EXPERIMENTAL TESTS ON CONSOLIDATION OF MASONRY BRIDGES USING "RAM-REINFORCED ARCH METHOD"

L. Jurina

Politecnico di Milano, ABC Department, Milan, ITALY.

e-mail: lorenzo.jurina@polimi.it

SUMMARY

In the consolidation of masonry arch-bridges the best goal is to obtain a uniform compression between all the blocks, without addition of mass or changes to the actual geometry, following the principle of "minimum intervention". The paper describe an innovative technique, called "RAM - Reinforced Arch Method", for the consolidation of masonry arches through the placement of post-tensioned steel cables, either at the extrados of the arch or at the intrados.

More than 500 small scale tests were conducted to verify the ability of the system to resist not only vertical forces but also horizontal loads, such as seismic ones.
Full scale applications of the technique are illustrated, such as the stone masonry "Sogliano" bridge, over Rubicone river, in Italy.

Keywords: *Bridges, consolidation, tensioned cables, seismic load, experimental tests, Reinforced Arch Method.*

1. INTRODUCTION

The study of arches is usually based on limit analysis that permits the determination of the safety factor related to the most probable collapse mechanism induced by the external loads.

The analysis of the collapse mechanisms is strongly related with the determination of the possible configurations of the funicular polygon.

In the last centuries many researches have been developed on the static behavior of arches, recently summarized by J. Heyman.

The limit analysis "safe theorem" states that if a thrust line can be found, which is in equilibrium with the external loads (including self-weight) and lies everywhere within the thickness of the arch, then the arch is safe.

The ultimate compressive stress of the material is not really the critical problem and, for this reason, its determination can be avoided, except in case of strong chemical or physical deterioration of the material. In most cases, in fact, the collapse of the arch is due to a global mechanism, not to a local fault.

This statement has been broadly supported by numerical and experimental evidence: the load that corresponds to the material collapse is usually much higher than the one that causes the collapse mechanism of the structure.

In most cases, also the drift between the blocks does not occur, since usually the thrust line exceeds the arch ring domain before the combination of axial and shear loads exceeds the local friction cone.

Therefore, the crisis of the arch is mainly due to the formation of plastic hinges, that alternate at the extrados and at the intrados of the arch itself.

The main possible collapse mechanisms of an arch are two: the first one involves the abutments; the second one concerns the arch itself, once the abutments remain fixed.

The overturning (or the horizontal translation) of the abutment is governed by the thrust acting on the abutment. In the illustrated case, the resultant of the forces in the right abutment goes outside from the cross-section and a rotation occurs, generating the collapse of the arch (Fig. 1 left).

In the second collapse mechanism, the thrust line is safe in terms of horizontal loads, but in various points it is tangent to the extrados or the intrados of the arch. Increasing the loads, a failure mechanism will occur with the formation of, at least, four plastic hinges. Four plastic hinges will form in a non-symmetric case (Fig. 1 right), while in a symmetric case five hinges will take form.

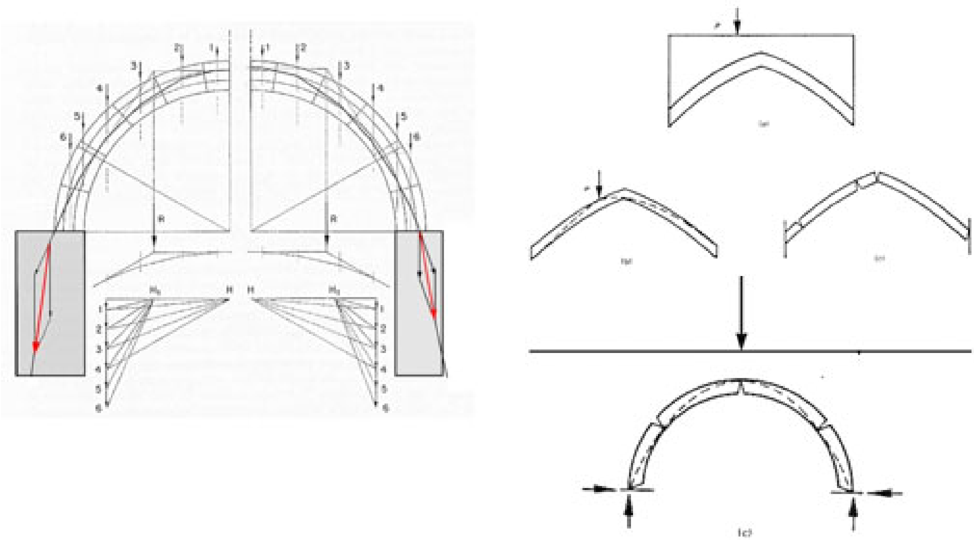

***Fig. 1**. Left: funicular polygon of an arch (A.Giuffrè, 1992); right: non–symmetric or symmetric loads cause the formation of four or five plastic hinges in an arch (Heyman 1966).*

2. THE REINFORCED ARCH METHOD: STATE OF THE ART

The reinforced arch technique seeks to oppose the formation of hinges, which open alternately on the intrados and the extrados, placing a stretched cable on either side of an arch or vault.

