Structural modelling of medieval walls

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ABSTRACT: Medieval construction systems usually involved the construction of multi-layer walls formed by two faces of ashlar work or masonry with a central infilling consisting of rubble bound with mortar, generally lime-based. It is a simple and efficient construction system which continued to be used in subsequent centuries.

Nevertheless, structural modelling of this type of wall is not easy to achieve. The two wall faces are not rigidly bound and on the other hand, vaults are normally supported only on the intemal face, resulting in reduced efficiency of the wall unit. Common models of finite elements are unable to solve many of the problems that arise when they are applied to a monumental construction.

This paper tackles the problem and puts forward various possibilities of solution with different element types.. It also provides two examples of Gothic monuments in Galicia (Spain) in which structural behaviour was studied using some of these calculation models: the churches of Guimarei and Cambados.

1. INTRODUCTION

In practically every case, the medieval wall is formed by a unit of two ashlar-work faces bound by a rubble infilling. In the major part of medieval buildings the ashlar work is of a good quality and well-dressed masonry, but on the other hand, the infilling normally consists of masonry rubble and is, as a result, of low quality and resistance.

The specific formation of this type of infilling varies according to the geographical area and the construction techniques used. Highly significant variations can be detected in the medieval kingdoms which make up the area of study: Castilla, León and Galicia.

Limestone rocks are in plentiful supply in both Castilla and León and as a result, lime was easy to make and transport was not required. Almost every area had a quarry and prices were, therefore, reasonably low. Furthermore, the rivers contained abundant supplies of pebbles. Subsequently, it was common practice to fill the wall interior with a mixture of lime and pebbles, known as “calicanto”. It was widely used and can be seen in pictures, such as that in figure 1, attributed to the Maestro of Ávila.

On the contrary, the area of Galicia, which has been most studied by our team, presents some very different characteristics. The rocks are granitic and there is hardly any lime. In medieval times, lime was transported from León by the river Sil and was scarce and expensive. Moreover, quarries in Galicia developed excellent techniques of working granite, a very hard rock, difficult to work, but of great durability. For this reason, walls in Galicia were almost always filled in

Figure 1 : Picture by the Maestro of Ávila

with ashlar rubble, which was, however, well-worked and dressed to save lime. In some cases even mud was used as agglomerate.

Other systems were also employed. For example, in the Arab kingdoms which gradually incorporated Castilla, such as Andalucia, brick was used to fill in walls and pillars, a technique employed by Moorish masons with great skill. For example we can observe the case of Seville Cathedral where a failure of the southern transept pillars led to its collapse in 1889.

2. MODELLING OF MEDIEVAL WALLS

An ashlar wall is highly complex structure in itself. It consists of stone elements, whose mechanical characteristics are relatively easy to determine, bound by a practically unknown mortar. In addition, this mortar's resistance to compression was considerably inferior to that of stone and its resistance to traction was practically zero, and as a result, its behaviour is evidently non-linear. The mortar joint ratio with regard to the stone is variable. Finally, the wall has an interior filling, whose thickness and quality are practically unknown. It is almost impossible in these conditions to try to obtain even a minimally reliable model.

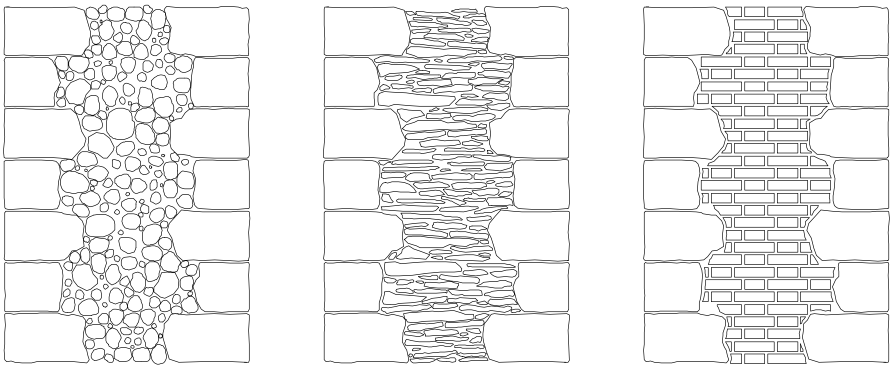

Figure 2 : Constructive systems for medieval walls

Complex models have been developed to recreate the behaviour of a wall or rubble, summarised by Lourenço [2] in three possible approaches:

- Detailed micromodelling.- The ashlars and mortar joints are represented by continuum elements and the interface is represented by discontinuous elements.
- Simplified mícromodelling.- The expanded ashlars (including mortar joints) are represented by continuum elements and the interface is represented by discontinuous elements.
- Macromodelling.- The ashlar, mortar joints and interfaces are smeared out in the continuum.

