STRENGTHENING ARMENIAN CHURCHES: SOME INNOVATIVE PROPOSALS

In the last two decades a *re-discovering* of the construction techniques and materials belonging to ancient buildings and heritage has grown up.

Professionals and researchers 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.

Consequently, 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 to analyze the consolidation cases here proposed, it is worth to mention some relevant principles concerning the meaning of "restoration".

First, the aspect that has to be considered as common to all restoration projects, that is the in-depth analysis of the constituent materials and of the structural condition of the monument under discussion.

Thus, each intervention must be "specific" and well calibrated, having in mind that each monument is irreplaceable, unique and a true witness of the historic memory.

It follows that the conservation of heritage must be planned and executed on the basis of an accurate analysis of the buildings, using materials and techniques that are compatible with the existing ones and adopting the well-known criterion of "minimum intervention" to provide the necessary structural resistance.

Study Cases

The Architectural Heritage of Armenia is characterized by an astonishing continuity of styles, materials and construction techniques, that often gave rise to analogous structural degradation phenomena.

One of the most frequent vulnerability problem was detected in the central dome and in the drum. Most of the seismically affected churches have suffered an evident crack pattern, and some of them completely collapsed under horizontal loads.

A second vulnerability problem concerns the lack of transversal connections between the big stones of the masonry layered walls.

1. Marmashen monastery

The ancient church of Marmashen was consolidated in the year 2000, after several surveys in which the crack patterns and the main structural damages were detected (Figure 1).

Some cracks in the drum and in the dome were evident, so that a consolidation intervention was introduced to provide a confinement effect.

To consolidate the dome, an encirclement at 2 levels was introduced, made by three segments of steel cables for each level, connected to the masonry through thread bars, located in the masonry and fixed using a special anchoring mixture of hydraulic binders and fines.

At the end of each threaded bar, a small tube was welded, through which the steel cable passed.

The link between the ropes was obtained by using a simple but efficient turnbuckle, so that the cable can be tensioned. (Figure 2).

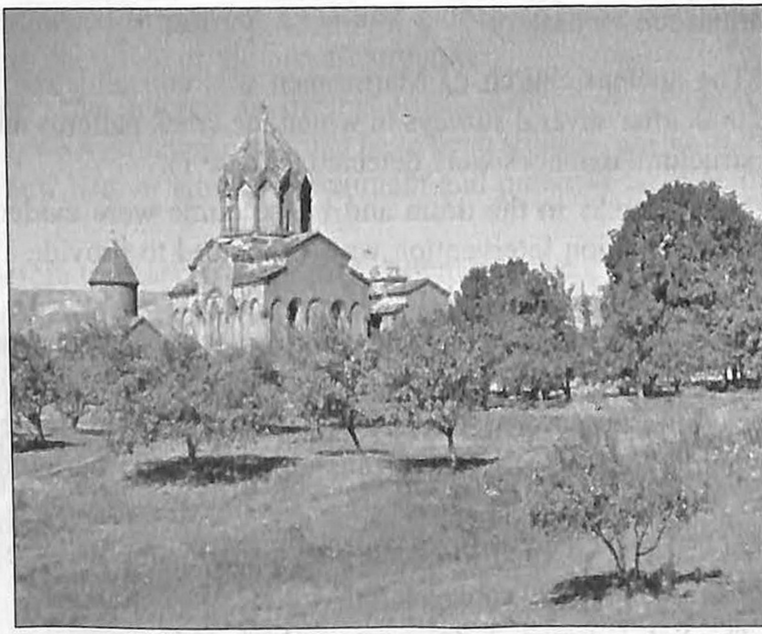
The post-tesion of the cable transfer a positive confinement to the masonry through the threaded bars, so that the axial compression between the stones increases and the resistance to vertical and horizontal loads increases too.

In this way, the formation of plastic hinges between the rigid masonry block is prevented thanks to the so called "Intradoxal Reinforced Arch Method".

The choice of placing the confining system inside the building strongly reduces the thermal effects on the steel cables.

In order to restore the global stability of some portions of the church that were close to a collapse mechanism, some steel chains were inserted inside the masonry.

Finally, some big stones were pinned each other, by means of steel bars (Figure 3), to guarantee the mutual connections between the blocks and to increase the resistance of the masonry.



