load of the structure. It must be pointed out that the limits of a linear elastic analysis in identifying a masonry structure are well known; nevertheless this choice follows the consideration that the masonry structure of a tower is mainly subjected to compression and the maximum compressive stress found in the masonry structures is lower than the stress limit determined by flat-jack tests.

The results of the static analysis for dead loading conditions are shown in figure 3a.

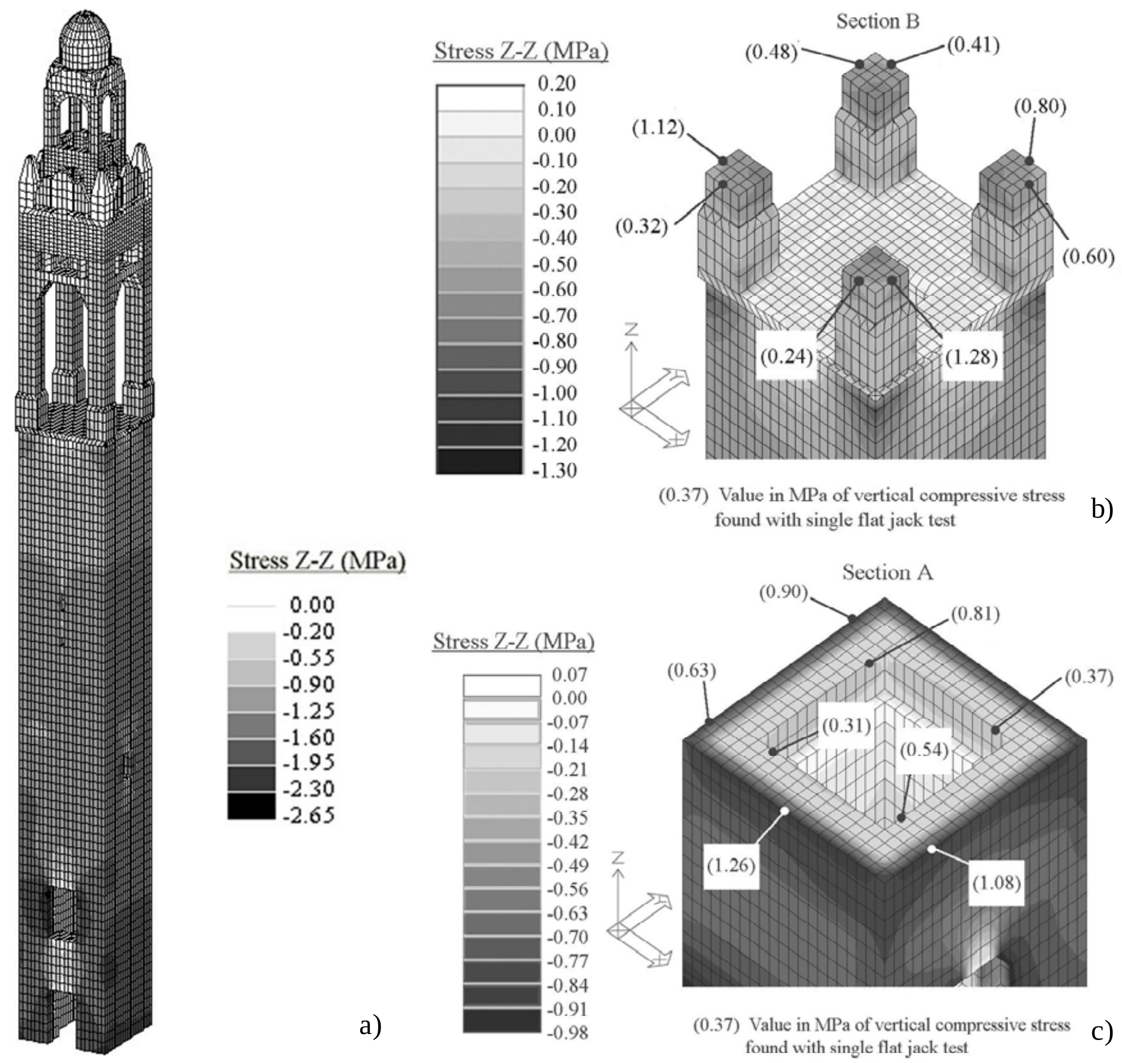

Figure 3 : a) Results of the static analysis for dead loading conditions; b) c) Comparison between the experimental and numerical vertical stresses in section B and A

It can be observed that quite all the elements are subjected to compression and the tensile stresses are quite negligible and may be considered “acceptable” within the limits of the linear elastic analysis.

