THE STRUCTURAL CONSOLIDATION OF OLD MASSIVE STRUCTURES

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Abstract
Some examples of structural consolidation of ancient massive structures are illustrated along with description of technological and theoretical aspects in restoration applications.

Introduction

The conservation of ancient massive structures represent a complex topic to be involved with. We have to consider the historical stratifications, the alterations due to changes of use, maybe the run-down state. Moreover, the conformation, the typological or structural differences among parts are specific problems to face; many structural changes occurred as consequences of variations of defensive methods, of tastes, of state demands.
Thus, massive structures are as example of coexistence of different materials, techniques, shapes, static models and loads distributions.

Besides, the current debate about restoration and consolidation of historical constructions assumes that an historical building is the primary source of knowledge, a significant testimony in its full complexity. Thus, it is essential to deal with the individual object as a unique, unrepeatable instance, assigning equal value, dignity, importance, and right to protection to all the components of the building and all the material evidence contained in it. Hence, a strengthening project has to be preceded by a scientific diagnostic approach and has to minimise the impact of the intervention, by choosing the most compatible solution with respect to the building's current state, with the aim of preserving it as better is possible.

Vigevano Castle – Italy

<u>*Covered Street*</u>
The heavy traffic loads was the main cause of the damage. Hence the covered street had been consolidated: the adopted solution was the application of a layer of extradossal collaborative reinforced concrete with steel connectors between masonry and concrete. Moreover tree couples of tie rods were used as a brace to take horizontal loads and to led them to the piers.

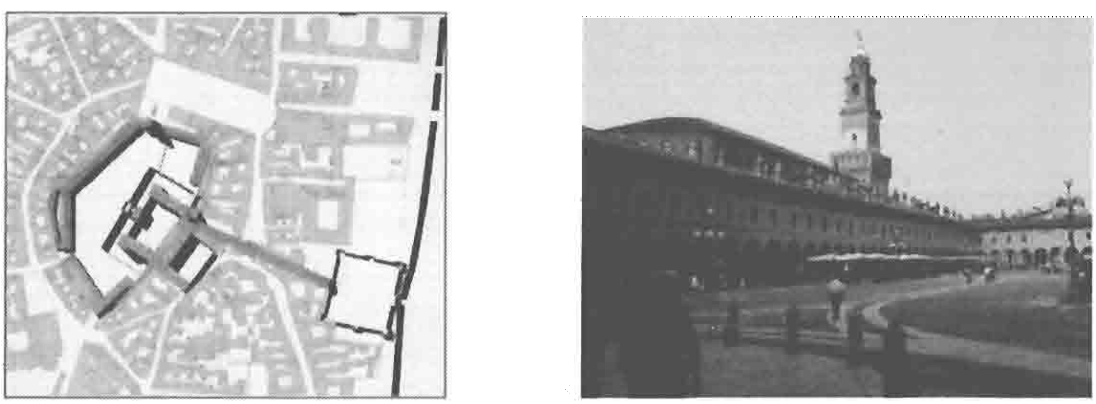


Figure 1. ***a)*** **plan;** ***b)*** **view from the court. It is clearly visible the covered street as connection between the older and latest parts**


Figure 2. ***a)*** **external view of upper part;** ***b)*** **inner view of the lower part.**

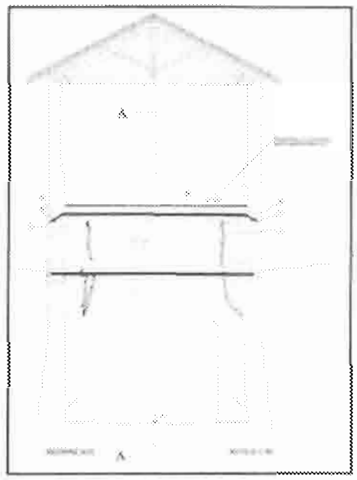



Figure 3. ***a)*** **Crack pattern on vault and arch;** ***b)*** **Scheme of the tie rods interventions.**

<u>The riding –school</u>

The building wooden span roof is carried by fouthteen trusses with short distance on center (2,5 m), but long span (22 m). The intervention was in order to restrict the transverse weakness occurring in those trusses. Steel cables were used to connect the secondary horizontal tie beams one to each others. Furthermore, existing joints at one third span of the main horizontal tie beam were strengthened.

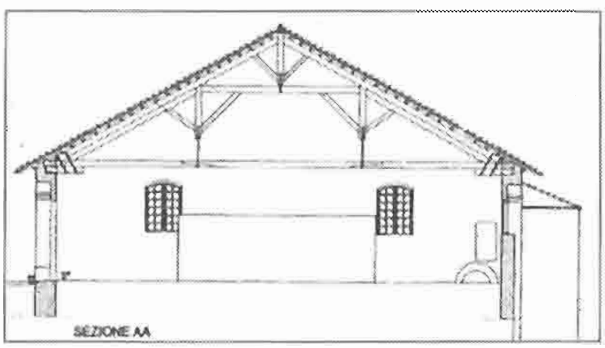


Figure 4. The typical truss: the two principal rafters are held by a main horizontal tie beam and a secondary tie beam (collar), with three posts to support the tie beams

Figure 5. "Palladiana" trusses after the intervention.

Visconteous Castle, Pavia - Italy

South-west Tower

In 1925 the Southwest Tower vault was consolidated in order to act against the serious ongoing damage. Flooring and filling material were removed and a new reinforced concrete floor was built above the existing vault, stiffened by rib beams. The masonry vault was suspended from the concrete floor by using twenty steel rods.

In 1995 the concrete floor, which had been left exposed for many years, was paved. Few months later the pavement unexpectedly lifted and cracked visibly. The diagnosis was viscous yielding of the reinforced concrete floor, subject to a considerable permanent load. The floor lowered and required the pavement itself to take on a structural role, subjecting it to compressive stress up to buckling phenomena. This was confirmed after inspection of the space between the vault and the floor: some of the 20 metal "safety" tie bars buckled because of compressive stress, so that a part of the reinforced concrete floor was resting on the vault below it.