The monastery of Marmashen in Armenia

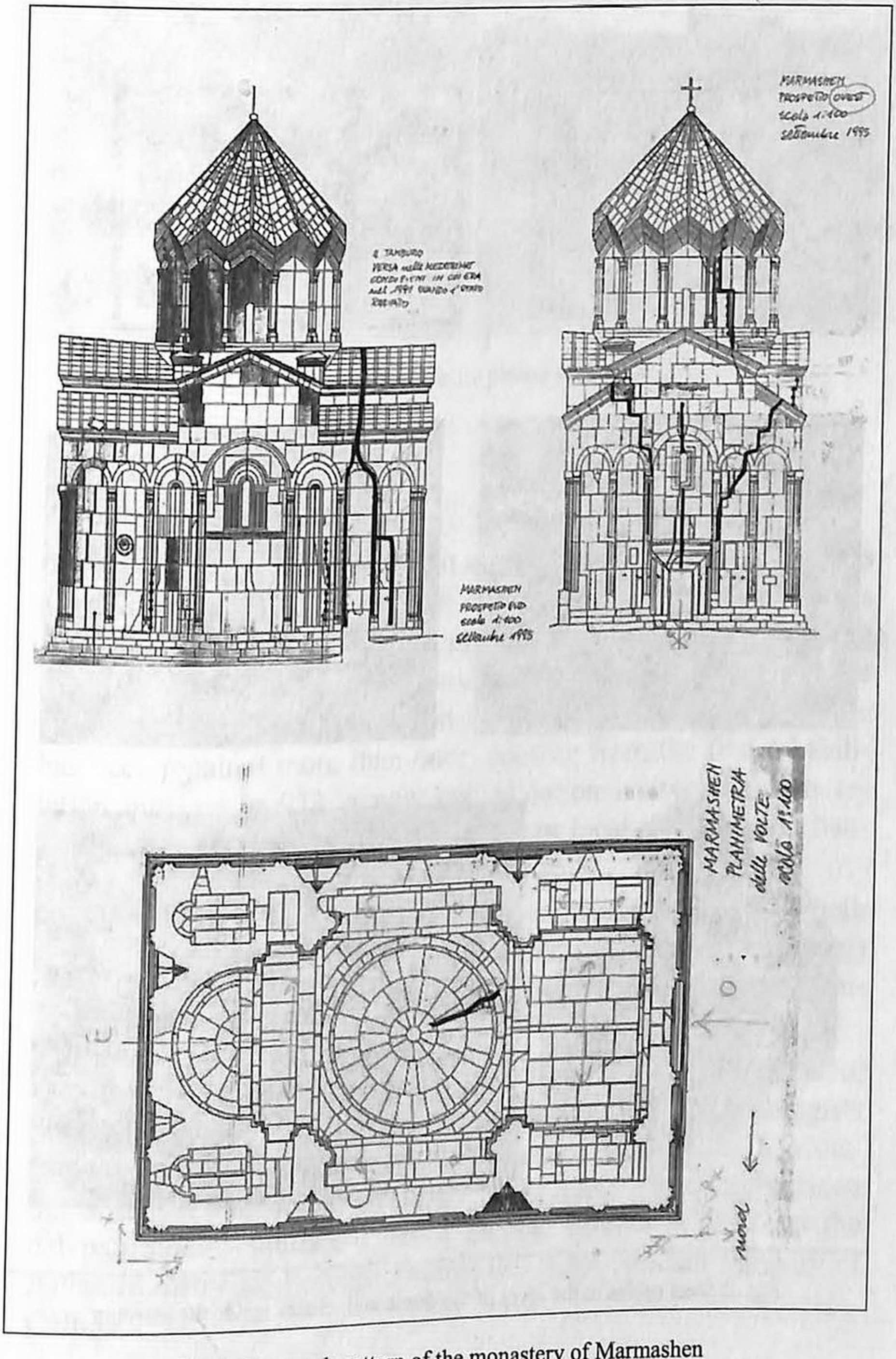


Fig. 1: The crack pattern of the monastery of Marmashen

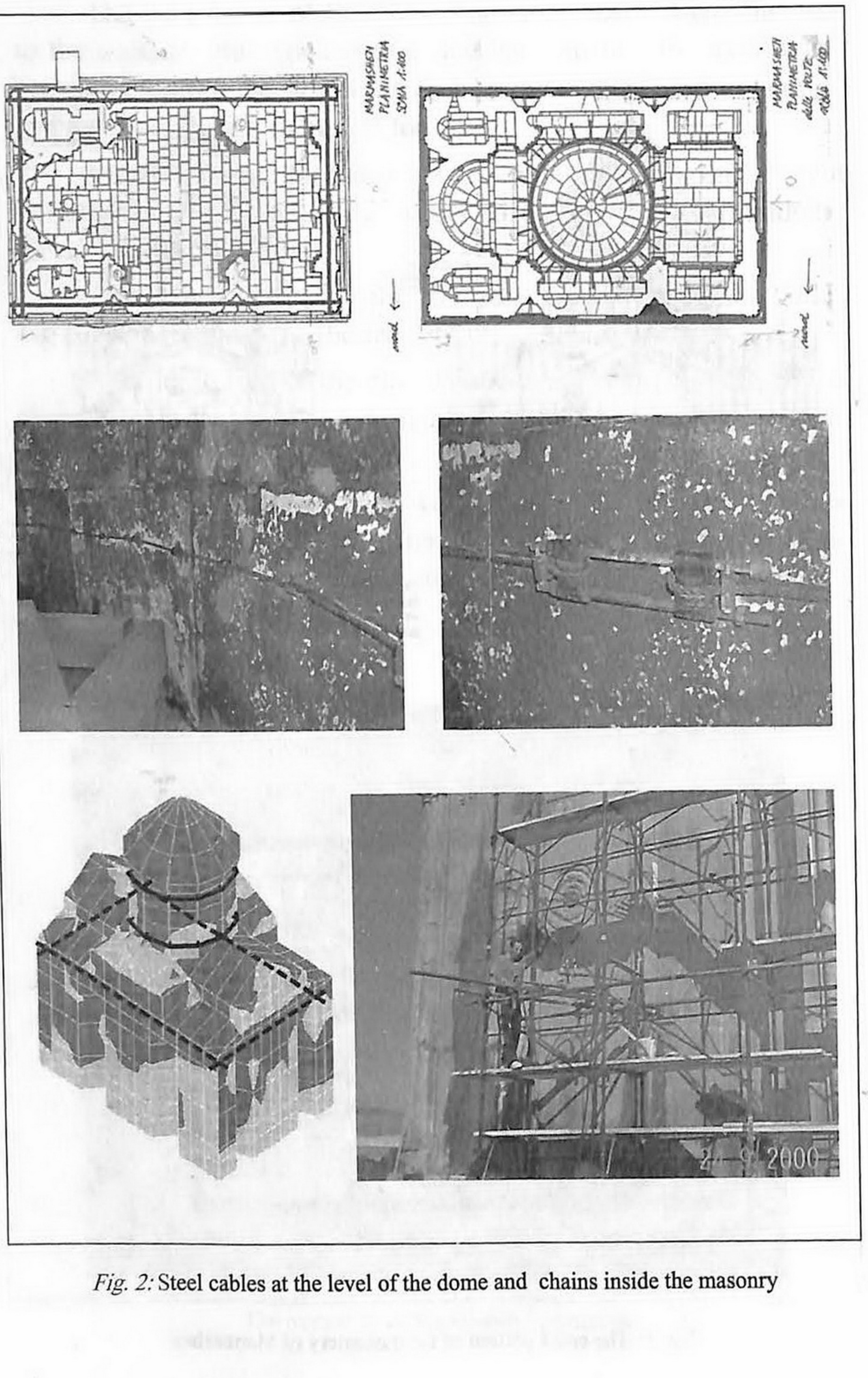


Fig. 2: Steel cables at the level of the dome and chains inside the masonry

Fig. 3: Big stones are pinned each other

2. Arudj temple

Arudj temple is the biggest among medieval domed churches in Armenia. During centuries it succeeded to resist to numerous earthquakes and invasions, which seriously affected it. A strong earthquake 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 was recently proposed. The aim was to prevent local or global mechanisms of the walls, in case of seismic events.

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 (Figure 5).

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 Foreign Affairs and the Armenian Ministry of Culture.

