THE "REINFORCED ARCH METHOD":
A NEW TECHNIQUE IN STATIC CONSOLIDATION OF ARCHES AND VAULTS

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Abstract

The principles of a new technique developed by the author for structural consolidation of arches and vaults, called "Reinforced Arch Method", are illustrated along with some full-scale experimental tests carried out and some applications in conservation interventions. Technological and structural aspects are illustrated in relation to some recent applications.

Introduction

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.
Therefore, the actual approach to restoration leads to the requirement of new "active" reinforcement technologies, able to work in parallel and in cooperation with the existing structures, and moreover characterized by the fact to be light, durable and possibly removable.
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 remouvable consolidation.
The method was tested with experimental full-scale investigations and a certain number of applications in restoration works were performed. Theoretical investigation and practical aspects could therefore be correlated.

The "reinforced arch method": principal aims and technical aspects

As well known, arches a vaults collapse by a collapse mechanism of four hinges (Figure 1).
The different blocks that form the arch transmit a compression force one to the other, and as long as it 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. In other words, the point through which the thrust transmits between the voussoirs approaches one of the side surfaces.

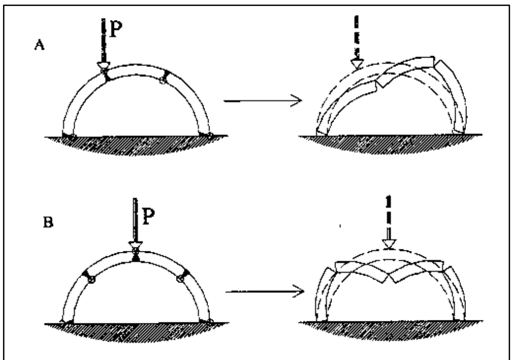

Figure 1

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.

It is possible to prove that the formation of the hinges between voussoirs take place alternatively in extrados and intrados.
Anyway, even if the collapse does not occur, the reached deflection may appear unacceptable.

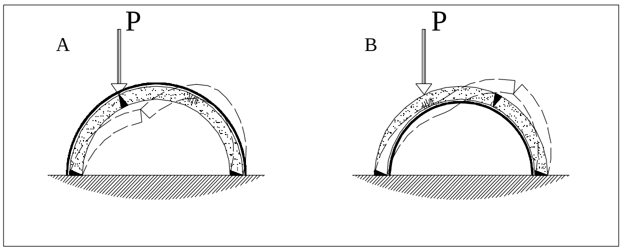

Figure 2

The problem can be approached by preventing the formation of almost one family of hinges (the extrados or the intrados ones). It can be achieved by introducing a structural cable that is able to carry on tensile stresses (Figure 2).

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.
As the compression resistance of the masonry is usually high, it is possible, and not risky, to strongly rise the axial internal load in the masonry, avoiding the formation of the four-hinges collapse mechanism.
All the structural section of the masonry will be more compressed as in the original state, thus postponing the formation of the cracks.
As much the tension in the cables, as much the limit resistance of the arch.
The main purpose of the method is to modify the distribution of loads acting on the arch so that the combination of the old loads plus the new loads will be the "right one" for the given geometry of the arch. The aim is to bring the thrust line of the forces acting between the blocks as near as possible to the central line of the arch, minimising the eccentricity of the internal load.

When it is not possible to work from above, placing the cables on the extrados, it is possible, even if more difficult, to work from the intrados. The steel cables can be connected to the masonry from below by means of a system of threaded bars, thimbles, fasteners, and eyebolts, all made of stainless steel. Afterwards, a system of screw couplings can be used to add post-tension to the cables and, at the same time, post-compression to the vault.

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 the passive reinforced concrete layer poured over the vault, from the extrados.
Using the cables of the reinforced arch method, the additional structure does not interfere with the in situ material and respect the structural behaviour of the existing building.

Stainless steel's versatility, strength and durability permit the consolidated structure to be easily maintained and kept under control over time by progressively tightening the tie bars.
The method permits a recognisable sign of contemporary interventions.
The reinforcement so applied works as an "active system", which allows calibrating the actions as it needs and, if loss of pre-stress takes places, allows re-tensioning.

