BEST PRACTICE IN HERITAGE CONSERVATION MANAGEMENT
FROM THE WORLD TO POMPEII
XII International Forum Le Vie dei Mercanti
Aversa / Capri, 12,13,14 June 2014

Armenian experiences in consolidation of ancient buildings: the study cases of Anberd, Tatev, Arudj and Ani

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Abstract
The ancient Armenian culture offers a wide number of historical buildings, that show interesting technologies and materials adopted during the construction phases.
In the least decades, some of these ancient heritages have suffered an evident structural deterioration, especially due to seismic events. In some cases, the structure has even reached local or global collapse.
Herein, four study cases are shown, analyzing some consolidation interventions proposed by the author.
The first case deals with the ruins of Anberd Castle. The ancient stone walls were subjected to a strong degradation phenomenon of washout, especially for the joints of mortar. Furthermore, some local overturns of the walls occurred due to out of plumbs and lack of material in the foundations. To prevent collapse mechanisms of the structure, among the consolidation interventions, the use of steel cable stays has been proposed.
The second case deals with Tatev Monastery. In 2002, the new use of the buildings, as well as the seismic vulnerability of the area, forced to reconsider the structural qualities of the buildings in order to assess the needed strengthening works. Some geotechnical interventions and consolidating solutions for the masonry structures have been proposed.
The third case has to do with Arudj church. Local kinematics have been detected during the survey, so that a global intervention of chaining to restore an overall "box-like behavior" has been proposed. Furthermore, the re-construction of the collapsed lantern and dome by a new steel and glass structure has been suggested.
The fourth and last case concerns the ruins of Ani, where several innovative applications of the RAM "Reinforced Arch Method" have been proposed.

Keywords: Seismic vulnerability, collapse mechanism, consolidation intervention, confinement

1. Introduction
In the last decade a *re-discovering* of the construction techniques and materials belonging to ancient buildings and heritage has grown up.
Professionals and researchers have made a strong effort to understand resisting mechanisms in masonry buildings, trying to evaluate the safety factor in presence of vertical and horizontal seismic loads. As a consequence, innovative techniques and materials have been introduced to prevent local and global collapse mechanism, increasing the safety of the overall structure.
The same interest in the historical matter has occurred in Armenia, where ancient buildings have been studied, trying to give them a new life, or simply to maintain and preserve them as they are.
Before analyzing the four study cases proposed in the present paper, it's worth to mention some relevant principles concerning the meaning of "restoration"..
Various "restoration charters" offer a useful, but not exhaustive though. In fact, the principles they set out demand reasoned adoptions. Anyway, there is one aspect that may be considered common to all restoration projects: in-depth analysis of the constituent materials and the structural condition of the monument under discussion.

The crucial value of reference in a consolidation intervention consists in safeguarding the ancient memory as the best foundation for the future, providing the necessary resistance to the structure.
It follows that the conservation of heritages must be planned and executed on the basis of an accurate analysis of the buildings, using materials and techniques that are mainly compatible with the existing ones and adopting the well known criterion of "minimum intervention".
Each intervention must be specific and well calibrated, remembering that each monument is irreplaceable, unique and witness of the historic memory.

2. The Armenian Architecture

The Architectural Heritage of Armenia is characterized by an astonishing homogeneity of styles, especially of materials and construction techniques. This homogeneity is mainly due to the fact that Armenians, victims of frequent invasions and wars, not being able to recognize in a politically stable Nation, identify their cultural foundations in Church and traditions, even in the artistic ones.
This strong identity is recognized in the "signs" of their culture: the spoken and written language, religion and artistic expressions. Armenians were the protagonists and creators of a wonderful season of art and architecture, which lasted through many centuries.
In the field of religious architecture, results were achieved at the highest level since the first realizations, that date back to the conversion of Armenia to Christianity in 301.
The previous architectural knowledge and the geographical position of Armenia have allowed a development of original and precocious synthesis, asserting (between the IV and VII cent.) almost all the construction schemes that have characterized Armenian ecclesiastical architecture until modern times, often anticipating the solutions adopted few centuries later in Europe.