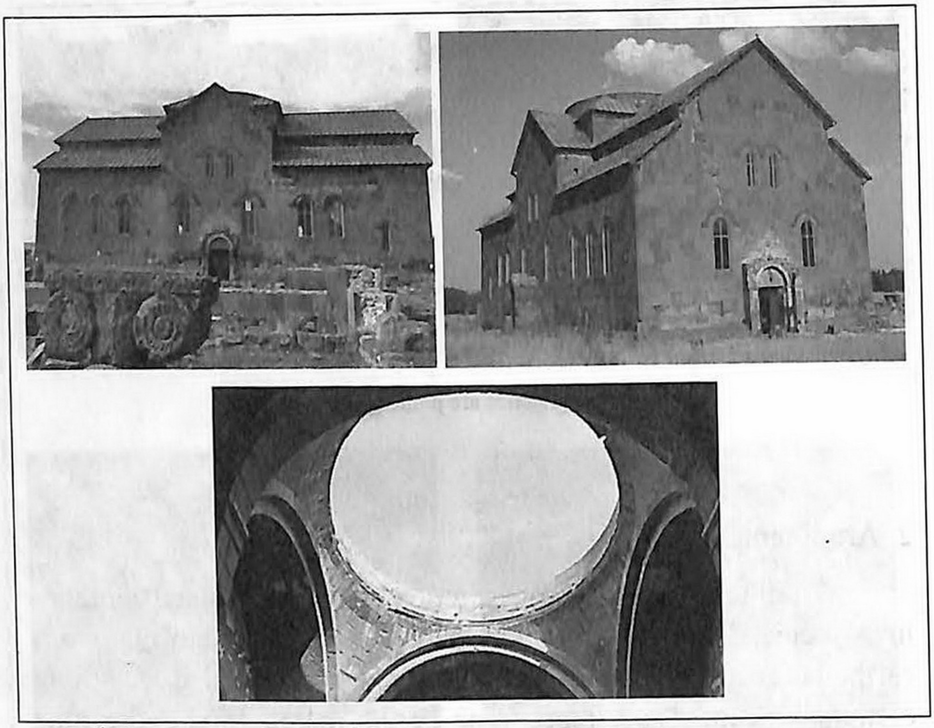


Fig. 4: Arudj temple: the huge dome collapsed due to an earthquake

The analysis of the crack pattern and of the mechanisms of collapse is an essential pre-requisite 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 suffered, and details of the structural response to vertical and horizontal loads.

Fig. 5: The thermography applied to the walls provided significant information about the masonry

The behavior (especially the seismic one) of the 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.

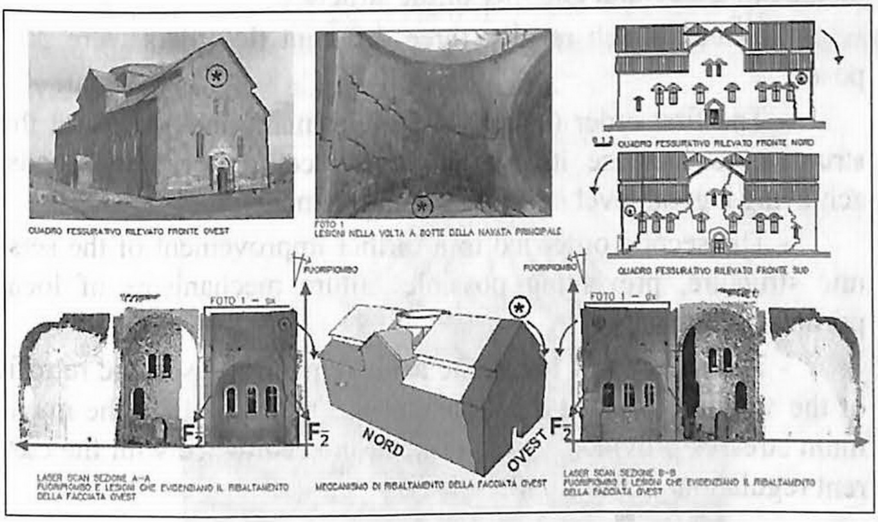


Fig. 6: The overturning of the façade detected during the surveys

Based on the information obtained, several consolidation intervention were proposed.

The first solution had the objective to prevent local collapse mechanisms due to the ejection of the big stone blocks, giving rise to a renovated monolithic behavior of the masonry.

The mutual connection of the large blocks of “tufo” was proposed introducing thin stainless steel bars arranged in a "pyramid" shape and fixed to the walls, without any glue or resin, alternately operating from the internal and the external layers.

Compared to traditional systems, "pyramids" are three-dimensional systems with a very reduced visual impact, because they are placed in correspondence of the mortar joints.

Another type of intervention proposed 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 presence 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 were proposed:

- The first order (we can say "the main one") 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 satisfy the maximum stresses provided by the project, in accordance with the current regulations (Figure 7).

