A quick and low-cost method for strengthening high buildings: the case of St. Stefano’s bell-tower in Venice.

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ABSTRACT: During the crack-pattern survey carried out on the walls of St. Stefano’s bell-tower with the aid of climbers, it was observed that the old confining steel chains were seriously damaged. The loss of efficiency of these chains required the prompt installation of a provisional strengthening system based on the use of high resistance steel cables with steel plates at the corners. The paper illustrates the phases of installation of the corner plates and the cables (carried out by few climbers) emphasizing the rapidity of the work as well as the flexibility and reversibility characteristics of this method.

1 FOREWORD

The St. Stefano’s bell tower, built in the middle of the XVI century, was lined in 1902 by a system of confining steel chains able to reduce the transversal deformations and to assure the safety of the tower. During the last century, these steel chains were subjected to high tensile stresses which induced considerable deformations in the junction points connecting the different parts of the chains, as it could be observed during the detailed crack-pattern and damages survey which was carried out on the walls by climbers.

The partial loss of efficiency of the chains advised the prompt installation of a new strengthening system based on the use of high resistance steel cables which were installed by climbers without the use of scaffoldings.

The methodological approach applied for the strengthening of St. Stefano’s bell tower, including the preliminary investigation, the construction and the installation of the reinforcing structures, for its low cost and rapidity of intervention, can represent a very powerful mean for the solution of delicate safety problems of tall structures involved by severe crack pattern or affected by some traumatic accident (fire, earthquakes,...).

2 STRENGTHENING INTERVENTION OF 1902

In 1902, the leaning of St. Stefano’s bell tower, built in the middle of XVI century, already measured 1.70 m; following the fall of St. Marco’s bell-tower in 1902, lively discussions and debates were carried out and led to the intervention planned by the engineers Pellandra and Piamonte, based on the use of temporary steel chains on the masonry of the tower in order to assure its safety (figure 1 and figure 2).

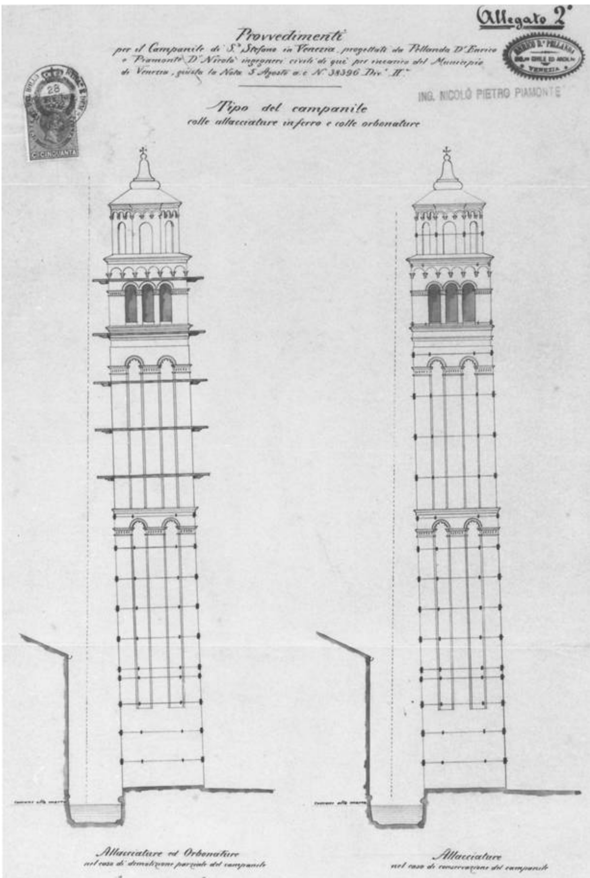

Figure 1: Design of the chains installed in 1902. Location of the chains.

Afterwards the engineers Caselli and Antonelli were charged to make the final plan for the consolidation and the strengthening of the bell-tower based on the strengthening both of the structural masonry and the foundations.

Using the scaffoldings ordered by the prefectorial commission, Caselli and Antonelli could verify directly the state of conservation of the structures: if the masonry structure, built with well cooked bricks of good quality and resistant mortar well preserved, revealed to be ‘sound, regular and resistant’, on the other hand the external coat of bricks, forming the pilaster strips and the arches of the cornice, were deteriorated and detached from the core of the masonry. During the works it was verified that, since the beginning, the central block of masonry had been built with the external front completely plain without any decorative or architectural elements and that only in a second time, probably not many years later, the pilaster strips and the arches of the cornice were realised simply laid next to the existing masonry structure with very few tooting-stones.

The damage due to the action of ice or to extraordinary natural events, increased by this constructive discontinuity, caused during the time the detachment of the surface layer of the masonry that also in the past had been repaired using, on the north front, the traditional Venetian technique for the consolidation of the tower structures with the insertion of connections made with long elements of “Istria stone”.