Fig. 1: The monastery of Haghpat and the church of Marmashen in Armenia

Ancient fortifications represent another architectural manifestation of the Armenian culture. The greatest period of development of military architecture in Armenia is placed between the VII and IX century a.C., when more than four hundred fortifications were built. Today, although only a part of that huge patrimony is preserved, it has been possible to conduct researches on the building techniques of this singular type of structures.
In particular, walls were made with the traditional technique called "midis"; it consisted in a double layer of stone, filled with a mortar of lime and aggregates of various sizes, often connected by horizontal wooden beams. The corners were usually refined with high accuracy: in some cases the curtain walls were adorned with the use of stones of various colors, with geometric decorations.
The interior of the towers and gates were usually barrel-vaulted or had a stone dome set on a square plan, recalling some geometrical aspects of the Armenian churches.

The large diffusion in all the Armenian areas of churches, monasteries, bridges, aqueducts and caravanserai was strictly related to trades. Dvin, Ani and many other famous cities of ancient Armenia were, in the fifth century, a great economic, political, cultural and spiritual power in international trade, retaining their status for many centuries. Greeks, Assyrians, Persians, Jews, Georgians and many other peoples from the far Est traded with the Armenians, contributing to the most flourishing artistic and architectural period.

Fig. 2: The ancient "Silk Road" that linked Est and West passing through Armenia

3. Study cases

3.1 Consolidation interventions of ruins: some proposals for Anberd Castle

Anberd Castle represents an important example of ruined structure, especially interesting from an architectural and structural point of view.
Many events, both natural and anthropogenic, have brought the Castle to be as it appears today, so that any attempt to "erase" the signs of aging and to restore part of the former would be conflicting with the principles of a conservative restoration. For this reason, the structural intervention has opted for a specific series of operations to be performed only where strictly necessary, respecting the authenticity of the monument and its peculiarities both aesthetic and structural.
The main problems regarding the ruins of the Castle were associated to the washout of the mortar in masonry and to the lack of mortar joints. Such problems were localized in few areas and clearly identified.
In particular, two were the portions of intervention: the south-est façade and one internal wall.
Regarding the south-est façade, the stone wall was a high diaphragm, not sufficiently thick and poorly connected with the rest of masonry structures. The slenderness was not sufficient to prevent the rotation of the façade, especially of the upper portion of the wall.
Something similar happened to the portion of the inner wall, where a remarkable out of plumb was recorded. Luckily, in this case, the collapse was prevented thanks to the presence of deposit, at the foot of the wall, that acted as "struts".

Fig. 3: The complex of Anberd castle

Looking at the structural problems, one of the first task consisted the integration and injection with mortar of the existing masonry. These interventions has been proposed only at those points where the static consolidation was absolutely necessary, so that the perception of 'ruin' couldn’t be compromised.
Furthermore, from a static point of view, each wall has been schematically represented as a cantilever, clamped to the ground. On the element, subjected to its own weight and horizontal loads such as earthquake and wind, axial force, shear and bending moment acted. Being the masonry a material not resistant to traction, a dangerous partialization of the resistant section has occurred due to bending.
A consolidation intervention, adopting post-tensioned bars, placed internally to the wall, has been proposed. The aim was to increase the axial load, acting on the masonry, so that the majority of the section could work in compression, limiting the tensile stresses as much as possible. In this way, the masonry could resist to higher horizontal loads.

Fig. 4: The consolidation intervention proposed for Anberd castle by adopting steel post-tensioned bars

A numerical FE analysis has been recently conducted by the author to a similar case in Italy, related to the Forte of Fuentes in Colico. In this case, the effects of post-tensioned external cables have been evaluated, confirming the beneficial effects of the system.
In the following the main results of the FE Analysis of Forte Fuentes are reported.