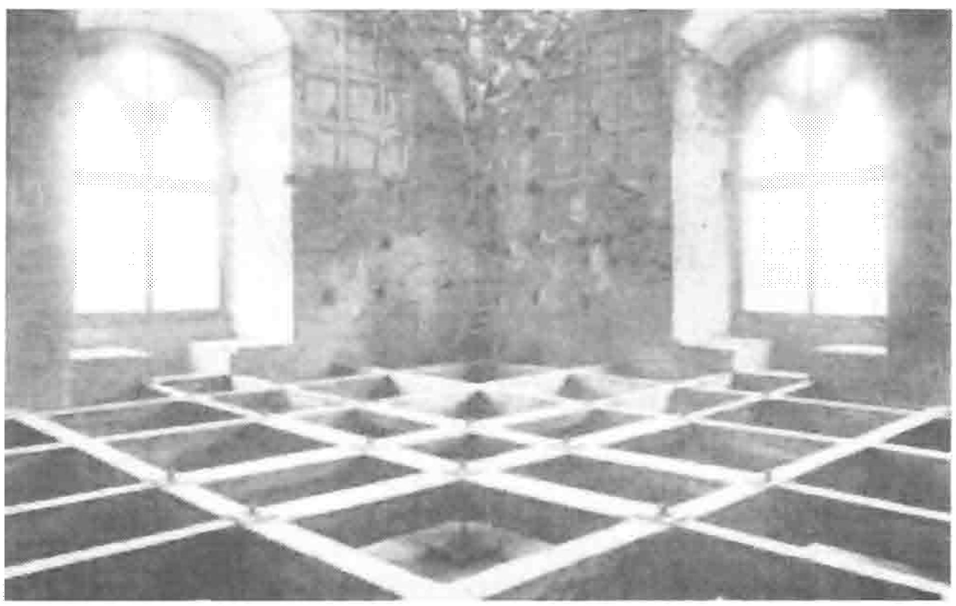


Figure 6. The 1925 concrete grid-beam solution

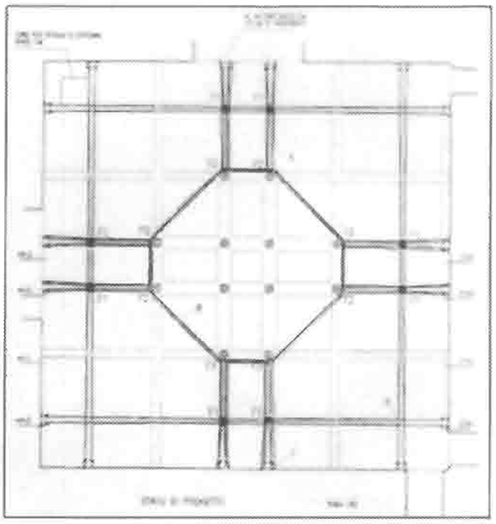
As first intervention, floor-vault connections were modified in order to make them working as struts, as well as tie bars. The embedding concrete top was removed to leave the connections free to slide vertically only in one direction.

The question was about the new structure to be realised alongside the existing floor, minimising any further yielding and having only 27 cm available between the vault and the floor at the crown.

The solution was an "octagonal ring" about 500 cm in diameter of stainless steel, set-up of bars and struts, all within the extrados of the vault and the intrados of the floor.

Eight pairs of diagonal tie rods converge from the upper edges of the grid to the ring.

In this way, the ring ensures to the tie bars the structural continuity, going around the top of the vault. The cables can be properly tensioned only by adjusting the eight stainless steel struts. A large screw at the end can be used to lengthen and buck the struts, constrained by the reinforced concrete floor above.



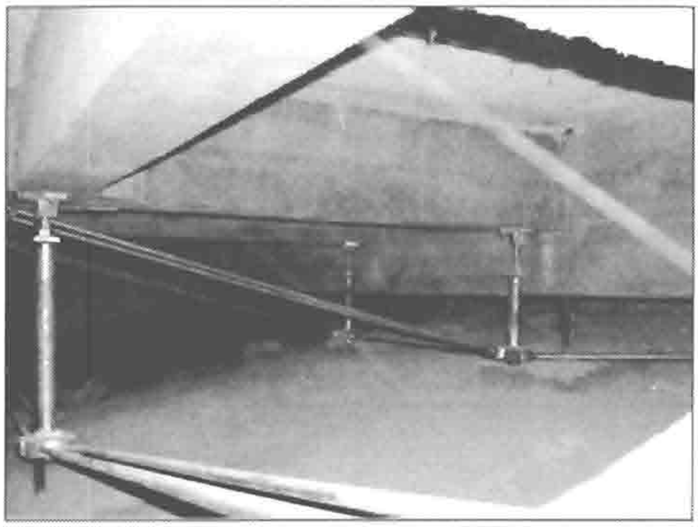


Figure 7. The 1996 active steel cable solution; *a)* scheme of stainless steel cables ; *b)* Detail of the telescopic struts

South-East Tower

The same principles were applied to the case of the hip wooden roof at the South-East Tower. A steel rope middle square connects the steel cable reinforcements placed underneath the four rafters, where a steel jack realise a new middle bearing foe for each beams.

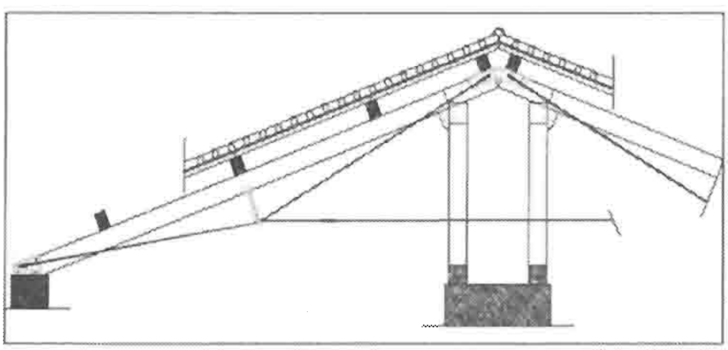


Figure 8. a) scheme of stainless steel cables ; b) View of the rafter with the telescopic struts and the steel cable consolidation.

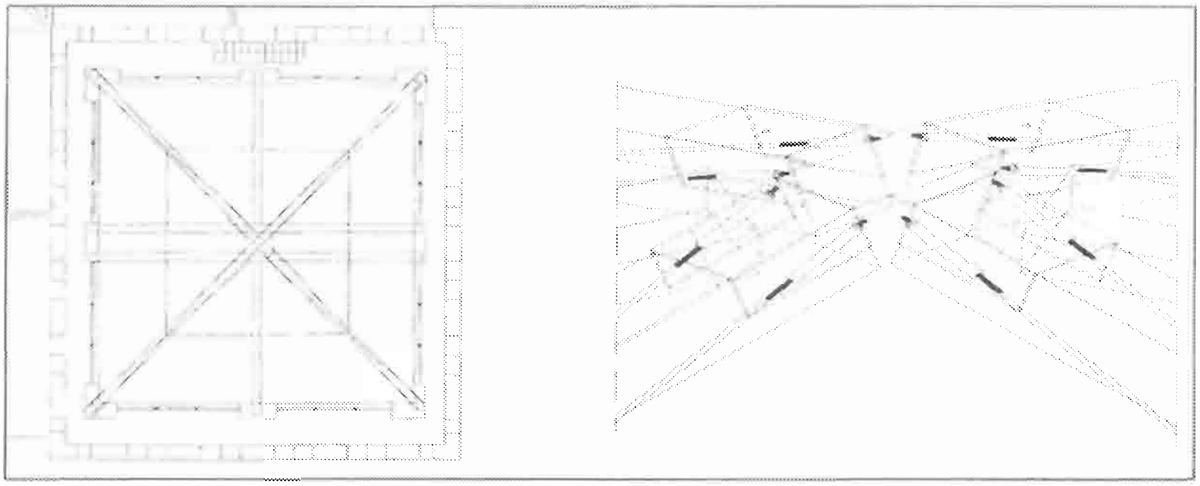


Figure 9. Scheme plan and details of the edges.