Any one of these approaches involve great complexity in the modelling, particularly when the effect of the infilling is taken into consideration. Furthermore, the vaults are normally supported on the internal face of the wall, thus necessitating consideration of the infilling resistance in the wall unit. In one of the studied examples, the church at Guimarei, the existing pathology can be clearly explained by the defects of this infilling.

In the cited article, extremely interesting calculation models for the modelling of medieval walls were developed. The results of experiments were atso íncluded to provide a contrast with the theoretic model. In those cases where the mechanical characteristics of the wall can be precisely identified, the proposed model is very interesting and useful.

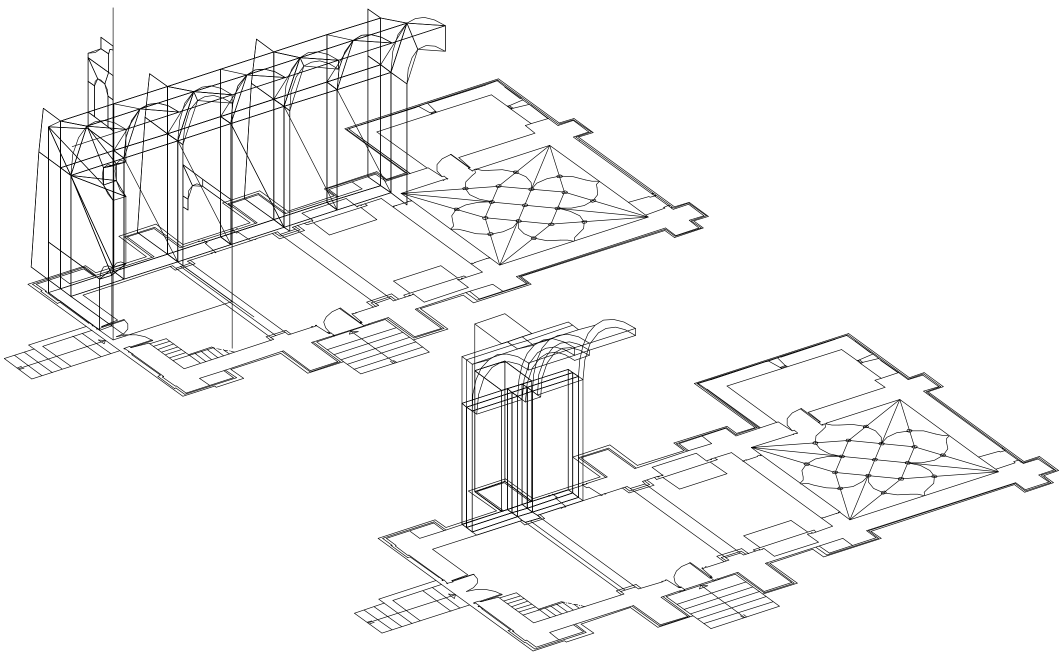

Figura 3 : Two models for the church of Guimarei.

However, when an attempt is made to analyse an entire building greater problems are usually encountered. In practically every case the only observable exact data are the cracks and leanings. The cracks indicate that the building has suffered damage at some point in its history and the leanings enable to define deformations accumulated through the centuries. The resistance of the wall is unknown. Samples of stone and even mortar can be extracted, often with great difficulty, but it is virtually impossible to determine the resistance of the wall unit with any certainty. It is not even possible to know the shape and the thickness of the infilling, except for the ruins.

A full description of a medieval wall requires the exact definition of three threedimensional elements: the internal and external layers, constructed with ashlar work and the interior filling layer. The vault and the ribs, which are normally of great importance in medieval construction, are the elements to be defined. Finally, the land also needs to be taken into consideration. In fact in the majority of medieval buildings the most serious pathologies relate to land problems.

In figure 3 a possible three-dimensional model of the church at Guimarei can be seen, which will be explained in paragraph 4. Here different elements such as the two wall faces, the infilling, the vault, the rib, the abutment and the land are taken into account. Once the model has been defined, it is possible to adjust its behaviour by using non-linear calculation. Plastic or creep models can be considered to adapt the model to the strains that have been really observed in the building.

