THE VIRTUAL CATHEDRAL - AN ESSAY ABOUT CAAD, HISTORY AND STRUCTURE

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Abstract

The Old Cathedral of Santa Maria in Vitoria is the most representative building of the Gothic style in the Basque Country. Built during the XIV century, it has been closed to the cult in 1994 because of the high risk of collapse that presents its structure. This cIosure was originated by the structural analysis that was entrusted to the University of the Basque Country in 1992.
The topographic works developed in the Cathedral to elaborate the planimetry of the temple revealed that many structural elements of great importance like arches, buttresses and flying buttresses were removed, modified or added along the history of Santa Maria.
The first structural analysis made in the church suggested that the huge deformations showed in the resistant elements, specially the piers, were originated by interventions made in the past. A deep historical investigation aIlowed us to know how the Cathedral was built and the changes executed until our days. With this information, we started the elaboration of a virtual model of the Cathedral of Santa Maria. This model was introduced into a Finite Elements Method system to study the deformations suffered in the church during its construction in the XIV century, and the intervention made later in the XV, XVI and XX centuries.
The efficiency of the virtual model simulating the geometry of the Cathedral along history allowed us to detect the cause of the structural damage, that was finally found in many unfortunate interventions along time.

The Cathedral

The Old Cathedral of Santa Maria in Vitoria is one of the most beautiful Gothic monuments in the Basque Country and one of the few Spanish temples still conserved with such a marked character of pure Gothic style. This is due to its strong French Gothic influence, sober and elegant, opposed to the influence of the Castillian-Leon Gothic style, excessively adorned and having numerous edifications attached belonging to later styles.
Despite showing a notable lack of richness on its exterior finish, the Cathedral of Santa Maria surprises us with a fine, elegant interior. The great height of the central nave (24 metres), the slenderness of the piers and its beautiful porch make this monument a must on the road to Saint James (Camino de Santiago).
The Cathedral of Santa Maria began to be built during the second Navarre domination of the city of Vitoria

(1366-1373). It is probable that the building was begun on the site of the old Romanesque church of the XII century located on the city wall, which had not only religious, but also defensive functions. This was a normal situation among the buildings at that time, and these temples were usually fronted by night watch patrol passes and watchtowers (see Figure la).