The method involves the setting of steel cables that will be placed in parallel to the consolidated arch, suitably connected to it, so as to pre-compress the segments, in order to make them able to withstand bending moments. It is possible to places the cables both on the extrados or the intrados, with the same results.

The extrados cable is simply leaning against the masonry surface, while the intrados cable must be duly connected to the single ashlar. When the cable is stretched, the system becomes immediately active, and it is able to apply to the arch a system of forces, with radial direction, capable of shifting the pressure curve toward the barycentre denying the possible hinges formation. The cable, whatever the geometric shape of the arch, tends to re-center the curve of the pressures, moving closer to the ideal state of pure compression between ashlar and ashlar.

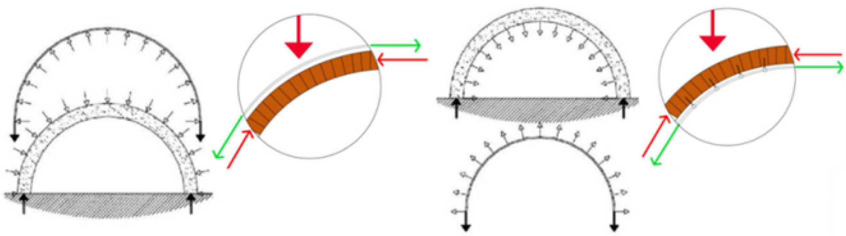

Fig. 2. Operating system of "reinforced arch" using extrados and intrados cables.

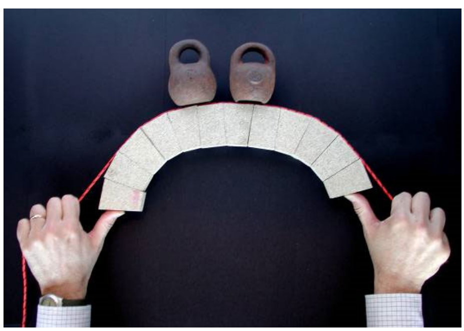

Fig. 3. Schematic functioning of "reinforced arch method". The ashlars are compressed according to the amount of tensioning given to the rope.

In the case of extrados applications, the cable can be stretched placing, between the cable and the vault surface, many forced wedges, uniformly distributed, or, more simply, using stretchers with right and left thread. In all cases a thin separation layer should be considered (usually fiber-reinforced mortar) for the cables support, while seeking to reduce friction by inserting, for example, a strip of Teflon between cable and masonry.

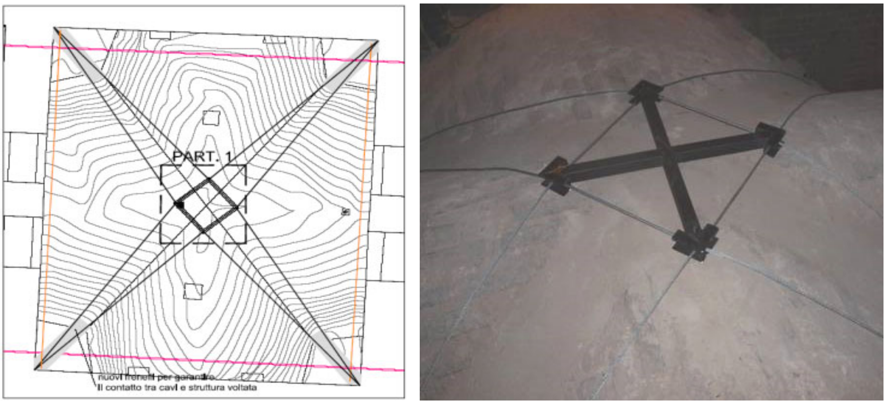

Fig. 4. *Reinforced Arch method applied to the vaults of Cremona Cathedral.*

Fig. 5. *Left: Intrados reinforced arch method in the Council Chamber of the former Convent of San Cristoforo in Lodi. Acting from the intrados, the cables were kept close to the surface of the arch by "V" brackets in stainless steel, connected with long metal anchors to the wall. The cables of the armed arch, inserted into the "V" brackets, have been extended to the ground and anchored to the floor slab to ensure overall stability; right: a similar application in Villa San Carlo Borromeo at Senago (MI).*

In intrados applications, securing the cable to the arch becomes more complicated (since it is not possible to create a simple support). It is therefore required the use of connectors capable of securing the cable to the masonry (eyebolts or specifically designed elements). The implementation is done by applying tensioning "right-left screws", which stretch the rope, or by shortening the connectors.