3. PROPOSED MODEL

Even after having realized these simplifications, the proposed model is too complex for a complete analysis of the building. Thus, a simpler formulation has been tried to achieve, sufficiently exact for serving as a guidance to a possible restoration of one building and at an operative cost which would be within the reach of technicians who have no access to a supercomputation centre.

The problem arose during a research project undertaken by the University of La Coruña in the study of Gothic structures in the north-west of the Iberian peninsula. It was considered to analyse the structural behaviour of various Gothic buildings, including some important ones as León Cathedral, and to put forward models for their study. For such complex structures it was necessary to develop models which were both simple enough to be able to support controlled and useful solutions and complete enough to take into consideration the elements which had a genuine effect on the entire monument structure.

To achieve this, various models were made for walls, vaults, ribs, arches, flying buttresses, etc. Initially three-dimensional models were made, and later simplifications, such as superficial models, were searched for.

In the way of modelling internal and extemal faces were considered surfaces which could be modelled with shell elements and the infilling was represented as a three-dimensional element delimited by both surfaces and with mechanical characteristics equivalent to those which could really appear.

Another model was also studied in which the internal and external wall faces are linked by a transversal surface, the thickness of which is real and reproduces the mechanical behaviour of the infilling. It is a sufficiently exact and simple model if both faces are bound in the zones of abutments, where there is a real link between them, and also in the casings of doors and windows, where a real ashlar binding between both faces exists too.

4. THE CHURCH AT GUIMAREI IN FRIOL (LUGO)

The first model relates to the church of Guimarei in Friol (Lugo). It is a church with a gothic presbytery with a ribbed vault, possibly built in the fifteenth century and which was completed, according to the signs, in the seventeenth century with a nave covered by a barrel vault. Practically from the time it was built, this vault has had serious problems with regard to pressure on the lateral walls, making its constructors strengthen tremendously the buttresses. Nevertheless, this reinforcement has been inefficient, the vault has continued to lose shape threatening with collapse. The ground plan of the church with an indication of the leanings measured by our team and a cross section of it, that gives a clear idea of dimensions of the abutments, are shown in the figure.

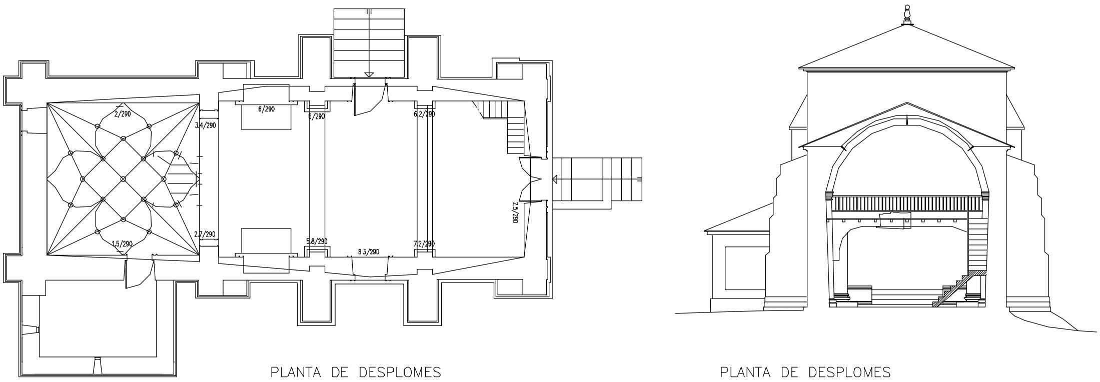

Figure 4 : Ground plan of the church of Guimarei indication of leanings in the walls.

Figure 5 :Inner view of Guimarei

Figure 6 : Grietas in the vault

Examination of the leanings demonstrates that while the external face of the wall has hardly become inclined, the internal wall has suffered displacements of a great magnitud. Taking into consideration the facts that the vault is supported on the internal face and that rubble infilling deterioration has been verified, there were reasons to assume that the pressures of the vault had deformed the infilling, which had not been able to transfer it to the external walls and, hence, to the abutments. The state of the church interior with serious deformations in the vault, leanings in the lateral walls and the arch voussoir, that supports the choir and that has given way, are shown in figures 5, 6.

To verify that, a three-dimensional model of a section of the vault and two models with the above mentioned simplifications were realized. The mechanical characteristics of ashlar work of the internal and external faces of the wall and the vault were defined and an estimate of the mechanical characteristics of the infilling was made.