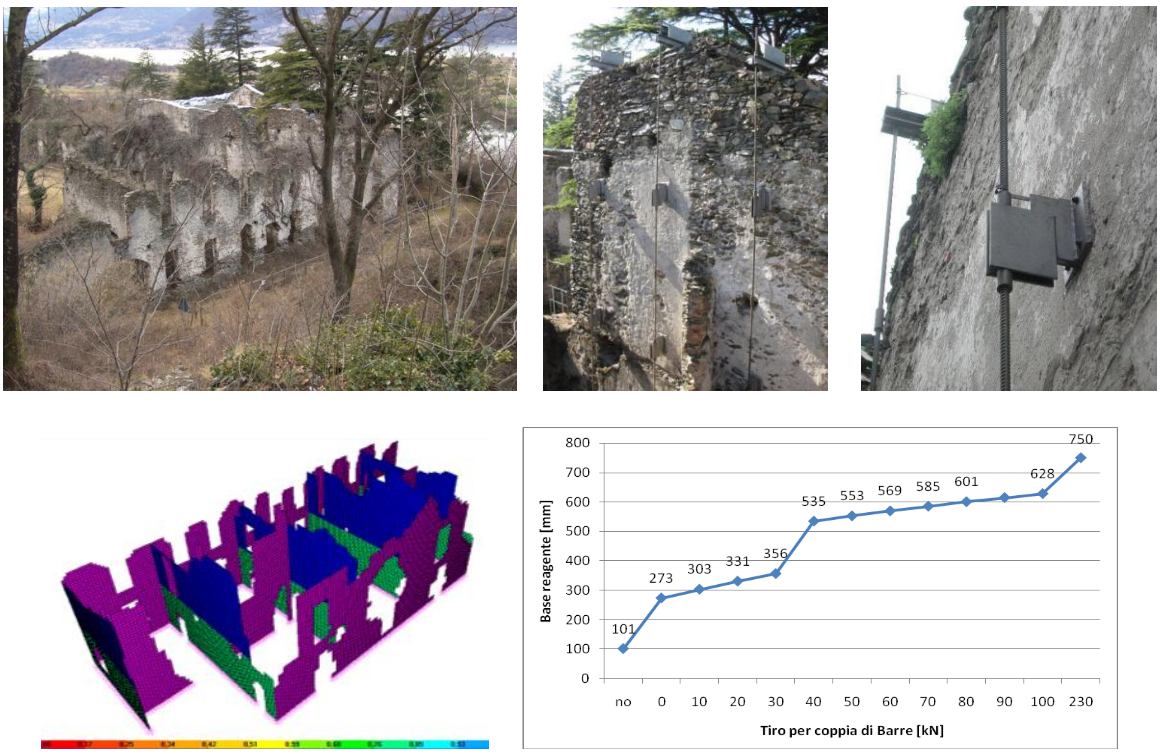

Fig. 5: The complex of Forte Fuentes in Colico (Italy). A consolidation system of steel post-tensioned bar (called EHT – Edera Hi-Tech) has been adopted. Results obtained by the FE Model show the increase of the reacting compressed section and the consequent reduction of tensile stresses, adding more tension applied in the bars.