Medici Castle, Melegnano, Milan - Italy

A consolidation project was developed in order to restore an adequate safety margin and permit public access.
After inspection of hidden parts, it was clear that replacement of the wooden chains with steel chains did not restore the load-bearing capacity of the vault and therefore its safety.
It was partly due to the wooden chains intersecting the vault and decreasing its resistance: they were left in place even when they no longer had a structural function, thus creating a sort of continuous weak joint.
This takes on a greater importance in the "pavilion-shape" vaults, because they behave almost like two perpendiculars arches spanning the distance between the walls.
The intervention involves restoration of the monolithic nature of the vault: at first the demolition of the wooden chains (working on small sections at a time), then replacing them with new masonry scarfed with the existing masonry.

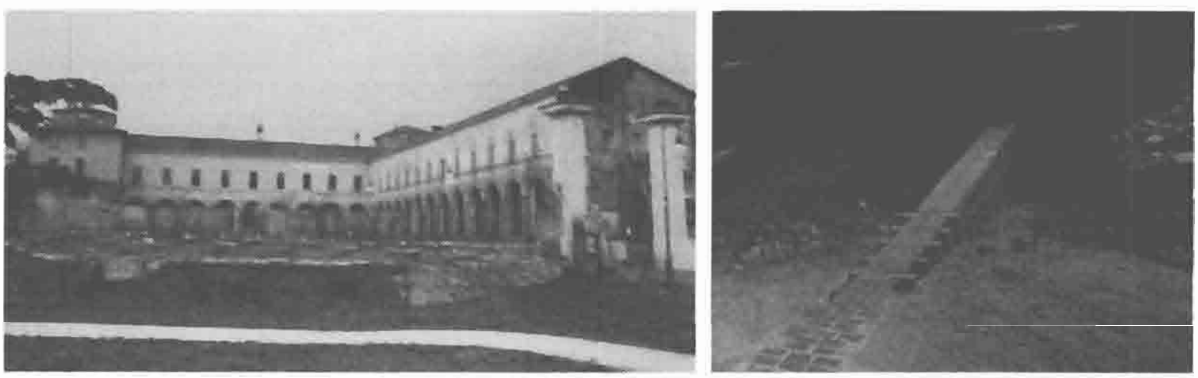


Figure 10. *a)* View of the castle from the inner court; *b)* View of the new masonry interventions.

After that, to increase the load-bearing capacity and safety of the vaults, a new technique, called "Reinforced Arch Method", was suggested by the author.

The principles of this technique, developed by the author for structural consolidation of arches and vaults, are briefly illustrated below.

As well known, arches a vaults fail by a collapse mechanism of four hinges. Different blocks of the arch transmit a compression force one to the other, and as long as that force stays within a certain "core" of the section, all the stresses across the section will be compressive. If the resultant load moves out the central zone, the voussoirs attempt to separate as they are enable to transmit tensile stresses. Thus the cracked section represents a hinge-point. While a three-pin arch is still a statically determinate and a satisfactory structural form, the fourth hinge converts the arch into a mechanism and collapse occurs. The problem can be approached by preventing the formation of almost one family of hinges (the extrados or the intrados ones), introducing a structural cable able to carry on tensile stresses.

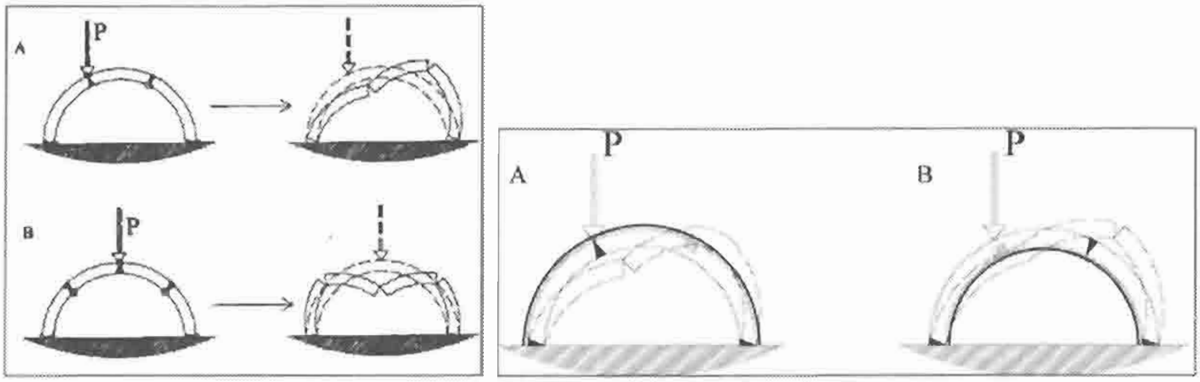


Figure 11. Collapse mechanism for arches.

The flexural limited resistance of the masonry can be overcome by introducing "passive" reinforcing steel in the arch construction, making it able to sustain substantial bending moment in addition to axial loads, but a better application of the method is the use of post-stressed cable elements. Loading the vault in radial direction the cables increase its compression and improve its resistance to pressure-flexure induced by incidental loads.
The consolidation effect is realised by simply placing one or more cables alongside the extrados surface of the vault. The cables are fixed to the masonry of the supporting walls and then post-tensioned. This fact implies the transmission of radial self-equilibrated forces between the curved cables and the arch. The masonry of the arch will be consequently compressed and the distinct blocks will be helped to better support flexion, especially originated by asymmetrical conditions.

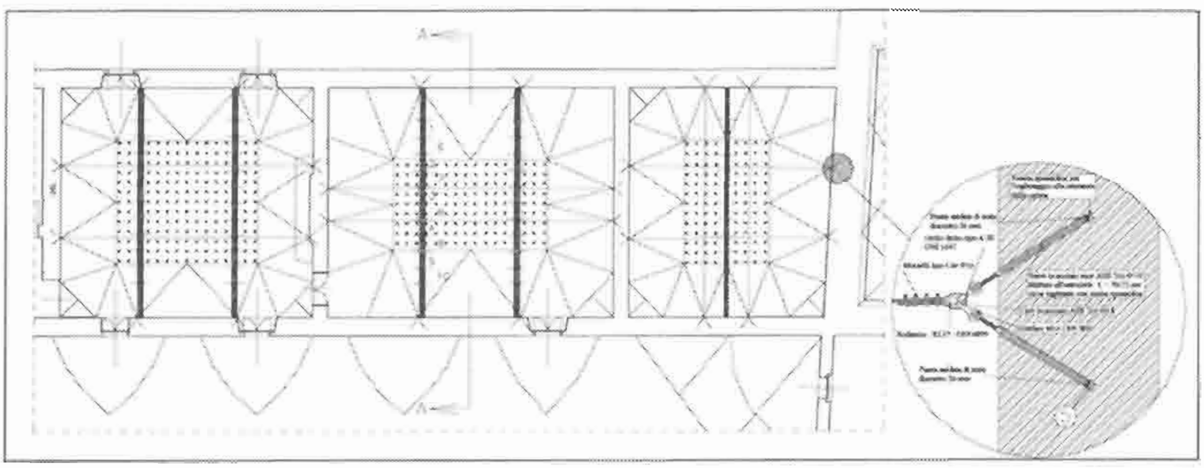


Figure 12. Floor plan and detail of the "Reinforced Arch Method".