In the figures one can observe both the model used and the results obtained. Some calculations not included were made for the vault and traverse arch of the choir area. Figures 7 to 9 correspond to the other traverse arch of the nave, where the choir arch does not exist, but the situation in spite of this is very similar. It is evident that the deformation model is coherent with the pathology observed and that stress areas are produced in the zones where cracking of the building has taken place. The analysis of all of this led us to the conclusion that the insufficiency of the initial abutments made the vault lose shape, thus recommending their strengthening. Subsequently, the infilling, that degraded undoubtedly due to the leakage of rain water through the roof, continued to give way worsening the problem, so the strengthening of abutments would not be efficient for solving it.

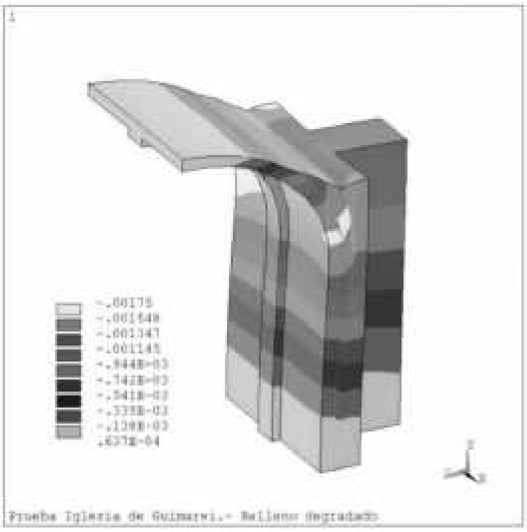

Figure 7 : Three-dimensional model

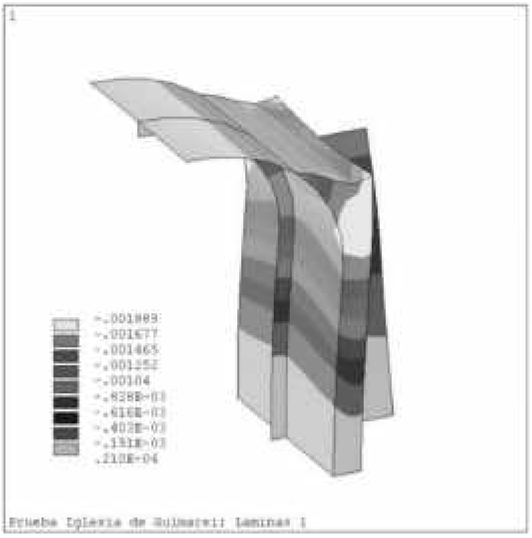

Figure 8 : Mixed model

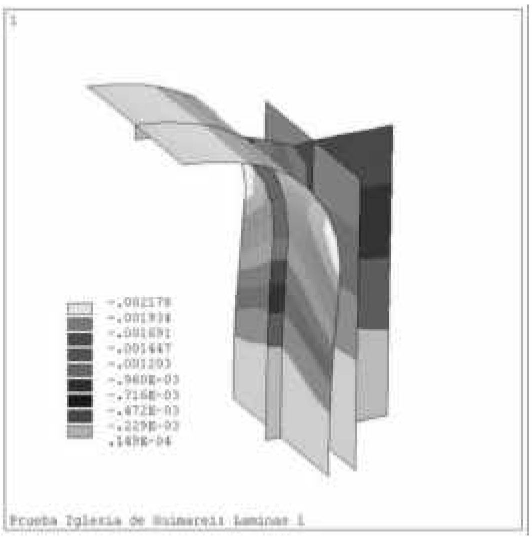

Figure 9 : Surface model

The comparison of three models show that differences is irrelevant for practical purposes. Take into account only the leaning values, because are the most representatives the mixed model causes an error of 7.99 % and the surface model an error of 10.85 %. The possible modelling errors are more important, and the simplicity of the model is very useful in order to analyse complex buildings.