3.2 A new life for Tatev Monastic Complex

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

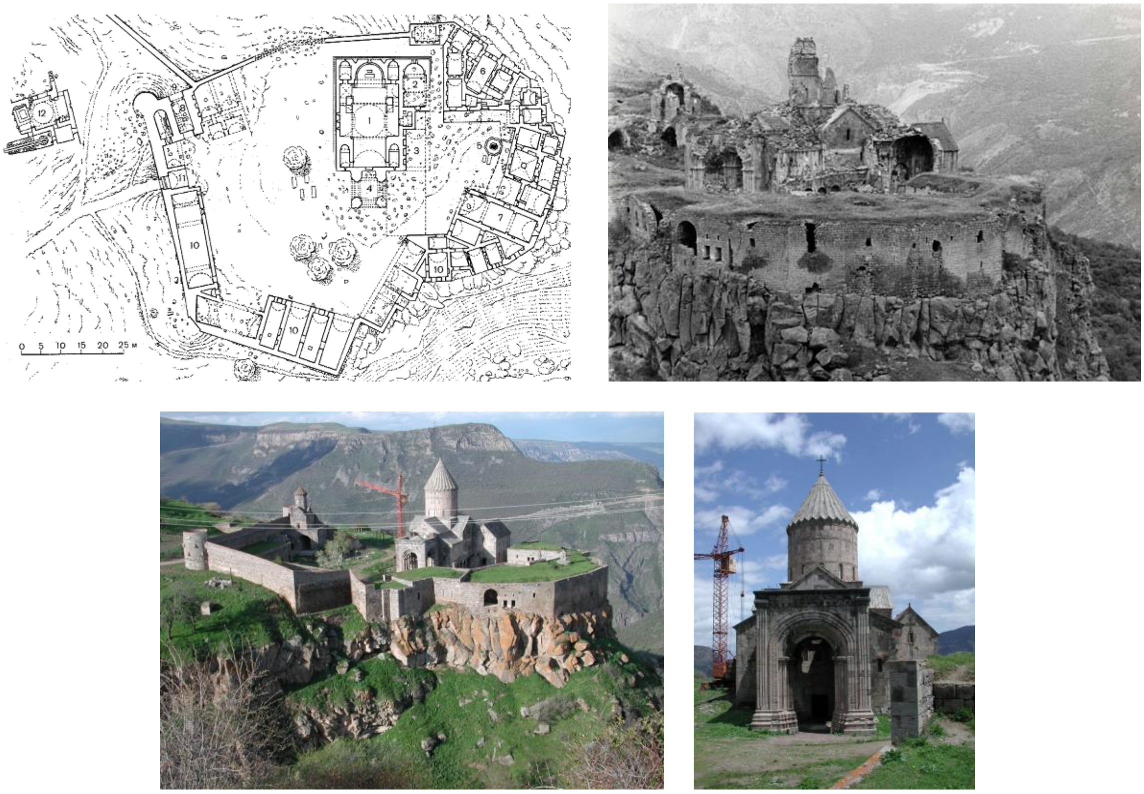

Fig. 6: Plant of the complex of Tatev, the monastery after the earthquake occurred in 1931, and the monastery during the restoration works in 2002

In 2002 His Holiness Karekin II, Catholicos of All Armenians, decided to bring the complex back to its importance. The project foresaw the reuse of the existing buildings in order to lodge 50 students, the classrooms, the library and all the functions and sets that a modern institution of higher education required.
In addition, the monastery would be also able to welcome pilgrims and tourists.
The new use of the structures, the increasing tourism and the seismic vulnerability of the area forced to reconsider the structural qualities of the buildings in order to assess the needed strengthening works.
Several surveys conducted in site highlighted the areas of intervention, mainly focused on the foundations of the monument resting on cracked rock, on the damaged buildings that hosted the library and on the principal church.
From a geological point of view, the area was quite interesting, since the southern monastery buildings rested directly on a basaltic crown, that showed the tendency to slide down. The rock mass, in fact, was characterized by discontinuities that caused the relative movement of the stone blades, especially in case of earthquake. At the same time, some other buildings rested on soft soil.
Another relevant fact influenced the structural performance of the buildings; in particular, edifices were built in different periods and the complex developed by subsequent additions. Thus, the connection between the bearing walls was not always well realized, and the reestablishment of the missed links was necessary, in order to assure the three dimensional monolithic behavior and to limit the seismic damages.
Two types of structural interventions has been proposed: the first one concerned the ground level, while the second one interested the upper parts of the buildings, especially arches and vaults.
As regards the intervention on the ground, grouted rock bolts has been foreseen to stabilize and strengthen the rock mass. To locate the bolts, some boreholes has to be drilled in the rock, and steel anchor bars provided to connect two or more rock blades in order to prevent them from any slippage.

Fig. 7: The reinforcing scheme of the connection bars in the ground and a detail of the fractures rock

In the upper part, the structural consolidation of ancient arches and vaults represented a difficult task. The solution named RAM "Reinforced Arch Method" has been suggested to consolidate and strengthen the Tatev monastery's vaults.

The main purpose of the "RAM" is to modify the distribution of loads acting on the arch 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 arch.

Steel post-tensioned cables can be applied either on the extrados or on the intrados (working as an "active" system), and a radial distribution of forces is immediately applied to the arch. This new load distribution induces an axial compression between the blocks and, as a consequence, the thrust line is re-centered. As shown by more than 500 experiments and calculations, the proposed technique achieves results that are equivalent, in many cases even better, than the ones obtained with the more traditional (but much more invading) method that consists in a "passive" concrete layer, poured over the arch, at the extrados. 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 vault.

