POLITECNICO DI MILANO

Cooperazione Italiana allo Sviluppo
Ministero Affari Esteri

DIPARTIMENTO DI
ARCHITETTURA E
STUDI URBANI

THE POLITECNICO DI MILANO IN ARMENIA

An Italian Ministry of Foreign Affairs project for Restoration Training and Support to Local Institutions for the Preservation and Conservation of Armenian Heritage

Structural analysis and structural consolidation methodologies

[1]Christian Amigoni
[2]Lorenzo Jurina

[1]Studio Amigoni
[2]Politecnico di Milano

Knowledge about a given building's every component, including both structural and non-structural, through an in-depth historical research and an accurate diagnosis is necessary before any design decision can be made. Therefore, the evaluation of the geometry, materials, and loads as well as the degradation and structural instability are priorities to be addressed and, as such, they are an integral part of the project.

First of all, it is important to evaluate the structural capacity of a building through the analysis of the residual strength compared with active loads to obtain more or less suitable safety related indications. In the choosing the type of the intervention, it is important that the structural scheme of the structural elements, with which the edifice was designed and built, be kept. These reflections and findings are intended to guide the designer in making precise structural consolidation choices. Indeed, the goal is to achieve conservation interventions that are least invasive and coherent with" the existing structure. Therefore, the diagnostic campaign, using a "minimum intervention" criterion, plays a very important role in guiding the design.

Nowadays, many direct and indirect non-destructive and semi-destructive techniques are available. According to the principle of monument structural preservation, non-destructive techniques are preferable. Direct investigation tests provide very useful tools to quantify to the parameters investigated, however they can damage the structural integrity of the building (modification of local static scheme, increasing of the damages, etc.). Indirect non-destructive techniques should be calibrated every time and, while rarely give absolute quantitative results, they nevertheless provide useful information compared with other tests.

The diagnostic campaign conducted in Aruch Cathedral was performed using indirect non-destructive techniques. This diagnostic campaign allowed the recovery of considerable important information to be used for the definition of the structural project. 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. *Diagnostics, monitoring and planning must therefore coexist* in a process aimed to ensure the protection and preservation of the historic monument through a conscious and effective methodological approach.

Aruch Cathedral structural consolidation design phases

The structural analysis process of Aruch Cathedral was performed in different and consequential phases. The structural knowledge was increased at every step, in order to define the best needed structural conservation interventions.

The *first step* consisted of a preliminary visual phase. Starting from a visual in situ analysis of the status quo, it included: a geometrical survey, a photographic survey, and stratigraphic and technical in situ surveys. In this phase the most important

geometrical, technological and structural 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. During the *second step* a comprehensive instrumental diagnostic campaign was performed in order to better identify the structural damages and to validate the previous hypotheses adopted. The understanding of the results took place during the *third step*. In this phase some previous vulnerability hypotheses were rejected, while several others were accepted.
During the *fourth step* a numerical analysis was performed. In this phase, taking both the engineering awareness and the architectural perception into account allowed creating a numerical model in which all the elements, including the cracks, the damages and the kinematic structural movements were quantitatively introduced. Thanks to the numerical and diagnostic results a quantitative vulnerability level, compared with a reference scale or a landmark value, was identified. In *the fifth and last step* some structural solutions were proposed for Aruch Cathedral and a structural consolidation project was defined.