3. EXPERIMENTAL TESTS ON "RAM"

Large scale experimental tests were conducted to measure the improvement obtained with the adoption of RAM Method.

More than 500 tests were undertaken, in which the arches have been subjected either to vertical loads or to horizontal-seismic loads.

The experimental tests showed that it is possible to increase the ultimate load of the arch, preserving reversibility in the consolidation procedure and respecting the original static building concept. No additional weight is needed (that is a relevant factor in seismic areas) and no modification of shape is requested. The applied confining actions can be calibrated where and how it is necessary.

The first experimental campaign was conducted in 1996, when twelve brick masonry arch specimens, 200 cm span and 12 cm thick, were built and tested to collapse. Several situations were recreated, with the aim of comparing the behavior of non-reinforced arches with reinforced ones.

In the experimental campaign, 3 arches were un-reinforced, 3 arches were reinforced with RAM method, applying different tensile forces to the cables, 3 arches were reinforced with a concrete layer not connected to the masonry structure and 3 arches were reinforced with a concrete layer connected to the masonry.

Two different point load conditions were applied to the arches, either at mid-span, and at ¼ of the length.

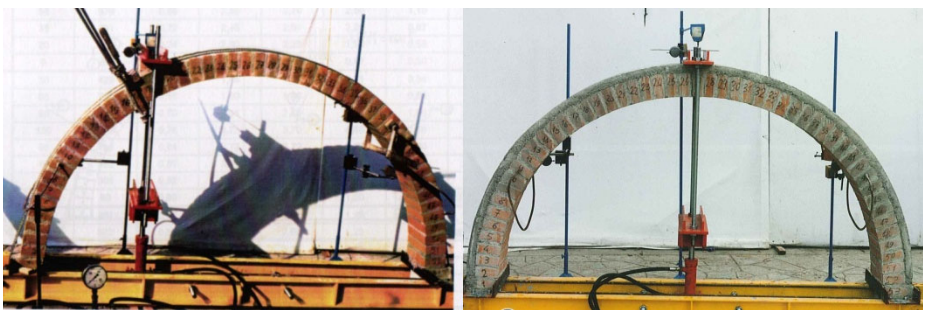

Fig. 6. *Experimental tests on masonry arches (L. Jurina, O. Cultrieri, G. Savoldelli, 1996).*

Compared to the traditional system, which makes use of concrete layers, the RAM reinforced arches showed an higher ductility and a lower residual inelastic deformation, when discharged.

In case of vertical concentrated loads, the increase of load capacity of the reinforced RAM arches *reached more than 1400%*, compared to non-reinforced ones (see Tab. 1).

Furthermore, different collapse mechanisms were pointed out. In particular, for the un-reinforced arches and for the ones reinforced using a concrete layer, the hinges were more opened and localized, while adopting RAM the cracks were smaller and more diffused. This fact is characteristic of a ductile behavior of the RAM reinforced masonry.

Table 1. *Results for Axial Load.*

	Collapse load Pc [kg]			
	Un-reinforced arch	**concrete layer**	**concrete layer + connections**	**RAM**
tested arch 1	100	2418	2700	2707
tested arch 2	49	2640	2788	2891
tested arch 3	191	3379	2948	2886

note: for arches 1 and 2 the point load is applied at mid-span,
for arch 3 the load is applied at 1/4 of the span