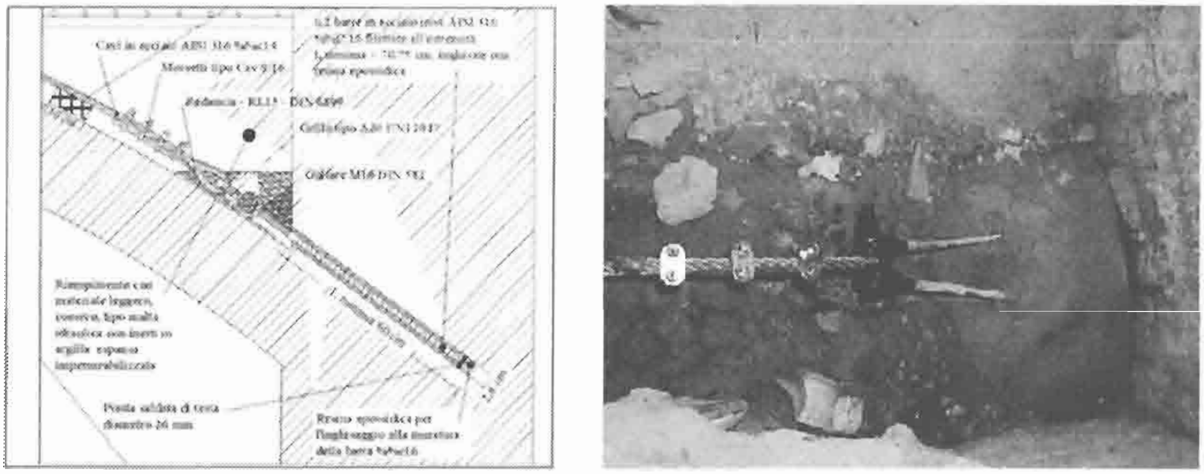


Figure 13. Detail and view of the stainless steel anchor to the masonry wall.

As shown by experiments and calculations, the technique achieves equivalent or in some cases better results than those obtained with the more traditional (but much more invading) method of passive reinforced concrete layer poured over the vault, from the extrados.
Using cables by the Reinforced Arch Method, the additional structure does not interfere with the in situ material and respects the structural behaviour of the existing building.
The method permits a recognisable sign of contemporary interventions.
The experimental tests showed that it is possible to increase the ultimate load of the arch, even preserving reversibility in the consolidation procedure and respecting the original static building behaviour. Moreover no addition of weight is needed, that is a relevant factor in seismic areas, and no modification of shape is requested. The confining actions can be calibrated where and how it is necessary.
The "reinforced arch method" acts in this direction, by using stainless steel cables as additional consolidation element, thus providing durability and considerable strength with minimum increase of mass. Moreover it represents an easy, quick and quite cheap innovative instrument for removable consolidation.

Trezzo d'Adda Castle, Milan - Italy

The thin and high wall was planned to be involved in a new development of the all castle uses. A quick and low cost solution was asked to be designed. The adopted solution consists of a double set of cross diagonal backstays from the sides to carry on tensile stresses.

The steel cables intervention has soft visual impact and effective results.
Stainless steel's versatility, strength and durability permit the consolidated structure to be easily maintained and kept under control over time by progressively tightening tie bars.

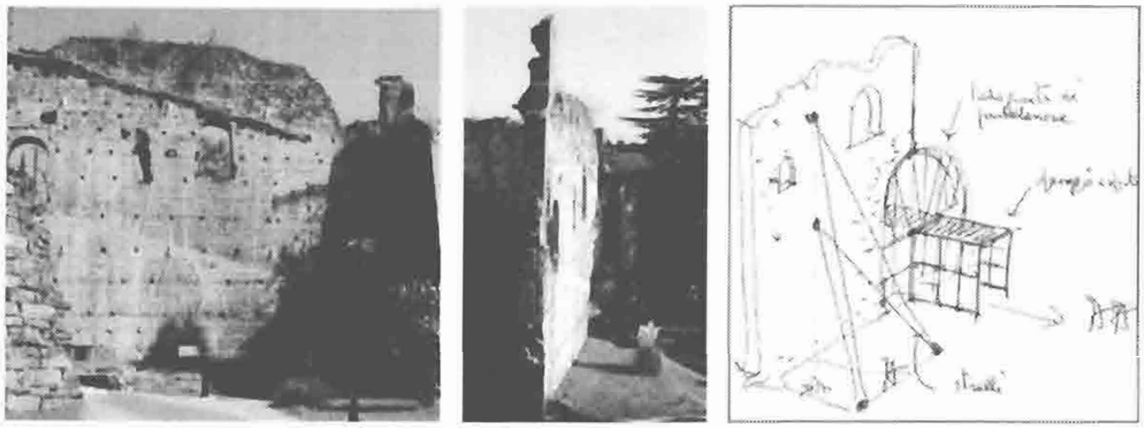


Figure 14. The masonry wall before the intervention and sketch of the solution

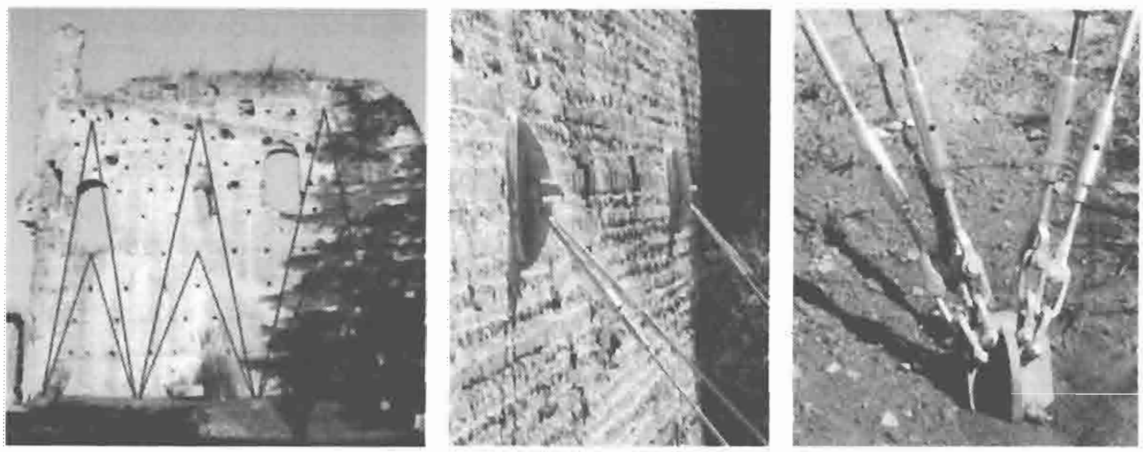


Figure 15. Scheme of the steel cables placement and details of the wall-anchors and the ground- anchors.