Another interesting reinforcing intervention has been planned on the church. Although this building had been restored few years before, structural problems persisted. The simplest thing to do was to provide a sort of bandage in the upper part of the walls in order to recreate a three dimensional monolithic behavior, by means of tie rods.

A last consolidation proposal has to be mentioned: the two masonry towers were completely filled by detritus that had to be removed. To consolidate the structure, an interior bandage made by 10 thread bars, located in the tower masonry and fixed using a special anchoring mixture of hydraulic binders and fines has been designed. At the end of each bar, an "eye" trough which a stainless steel rope passes was fixed. The link between the two ends of the rope was obtained by using a turnbuckle so the structure can be tensioned.

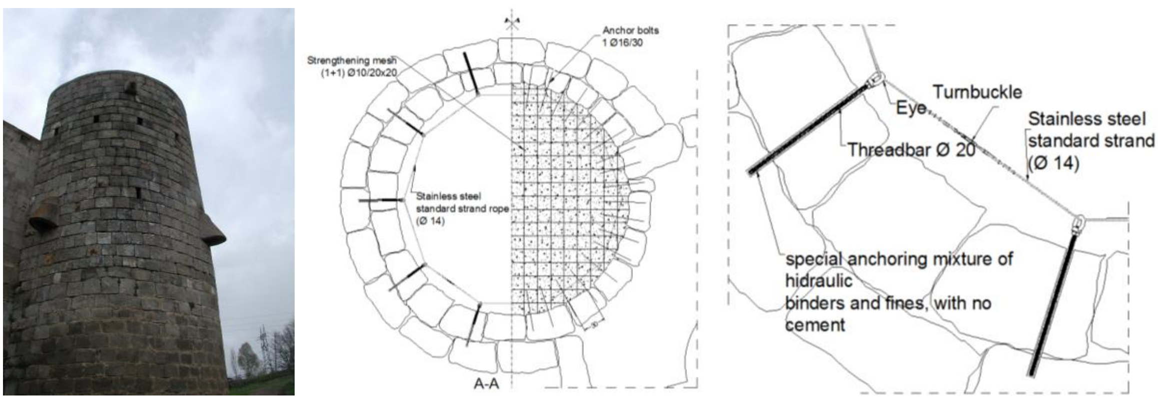

Fig. 8: The confining system for the consolidation of the two masonry towers

3.3 Arudj temple

Arudj temple is the biggest among medieval domed churches in Armenia. During centuries it had stood numerous earthquakes and invasions, which seriously affected it. An earthquake in ???? ruined the huge dome of the temple, and caused the opening of significant cracks on the façade. Although the temple has been repaired more than once, starting from the first rehabilitation initiated in 973, a new consolidation intervention has been recently proposed. The aim was to prevent local or global mechanisms of the walls, in case of seismic events.

Fig. 9: Arudj temple: the huge dome collapsed due to an earthquake

An accurate diagnosis has been carried-out, applying both in-situ tests (sonic tests, thermography, crack opening monitoring) and laboratory tests, in order to analyze the chemical and mechanical properties of constituent materials. The diagnosis has been developed by Politecnico di Milano, inside the II° Level Master for Architects and Archaeologists called "Progettazione al restauro, formazione al restauro in Armenia, sostegno alle istituzioni locali per la tutela e la conservazione del patrimonio culturale", based on the agreement between the Italian Ministry for the Foreign Affairs and the Armenian Ministry of Culture.

The analysis of the crack pattern and of the mechanisms of collapse is an essential prerequisite for a careful assessment and effective interventions.
The safety evaluation, with respect to static and seismic actions, required a conscious reading of both the damage that the church has historically manifested, and details of the response to vertical and horizontal loads.

Fig. 10: The thermography applied to the walls has provided significant information about the masonry

The behavior (especially seismic) of churches with a longitudinal development plan, like Arudj, has been interpreted through the decomposition into portions, called macro-elements, characterized by a structural response that is substantially independent from the church, considered as a whole. Among the main macro elements, the facade , the apse , the dome, the arches and the vaults have been identified.