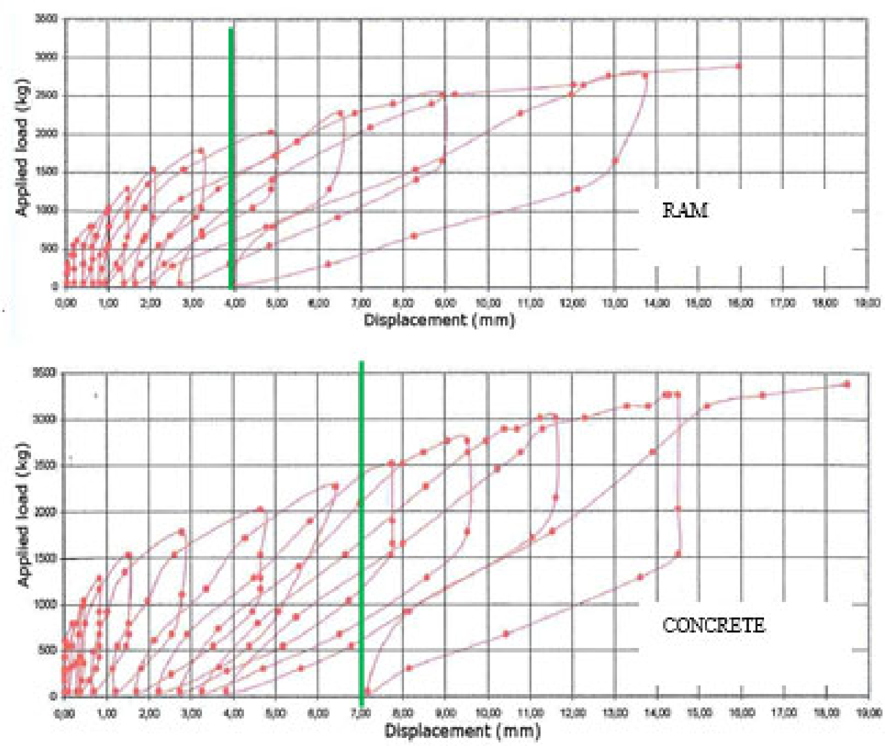

Fig. 7. *Experimental load-displacement curves for RAM reinforced arch (top) and concrete layer masonry arch (bottom). The residual deformation is almost 40% smaller in the RAM than in the concrete layer solution, due to the presence of the steel cables that still work in elastic range.*

It must be pointed out that, for one of the arches reinforced with RAM, the failure occurred for excessive compression of the brick, that gave rise to the formation of 4° plastic hinge.

Some results of the experimental campaign are shown in the following. The collapse load and the load-displacement curves, comparing the 4 different configurations tested, confirmed the efficiency of the Reinforced Arch Method.

Even in terms of residual deformation after cyclic loads, the RAM arches offered reduced values (about 40% less) if compared with the concrete layer consolidation solution.

Fig. 8. *The six geometries of the models tested under concentrated vertical load. From the top: circular, ribbed, ribbed+small depression, ribbed+large depression, polycentric and gothic. (Jurina - Giglio, 2008).*

In the years 2008-2009 a second experimental campaign was conducted by the author applying *vertical loads* in different positions of 120 cm span wooded RAM reinforced arches (see fig. 8).

Six different shapes were investigated up to collapse, for a total amount of 414 arch specimens, comparing the behaviour of plane arches and arches reinforced with RAM Method, with cables placed at intrados and extrados.

Experimental and numerical results showed *a linear relationship* between the load multiplier factor μ and the tension force N applied to the cables. Two different configurations of the RAM were tested: a first one adopted sliding cables, in which the tension force was constant, corresponding to the N_t applied to the extremities at the beginning of the test. The radial forces between the cables and the arch were constant too. In a second configuration, cables were fixed at the extremities, after the initial tensioning. In this second case, the deformed shape (whose length was greater than the original one) induced an increment of the tensile force in the cable which caused a beneficial increment of compression in the arch. The maximum load at collapse was 240 kg (compared with 70 kg obtained with the sliding cables for the same arch) without reaching the collapse of the arch. It's worth to mention that the cables fixed at the two extremities correspond to practical application procedure of the RAM, in real cases.

A third experimental campaign was conducted in 2011 in order to evaluate the effect of the RAM Method in case of *horizontal loads*, simulating seismic loads.