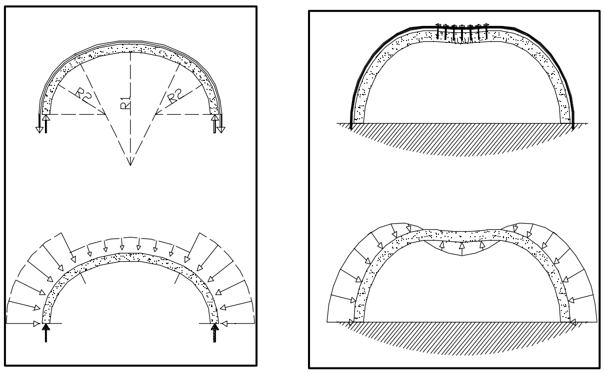

Figure 3

Even in case of variation of curvature along the arch ring, the reinforcement cables act in a beneficial way, as the mutual forces applied by the cables perpendicularly to the surface are maximal exactly in the zones where the radius of curvature is minimal (Figure 3).

It has to be noticed that the proposed consolidation technique works well only if the piers are able to sustain the lateral thrust induced by the arch. If they were too weak, the arch would break in a section somewhere between the springing and the keystone. This means that, in this case, the reinforcement cables have to be prolonged till the base of the piers.

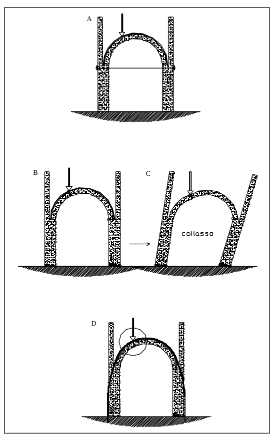

Figure 4 a

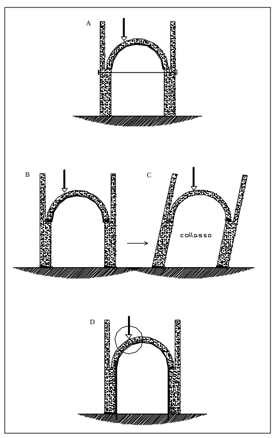

Figure 4 b

They have to help balancing load across the spans and thus they have to be placed up to the spans (Figure 4a, 4b).
In some case shear failure may take place in the arch and a sliding failure mechanism can occur.
The "reinforced arch method", although less efficient than in the flexural induced collapse case, still bring to an increase of ultimate load.

The experimental tests

A series of tests were undertaken at the Politecnico di Milano to investigate the static behaviour of arches strengthened by using "reinforced arch method". It has been the first step to assess the method before proceeding to real applications on historical buildings.
The aim was to compare the new technique to traditional strengthening technologies on the basis of confrontation of collapse mechanisms and ultimate load capacity.

Twelve masonry arch specimens, 200 cm span and 12 cm thick were built.
Four reinforcement types were compared:
plane arch specimens (1); specimens strengthened by a layer of extradossal collaborative reinforced concrete with steel connectors between masonry and concrete (2); specimens strengthened by a layer of extradossal collaborative reinforced concrete, connected to the arch only at the basis, with no intermediate connectors (3); specimens strengthened by two unbonded steel cables, placed in extrados and post-tensioned (4).

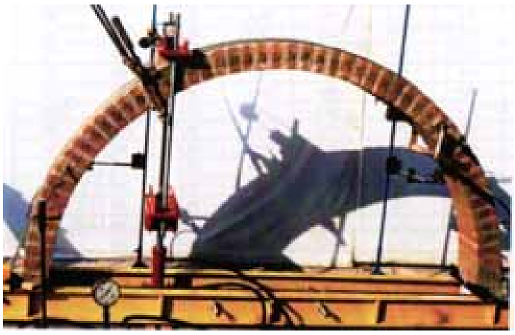

Figure 5

Figure 6

All the arches were vertically loaded either at mid - span and either at a quarter - span, using hydraulic jack and a steel tie rod. As contrast element, a double C beam was used to take up the loads at the basis.
Cycles of loading and unloading were performed and the displacements in six points were measured (Figure 7).
The compressive strength of the adopted bricks was 28 daN/cmq (four bricks pile compression test). The concrete slab was 4 cm thick, with $\phi 6$ /15x15 mesh and R_{ck} 250 concrete. The connector bolts were ϕ 10 bars placed every 22 cm. The cables adopted for the "reinforced arch method"(4) were two ϕ 12 zinc-plated steel cables with 4% elongation limit and 6000 daN/cmq collapse load, tensioned by high-tensile bolts connected to the base beam.

