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Constructive Analysis of the Arches and Ribs of the Vault on High Altar of "Santa Maria" Church of Tolosa (Basque Country)

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ABSTRACT: The paper describes the studies and the analyses carried out on the Santa Maria Church of Tolosa. Few years ago, after some works carried out in order to restore the vaults, part of the stony materials of the arches and ribs placed on the high altar began to come off and important local de-formations happened. Immediately the church was closed and the architect in charge of the building required LABEIN to study the strange phenomenon. All the developed works and the final diagnosis are described.

1 INTRODUCTION

1.1 History and general features of the building

In 1548, on the ruins of a primitive church, the construction work of the actual "Santa Maria" Church of Tolosa (an important town of the Basque Country) was initiated, see Fig. 1. The works were finished one hundred years after.

Figure 1 : General view of the church.

In 1781, an important fire broke out, and the high altarpiece, and fifteen lateral altars with their respective images were burnt. The building was seriously hurt and it was necessary to re-construction some of the parts of it.

In 1992, after one of the keystone of one of the vaults come off, all the ribs were stitched and the vaults were reinforced with concrete on their side not visible to public, see Fig. 2.

Figure 2 : Reinforcement works in the extrados of the vaults.

The building consists of three naves of 54 metres long and 26 metres high. The main structural elements are the followings:
- Perimeter masonry wall with buttresses
- Cylindrical piles of stone
- Arches, ribs and plaster filling forming the vaults (all of stone)

1.2 Damages detected

Few years ago, after the works carried out in 1992, in order to restore the vaults, part of the stony materials of the arches and ribs placed on the high altar began to come off and important local deformations happened. Immediately the church was closed and the architect in charge of the building required LABEIN to study the strange phenomenon, see Fig. 3.

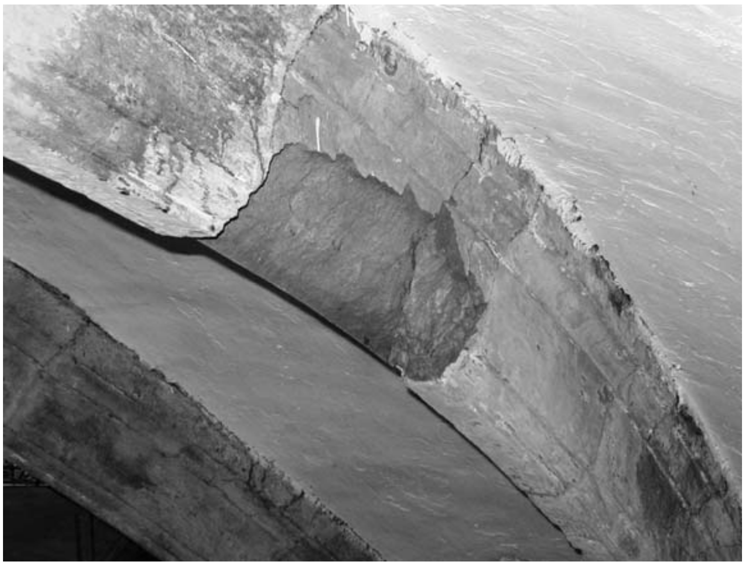

Figure 3 : Damage detected.

Bellow, are described all the works developed and the final diagnostic of the structure.

1.3 Works developed

The following works were performed to determine the cause of the pathologies:
- Analysis of existing documents dealing with the structure: history of the construction, repairing actuations in the past, punctual collapses, etc.
- High precision topographical survey of the vault in trouble, quantifying the leaning of the pillars and all the deformations of the arches and ribs. Measurements were done in both sides of the vault.
- Specimens of the stony material were taken to carry out the laboratory tests.
- Macroscopic and microscopic study of the rock
- Mineralogical analysis by X-rays
- Unconfined compressive strength tests
- Module of elasticity tests
- Resistance to indirect traction tests
- Structural calculations by the finite element method.