In the next figures the results of analysis of a half of Guimarei church using the mixed model are showed. Is a practical model for a building very difficult to analyse

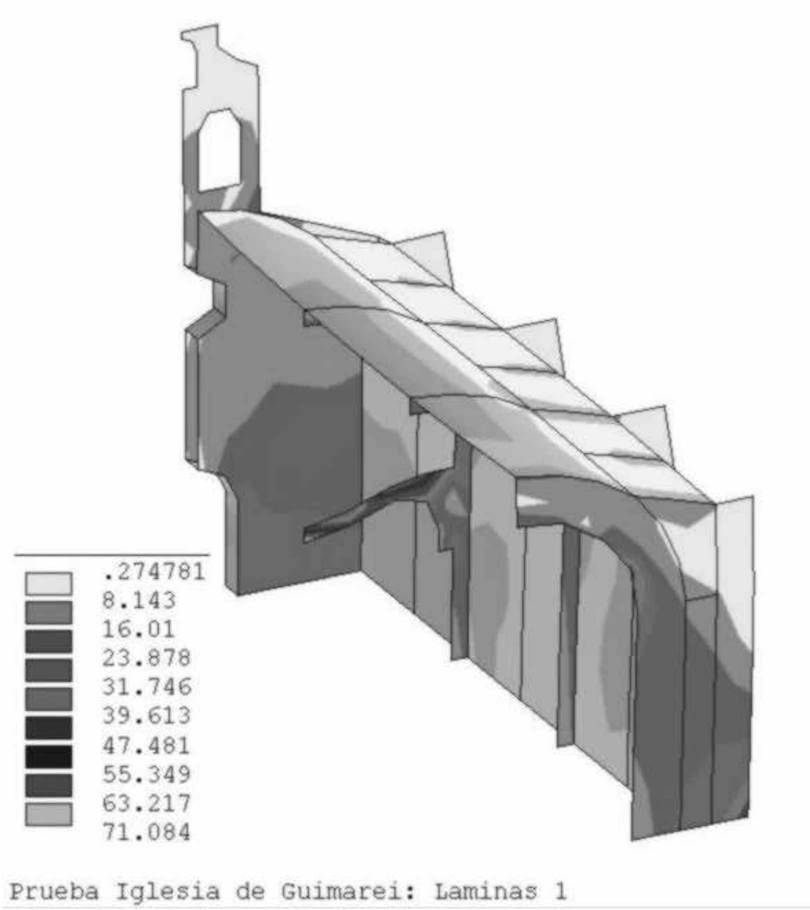

Figure 10 : Structural mixed model for the church at Guimarei. Principal stresses.

5. SANTA MARIA D'OZÓ CHURCH IN CAMBADOS (PONTEVEDRA)

This is a late-gothic church, which is almost in ruins, thus facilitating the observation of the wall structure. Contrary to the preceding case, both faces of the wall are solidly bound, so the wall practically functions as a unit.

Figure 11 : Ruins of church at Cambados.

Figure 12 : Wall structure of church

On the figures the measured leanings and various aspects of the model with behaviour very similar to that of the really observed one are shown. In this case, the two faces have been modelled as surfaces and the infilling - as a surface orthogonal to the surface of the walls with the appropriate thickness. The binding elements between the doors and windows have also been considered

