Some proposals for Arudj Cathedral: from diagnosis to static consolidation

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Preface

The development of early-Christian Armenian architecture took place in a period of struggle between Roman and Persian Empires; in the meanwhile, Christianity rapidly diffused and became the state religion in 301.
In this climate, two main factors influenced the new architectural style: on one side the existing rich civil and religious cultural patrimony, especially pagan temples and residential complexes; on the other side the influx of values from the neighboring Cappadocia, Mesopotamia and Syria.
Thus, architectural activity proceed towards new forms, new technologies and innovative materials between the IV and VI centuries.
Among these renovations, a singular architectural form, called "dome–hall", became the most widespread typology of religious building in Armenia.
It represents the outcome of a vaulted longitudinal space (generally a barrel vault that covers the single nave), reinforced by transversal arches and square panel dome in the center of the hall.
There is an internal cohesion between the longitudinal and central plans that derives from two elements which have similar properties: the dome and the barrel-vaulted hall.
The stability of this form is no longer entrusted only on the dimension and continuity of the perimetral masonry walls, but rather to the system of transversal arches, that rest on two pairs of pillars placed in the center of the hall.
Furthermore, the squared-planned dome in the middle of the hall is not supported by buttress-work niches (typical of central planned buildings), but by quadrangular niches that are arranged to correspond to each of the bays, obtained by enlarging of the longitudinal hall and keeping the impost line of the roofing fixed.
Such a system of arches and supports guarantees the stability of the whole building, transferring the loads on elements able to counter the horizontal thrusts of vaults and roof.
Between the base square and the impost circle of the dome there is the drum; the transition to one section to the other is realized through spherical pendentives.
Another structural feature of this type of Armenian churches is the central disposition of the four pillars. They are rectangular in section and disposed in a sidescreen layout, in order to reduce the thickness of the external wall and to allow the opening of windows. Due to this, the masonry is characterized by a "rubble- core" technique.
Such structural clarity is not the outcome of some "abstract theoretical schemes", but rather of a true proper synthesis blending all the structural elements into a single unit of expression.
Abstract from "*The Growth and Development of the «domed-hall»"* by Armen Zairan and "*Armenian «domed-hall»*" by Francesco Gandolfo in [1]

The study case of Arudj Cathedral

Arudj Cathedral is an example of early-Christian domed-hall that dates 671-672.
A deep recent analysis of the building was developed by Politecnico di Milano, during the II° Level Master for Architects and Archaeologists named "Restoration Training and Support to Local Institutions for the Preservation and Conservation of Armenian Heritage".
The present paper mainly focuses on the structural aspects concerning Arudj Church, proposing alternative solutions for static and seismic consolidation, reached through an analysis process performed in different and consequential phases.

Fig 1: Arudj Cathedral in Armenia

The **first step** of the investigation activities consisted in a preliminary visual phase, including a geometrical survey, a photographic survey, and stratigraphic and technical in situ surveys. In this first phase the most important geometrical, technological and structural features were identified and the critical themes were underlined. The actual and potential building vulnerabilities were highlighted through in-depth observation and a careful recording of the structural damages. This information allowed understanding the overall the structural behavior of the edifice.
Overturning of the gable, thrust of arches and vaults on lateral structural elements and weak connections of the principal façade were the mainly global mechanisms detected.

Fig 2: Results the visual inspection phase

During the **second step** of the investigation activities a comprehensive instrumental diagnostic campaign was performed in order to better identify the structural damages and to validate the previous hypotheses adopted.
It's worth to remember that diagnostics, monitoring and planning must co-exist in a process aimed to ensure the protection and preservation of the historic monument through a conscious and effective methodological approach.
The diagnostic campaign conducted on Arudj Cathedral was performed using indirect non-destructive techniques, and it allowed the recovery of considerable important information to be used for the definition of the structural project.
All the masonry walls were analyzed to understand their internal geometry and to verify the presence of voids and humidity, which possibly caused degradation in strength.
All the results obtained through in situ tests, as thermography and sonic, were efficiently supported by laboratory tests conducted on stones and mortar, in order to evaluate their chemical and mechanical properties

Fig 3: thermography of lateral front

Fig 4: Samples of mortar and stone taken from the Cathedral

An accurate structural cracks' monitoring was performed as well. This activity played a very important role for defining the ongoing presence of kinematic movements of the structure.
The understanding of the results took place during the **third step** of the activities, where a numerical analysis was performed.