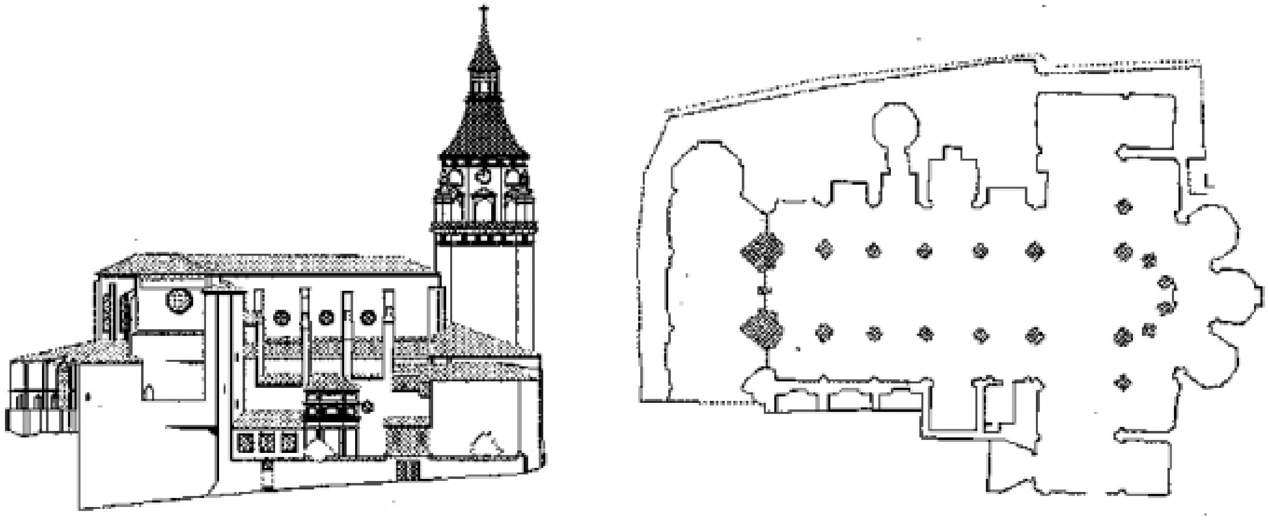

Fig. 1 - The Cathedral of Santa Maria: a) Front elevation, b) Ground plan.

The CAAD

To get to know a building with these characteristics it is necessary to carry out a thorough planimetry, on which the distortions and overhang suffered by the temple are clearly shown.
Unlike the architectonic plan usually employed, for a planimetry with these features symmetry and repetition cannot be employed in its confection. It is necessary to show the real state of each structural element with total precision. Only in drawing up the ground plan of the Cathedral of Santa Maria 2000 points had to be taken with high precision topographical instruments (see Figure 1b).
These maps were taken at different heights in order to thus study the progression of the sagging or bending suffered by the building, and were complemented with the planimetry of numerous transversal sections of the nave and aisles.
The set of plans drawn up from the topographical work were used as a basis for a three-dimensional model showing the structural state of the temple. All the decorative elements without any structural character (sculptures, tracery, added chapels, etc.) are, however, eliminated to simplify the three-dimensional model. The final model shows the sober character of the Cathedral reduced to its basic structure, but maintaining all the information required for the study of its structural wholeness.
Nevertheless a structural study of the Cathedral of Santa Maria in its actual situation may not show the true state of its deformations, which may have their origin in problems arising centuries ago.
One of the unique features of buildings in the Gothic period is their development with time. The buildings were constructed extremely slow, both for economic problems as for the technical difficulties themselves and the actual size of the work undertaken. Moreover, during the long building time important technological advances were discovered, which were incorporated in the different parts of the building according to its state of development. In the same way, mistakes in the original design were constantly corrected.