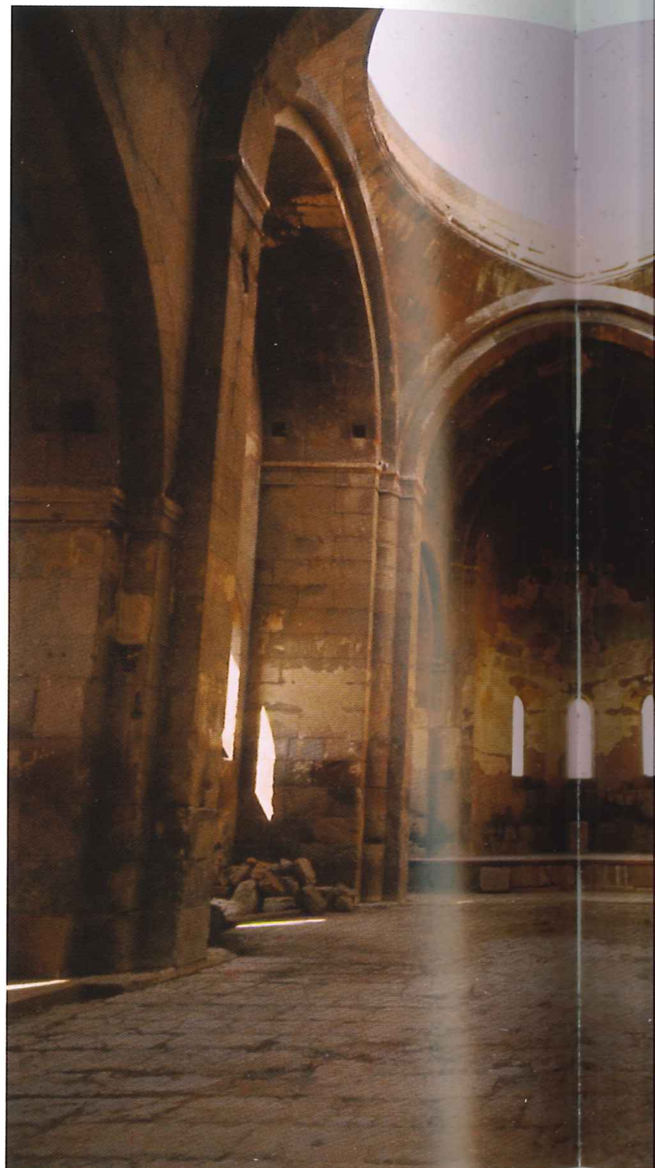
Step 1: visual macro-element structural analysis

In this first phase the logical process for the definition of the restoration and structural consolidation design, underlining the fundamental elements of the analysis concerning this type of building underwent an in-depth study. It is important to note that the geometrical, material and building features of Armenia's edifices are similar throughout the country. Therefore, the proposed structural consolidation criteria are *replicable to other similar buildings*.
The surface degradation of the structural material, the main cracks, and the irregularity of the walls were the most critical aspects to be studied at Aruch Cathedral. These damages are due both to some original geometrical imperfection and to exceptional events, such as strong seismic activities, which took place in the past.
In fact, it should to be noted that Aruch Cathedral is located in a high seismicity zone, at the intersection of the Euro-asian, African and Arabic tectonic plates.
The principal sources of vulnerabilities can be summarized as follow:

- Overturning of the gable;
- Thrust of arches and vaults on lateral structural elements;
- Weak connections of the principal façade.

Step 2: diagnostic campaign planning

The diagnostic campaign was defined after the definition of the objectives. Thanks to the combination of different instrumentations and diagnostic techniques, it was possible to achieve said objectives. All the masonry walls were analyzed to understand their internal geometry and to verify the presence of voids and humidity, which possibly cause degradation in strength.
Let us remember that the masonry used in the construction was constituted of *rounded blocks of weak stone, external cladding of high thickness but poor connection capacity, and an inner core*. The wall composition was analyzed in order to better understand the instability phenomenon induced by the presence of two unconnected masonry portions.
Additionally, the mechanical and physical features of mortar joints were analyzed



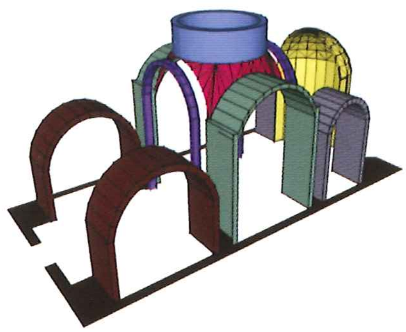
1

in detail (See the following specific paragraphs for more details about analysis results and diagnostic activities).