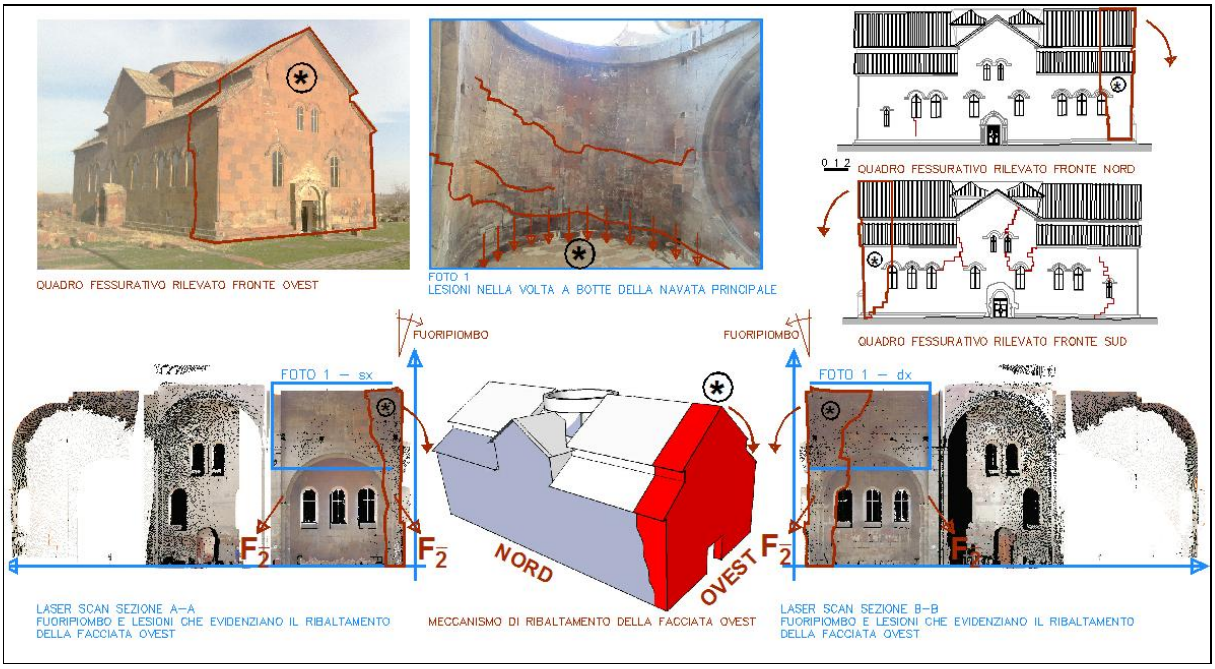

Fig. 11: Among the possible kinematic, the overturning of the façade has been detected

Based on the information obtained, several consolidation intervention were proposed.
The first solution aimed to prevent local collapse mechanisms with ejection of the stone blocks, returning a monolithic behavior of masonry.
The mutual connection of the large blocks of tufo was obtained by thin bars arranged in a "pyramid" shape and grouted inside the walls, alternately in both internal and external layer.
Compared to traditional systems, "pyramids" are three-dimensional systems that limit the visual impact, because placed in the joints of mortar.
Another type of intervention has involved the insertion of chains of containment, formed by steel bars able to connect the masonry walls in the longitudinal and transverse direction at different levels .
The main objective of the project was to ensure a " box-like behavior " of the entire building, in respect of seismic actions, increasing the resistance to horizontal loads, but at the same time maintaining a certain ductility of the structure.
To obtain such results, three different tie-orders has been proposed:
- The first order, the main and indispensable, allowed the structure to increase its overall resistance to horizontal loads, achieving a good level of seismic improvement;
- The second order led to a further improvement of the seismic structure, preventing possible failure mechanisms of local portions of masonry;
- The third order led to the achievement of a seismic retrofit of the structure, so that the structure was able to fully satisfy the maximum stresses provided by the project, in accordance with the current regulations.