Figures 3b and 3c show a comparison between the values of the state of stress measured by flat-jack test and those calculated with the numerical model. Figure 3b shows the comparison of the results in the section A of the old tower; in the external surface the mean value of the state of stress measured by flat-jack is 0.96 MPa which is very close to the value 0.91 MPa calculated by the model and in the inner surface the mean value of the measured state of stress is 0.42 MPa which is higher than the calculated value 0.22 MPa. This difference is probably due to local stress concentration in one of the two testing points due to irregular shape of the stone elements. Figure 3c shows the comparison of the results in section B, at the base of the four sandstone pillars which supports the bells-cell. The mean value of the state of stress measured by flat-jack along the joints between the sandstone blocks which compose the pillars, is 0.65 MPa which is very close to the calculated value 0.62 MPa. [3]

The static analysis included also the study of the effect of wind load; it could be observed that this loading condition induces an increase of the compression stresses by about 30%.

3.3 Result of dynamic analysis

The numerical model was also used for analysing the dynamic behaviour of the bell-tower. A modal dynamic analysis was carried out, by applying a dynamic horizontal force, in order to determine the first five vibrating modes of the structure. These vibrating modes determined by the model have been compared with those measured by experimental vibration tests, as shown in Figure 4. As concerns the first two modes, a very good agreement can be observed between the calculated frequency values and those measured by vibration tests. As concerns the three remaining vibration modes, small differences can be observed in the frequency values but their entity is not able to influence in a significant manner the dynamic behaviour of the structure.

After this first phase of analysis to determine the vibrating modes of the tower, the finite element model was used to examine the behaviour of the tower subjected to seismic load according to the new seismic code.

The state of stress induced by seismic load is very severe for what concerns the pillars of the bells-cell and some portions of the lower masonry. High increase of compression stress values can be observed, as well as high tensile stresses mainly in the four pillars of the bells-cell which represent the weakest point of the whole structure. Very high horizontal deformation is also observed in the bells-cell and in the higher smaller cell.

The results of the dynamic analysis clearly showed that the seismic vulnerability of the upper part of the bell-tower (built in 1903 by the architect Muzio) is very high as concerns the induced states of stress and the horizontal deformations. For this reason it seemed advisable to design a strengthening intervention able to decrease as much as possible the vulnerability of the tower against seismic actions.