Tatev: Monastery and Castle - Armenia

From its construction to the earthquake that in 1931 destroyed most of the buildings, Tatev monastery has been a very important centre and for twelve centuries its cultural skills have been wildly appreciated.

Figure 16. View of the Monastery

The new use of the structures, the increasing tourist pressure and the seismic vulnerability of the area forced to reconsider the structural qualities of the buildings in order to asses the needed strengthening works.
The attention had to be focused on foundations, on damaged buildings to host the service premises and on the library and the principal church.
The southern monastery buildings rest directly on a basaltic crown that shows the tendency to slide down. This rock mass is characterized by discontinuities causing relative movements of the stone blades. During an earthquake, the rock elements are free to move in a random fashion in all directions improving the seismic motions and increasing the destroying effects on the upper buildings.
The consolidation project provided first to a rock reinforcement by grouted rock bolts.

Figure 17. Base-rock to consolidate.

The anchor bars are to connect two or more rock blades in order to prevent them from going away. Around each bar, 70 cm far from its end are to be fixed a synthetic rubber sealing that will avoid the pumped epoxy resin from overflowing. The bar is placed till the very bottom of the hole and will be slightly pulled to close hermetically the borehole's final section; then the epoxy resin is forced in. On the other side, the bar is tied to the anchorage system by using a sleeve so that it will be possible to remove the anchor plate after having fixed and tensioned the bar. Doing this, the strengthening system is not visible.

Figure 18. Consolidation of the base-rock

For the structural consolidation of ancient arches the common technique (reinforced concrete layer) wasn't used: it is very invading and modifies strongly the mass and the stiffness distribution in the structure. The new active consolidation procedure, the "reinforced arch method" has been suggested. It has to be underlined that this technique not only is a strong help for the ultimate resistance and ductility, but no new mass is added in the reinforced structure. This is particularly useful in a seismic areas like the current one.

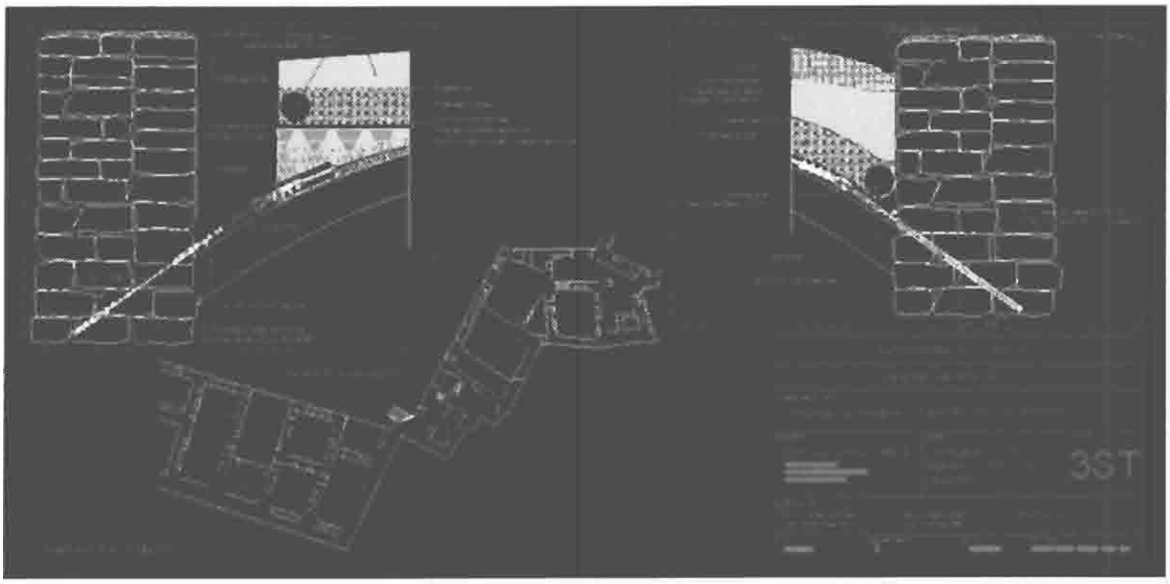


Figure 19. Consolidation of stone voults

Anberd Castle - Armenia

The consolidation interventions had to preserve the imagine Anberd Castle as ruin.
The project mainly focused on the stability of the external walls, opening out from their position. First of all, orthogonal inner walls were raised at 2 meter height and were connected to the existing external walls throw steel anchors.

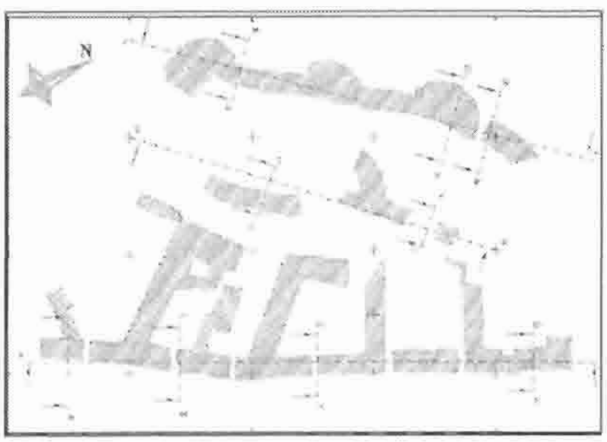


Figure 20. View of the castle and ground plan.