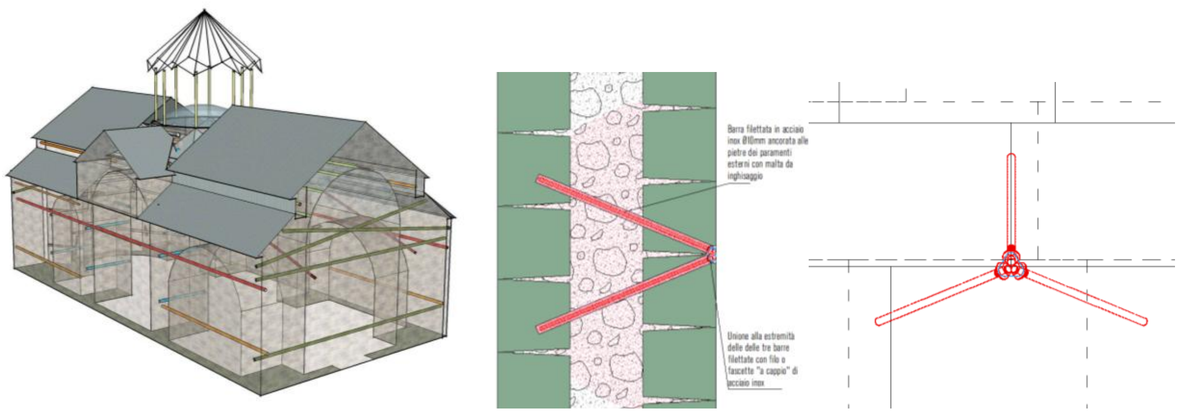

Fig. 12: The insertion of new chains and steel connections (pyramids) guarantees the box-like behavior

Furthermore, an interesting proposal has been advanced for the collapsed dome and lantern.
A new octagonal lantern in steel has been proposed, providing only the "skeleton" steel perimeter, without closures or coverage. The purpose of this solution was to perceive, in a discreet manner, the presence of a structure common to other churches of Armenia, now missing.
Concerning the dome, a new steel and glass covered has been proposed to close the actual hole, but at the same time without erasing any evidence of the past history of the church.

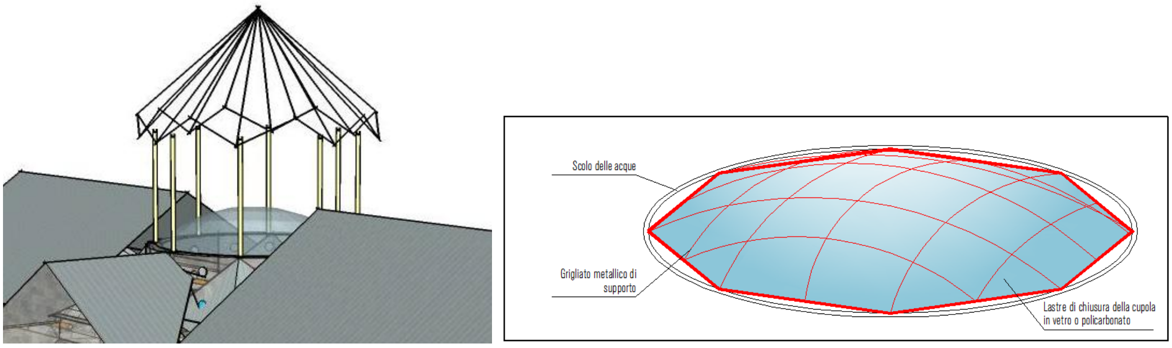

Fig. 13: A “light solution” for the reconstruction of the lantern and dome of Arudj temple

3.4 The “Reinforced Arch Method”: an alternative solution for Ani

The ancient church of S. Amenaprgitch in Ani (Turkey), represents another interesting case of “ruined” structure. The only part that is still conserved corresponds to the apse. The remaining portion of the building collapsed for a strong earthquake years before.
In order to guarantee the necessary strength to the dome and the walls, an alternative solution of the “RAM” was proposed.
The general principle of the Reinforced Arch Method fulfilled even in this case, where two different possible configuration of cables has been proposed.
In the first configuration, several steel post-tensioned cables were positioned in the horizontal direction, along the parallel. In the second case, steel cables were placed vertically, connecting the top of the dome to the ground.
In the following some sketches of the two solution are reported.