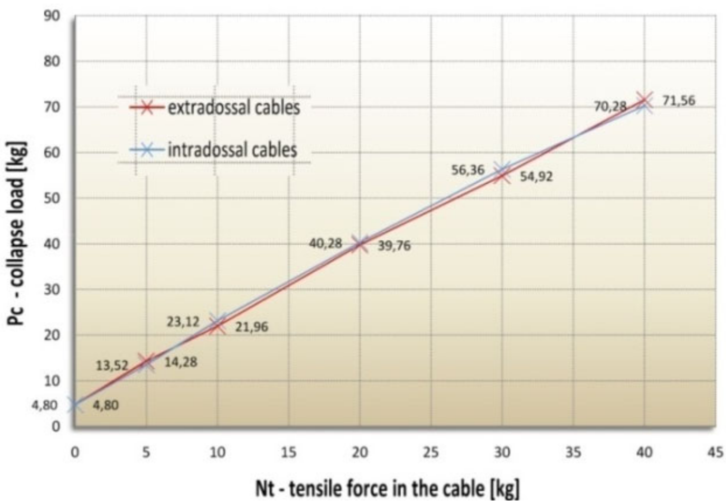

Fig. 9. *Test results on the circular arch during the experimental campaign in 2011. Seismic tests were performed with 4 point loads applied. The increment of the collapse load goes from 112% to 1132% by increasing the N applied to the cable. Collapse load Pc is a linear function of the tensile force in the cable N (either positioned at extrados or intrados) (Jurina, Bonfigliuoli, 2011)*

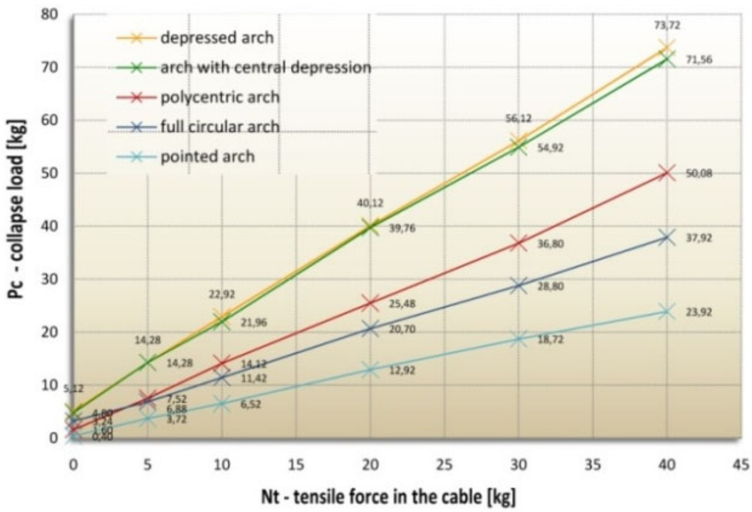

Fig. 10. *Comparison between all the horizontally loaded tested arches. A linear relation between the N applied to the cable and the collapse load occurred. The table summarizes the collapse loads for different tension applied to the cable, for several arch shapes during pseudo static tests.*

The 117 conducted tests showed that, even in this case, the RAM technique induces an high increase of the collapse load and of ductility. With the application of the RAM Method it is possible to obtain not only a seismic improvement of the structure, but, in some cases, even a seismic retrofit according to the current Standards.

By means of the limit analysis kinematic theorem, it was easy to check the increase of the ultimate load capacity of the structure when the post-tension force applied to the cable was modified. In fact, an extra term in the computation of the Virtual Work principle appears, taking into account the **N** (i.e. the applied tension in the cable) times the local displacement due to the mutual rotation of the blocks Φ, in correspondence of each plastic hinge. In the following, some numerical and experimental results are presented, concerning different geometries of the arches (see Fig. 9-10).

4. THE APPLICATION OF RAM ON SOGLIANO AL RUBICONE BRIDGE

After having described the principles of the Reinforced Arch Method, it’s worth to illustrate its application in the consolidation of a XIV century pedestrian bridge in Sogliano al Rubicone – Italy.

The stone bridge was in a very critical static condition due to the partial collapse of the masonry spandrels that affected the overall structure.

The cross-section was extremely compromised, especially in the fill and king-stone zones. The masonry texture was disconnected and it lost almost entirely its capacity to resist gravity loads.

Fig. 11. *The masonry bridge of Sogliano al Rubicone, before and after the consolidation with RAM Method.*