It was verified that the vaults and the arches were the most vulnerable elements, and that also the facades were subjected to global overturning.
With regards to verticality, the analysis focused on the restraining reactions of the arch, whose horizontal component, if not sufficiently counteracted by the vertical element, gives rise to a thrust that causes the rotation of the element and the formation of plastic hinges.
In absence of chains, Arudj buttresses have shown to have an inadequate strength against horizontal thrust, especially during high seismic actions.
Furthermore, a careful examination of the masonry texture of Arudj Cathedral helped to discover some critical technological choices adopted in the original construction.
The main walls, in fact, are constituted of two independent thin wall layers. This implies a considerable increase in the slenderness of the wall when compared to the entire wall thickness. Orthogonal elements called *diatones* could create an adequate connection between the wall layers, and consequently a better global behavior of the masonry wall. Unfortunately these elements are not present in Arudj Cathedral.

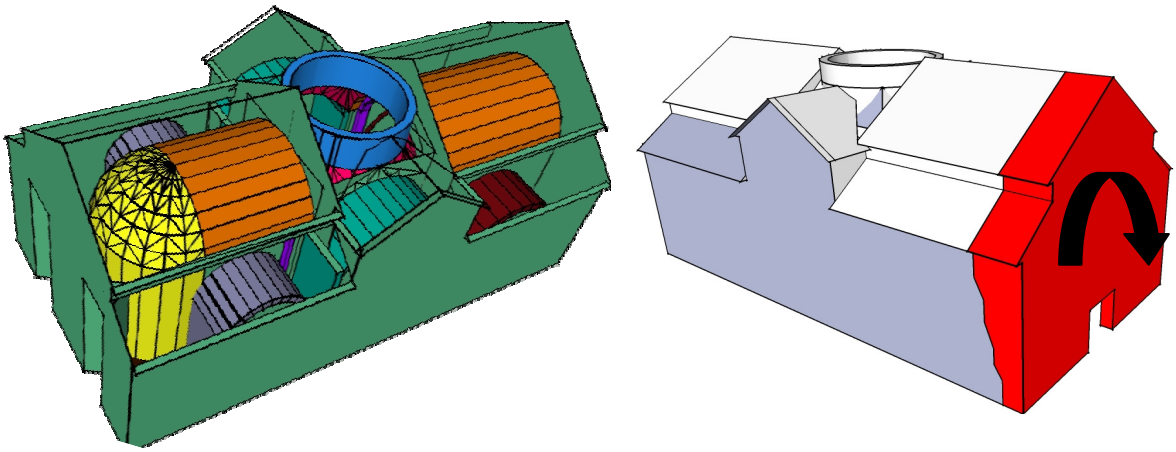

Fig 5: The macro-element model adopted for the numerical analysis

In the **last step** of the activities, some structural solutions were proposed and a structural consolidation project was defined.
The local mutual connection of the large blocks of tufo was proposed using thin bars arranged in a "pyramid" shape. They are 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, as they are placed in the joints of mortar.
An alternative solution can be the use of helical bars, simply introduced with a dry rotation

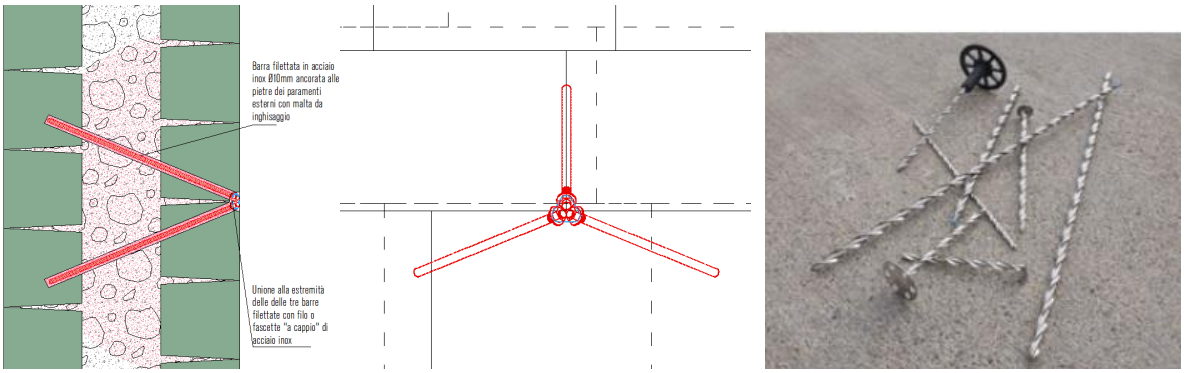

Fig 6: Pyramids system for the connection of the stone blocks or "diatones" realized with stainless steel helical bars

A proposal for a global consolidation of the church involved the insertion of steel-bar chains of containment, able to inter-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, acting against seismic actions, increasing the resistance to horizontal loads, but at the same time maintaining an adequate ductility of the structure.
To obtain such results, three different tie-orders were proposed:
- The first order of chains , the most important one placed near the top, allowes the structure to increase its overall resistance to horizontal loads, achieving a good level of seismic improvement;
- The second intermediate order led to a further improvement of the seismic structure, preventing possible local failure mechanisms of portions of masonry;
- The third order, at the base, 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.