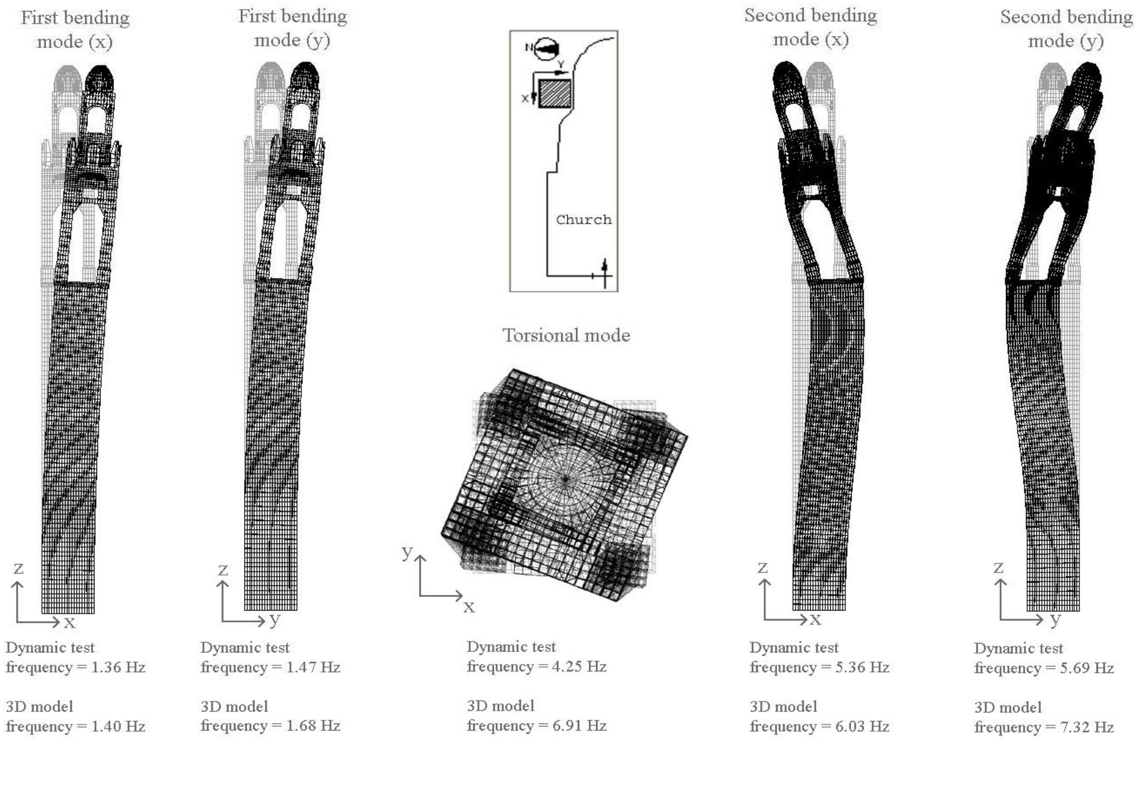

Figure 4 : Comparison between vibrating modes determined by the model and those measured by experimental vibration tests

4 STRENGTHENING INTERVENTIONS

The finite element model described in paragraph 3 was used as a design tool for the study of the most suitable strengthening interventions. This use was allowed by the fully satisfactory validation of the model based on the comparison between the results of the experimental investigations and those obtained by the model; in this way the reliability of the model was proved and different strengthening solutions were examined. [4]

The strengthening structure which was chosen for decreasing the seismic vulnerability of the tower is a good compromise between the need of increasing as much as possible the seismic efficiency of the structure and that of reducing in the meantime the visual impact of the intervention.