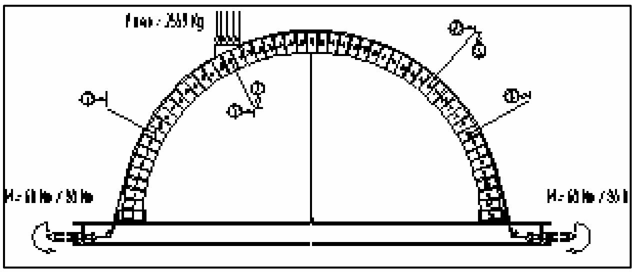

Figure 7

Test results, analysis and comment

Test results (some of them summarized in Table 1, with reference to a quarter-span load) show a strong increase of the ultimate load in all the consolidated arches.

	P limit	displ 1	displ 2	displ 3	displ 4	displ 5	displ 6
1- plane arch	191	0,04	0,84	1,35	1,16	0,60	1,50
2- arch + collaborative reinforced concrete	3379	3,78	10,60	13,34	15,20	6,84	13,00
3- arch + collaborative reinforced concrete + connectors	2948	2,10	5,82	7,33	8,17	3,03	7,36
4- "reinforced arch" (M=60 Nm)	2559	5,18	20,22	19,70	23,10	10,50	16,73
5- "reinforced arch" (M=80 Nm)	2886	1,30	11,64	12,75	11,98	5,03	9,42

Table 1

Both the limit resistance and the ductility of the arch system can be strongly increased by applying a higher tension to the confining steel cables. The last two rows of Table 1 show the

beneficial effect of a higher tension induced in the cables, applying a torque of 60 or 80 Nm to the end fasteners, respectively. Obviously a higher torque could be applied.
With respect to other systems, the arches reinforced with cables show a higher ductility and a lower residual inelastic deformation when discharged. (see diagrams of Figure 8a and 8b, respectively referred to an arch consolidated with traditional concrete and an arch consolidated with cables).

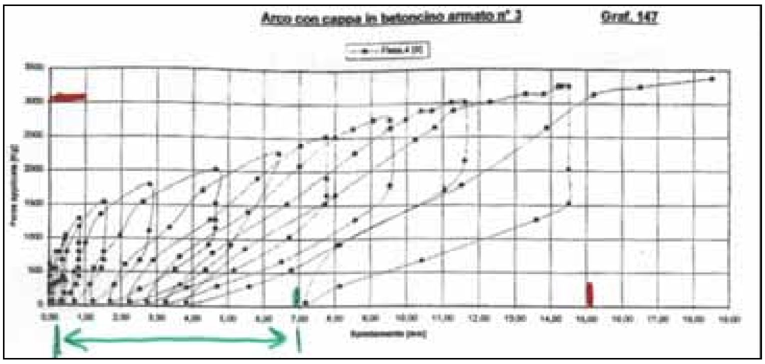

Figure 8a

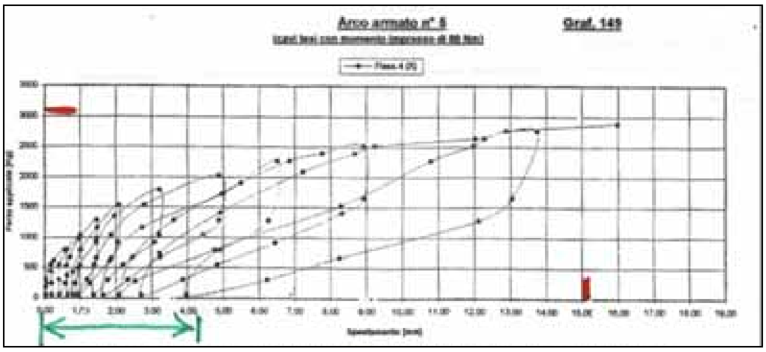

Figure 8b

It has to be noticed that the proposed method affects the usual four-hinges collapse mechanisms. The last hinge that leads to collapse, in fact, is usually due not to the formation of a flexural crack caused by excessive traction, but to local compression collapse failure. (Figure 9 a, b).

Figure 9 a

Figure 9 b

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.
More test have to be made on stone masonry arches and in arches with shapes different from the usual circular one. Full-scale tests are needed also on differently shaped vaults.