The two engineers considered that it was necessary for the safety of the bell-tower the installation of a system of steel chains in order to line the tower. Ten new chains were installed, six external and four internal, connected by the bolt of the inside chains in order to obtain the tension required for the final intervention; moreover, according with the structural plan, some new steel tie-beams were installed across the walls in order to obtain a rigid and efficacious strengthening system. The steel chains were also extended to higher areas of the bell-tower including the bells’ cell and the pinnacle.

The damaged portions of the external walls were replaced and the detached areas were connected to the inner masonry by using steel bars inserted into drilled boreholes and connected to steel plates with screw system for tensioning.

Finally, in order to complete the consolidation works on the structural masonry, it was realised a complex of brick vaults crossing the entire section of the bell-tower at two different levels. These vaults had the effect to increase the stiffness of the whole tower and its attitude to resist to extraordinary earth-quake shocks.

In conclusion the aim of the intervention was to transform a bell-tower built with bricks and lime masonry, where the cohesion between the elements is only due to the lime, into a structure made with bricks and steel connections which presents solidity comparable to that obtainable by the modern system of reinforced concrete.

3 ANALYSIS OF THE ACTUAL STATIC CONDITIONS OF THE CHAINS INSTALLED IN 1902

During the investigation phase carried out with the aid of climbers, a detailed crack-pattern survey of the external walls of the tower was carried out. In this phase, besides the detailed analysis of the damaged zones of the masonry walls, special attention was devoted to the static conditions of the existing steel chains which line the tower at four different levels.

Clear signs of oxidation have been observed which reduce the effective section of the chains.

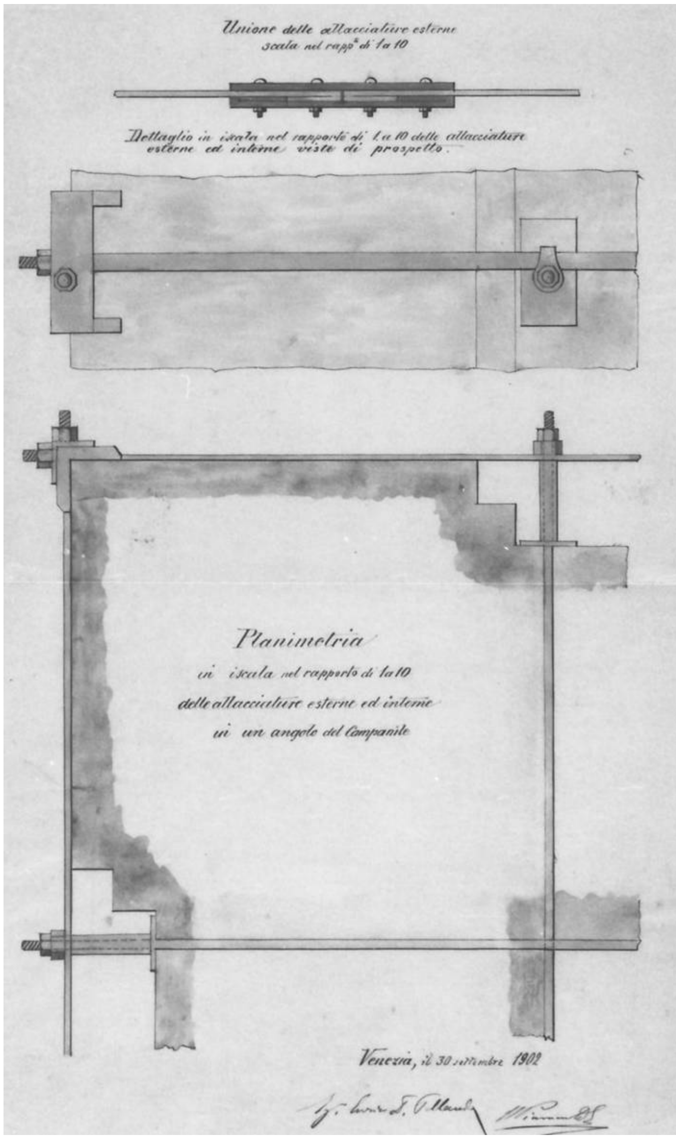

Figure 2: Design of the chains installed in 1902. Detail of the connections between chains and masonry.

Figure 3. Deformations of the old chains installed in 1902 observed during the crack-pattern survey.

Figure 4. Deformations of the old chains installed in 1902, detail.

But the most serious problems are concerning the conditions of the junction points which connect the different parts of the chains. Almost all the junctions show high deformation processes due to a severe tensile state of stress exceeding the resistance capacity of the junction points.