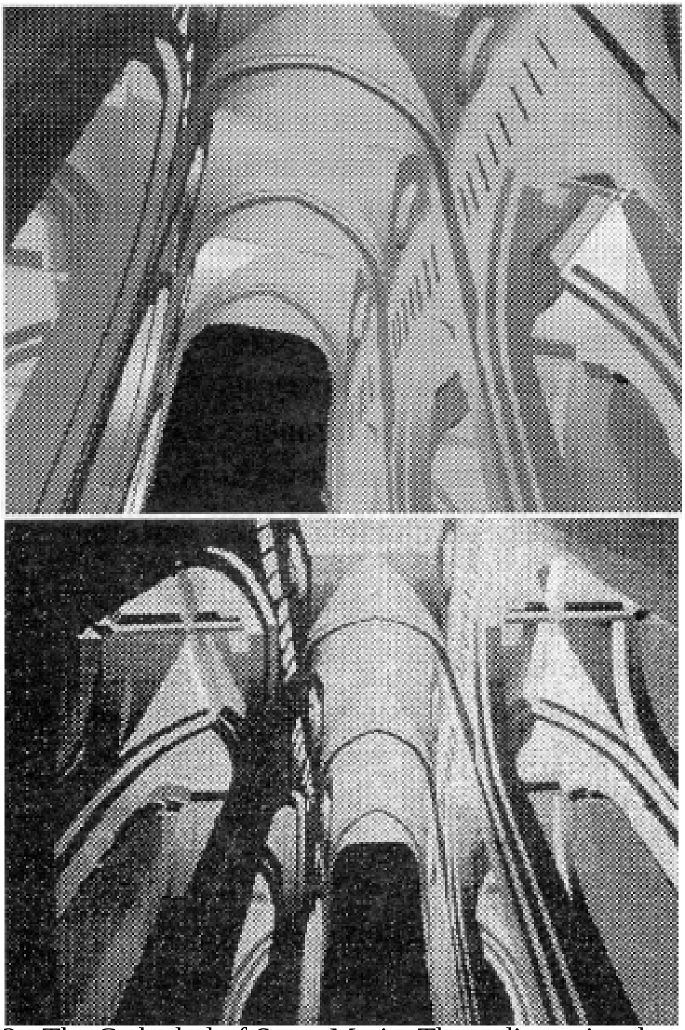

Fig. 2 - The Cathedral of Santa Maria: Three-dimensional model.

The custom of building temples beginning from the head and going forward to the feet of the nave and aisles is well known.. This type of construction imposed a complete structural resolution of the building part by part. With this system the required total equilibrium of the whole building was not achieved and the distortions as the structure settles to the provisional stress situation were inherited by the entire building once it was finished. Not only did this occur but, moreover, normally the problem of advances in technology during the building process forced the correction of the original design, on incorporating the new solutions in parts which had already been built, while in the new ones this was done from the start.

When studying the state of strain of Gothic buildings these questions must not be forgotten. Therefore, our three-dimensional model should show not only the actual geometry, but change itself into a virtual global model capable of showing the evolution of the temple throughout different periods of time. After a constructive historical analysis, a virtual reconstruction of the model in four main phases from its origin to today was carried out. sections of the model showing the four main construction stages can be seen in Figure 3.

The History

In a early stage, the Cathedral was designed as a temple made up of a large main nave and two simple side aisles. No sooner the building was finished than it began to show deformations due to the lack of proportion between the nave and the aisles, which tended to open the vaults of the nave and fall down the vaults of the aisles (see Figure 3a).

An emergency solution was applied to stop this deformations, the addition of flying buttresses on the buttresses of the aisles to neutralise the horizontal strain. However, this technique, widely used in France, was not correctly applied: the flying buttresses are too horizontal, they are not embedded enough in the walls and their section is insufficient (see Figure 3b). The temple continued with its long process of impairment.

At this time, in the northern area of Spain, an autochthonous solution is found which gives a very good result consisting of the use of a kind of arches for reinforcement called strut arches. These arches run from the pillars of the nave at half height coinciding with the aisle arches and placed at the same height (see Figure 3c). This ensemble forms an excellent compensation to the horizontal push from the main nave and thus the general tendency of the piers to bend towards the centre of the nave is absorbed by the push of this arches.

This good solution in the XVI century, which to a large extent corrected the mistake made by the erroneous emplacement of the flying buttresses, was eliminated in the XX century. In 1960 an unfortunate intervention decided to substitute the arches with tie beams at the height of the salmers of the aisles (see Figure 3d). This mistake has been so great that a study carried out on the actual situation has recommended the closure of the building and the adoption of emergency measures.