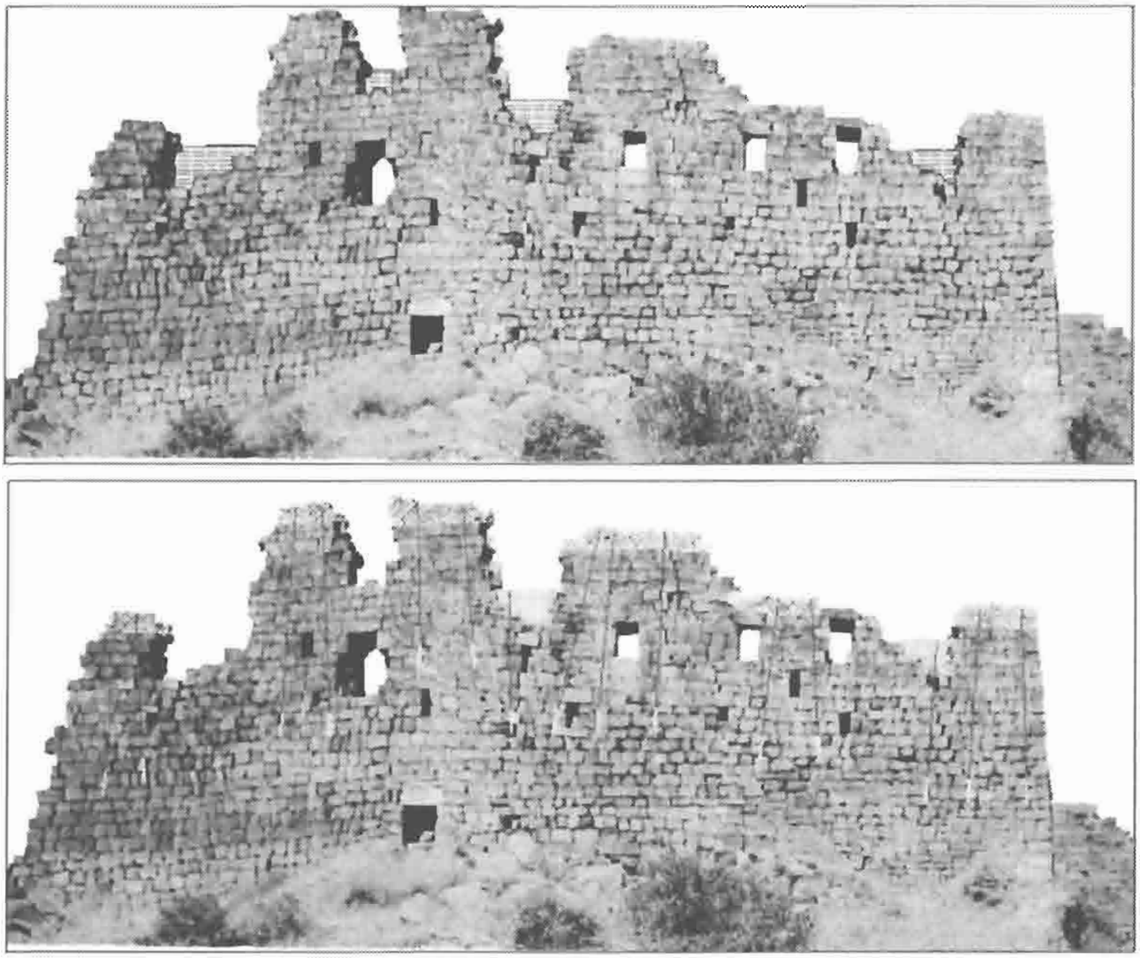


Figure 21. Scheme of south east wall interventions: edges reinforcement of the masonry ridge caps, integrations, steel bars consolidations.

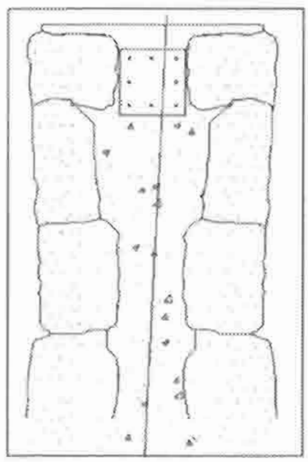


Figure 22. Outer and inner cables solution.

Than, same new parts of masonry were rebuilt to avoid local weakness and the masonry ridge caps were reinforced.
Stainless steel bars consolidation was realised to contrast the ongoing mechanism. The steel elements are led from a new connecting concrete beam from the top to the root. By the mean of post-tension, it is possible to resist displacement and restore a safety condition.

Medioeval towers

<u>*San Dalmazio Tower, Pavia - Italy*</u>

The XI century brick tower, 45 meters high, showed many local damages, lacks in the masonry and long vertical cracks along the four walls.

According to the strengthening project, a new inner steel tower was built inside the masonry one. So, a "tower within a tower" was realised. The new one is fully exposed and completely renewable but entirely located inside the ancient one: it cannot be noticed from outside but declares its presence for of a number of discrete signals.

The dead load of the masonry is partially transferred to the inner tower by means of about 300 prestressed sub-vertical cables, laying in the thin space between the masonry and the steel tower. According to the culture of preservation, the new construction works alongside the existing structure, is reversible and easy to be understood as sign of current culture. The new construction collaborates structurally with the masonry tower: it provides static assistance by removing part of the vertical load, increases resistance to horizontal loads and improves ductility, allows inspection and ongoing planned maintenance for both structures.

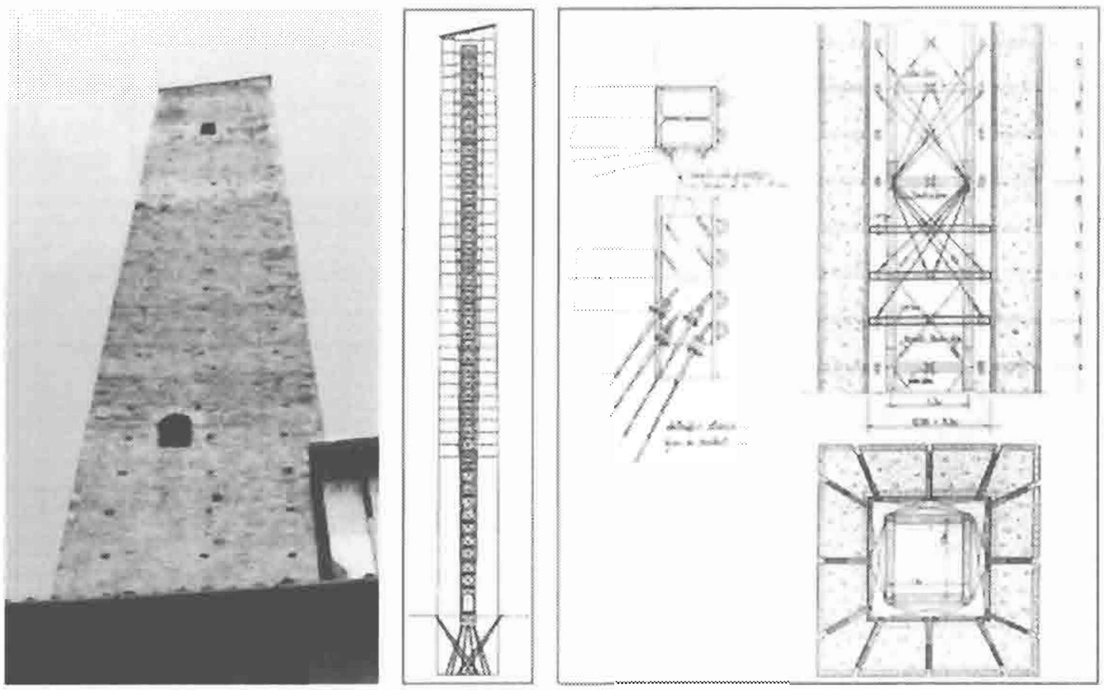


Figure 23. View of the medioeval masonry tower from below and design details.