The photographs taken during the survey of the external walls clearly show the marked tendency of opening of several joints which connect the parts of the chains (figure 3,4).

The high state of stress which is responsible of the deformation of the joints, can be related both to the reduction of the section of the steel chains due to oxidation processes and to the increasing of the transversal deformation of the tower due to progressive opening of the vertical cracks.

As a result of the survey carried out by the climbers concerning the conditions of the chains, it was concluded that the safety conditions of the tower are non satisfactory because the chains are non able to guarantee a reliable lateral confinement of the structure.

4 NEW STRENGTHENING INTERVENTION

The results of the survey described in paragraph 3, advised the prompt execution of a strengthening intervention in order to give back to the bell-tower an efficacious lateral confinement able to guarantee the safety of the tower against transversal deformation processes.

It was decided to leave the old external chains in their actual conditions and to add, at each of the four levels, new external chains able to guarantee the same confining effect of the old ones in the hypothesis of their structural integrity.

With this solution, the old chains, even if they have partially loosed their integrity, will remain to give an additional contribution to the safety of the tower against transversal deformation.

The new confining system, on purpose designed to let an easy and rapid installation, is composed by steel plates anchored at the corners of the bell tower and high-resistance steel cables provided with mechanical tensioning devices to apply the desired confining effect.

The location of the four new chains is shown in figure 5, while in figure 6 the design of the tensioning apparatus is shown.

In each layer, the new confining apparatus is composed by steel corner plates (obtained by welding two plates 300 × 300 × 20 mm) on which two high-resistance steel cables with a diameter of 10 mm are installed on circular shaped supports. In order to avoid any risk of damage of the masonry, the faces of the corner plates which are in contact with the masonry are covered by a layer of neoprene 10 mm thick.

On the opposite sides of each cable, tensioning devices are installed with a screw system in order to apply the tensile force required.

The ultimate tensile load which a couple of high-resistance steel cables can bear is 186.0 kN, which is a little higher than the estimate bearing capacity of the old chains (168.0 kN).

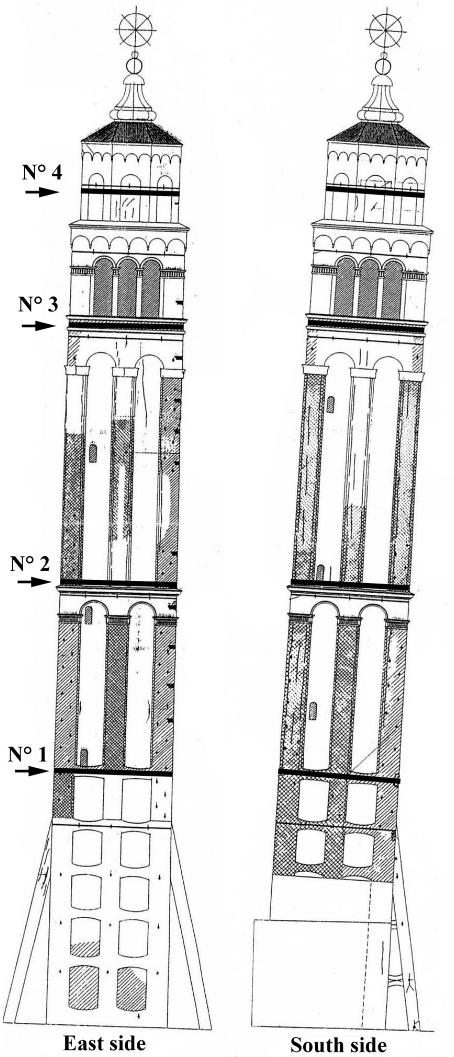

Figure 5. Location of the four chains of the new strengthening system

It was decided to apply to the cables a low value of the initial tensile stress (about 20% of the tensile resistance) in order to avoid the application of high initial concentrated loads, leaving to the tower the possibility of increasing automatically the confining effect with the increasing of the transversal deformation.

For the final decision concerning the initial load to apply to the cables, an analysis of the thermal effect on the tensile stress was carried out. The initial tension applied with a temperature of 25 °C was 37.0 kN; this value will decrease to 34.0 kN at a temperature of 40 °C and will increase to 43.0 kN at a temperature of -5°C.

5 THE INSTALLATION TECHNIQUE

The strengthening technique proposed in this paper has been designed in order to permit an easy installation without the need of scaffoldings.

The mechanical apparatus was set up at each level by four climbers with a specific experience on this type of intervention (Fig. 7). At first, the steel plates with the neoprene layers were placed at the corners and fixed to the masonry walls by using stainless-steel anchors grouted with epoxy resin (figure 8,9). Before the installation, the plates were treated against oxidation and corrosion.