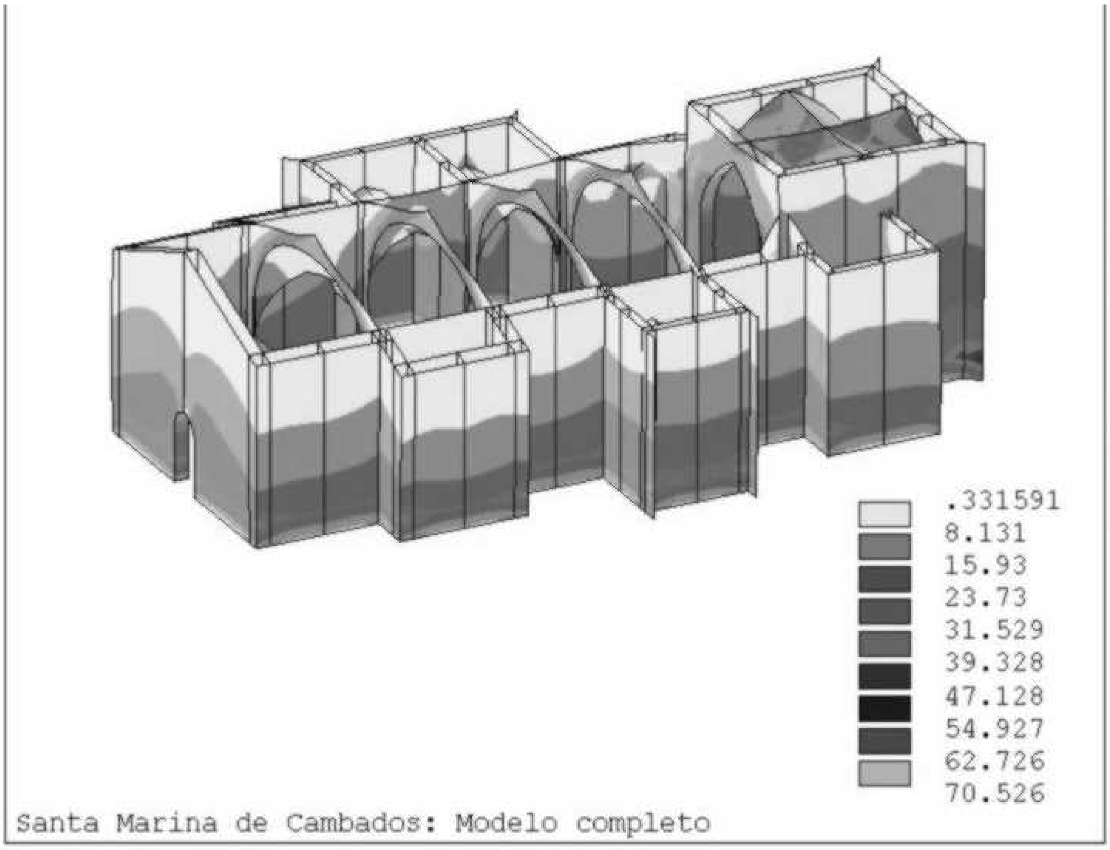

Figure 13 : Surface model of Church at Cambados. Equivalent stresses

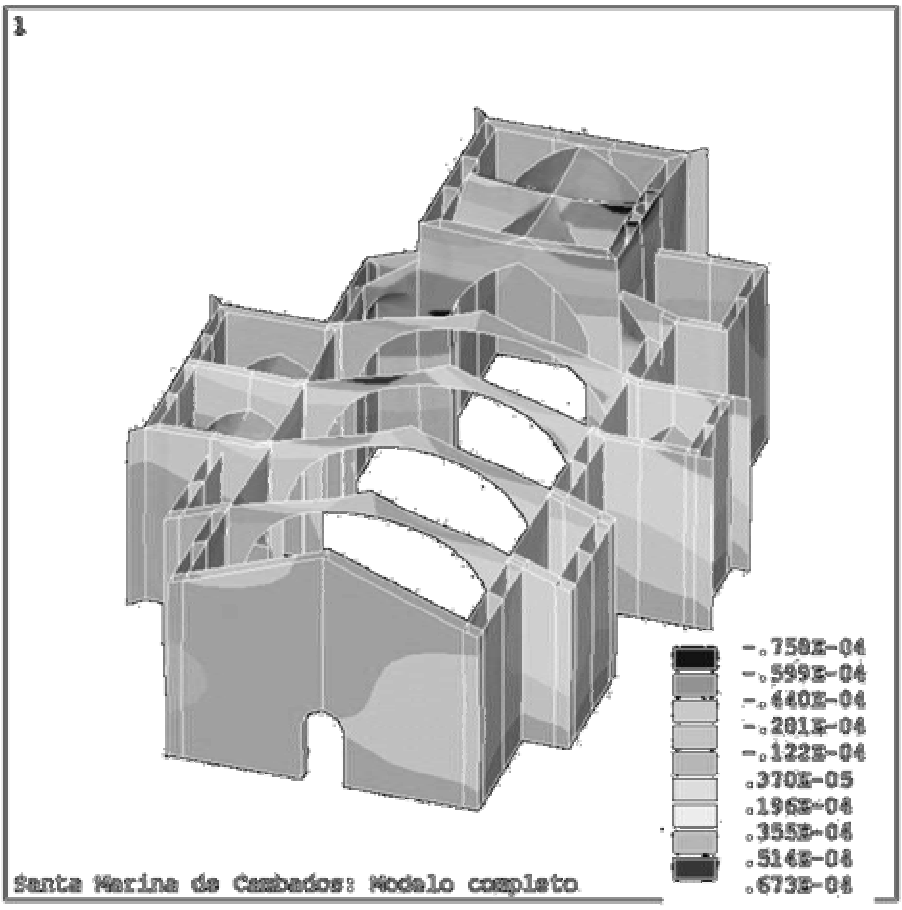

Figure 14 : Church of Cambados. Leanings

4. CONCLUSIONS

In this paper various possibilities of solution was proposed with different element types. The best approaches were obviously with brick elements, but the results for a mixed model (shell elements for walls, arches and vaults and brick elements for infill) are excellent. Even the results in surface model, using shell elements for the whole building are very useful for practical purposes. The same approach can be used for plastic and cracking models.

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