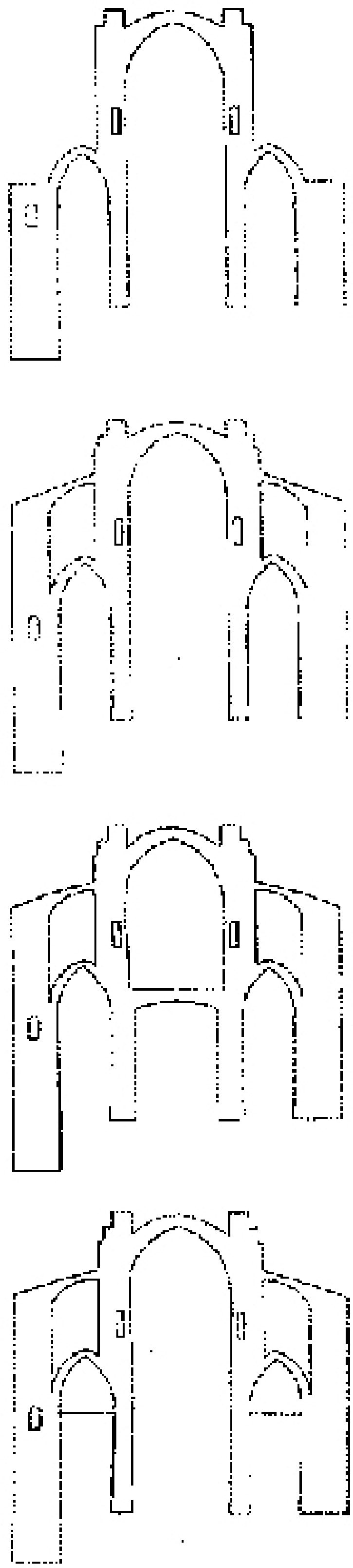

Fig. 3 - Four historical stages.

The Structure

In a detailed stress analysis of a temple, a direct relationship between the mathematical model and the building itself cannot be established. The heterogeneity of the material due to the long building process, the technical changes introduced by craftsmen, the different types of mortars used, the additional parts and substitutions carried out during the construction period, the stages of construction both horizontal and vertical, the total or partial collapses rebuilt, the works done during later times, the history of the construction, etc. make a direct and unquestionable relationship between a unique model and the reality very difficult.
The use of the virtual CAAD model which gathers in time the history of the deformations and interventions carried out in the building is essential in order to know the situation of equilibrium and the stress tendency of the temple.

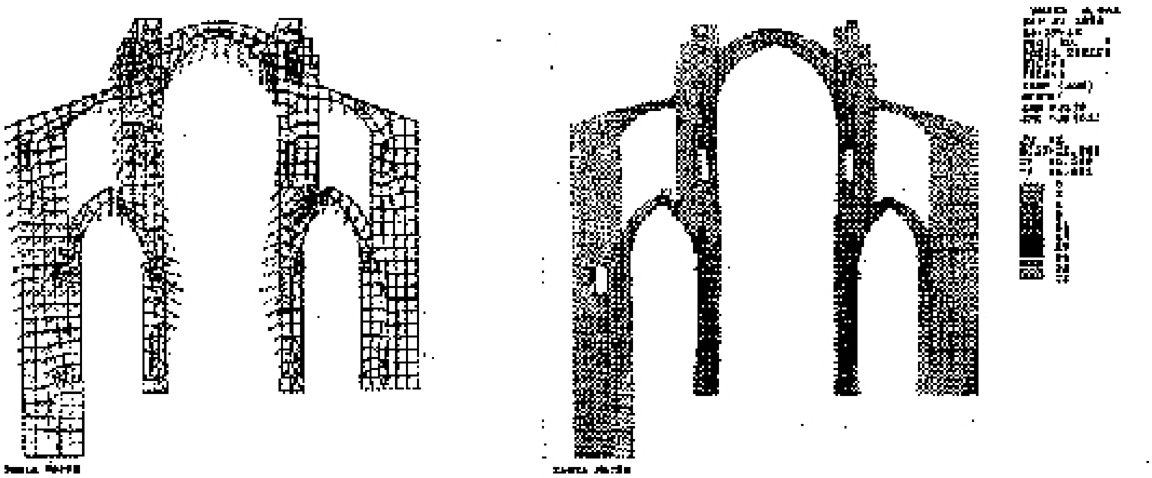

Fig. 4 - Finite Elements Method: a) Displacement, b) Stress.

The structural analysis of the cathedral of Santa Maria was carried out checking the succession of deformations in the different stages of the equilibrium of the temple using the Finite Elements Method software ANSYS 5.0 (see Figure 4). Each intervention could be evaluated and the errors and successes achieved by the introduction of the consecutive building elements were studied.
To complete this structural analysis, a new technique of measuring stress in situ called 'Hole drilling', was developed. This technique consist on the measurement with strain gages of three control points positioning concentrically around a drilled hole. As the stress field is relieved by the drilled hole, the strain is obtained by the gages and the principal stress and their directions may be calculated. The hole diameter is 5.6 mm, so the damage created by this procedure is easily repairable.
This technique was perfectioned during this work and presented in the ICRS-4 (Barrallo et al. 1994). From the analysis on the site of the strain taken in a section of the Cathedral, it was deduced that the structural model created was significant enough to reflect what was happening to the Cathedral (see Figure 5).