Then the cables were installed and gradually tensioned up to the desired load, by acting the screw system of the tensioning devices located on the opposite sides of the tower. In figure 10 some installation phases are illustrated, and figure 11 shows a view from below of the recently positioned strengthening system.

The time required for the installation of all the strengthening systems (corner plates and cables at 4 different levels) was about 9 days with a total cost of about € 22.000,00.

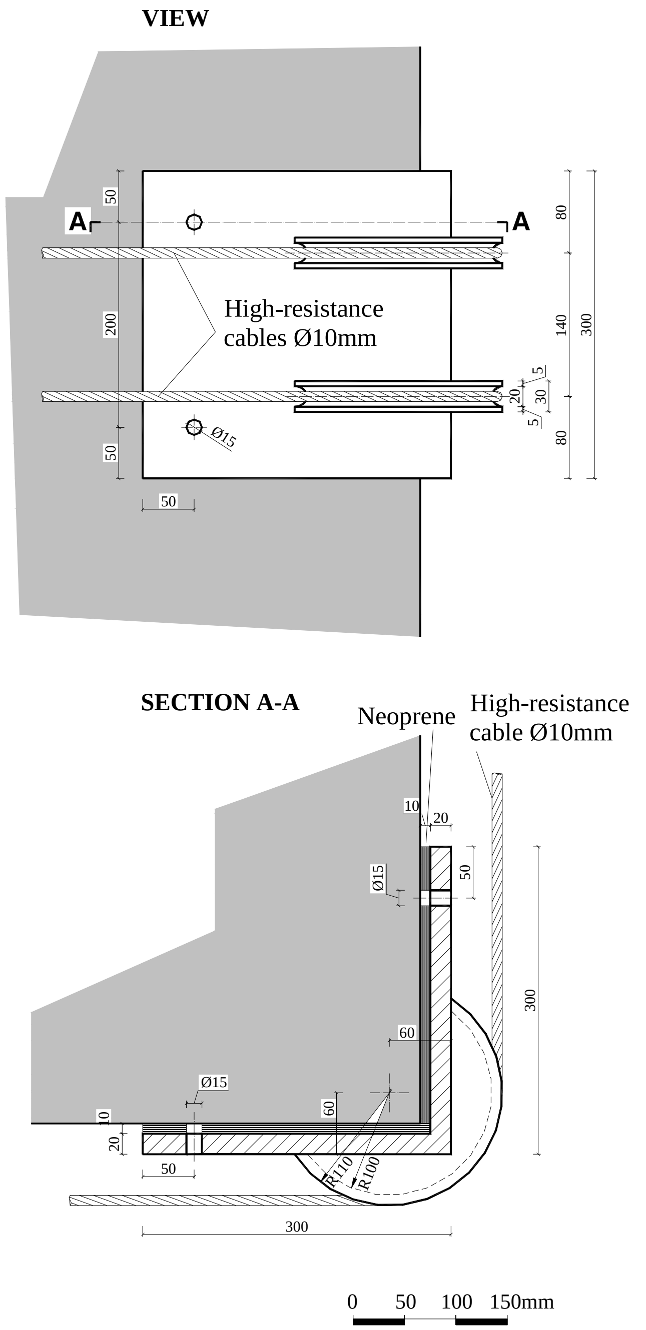

Figure 6. Design of corner steel plate and high-resistance cables

Figure 7. Phase of installation of the strengthening system

Figure 8. Installation phases of the steel plates

Figure 9. Positioning of the steel plates at the corners of the bell-tower

Figure 10. Installation and tensioning of the cables

Figure 11. View of the new strengthening system

6 CONCLUSIONS

The methodological approach here described can give a precious contribution to the re-establishment of the required safety conditions of damaged tall structures. All the phases of the intervention (including crack-pattern survey, construction and installation of the strengthening system) can be carried out in a very short time at a low cost. This marked reduction of time and cost is due to the simple design of the mechanical components and to the use of specialized climbers thus avoiding the installation of scaffoldings which are very expensive and with a very high visual impact.

The proposed strengthening intervention has the character of a temporary intervention even if the characteristics of the materials used are able to guarantee a long life to the plates and cables. Besides, the intervention is totally reversible and can be easily removed in the case that a definitive strengthening project is performed.

In all the cases in which some doubts will arise concerning the safety conditions of a tall building and a collapse due to high transversal deformation is afraid, the use of this simple and reliable strengthening technique can give a very significant contribution.

Its use is particularly recommended in the case of a structure involved by a sudden catastrophic event (earthquake, fire) with a crack-pattern which indicates that the structure is near to collapse.

Finally it is also important to observe that the visual impact of the strengthening system installed on the St. Stefano's bell tower is completely negligible and from the ground is rather impossible to see the confining cables and the corner plates.

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