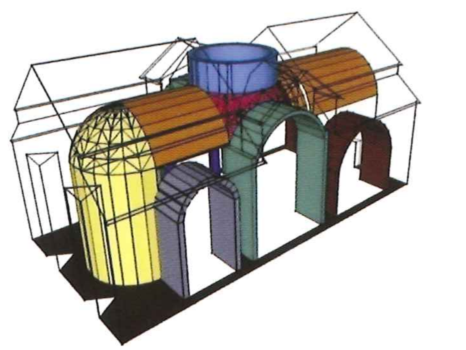
Steps 3 and 4: results interpretation and kinematic mechanism analysis

The main geometric critical aspects were identified through the analysis of the gravitational action flows, which persist on the principal macro-elements under ordinary static loads. Once it was verified that the *vaults and the arches* were the most vulnerable elements, it was possible to analyze the principal flow that follows the geometry of the arc, from the top to the bases (made of single pillars or walls).
With regards to verticality, the analysis focused on the restraining reactions of the arc, which has a vertical component and a horizontal component. The latter, if not sufficiently counteracted by the vertical element, which gives rise to a thrust that causes the rotation of the arc and the formation of plastic hinges.
It must be noted that wood or steel chains, which act against the horizontal thrust have been introduced centuries ago in the Italian traditional building design procedure. Using a different technique, and in order to avoid chains, the solution mostly adopted in the Armenian tradition consisted in the use of buttresses.
Nevertheless, the *Aruch buttresses have shown to be inadequate in strength against horizontal thrust, especially during high seismic actions. An overall description of the existing cracks is presented below.*

The apse of Aruch.



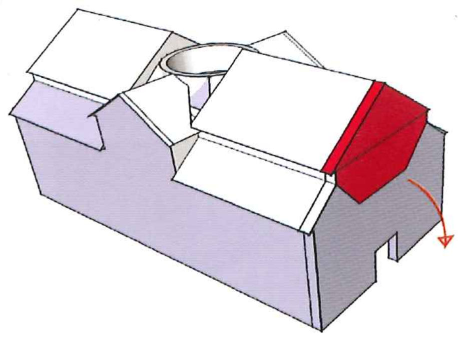
2



3

4

5

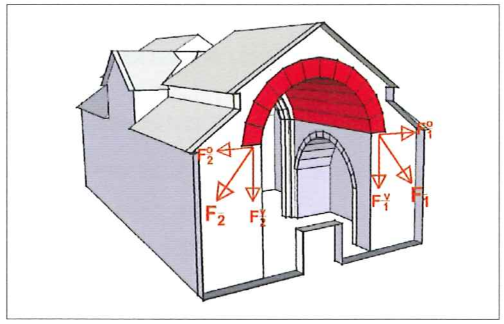


6

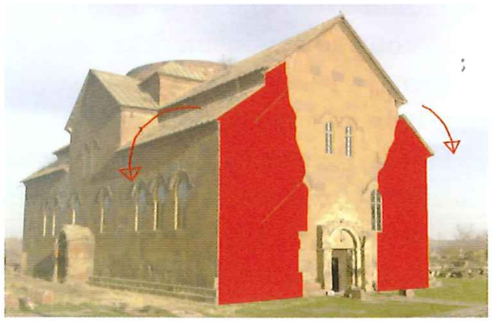
7

Macroelements – arches and vaults of Aruch Cathedral
Gable's instability
West elevation - the cracks.
West elevation - the gable's cracks.
Gable's overturning mechanism.
West elevation - the gable's cracks.