2 MECHANICAL CHARACTERIZATION

2.1 Field investigations

During one week, structural experts of Labein study in situ the problem. One detailed visual inspection was carried out in the affected vault. To see the damages of the vault close up it was necessary to set up a scaffold, see Fig. 4.

Figure 4 : Scaffold used in the study.

Likewise multiple small testings were done in the extrados and in the extrados of the vault, and five specimens of the stony material were taken.

2.2 Geometrical control

Geometrical and dimensional control of the vault consisted on high precision topographical survey of the vault in trouble (scale 1/50), quantifying the leaning of the pillars and all the deformations of the arches and ribs. Measurements were done in both sides of the vault.

In the pillars fixed in the apse wall invaluable leanings were detected, so the deformation of the arch between them was not owing to movements in its supports.

In the other pillars, the strains are bigger but not sufficiently big to account for the deformations of the vault.

2.3 Material studies

An extensive program of analysis were done: macroscopic and microscopic study of the rock, mineralogical analysis by X-rays, unconfined compressive strength tests, module of elasticity tests and resistance to indirect traction tests.

All the studies highlighted considerable differences between the rocky material (sandstone) of the arches and ribs from the intrados and the material from the extrados of the vault. Specimens from the same keystone presented different values of stiffness, cohesion and resistances depending of the location.

The values of cohesion and resistance in the sandstone from the intrados were bigger than in the sandstone from the extrados, but the module of elasticity was appreciably lower in the intrados, what indicated that the first was more fragile.

The petrology studies allowed to give an explanation to this phenomenon. The composition of the sandstone is the same in all the specimens, but the ones from the intrados was disturbed and the materials clayey present in it had been fired, increasing the fragility in this part.

In the figures included bellow it is possible to appreciate the differences between the materials relating to the microscopic structure, see Figs. 5 and 6. The clay between the grains of quartz in the Fig. 5 is crystallized.

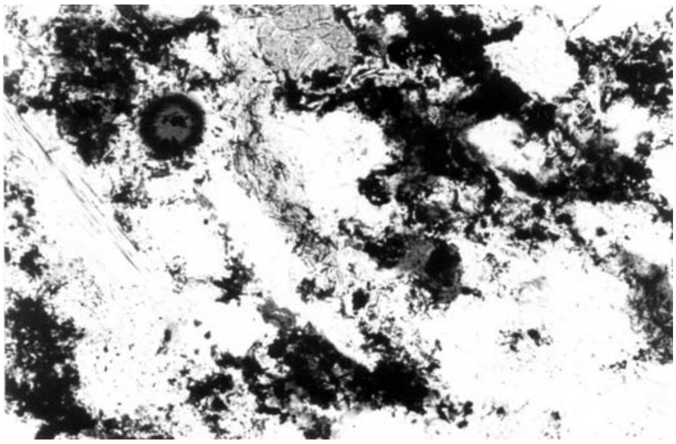

Figure 5 : Sandstone from the intrados.

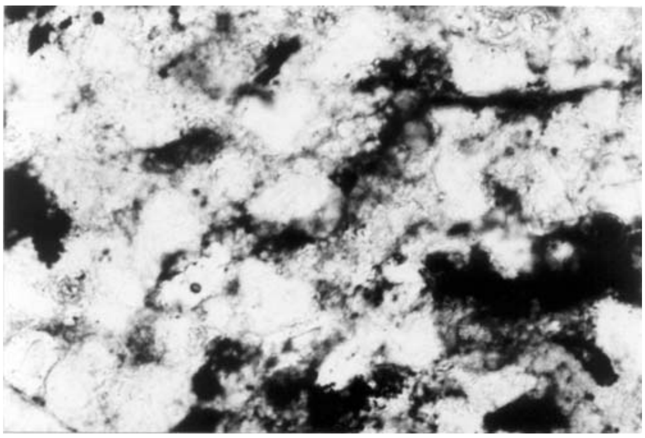

Figure 6 : Sandstone from extrados.

