New proposals for static consolidation of a damaged monument in Ani

Lorenzo JURINA,[1]
(1) A.B.C. Department, Politecnico di Milano, Italy
lorenzo.jurina@polimi.it

Preface

The ancient city of Ani represents one of the most important example of Armenian culture, showing relevant aspects from historical, economical and architectural point of view.
About the year 1000 Ani took on the characteristics of a great urban center, architecturally defined in all its parts, thanks to its geographical position and topographical conformation that allowed economic growth and safety.
The capital's economic, social and cultural progress was accompanied to an expansion of building and architecture, so that Ani deserved the name of "the city of the thousand and one churches".
The sheer evidence of architectural patrimony that has survived to our days allow us to determine some common principles or reference points, leading us to formulate the hypothesis of an "Ani school of architecture", influencing the whole Armenia.
Regarding the influence of the national architectural tradition on the activities of Ani school, it can be observed that one of the most obvious indication was the revival, with new interpretation, of every kind of building typology used in paleo-Christian time, especially the combination of longitudinal vaulted and central domed ground plans.
A study case of this revival is the church of the Savior (or Amenaprgitch), an octofoil type central plan that greatly modifies the classic example of former churches as Irind and Zoravar.
Furthermore, the analysis of the monuments in Ani reveals a deep study of the overall composition of the building, with special care to external volumes. These volumes are articulated according to the juxtaposition and integration of various elementary solids with clearly interpretable surfaces.
At the same time they act as casing that are far more compact than their interiors, in which the space extends in many directions without ever losing its continuity, and which is delimited by well designed outlines, mostly curving surfaces and hollow volumes.
In this way, an intentional independence of external volumetric configuration and the articulation of internal space is obtained.
The church of Savior represents an example where neither of the space arrangements corresponds to the casing.
As regards the role of creativity, it must be emphasized the definition and diffusion of a generalized architectural language based upon a certain number of sober, refined decorative features, as blind arcades, dihedral niches, decorated bands that frame the windows.
For this aspect the architecture of Ani is far from the severe classical rigour of the great paleo-Christian Armenian monuments.

Abstract from "*The architecture of the city of Ani*", by Paolo Cuneo, in [1]

The study case of the Savior church

In the present paper, a study case is illustrated, concerning the ruins of the ancient church of the Savior (or S. Amenaprgitch) in Ani (an Armenian town nowadays located in Turkey).
The church represents an interesting case of "ruined" structure, where only half of the original central plan church is still conserved, while the remaining part of the building collapsed for a strong earthquake years before.

Fig 1: The ancient Church of the Savior in Ani

In order to guarantee the necessary strength to the dome and the walls, an innovative solution called "Reinforced Arch Method - RAM" was proposed by the author.
It's worth to remember that in masonry arches, and also in vaults and domes, the formation of plastic hinges give rise to cracks in the intrados or the extrados side of the element.
The cracks can be generated either by high vertical static loads, especially in case of non-symmetric application of the loads, or in presence of horizontal loads, wind or earthquake.
If we're able to prevent everywhere the formation of at least one plastic hinge among the two possible families (either the intrados and the extrados ones) the failure of the arch or vault cannot occur. In fact, a three-pin arch is a satisfactory, statically determinate, structural form and, as a consequence, the funicular polygon related to a given distribution of load is unique.
There are several possible interventions that can be adopted to avoid the formation of hinges, as the use of a distributed reinforcement, the use of FRP on the extrados or on the intrados, or the traditional (but critizied) reinforcing concrete layer. Although they are efficient systems, in many cases they appear quite invading, non-reversible and mainly passive.
As an alternative, post-tensioned cables can be adopted (working as an "active" system), which apply a distribution of radial forces immediately on the whole surface of the arch. This new load distribution induces a pure axial compression between the blocks and, as a consequence, the thrust line is re-centered, avoiding or retarding the formation of plastic hinges.
Thus, the main purpose of the "RAM" is to modify the distribution of loads acting on the arch or dome so that the combination of the old loads plus the new loads can be the "right one" for the given and known geometry of the residual portion of dome.