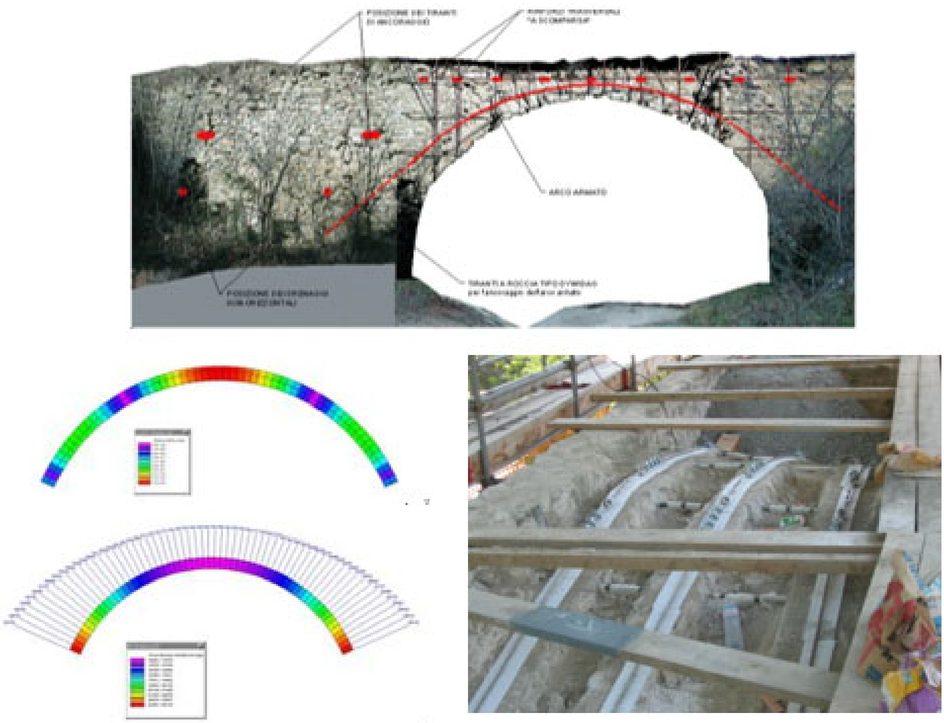

Fig. 12. *Numerical results: state of stresses in the arch and axial force between the blocks subjected to gravity loads and consolidating interventions on the masonry bridge of Sogliano, using the RAM method.*

The Romanic bridge of Sogliano could keep its safety only thanks to a temporary steel protection scaffold. In order to restore the possibility of public access and use, a consolidation work was developed, that included rebuilding of the crushed zones, injection and stitching of cracks and restoration of the surfaces.

Thanks to these interventions, the load capacity of the bridge was strongly increased. At the date, the restored geometry, together with the improved mechanical strength of the stone masonry permitted the bridge to resist the pedestrian loads but not possible seismic event, as requested by the National Italian Code.

For these reasons, in addition to the restoration of the masonry texture, the RAM Method was applied. Three stainless steel cables, 20 mm in diameter, were placed at the extrados of the bridge, strongly connected to the lateral bedrocks by means of micro-piles, and then shortened.

The post-tension in the cables induces a beneficial compression effect on the arch, closing the cracks and compacting the stones of the bridge.

As a results a seismic retrofit of the bridge was obtained , thanks to the RAM Method. A satisfactory safety factor C=1,65 >1 was obtained. This positive effect was proved by a numerical analysis conducted on the bridge.

Apart of the extrados cables, other interventions were applied to reinforce the bridge and to increase the safety factor.

Seven steel chains were placed to connect the opposite spandrels, to avoid any opening of the arch in presence of non-symmetric loads. This concept was surely well known and adopted also during the original construction of the bridge. Some cross timber chains, in fact, were discovered during the restoration.

5. CONCLUSIONS

RAM Method represents an innovative technique that places itself among the possible solutions for consolidating masonry arches and vaults, and, in particular, masonry brick or stone arch bridges. The basic idea consists in laying one or more steel cables on the extrados (or at the intrados) of the arch and tensioning it. Thus, a beneficial compressive force is induced between the masonry blocks. Several experimental campaigns, on large and small scale, have been conducted by the author, analyzing different shapes of arches and different load distributions. By comparing numerical and experimental results, relevant considerations can be underlined in terms of load capacity and ductile behavior of the reinforced arches, even in presence of seismic loads.

REFERENCES

[1] HEYMAN J., The stone skeleton, *International Journal of Solids Structures*. 1966.

[2] SENINI A., ZANON P., I ponti storici in muratura. Adeguamento a nuove condizioni di esercizio: una modifica sostenibile, Tesi di Laurea, Fac. Architettura, Politecnico di Milano, rel. L. Jurina. 1999.

[3] JURINA L., Tecniche di consolidamento dei monumenti. Una panoramica attuale. *Proc.intern. symp. IF-CRASC '12, V Convegno su Crolli, Affidabilità Strutturale, Consolidamento;*Pisa, 15- 17 November 2012.

[4] JURINA L., Strengthening of masonry arch bridges with "RAM" – Reinforced Arch Method. *Proc. Intern. symp. IABMAS;* Stresa, 8-12 July 2012.