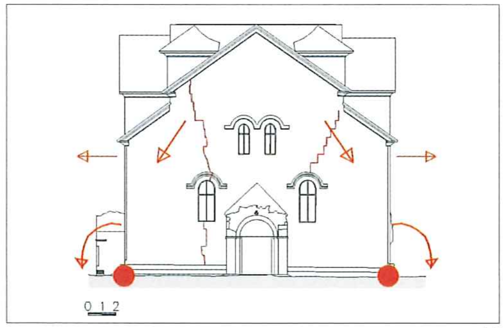
8



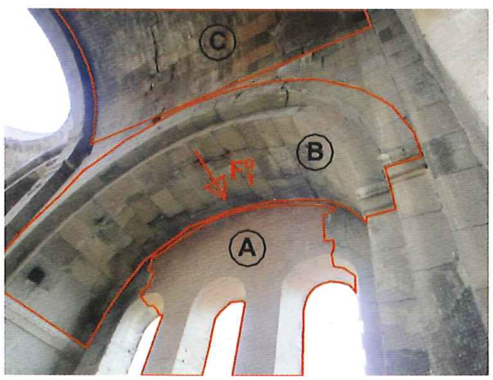
9



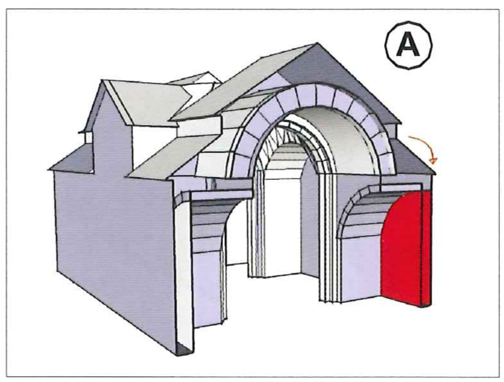
10



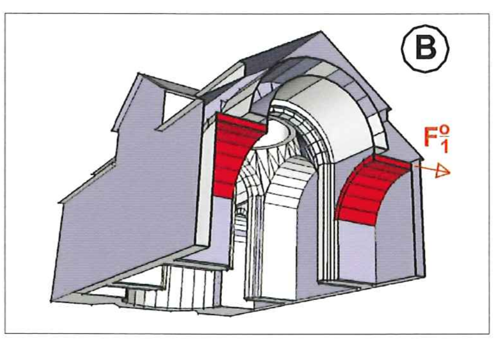
11



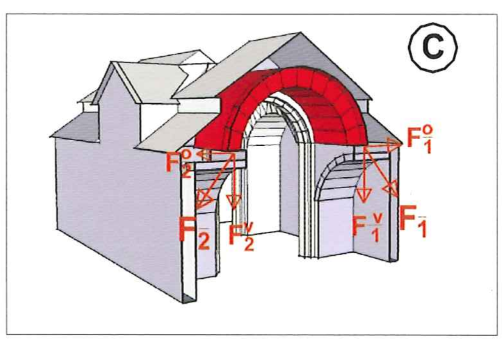
12



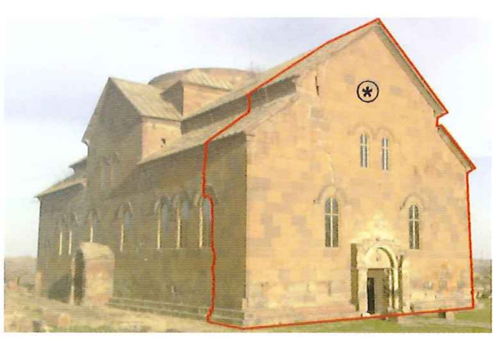
13



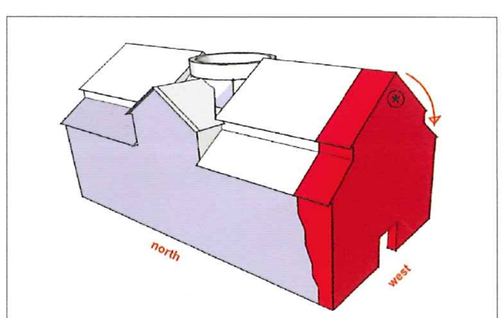
14



15



16

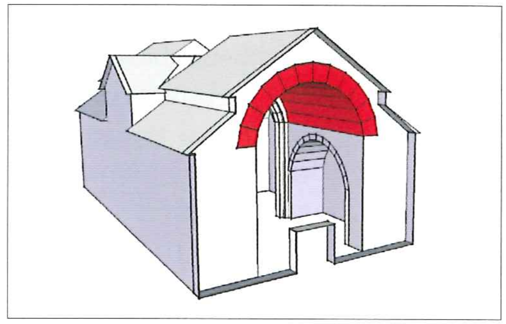


17

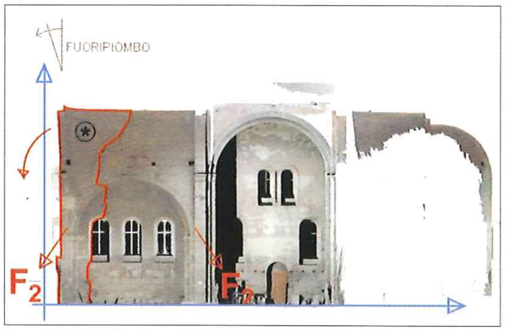
Thrust of the vaults and arches on the side elevations
West elevation.
Acting forces scheme.
West front – macroelements.
Acting forces scheme.
North front – macroelements.
Acting forces scheme.
Acting forces on the macroelements.
Acting forces on the macroelements.
Acting rotation on the principal facade
West elevation.
West front – macroelements.

Cracks on the aisle vault roof.
Laser scanning survey – localization of uneven walls and macroelements.
The placement of the chains in the walls, arches and vaults.

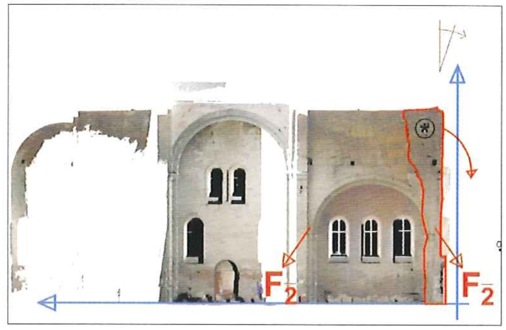
18



19



20



21