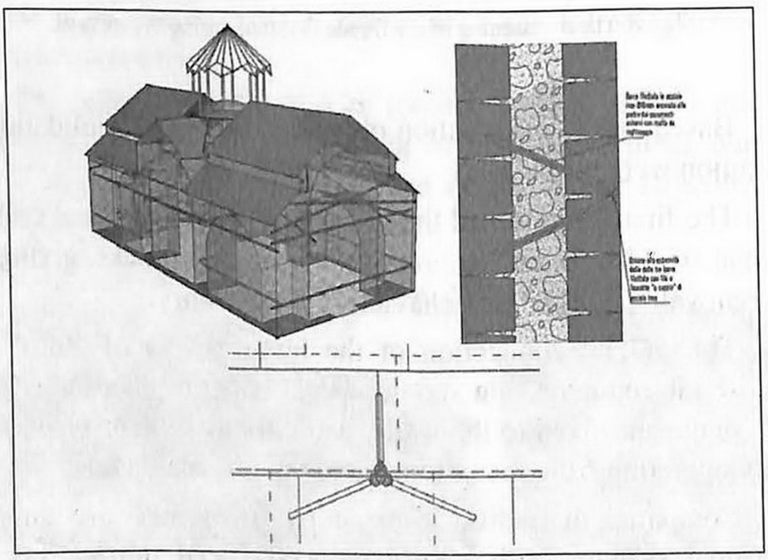


Fig. 7: **The insertion of new chains and of steel connections (pyramids) guarantees the box-like behavior**

Furthermore, an interesting proposal was advanced for the collapsed dome and lantern.

An octagonal steel lantern was proposed, providing only the thin "skeleton" perimeter, without any closures or coverage. The purpose of this solution was to suggest, in a discreet manner, the presence of a structural element common to many other churches of Armenia, that now is missing.

A new steel and glass shallow dome was then proposed to close the actual hole at the base of the lantern, without erasing any evidence of the past history of the church.

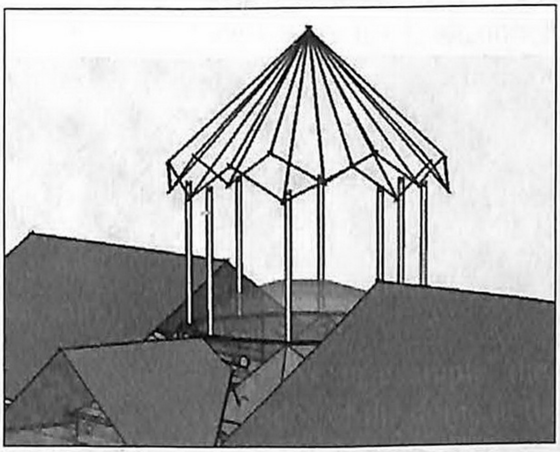


Fig. 8: **A"light solution" for the reconstruction of the lantern and dome of Arudj temple**

3. Ani
The "Reinforced Arch Method": an alternative solution

The ancient church of S. Amenaprgitch in Ani (today located in Turkey) represents another interesting case of "ruined" very precious structure. The only part that is still standing corresponds to the apse. The remaining portion of the building collapsed due to a strong earthquake (Figure 9).

In order to guarantee the necessary strength to the dome and to the walls, a special variation of the so called "RAM- method" was proposed.

It is useful to remind that the final purpose of the "RAM-method" is to modify the distribution of loads acting on the arches, vaults or domes so that the combination of the old loads plus the new loads can be the "right one", structurally speaking, 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, as a consequence, a radial distribution of forces is immediately applied to the masonry. This new load distribution induces an axial compression between the blocks and, therefore, the thrust line is re-centered, avoiding the formation of hinges.

Fig. 9: Ruins of the ancient church of the Savior in Ani

As demonstrated by more than 500 physical experiments and calculations, the proposed technique achieves results that are equivalent, or, in many cases, even better than the ones obtained with more traditional but much more invading method (for example "passive" concrete layer over the dome).

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 arch, vault or dome.

The general principle of the Reinforced Arch Method was proposed also in the case of Ani church, where a "double" family of cables was analyzed, considering different possible geometries.

To evaluate the efficiency of the method, the structure was 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-method, mono-dimensional beam elements were used, tensioned to 20 kN each one.