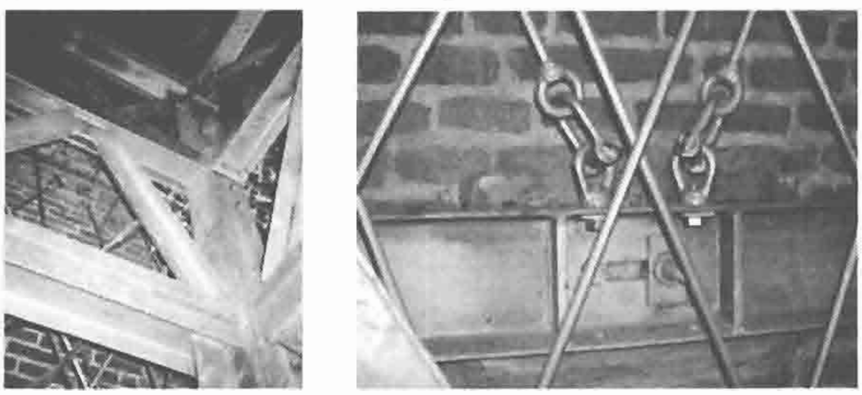


Figure 24. Details of the inner steel tower.

In the strengthening project on this masonry tower, additional stainless components were applied as tie bars through the existing holes in the masonry. The aim is to confine laterally the walls by adding horizontal loads, thus connecting the vertical layers of the masonry.
About materials, the inner tower is partly built of carbon steel, but is stainless-steel made in the most air-exposed areas and in the closest parts to old masonry.

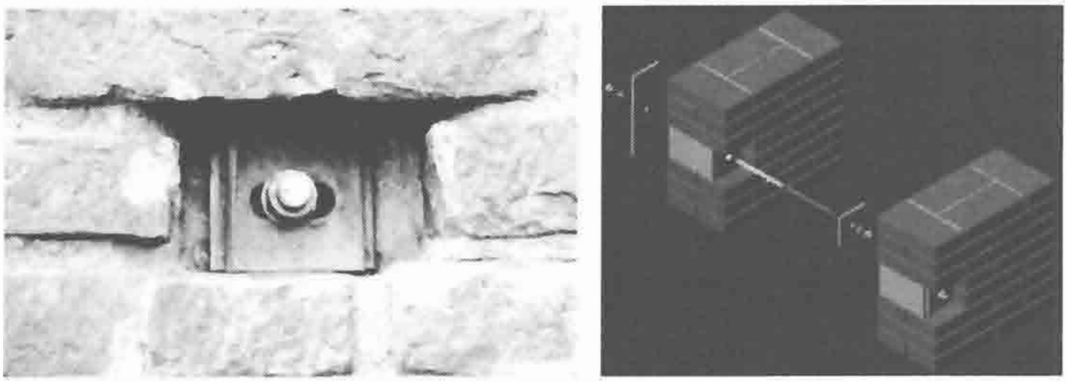


Figure 25. Tie bars through the existing holes in the masonry.

Polpenazze Castle, Brescia – Italy

The following case is another example of tower in a tower. While for San Dalmazio the steel inner structure has a structural task to help the ancient one, in case of Polpenazze tower the masonry walls did not need such kind of contribute. Since the walls shown to move away one from the other and the wooden floors did not contrast this movement, a tie bars system was proposed and it was considered as enough to solve the structural problem.

Figure 26. *a)* External view of the masonry tower; *b)* inner view with the applied tie bars system

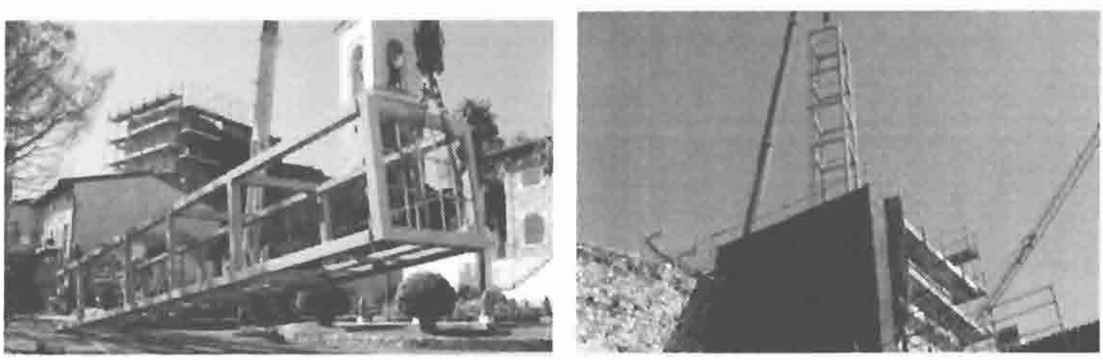


Figure 27. Insertion of the lift and stairs tower

In this situation a new steel inner tower was realised only as the stair an lift service, with no consolidation mean.
As can be observed from the picture below, the new structure does not interfere with the ancient walls, as minimum impact intervention.

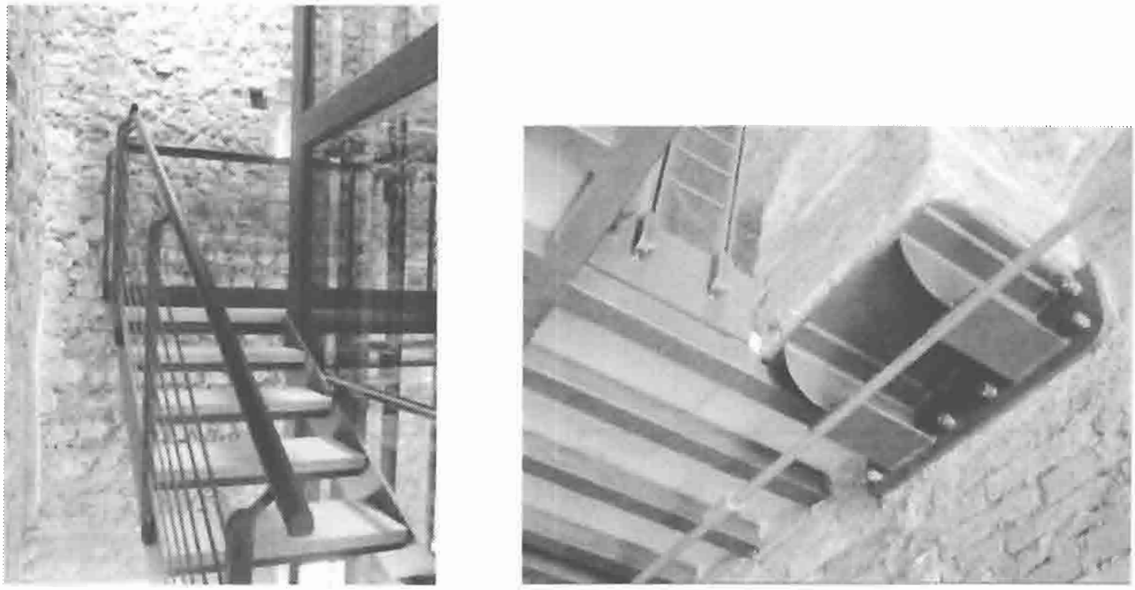


Figure 28. Details of the stair- lift steel tower.