In addition to the above analysis, a careful examination of the masonry texture of Aruch Cathedral helped to identify a certain number of critical technological choices made in the original construction.

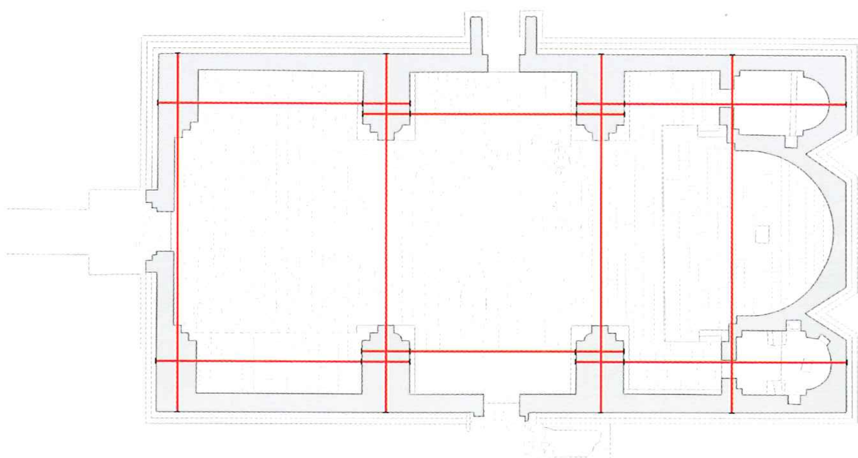
The main walls are constituted of two independent thin wall layers, implying a considerable increase in the slenderness of the wall when compared to the entire wall thickness. Orthogonal elements called *diatones* could create a better connection between the wall layers, and consequently a better global behavior of the masonry wall. Unfortunately these elements aren't present in Aruch Cathedral. Therefore, the structural consolidation also proposes the use of *diatones.*

Phase 5: some information about the structural consolidation measures

While noting that the same solutions can also be applied to other similar buildings; some structural guidelines for Aruch Cathedral can be summarize as follows:

CHAINS

The inter-connection of the piers and the balance of static and seismic actions of the main arches and vaults are essential elements in the structural strength of a building of this size and of this historical significance.