When we discovered this we thought that probably we were facing a very special and difficult situation: the changes generated in one material by one fire two centuries before could be the key to the problem.

We suspected the reinforcement works in 1992 and the condition of the structure of the roof, with beams resting on the vault (see Fig. 7) were important to explain the collapse of the vault, but in that moment we had another factor to introduce in the diagnosis.

Figure 7 : Beam resting on the vault.

3 STRUCTURAL ANALYSIS

The structural analysis allowed to identify the critical points of the arches and ribs, valuate the importance of the different mechanical behaviour of the material and the effect of the interface in the arches.

3.1 Modelling of the structure

The commercial program ANSYS was used to analyse the structure by the method of the finite elements, see Fig. 8.

Two materials models were considered:

- Linear elastic analysis. Used like auxiliary tool, having account its limitations and without the pretension to obtain exact results. This type of analysis constitutes a very useful approach.
- Nonlinear analysis. Realized to represent the main characteristics of the masonry, practically null resistance to traction and essentially fragile character. By means of a model of elastic-fragile material to traction and elastic-plastic to compression, the type of element makes specific of ANSYS (SOLID65) allows, with measure models of sophistication, to reach sufficiently realistic conclusions.

The results were very explanatory, the deformations obtained in the calculations were very similar with the deformations measured, and the critical points, with the maximum values of the traction tensions coincided with the parts of the arches with problems.

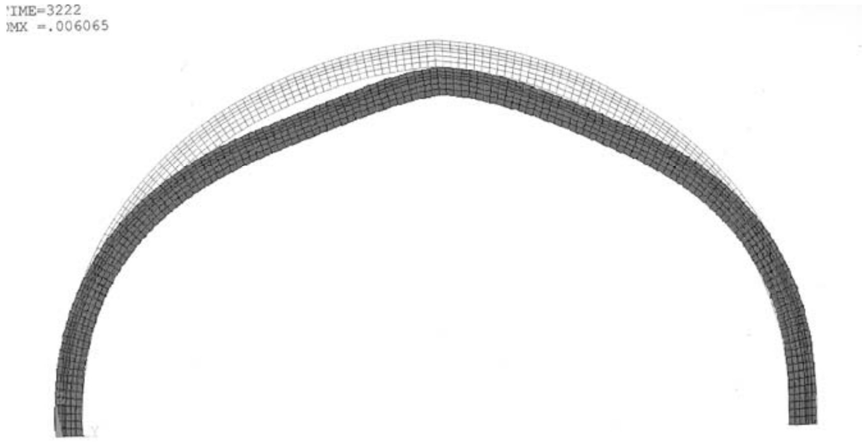

Figure 8 : Deformed shape of the one of the arches studied.

4 CONCLUSIONS

Structural calculations proved that the vault's deformations, obtained by topographical methods, did not mean that the stability of the whole of the vault would be compromised. In addition, the absence of important cracks in the vault seemed to point out that deformations had been assumed by the structure without great problems.

In the same way, the tensional levels calculated would not imply structural problems, as long as the mechanical behaviour was homogeneous.

Nevertheless, the structural problem was real and it was the petrography research and the laboratory tests, what discovered that the material's surface had suffered important changes and that the mechanical behaviour of the material in its surface was different than inside.

Analysing the history of the building, it was discovered that in the 18th century an important and destructive fire took place just under this vault. During the fire there were very high temperatures that would have caused the changes in the material's surface.

These facts, together with the analysis of the last restoration in the church, were the key to understand what was happening.

The last restoration increased notably the rigidity of the vault, in the same way, the tensions increased owing to the effect of the beams resting on the vault.

This increase could not be absorbed by the structure and it collapsed by the surface that separated the disturbed material and the no disturbed.

Last year, interventions to solve the problem were finished and to date everything is going well.