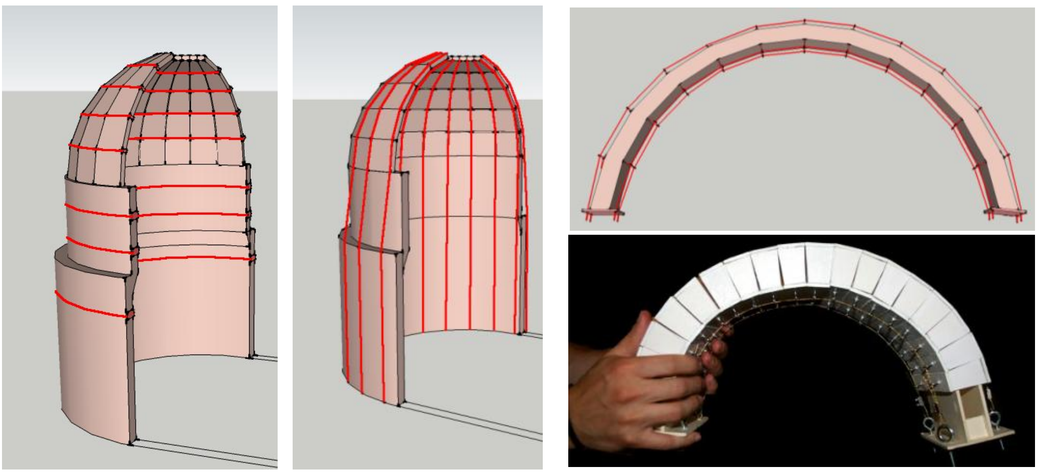

Fig. 14: The “RAM” applied to Ani apse and some small scale models of the intradox end extrados cables

A numerical FE analysis has been recently conducted by the author to evaluate the seismic response of a masonry dome of Santa Caterina Church in Lucca (Italy), where the RAM method has been applied.
Three different models have been developed: in the first one cables are placed along the parallels, in the second one cables are placed along the meridians, while the third one is the combination of the previous two models. The dome is subjected to horizontal seismic forces.
Numerical results obtained in the consolidated situations, if compared with the non – consolidated one, provide a significant reduction in terms of tensioned areas and displacements.

For example, the maximum tensile area at the extrados of the dome in the non-consolidated situation corresponds to 75% of the total area. Thanks to the RAM, the tensile are is reduce to 55%, 42% and 33% in the three different configurations analyzed.
The table below summarizes the main values obtained with FEM calculations

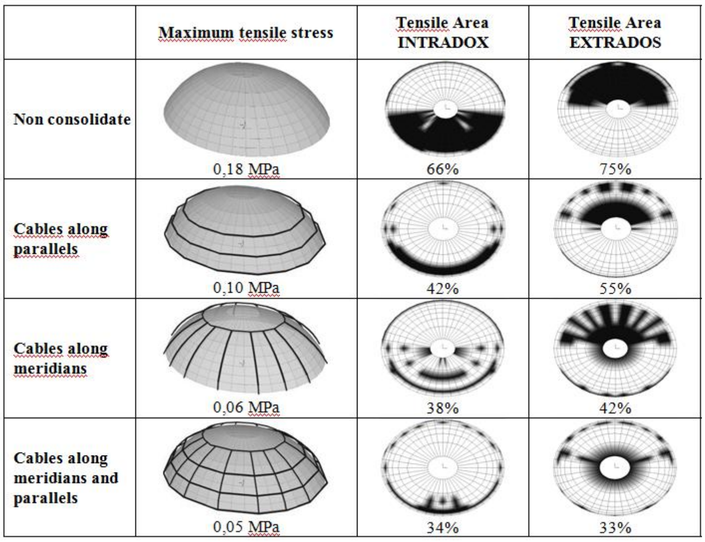

Fig. 15: Results obtained by a numerical analysis on the dome of Santa Caterina Church in Lucca (Italy)

4. Conclusions

The city of Ani, as many other Armenian cities, were partially destroyed after II° World War, causing a huge loss of ancient heritages. Among them, the ancient bridge upon the Akhurian River, that separates Armenia and Turkey.
The author has the hope of re-building the ancient bridge, by creating an essential and light new steel structure, to re-connect Armenia and Turkey.

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