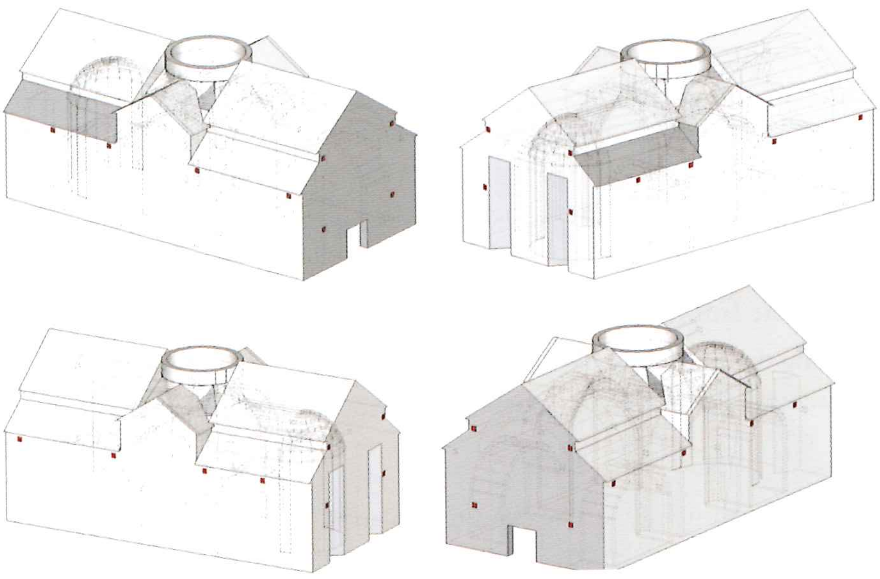
22

It is possible to envisage a pattern of chains represented by steel bars placed in correspondence with the base of the arches and anchored to the façade. In order to minimize the presence of external steel plates on the existing walls, and especially on the external façade, a fairly invisible "root anchorage system" can be adopted. These elements have a discrete appearance (sufficient to declare their own presence in the correct position). They constitute an important help for building resistance.

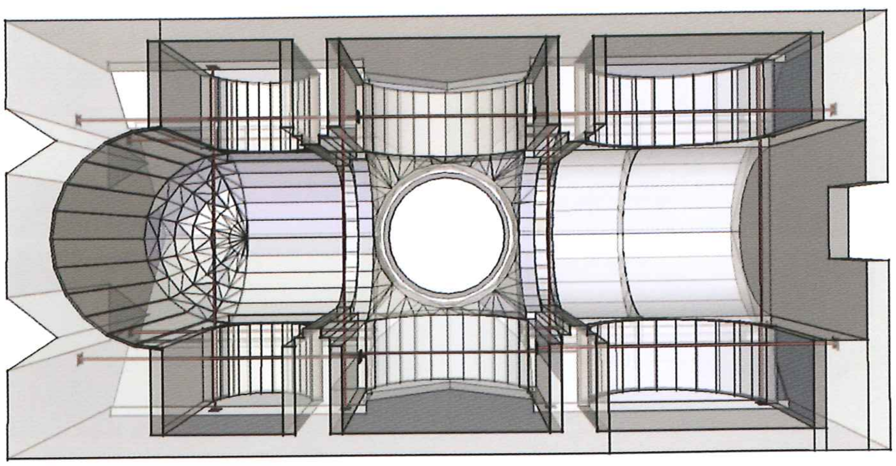
It should be noted that long steel tubes placed at the base of the arches are often seen inside some Armenian churches. They are frequently used to support tents or partitions. Accepted by Armenian Church users, these items are similar, in terms of shape, to the chains proposed in our project. We understand that the chains constitute a new structural element, sometimes difficult to accept, but they are extremely useful, inexpensive and minimally invasive. The method can, at the very least, be used as a provisional solution and be tested for acceptance.