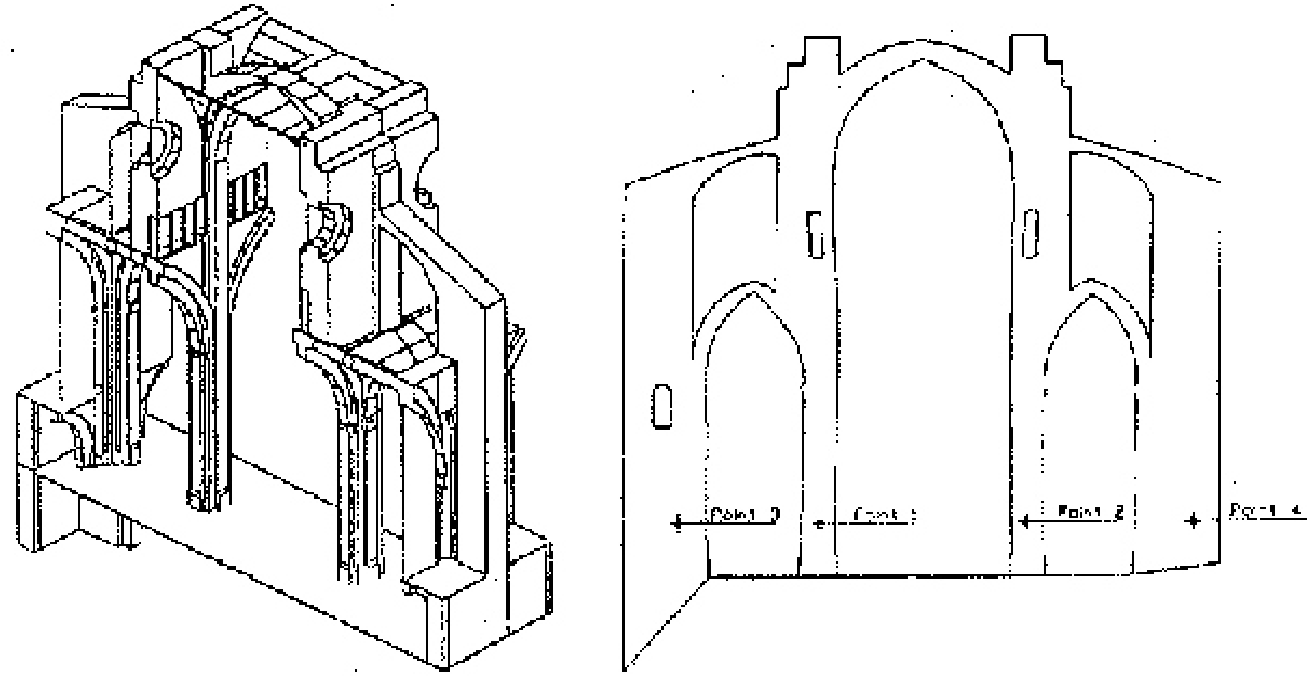

Fig. 5 - Measurement points using the "Hole Drilling" method.

Conclusions

The case of the Cathedral of Santa Maria de Vitoria is significant although it is not unique nor extraordinary. Many buildings have suffered interventions during their long lives that have substantially altered their equilibrium. The use of a virtual CAAD model capable of containing the different stages of construction is specially interesting for these type of studies.
For educational purposes, the incorporation of subjects so varying as Topography, Mathematics, Physics, Structures, Construction and History in perfect inter-relationship signifies a great advance in the global understanding of the building.

References

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