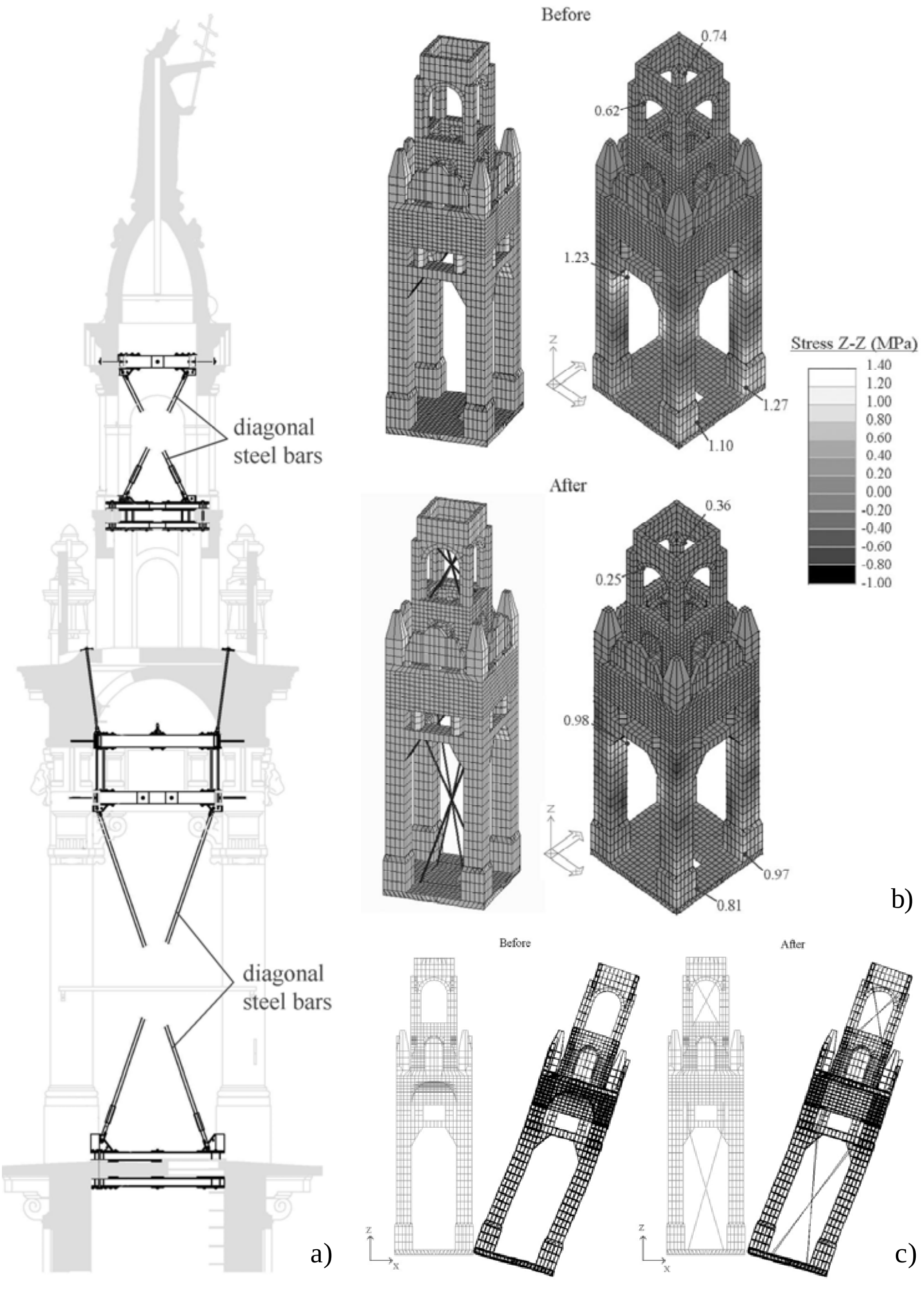

Figure 5 : a) Scheme of the strengthening solution based on the use of steel frames and diagonal bars; b) c) effect of the strengthening structure on state of stress and lateral deformation of the cell.

The scheme of the strengthening solution which was chosen is based on the use of steel frames and diagonal bars, as shown in figure 5a. The strengthening of the lower bell-cell consists of two systems of steel frames installed on the base and on the top of the cell, connected each other by means of steel bars with tendons. A similar system of steel frames connected by diagonal steel bars is used for strengthening the upper smaller cell.

The comparison between the results obtained by the numerical model before and after the intervention, clearly shows that the major effect of the strengthening structure is represented by the reduction of the lateral deformation of the cell, as shown in figure 5c. The presence of the strengthening structure sensibly decreases the flexus of the deformation line which was observed with particular evidence in the sandstone pillars of the lower cell before the intervention. As a consequence of the reduction of the lateral deformations, a decrease in the maximum compression and tensile stress values can be observed. As an example, figure 5b shows the difference between the maximum tensile stress values before and after the intervention.

Besides the installation of the strengthening system, a restoration design of the whole tower was defined in order to repair all the damages caused by the impact of lightnings against the walls with special attention to the precast concrete structures which suffered the main damages. In the meantime the restoration design includes also the repair of the damages due to the injury of time, through the consolidation and protection of the surface of all the materials (masonry, mortar, concrete, steel and copper) and the removal of the wrong materials which were applied during past restoration interventions.

The installation of the strengthening intervention and the complete restoration work of the bell-tower is starting at the beginning of May 2006. A new reliable protection system against lightnings will also be installed as well as an efficacious system against pigeons.

5 CONCLUSIVE REMARKS

The methodological approach which has been followed for the design of the strengthening interventions of St. Sisto’s bell-tower, is based on the combined use of finite element model and experimental investigations. The parameters which define the mechanical behaviour of the tower have been determined through a wide experimental investigation based on the use of corings, flat-jack and vibration tests. By using these parameters and the photogrammetric survey, a 3D finite element model was carried out. The model was validated trough a comparison between the results of the model and the experimental ones. After the process of validation which was fully satisfactory, the finite element model was used as a design tool in order to verify the efficiency of the different strengthening solutions. The choice was addressed toward a solution which is able to decrease the seismic vulnerability of the tower without inducing heavy visual impact. The strengthening solution adopted, based on the use of diagonal steel bars connected to the corners of steel frames, is very simple and its installation will be very easy and rapid.

6 REFERENCES

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