To analytically verify the collapse load of the tested cable-reinforced arches a simple mathematical model has been used. A cinematic approach to limit analysis was adopted, using various attempts four hinges geometrical arch configurations. As the position of the four hinges is assumed, the motion of the three rigid blocks of the mechanism can be easily determined by finding the rotation around their instantaneous centres. It is thus possible to obtain the components of the first order movement in the vertical and in the horizontal direction, as graphically shown in Figure 10. The ultimate load of the arch is obtained by equating to zero the total work done by all the loads, either the vertical or the horizontal ones. Obviously, the radial loads induced by the cables have to be previously subdivided into components.

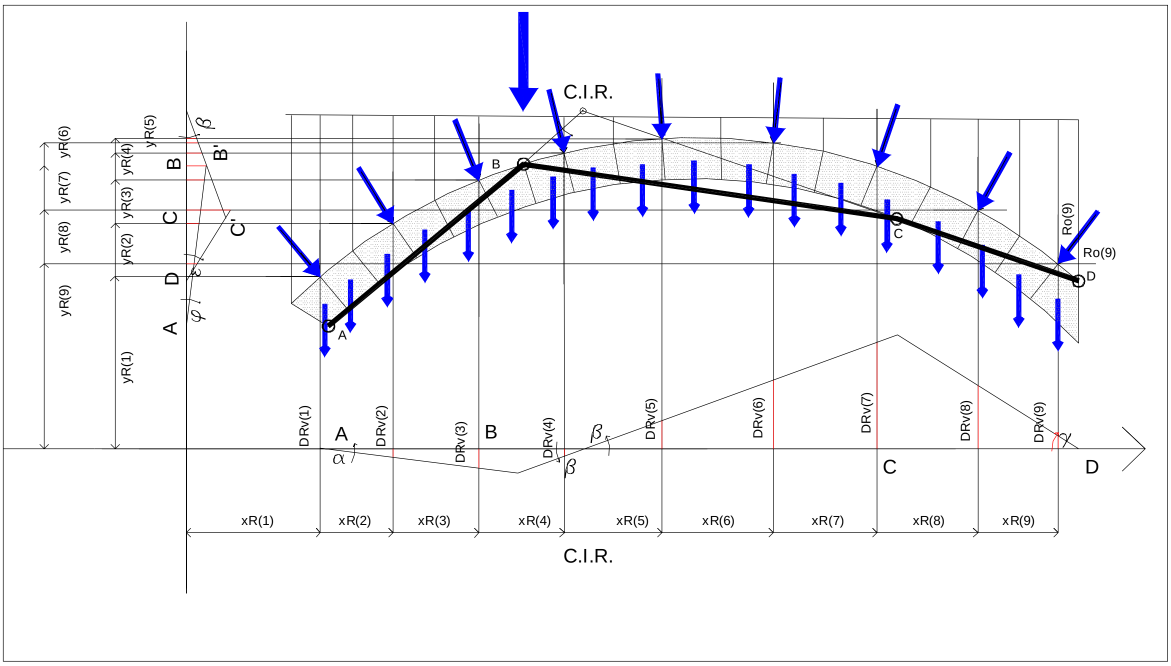

Figure 10

Repeating the procedure with different locations of the hinges, the “true” limit load will be found, as the minimal one among the possible ones.
The presence of radial forces induced by the cables, added to the vertical ones due to dead and live loads, was thus verified to be very effective in term of safety of the structure.

Applications of the “reinforced arch method” in consolidation works

Sogliano sul Rubicone (Forlì-Cesena)

This Romanic bridge could keep its safety only thanks to a structural protection scaffold built more than ten year ago. In order to restore an adequate safety margin and permit public access, a consolidation project was developed. Works will include rebuilding of crushed parts, stitching of cracks and restoration of the surfaces.
To strength the bridge, grouted tie rods and reinforced arch method cables will be adopted.