Diatones

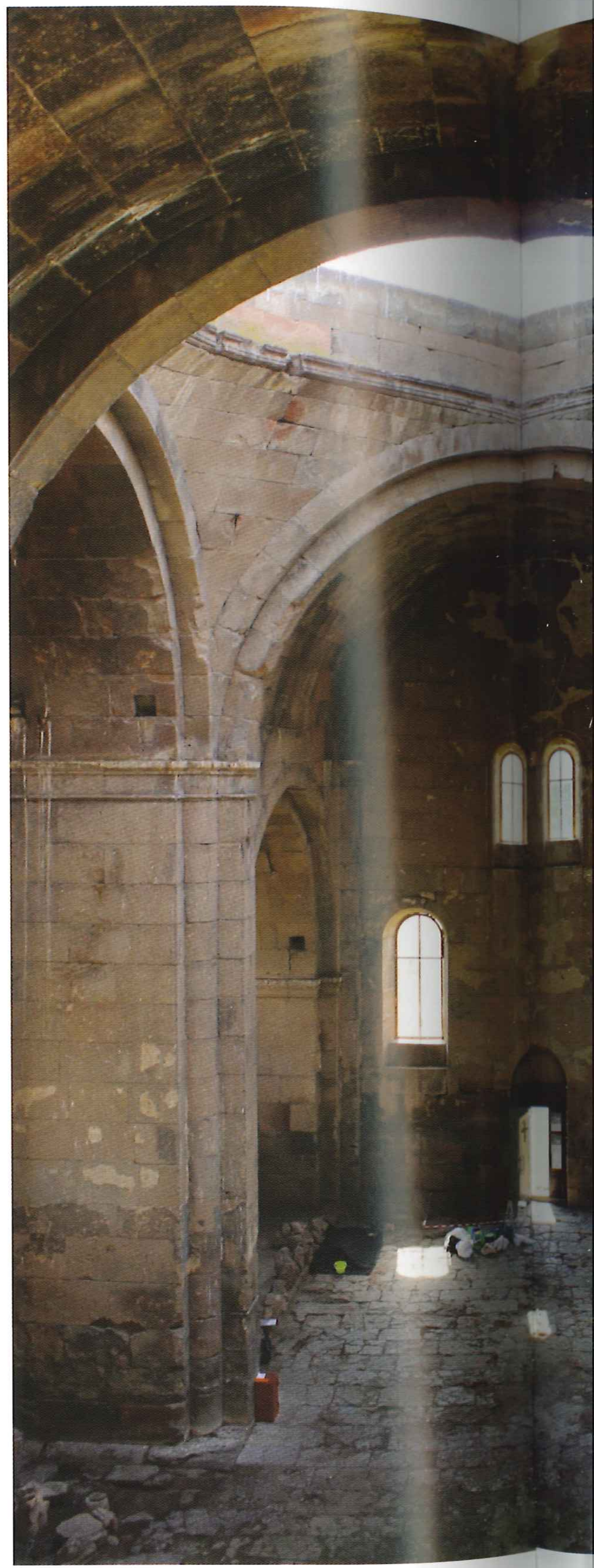
The lack of connection between the wall masonry layers is also a theme to be solved for the local consolidation of the building. We proposed a solution that involves dry perforations reinforced with helical stainless steel bars, which are characterized by a good elasticity and the absence of grouting material.