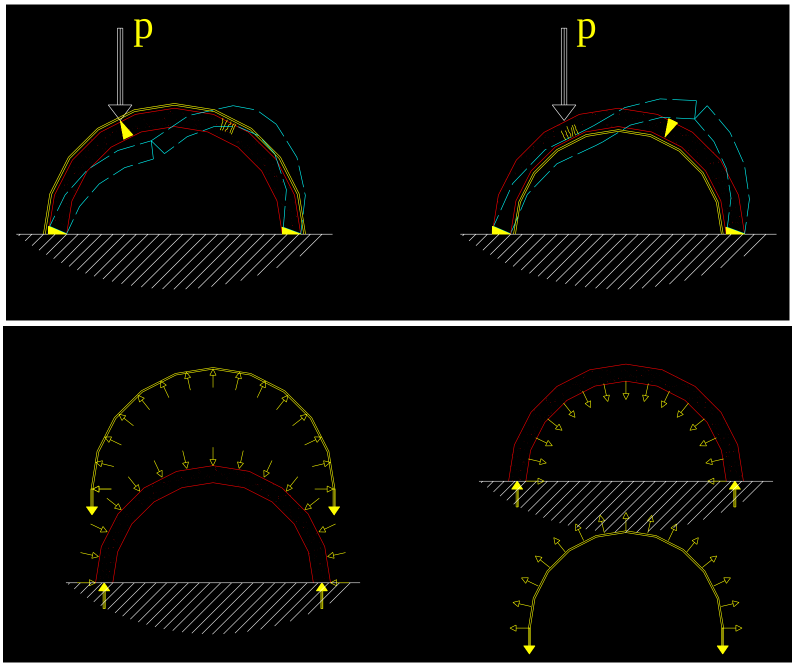

Fig 2: the working principle of the RAM

As shown by experiments and calculations, the proposed technique achieves satisfactory results that are equivalent, or in many cases even better, than the ones obtained with the more traditional methods.

Using the RAM method, the additional reinforcing elements (i.e. the cables) do not interfere with the in situ masonry material and respect the original structural behavior of the existing structure.

Large scale experimental tests have been conducted by the author to measure the improvement of safety obtained with the adoption of RAM Method. Several tests were undertaken, in which the arches were subjected either to vertical loads or to horizontal-seismic loads.

Fig 3: experimental test on reinforced arches conducted by the author

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 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.

In the years 2008-2009 a second experimental campaign was conducted by the author applying vertical loads in different positions of RAM reinforced arches.
In this case, seven different shapes of arch were investigated up to collapse, for a total amount of more than 400 arch specimens, comparing the behavior of plane arches and arches reinforced with RAM Method.
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.
A new experimental campaign is going to be carried out by the author, realizing a real scale masonry dome, with the aim to test the beneficial effects of the RAM.
Concerning this last purpose, up to now several FEM model has been developed in order to numerically evaluate the increment in strength provided by RAM on masonry domes.
The first case analyzed deals with the ancient church of Santa Caterina in Lucca (Italy), the second case deals with the dome of the Cathedral of Matera (Italy), and the last case has to do with the Savior church of Ani.

Fig 4: some applications of the RAM. The Church of Santa Caterina in Lucca (Italy) and San Carlo Borromeo Villa in Senago (Italy)

Focusing on this last case, the ruined structures has been modeled by adopting three-dimensional brick elements, either for the vertical walls and for the portion of the dome. To simulate the post-tensioned cables of the RAM, mono-dimensional beam elements have been used, tensioned to 20 kN each one.
Geometrical properties of the building have been obtained by the plan in ref [1].