Figure 11

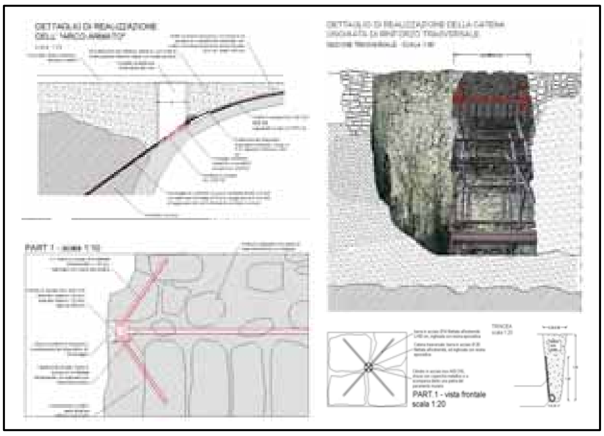

Figure 12

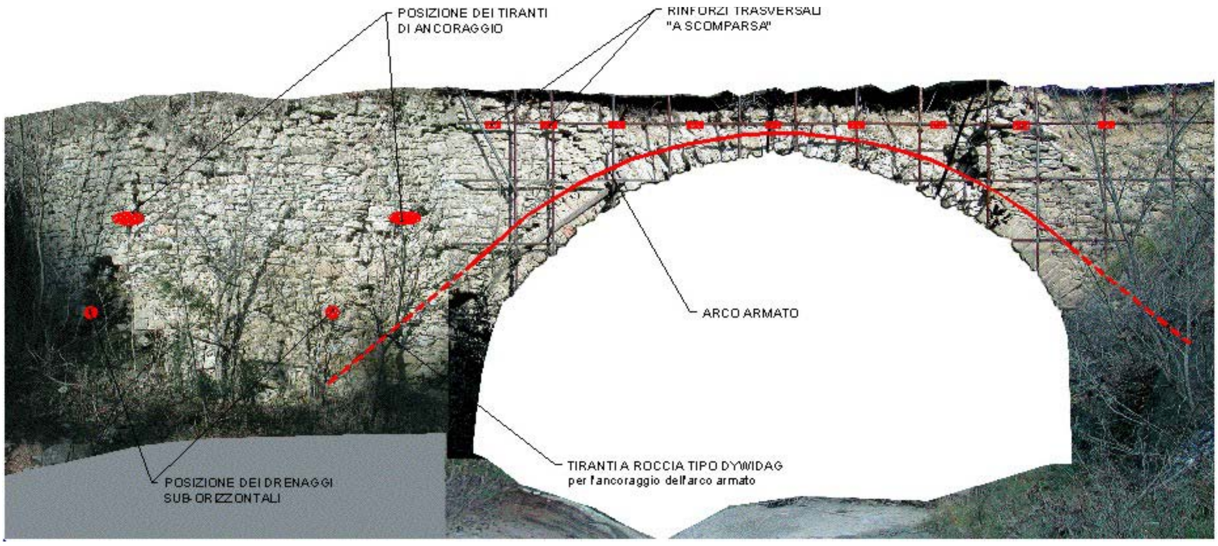

Figure 13

Bridge on Strona torrent, Postua (Italy)

The solution chosen for the consolidation of this three span stone bridge underline some additional innovative technological aspect involved in the method. The bridge could be consolidated to resist heavy first category traffic loads simply using seven stainless steel cables laid on the extrados. The reinforcing cables could be applied by removing only a little amount of soil below the road paving and simply drilling diagonal holes through the piers.