23-26

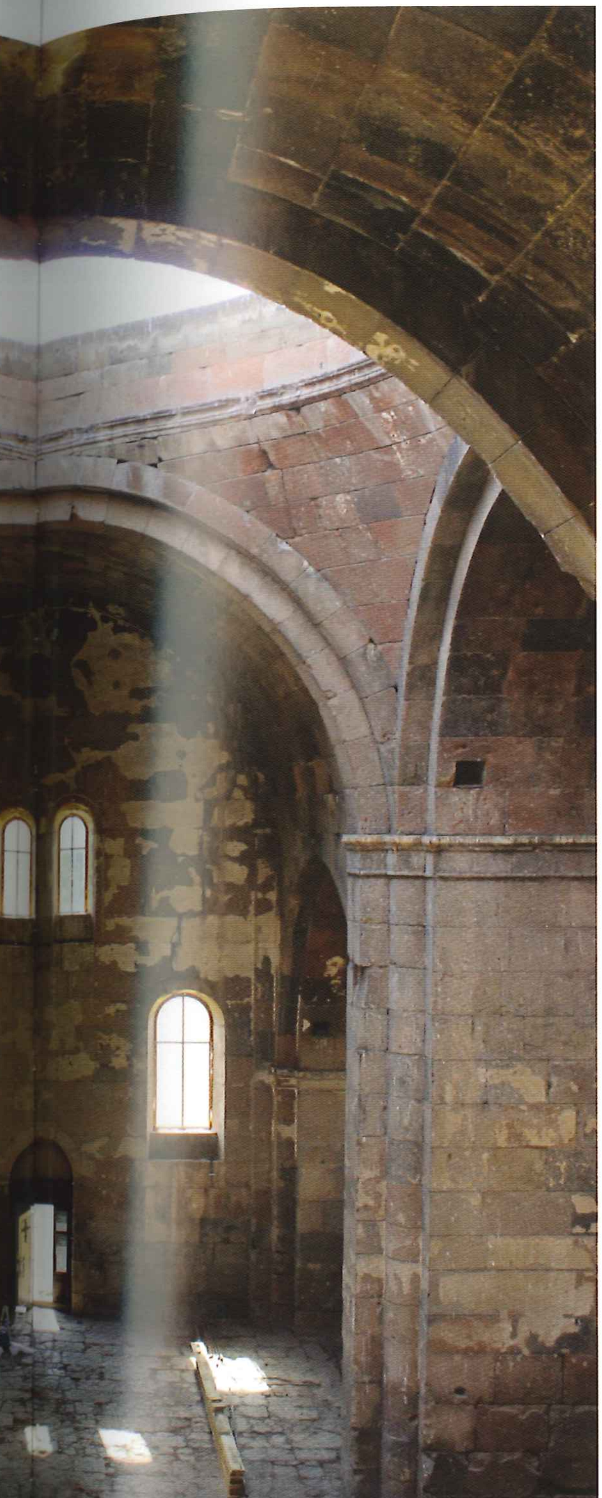


27



28

Inserting contrast elements of the chains on the facades.
A shackling scheme of masonry piers, arches and vaults.



Interior of the Aruch cathedral.

Injections

As described in the analysis of the sonic tests' results, the presence of voids in the walls represents a significant structural weakness and, unfortunately, they are mainly located in places that correspond to the areas where the main structural vulnerabilities are present. Injections are a very viable technique for structural reinforcement for the masonries of the Cathedral, if and when carried out with the necessary care. Based on the results of sonic tests it is possible to estimate how much material must be injected to fill the gaps, and to identify the location for the injections in accordance with the graphs obtained. It must be noted that, thanks to laboratory tests on mortar, it was possible to recreate a mortar consisting of a mix that is appropriate, compatible and not dangerous for the execution of the injections.
Lastly, and as a final intervention, it is important to correct the degradation due to humidity rising up from the foundations. An appropriate intervention would consist of excavating a sufficiently deep draining trench around the outer perimeter of the Basilica.

Conclusion

The Aruch Cathedral critical structural aspects such as: lack of diatones, ineffective buttresses, presence of holes, cavity and capillary humidity rising into masonry walls, have been 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 have been identified. Finally, some structural consolidation criteria have been proposed in order to counteract these phenomena. The main interventions consist in:
1) Applications of tie rods confining the Cathedral external walls,
2) Local consolidation injections, and
3) Connection between the external wall layers through diatones.

The methodologies of analysis and the proposed consolidation solutions can be useful tools for other Armenian structures, which present features similar to Aruch Cathedral, as well; while bearing in mind that structural applications have to be adjusted and "tailored" for every specific case.

A technical meeting held by Professor Jurina with his colleagues in the Armenian University of Architecture and Construction.

28