Four different FEM models were studied, considering the vertical dead load and two horizontal seismic loads (in x and y direction) equal to 0.3g:

In particular,

- 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 (Figure 11)

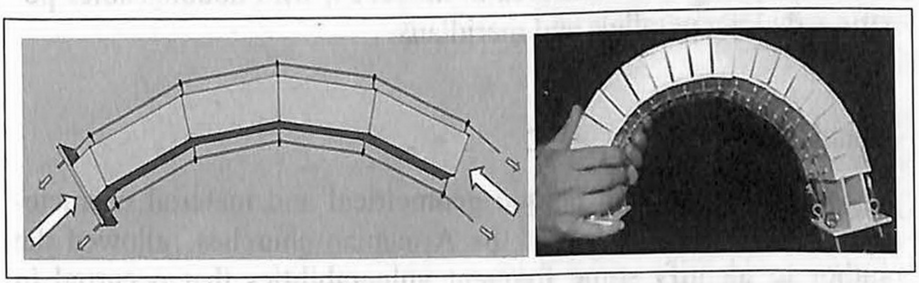


Fig. 10: (a) The "double cable" Reinforced Arch Method can be adopted when no fixed point are available (for example no stabilized abutements). (b) A physical scaled model illustrates the "double cable" RAM

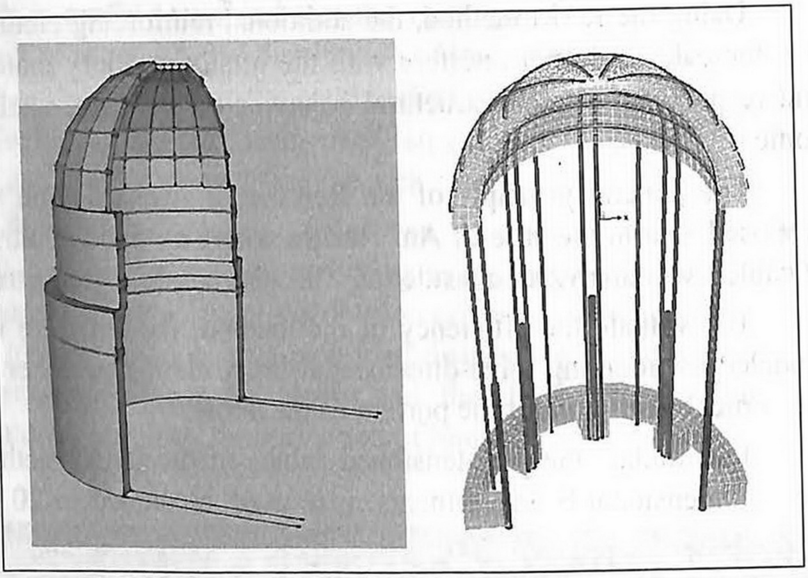


Fig. 11: FE Models J2 and J4.

Numerical results obtained in the three proposals of consolidation, compared with the non-consolidated one, demonstrated a significant reduction in terms of tensioned areas and of displacements.

As an example, the area that is subjected 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 finally reaches the value of 31% of the total area in model J4, whit double cables positioned along parallels and meridians.

Conclusions

The special and unique geometrical and material characteristics common to many of the Armenian churches allowed the author to identify some frequent vulnerabilities that occurred in case of seismic events, which need to be mitigated, in order to preserve the national cultural patrimony.

First, it has to be stressed the need to strength the masonry by connecting the big surface stones using transversal steel pins (diatoni). Second, it is evident the need to strength domes and drums, that frequently collapsed under horizontal loads.

The specific capacity of steel cables to work exclusively in traction, conjugated to the high load bearing capacity of the masonry, which works in compression, leads to effective consolidation solutions characterized by a minimally invasive approaches that improves the flexural behavior of the curved wall surfaces, i.e. arches, vaults and domes.

The Reinforced Arch Method, in its several variations, is an innovative solution that adjusts many different geometries, with acceptable aesthetic results and other important advantages, such as necessity, lightweight, minimally invasive, removability.

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SUMMARY

STRENGTHENING ARMENIAN CHURCHES: SOME INNOVATIVE PROPOSALS

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The ancient Armenian culture offers a wide number of historical buildings which show interesting technologies and materials adopted during the construction phases. In the last decades, some of these pieces of ancient heritage have suffered an evident structural deterioration, especially due to seismic events. In some cases, the structure reached local or global collapse. Three case studies are illustrated in this article, analyzing some consolidation interventions proposed by the author. The first case deals with Marmashen monastery, where a not invasive, reversible, and efficient consolidation solution was adopted to strengthen the drum. The second case has to do with Arudj church. Local kinematics were detected during the survey so that a global intervention of structural steel ties was proposed to restore an overall "box-like behavior". The third case concerns the ruins of a very famous church in Ani, where several innovative applications of the Reinforced Arch Method (RAM) were proposed.