Four different FEM model have been analyzed, considering the vertical dead load and two horizontal loads (in x and y direction) equal to 0.3g:

- Model (J1): represents the current non-consolidated situation;
- Model (J2): post-tensioned cables are disposed along parallels, at the intrados and at the extrados;
- Model (J3): post-tensioned cables are disposed along meridians, at the intrados and at the extrados, going parallel to the vertical walls, down to the ground;
- Model (J4): represents the combination of J2 and J3

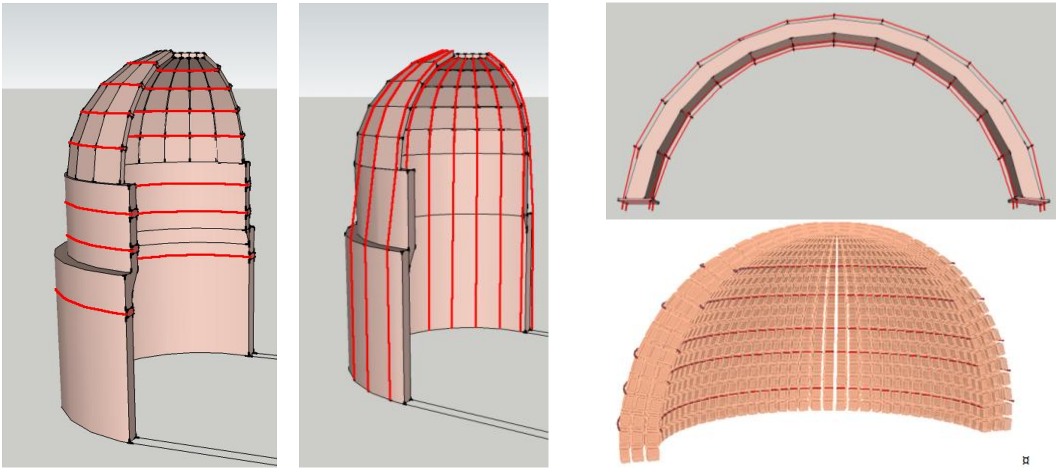

Fig 5: the RAM proposed for the Savior church

Numerical results obtained in the three consolidation proposals, compared with the non consolidated one, demonstrate a significant reduction in terms of tensioned areas and displacements.
As an example, the area subject to tension at the extrados of the dome in the non-consolidated situation corresponds to 56% of the total area. Thanks to the RAM cables, the tensile area is reduce to 43% in model J2, is reduced to 33% in model J3 and reaches the value of 31% of the total area in model J4, whit cables along parallels and meridians.
The table below summarizes the main values obtained with FEM calculations.
The positive effects of the Reinforced Arch Method on masonry domes can be illustrated by fig.6 in the case of the Savior church.