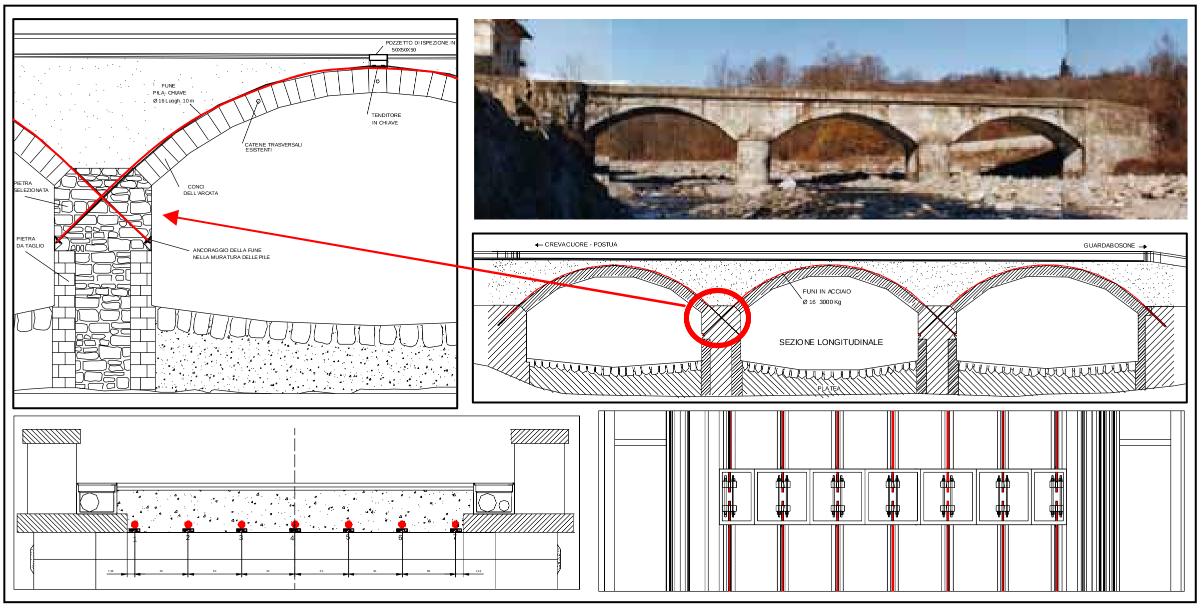

Figure 14

Manta Castle, Cuneo, Italy

The decorated pavilion vaults show a typical crack pattern caused by spreading of the abutments. The adopted cross distribution of cables of the reinforced arch method was particularly suggested to minimize the impact on intradossal frescos. The aim was to avoid permeations of mortar from above as a problem possible with traditional technologies.

The consolidating steel cables were located mainly in positions near extradossal arch ribs, as the most appropriate place to obtain an increase of strength.

Figure 15

Figure 16

Figure 17

Figure 18

Casa Giacobbe, Magenta (Milan, Italy)

The clawed barrel vaults were strengthened by “extradossal reinforced arch method”.
Various couples of stainless steel cables were placed at each segment of the vault. Turnbuckle was used to post-compress the vault. Problems related to permeation of mortars from above to frescos were so avoided, while ultimate strength was strongly increased.

Figure 19

Figure 20

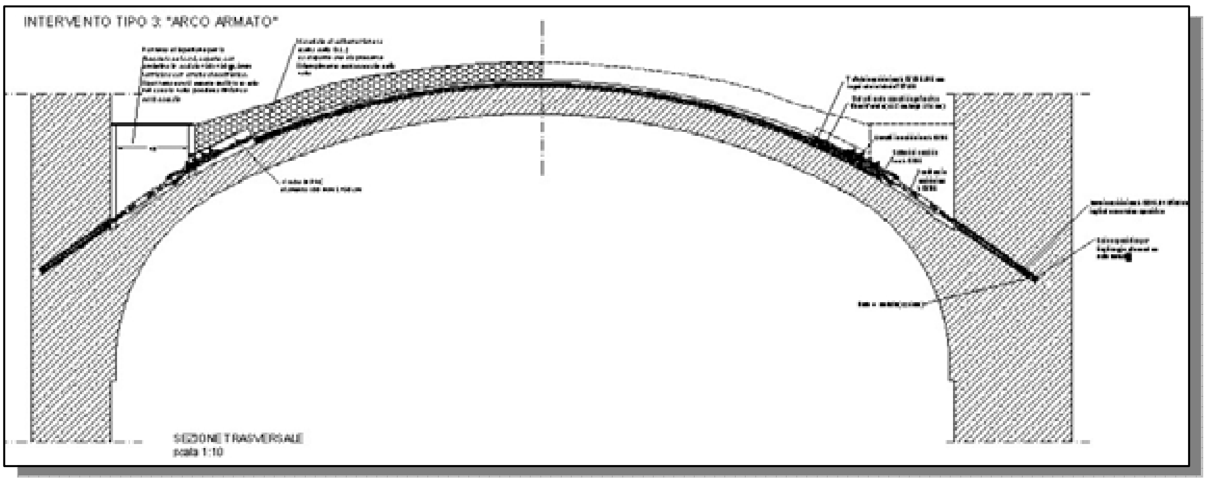

Figure 21

Villa S. Carlo Borromeo, Senago (Milan, Italy)
The seventeen-century Villa showed cross vaults strongly deflected above some cellar rooms. Because of a valuable overhanging marble flooring, it was impossible to consolidate the vaults operating from above. It vas compulsory to work from below.
An intradossal application was proposed, as a first carried out example of this technique: stainless steel cables were placed parallel to the intrados, in proximity to the groins and the main transverse ribs.

Figure 22

Figure 23

Monastero degli Olivetani, Nerviano (Milan, Italy)
This application on clawed barrel vaults can be distinguished from other examples because of the adopted method for post-stressing the cables, using wooden cuneus instead of turnbuckle.

Figure 24

Figure 25

Figure 26

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