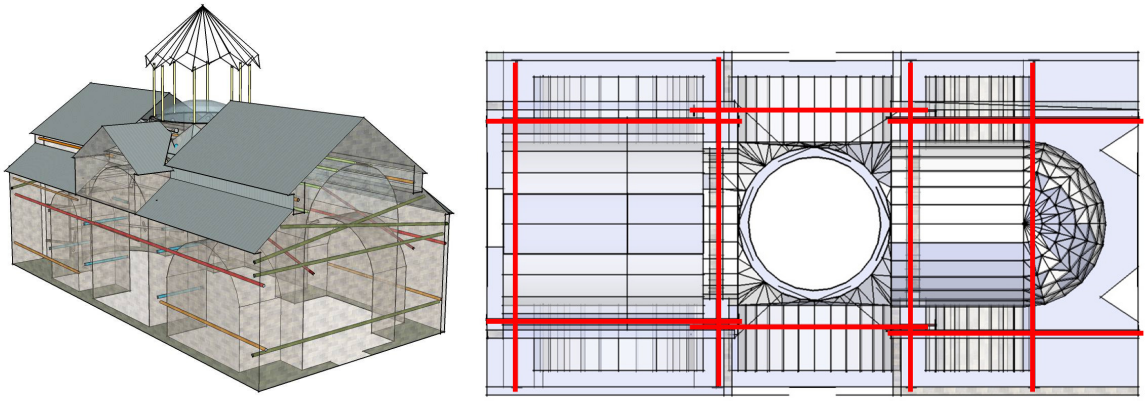

Fig 7: new chains for a global "box like behavior" of the Church

Furthermore, a suggestion was advanced for a re-proposition of the collapsed dome and the lantern. It consists in a new octagonal steel bars lantern structure, providing only the "skeleton" perimeter, without closures or coverage. The purpose is to permit the perception, in a soft way, the presence of the missing structure, common to almost all churches of Armenia.

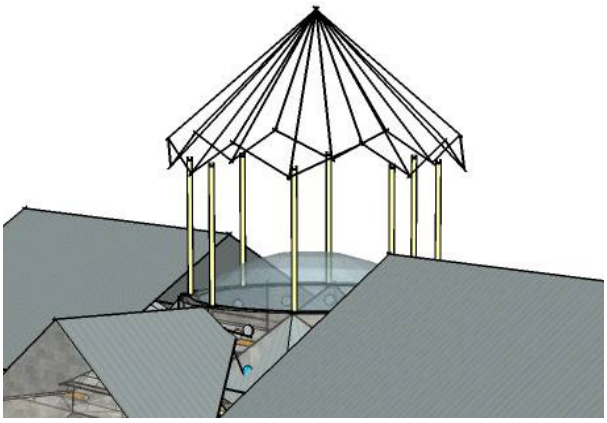

Fig 8: The proposal for a new lantern, only made of a steel light skeleton

As for the cover, a new steel and glass dome was proposed to close the actual hole and to permit the use of the church, without erasing any evidence of the past history of the church.

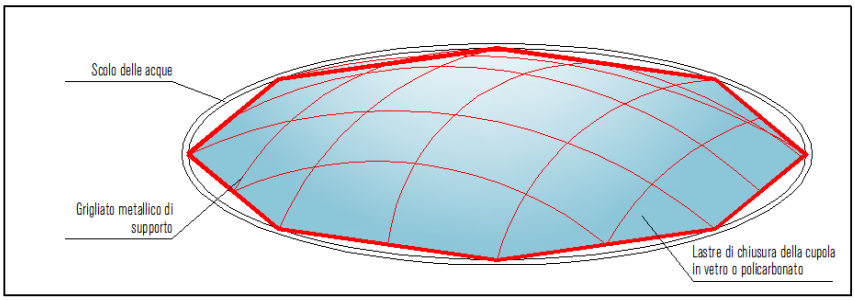

Fig 9: The proposal for a new steel and glass cover for the dome

Conclusions

The main critical structural aspects of Arudj Cathedral, such as the lack of *diatones*, the statically insufficient buttresses, the presence of holes, cavity and capillary humidity rising into masonry walls, were highlighted by proper visual inspections and non-destructive technique performed on the Cathedral.

Moreover, the main active kinematic movements, such as facade rotation, gable's overturning and thrust of arches and vaults on lateral structural elements were identified. Finally, some structural consolidation criteria were proposed in order to counteract these phenomena and a soft solution was "sketched" for the reconstruction of the collapse dome.

Even if a good technician have to bear in mind that every structural proposal has to be adjusted and "tailored" for the specific case, the methodologies of analysis and consolidation solutions proposed for Arudj Cathedral can represent an useful tool for other Armenian structures, with similar features and problems.

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