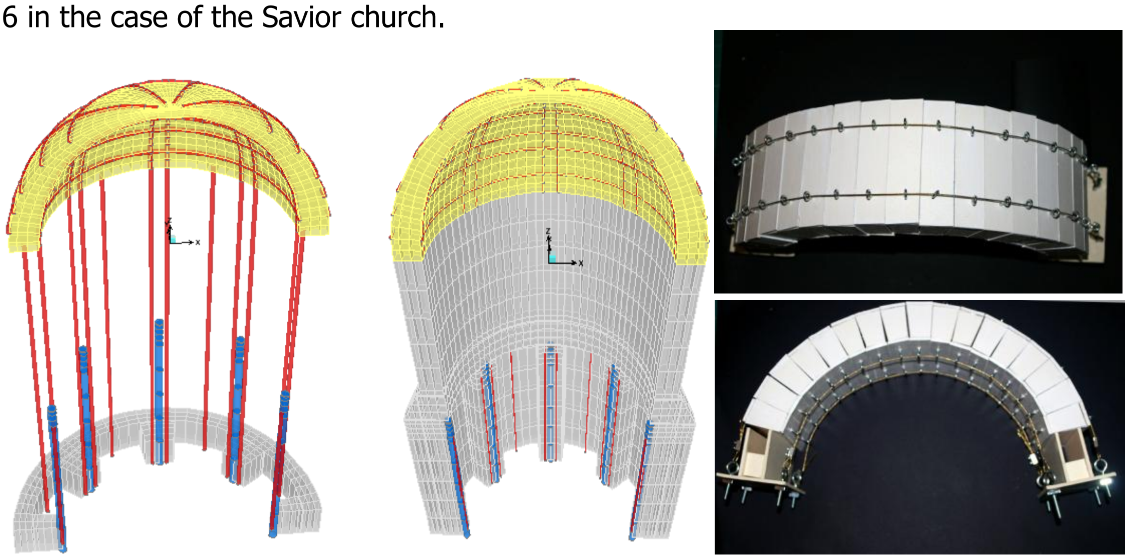

Fig 6: the FEM of the Church and the physic model of the RAM

	ACTUAL STATE	Cables along parallels		Cables along meridians		Cables along meridians and parallels	
Tensile area at the estradox	**44%**	36%	**– 18%**	**29%**	**– 35%**	**24%**	**– 45%**
Tensile area at the intradox	**56%**	43%	**– 22%**	**33%**	**– 41%**	**31%**	**– 45%**

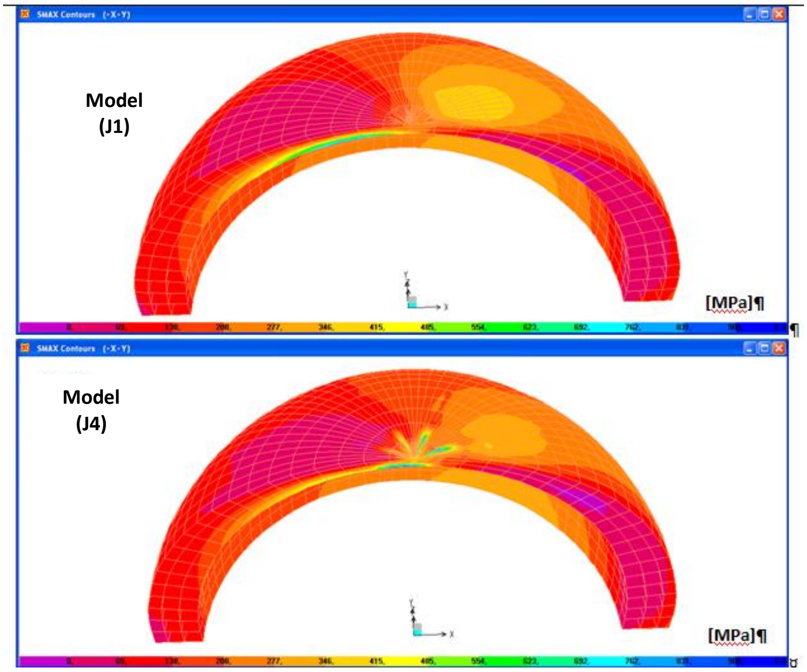

Fig 7: (Model J1) VS (model J4): on the top the non-consolidated situation (J1), on the bottom the dome (J4) with steel cables along parallels and meridians.

Conclusions

The ancient city of Ani represents one of the most relevant and interesting example of Armenian architecture. Starting from year 1000, it developed a huge monumental patrimony, that unfortunately was partially lost.

Among the many ruined structure in Ani, the ancient Savior church has been studied by the author, and an innovative consolidation intervention has been proposed.

It consists in the adoption of a solution called RAM, Reinforced Arch Method, that make use of external post-tensioned steel cables applied on the dome, able to provide a beneficial confinement to the masonry, avoiding the formation of cracks and preventing the collapse of the remaining portion of building.

A strong increase of the collapse load, especially seismic –horizontal load, was experimentally detected during several experimental tests conducted by the author, and the beneficial effects of the RAM were numerically evaluated by means of FE Models.

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