Montorio Castle, Verona - Italy

Among the several conservation problems, a specific question to answer was how to consolidate the stone brackets. Most of them were strongly cracked and some already collapsed. Their damage was partially due to the material, partially to human and accidental causes. Substitutions or reinforcing bars to embed were considered too riscky, and an external solution was chosen.

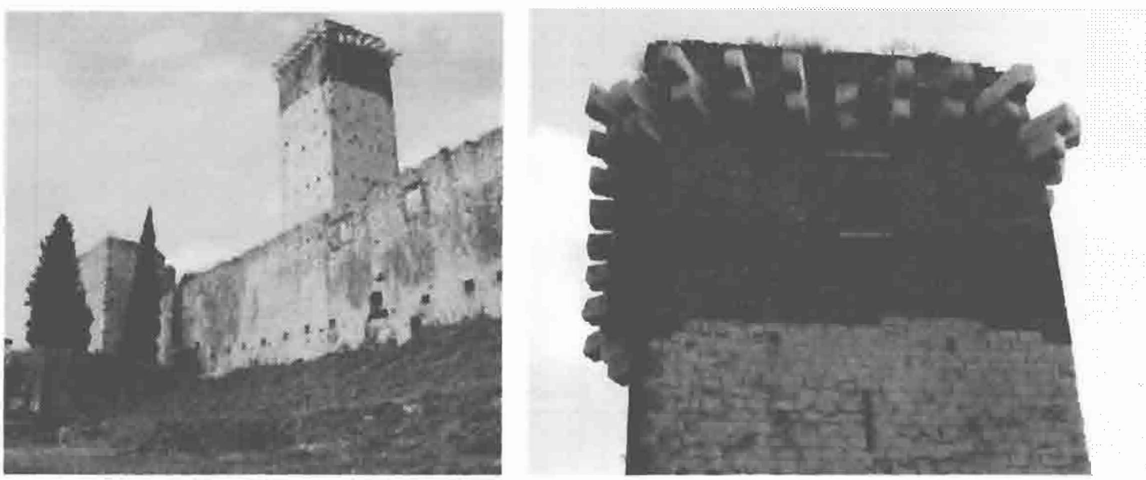


Figure 29. The damaged brackets.

Steel cable stirrups were suggested to support and costrain the damaged brackets. By the connection to the masonry wall, the steel cable stirrups help to sustain substantial bending moment, but a better application of the method is the use of post-stressed cable elements. Afterwards, a post-tension can be add to the cables to post-compress to the brackets.

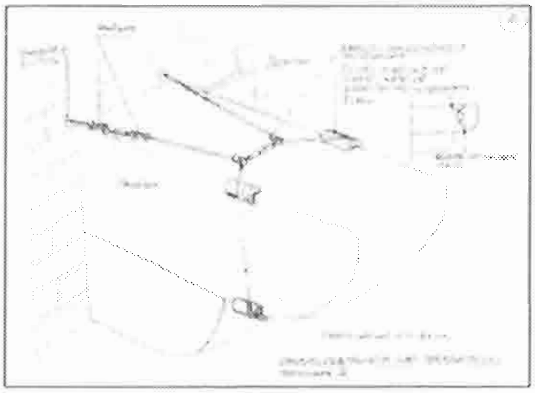


Figure 30. Steel cable stirrups to sustain the brackets.

Portoni della Bra', Verona -Italy

The swallow-tailed merlons shown to be unbalanced outer. The usual solutions, as grout injections, stays, inner or external steel cables, were not adoptable. A soft, removable solution was suggested. It was chosen to apply new eccentric loads by applying in order to re- stabilise the wall.
A tubular beam connects the opposite swallow-tailed merlons, with a pin-join-end and a roller-end to allow horizontal displacements due to thermal expansion. Two vertical cables are connected to this beam. One is jointed with a telescopic struts in order to apply the planned force to the merlon.

Figure 31. External view of Portoni della Bra'

Both cables end in a steel beam used as proper ballast, anchored in a couple of L shape beams placed on the tread alongside the existing walls but with no nogs.
Both tie rods have a tendon to regulate the force contribute as need.

This intervention is planned in order to avoid its sigh from the street below and in order to let longer the use of the structure as walkway.

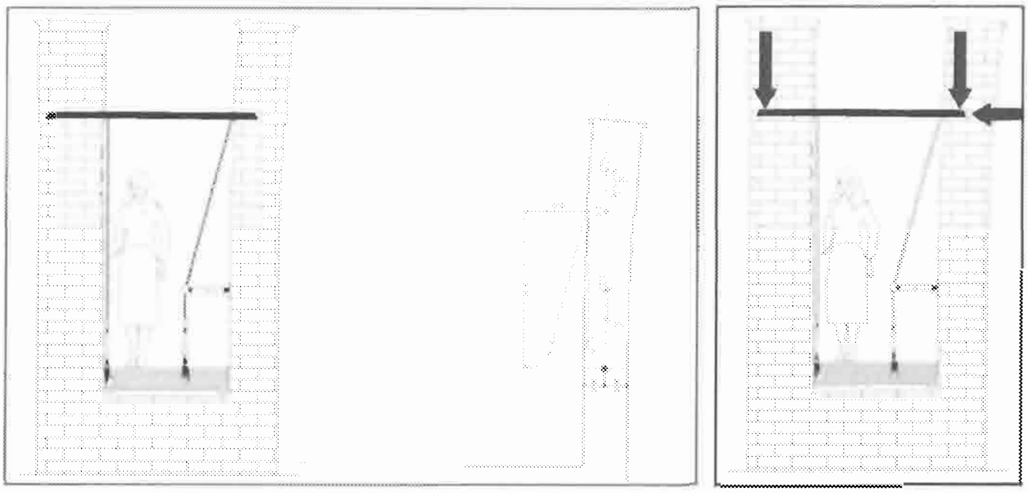


Figure 32. Design of the external cables with "no connection" to the walls

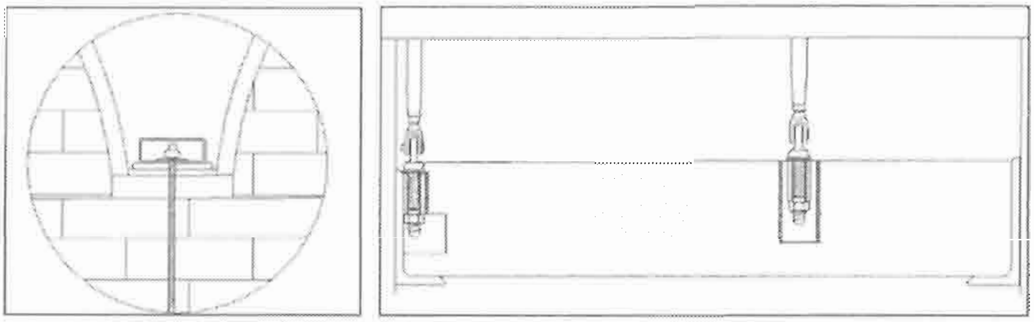


Figure 33. Details of the anchor

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