Vaults and Other Constructive Singularities in the Monastery of San Martín Pinario

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INTRODUCTION

The historic quarter of Santiago de Compostela, a World Heritage Site, is an extraordinary monument, which has been officially recognised for its collection of historic-artistic buildings since April 1940 (Decree of 9 March 1949, BOE 18 April 1949)**(fig.1)**. Among the great number of monuments that the city has, the ancient Benedictine monastery of San Martín Pinario stands out for its historical importance and its first-rate architectural quality. Although many other Benedictine monasteries are still conserved in Galicia, these buildings are generally located outside cities and they represent authentic colonising outposts in the rural world. San Martín Pinario, however, is an important urban monastery, which is located in the religious capital not only of Galicia, but also of Spain.

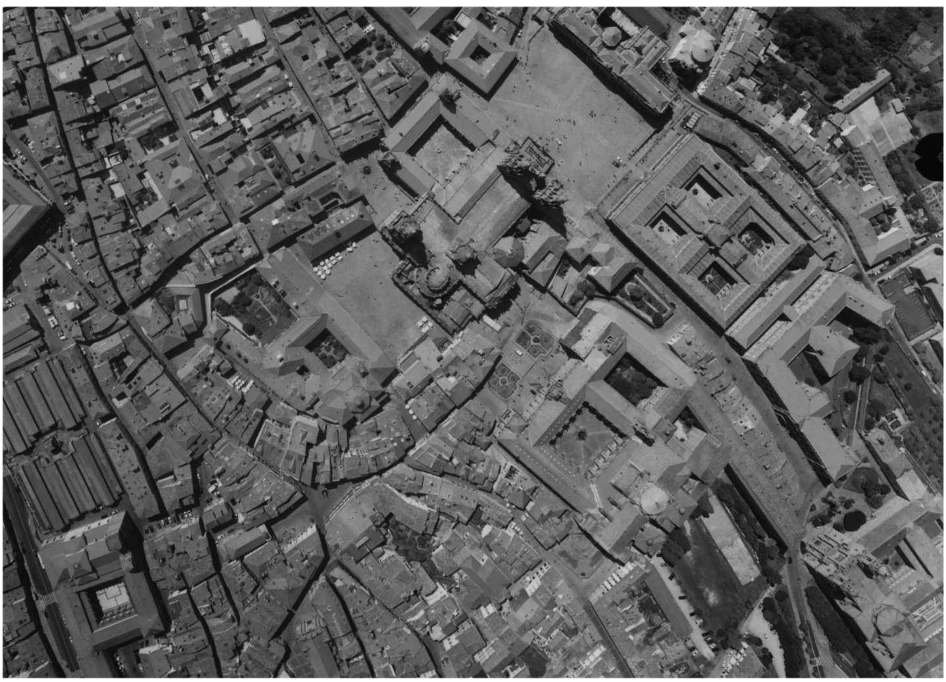

Figure 1. The historic quarter of Santiago de Compostela (partial reproduction). The Monastery of San Paio Antealtares, Plaza de la Quintana, the Cathedral, Plaza del Obradoiro, the Hospital of the Reyes Católicos and The Monastery of San Martín Pinario.

The monastery was founded in the ninth century but a new Romanesque building, consecrated by Diego Gelmírez in 1102, was constructed during the twelfth century. This building was still standing at the end of the sixteenth century. In the fifteenth century, the addition of the Monastery of San Martín Pinario to the large group of established monasteries (there were thirty-two) forced the monastery to be rebuilt from 1590 onwards. This building activity continued throughout the seventeenth and eighteenth centuries. During this period, the monastery's historic hostel became famous and today the monastery continues to support this service. After Mendizábal's law requiring the sale of church lands (known as the *Desamortización de Mendizábal*) in 1835, the monastery lost its important library (today found in the University of Santiago de Compstela), among other possessions. In 1868, the Compostelan Seminary (*Seminario Mayor Compostelano*) was set up in the monastery.

The monastery is an impressive building because of its size – an area of more than 20,000 square metres – and it has the second largest church after the cathedral in Santiago de Compostela. It is also impressive because of its architectural characteristics, which reflect the Renaissance style in part, but the Baroque style above all. According to Castillo (1987), the façade of the monastery was begun by Master Mateo López in 1590, but it was not completed until 1738. The main cloister or the "Processional cloister" was built between 1638 and 1743 and was the work of Bartolomé Fernández Lechuga. The accessory staircase and its dome are from 1861, while the main ones are from 1790. A big monumental fountain was erected in the centre of a seventeenth-century patio.

The church was planned at the end of the seventeenth century, possibly by Ginés Martínez **(fig. 2)**. However, it was based on an original design by Master Mateo López in 1590 and was finished in 1740. It has a Latin cross-shaped floor, a main arm made up of a nave and lateral chapels, and a large dome supported by pendentives in the crossing. This was the work of Bartolomé Fernández Lechuga. The church's façade is a beautiful example of plateresque architecture. Its construction was directed by Mateo López and was completed in 1652. During the consolidation of construction works planned in the seventeenth century and commissioned to the architect José Peña de Toro, some towers began to be erected, but the work ended up being brought to a standstill by the Chapter of Santiago de Compostela. In 1772, the monastery was finished with an original Baroque staircase leading to the main door. This was made by Fr. Manuel de los Mártires, but completed by Fr. Plácido Camiña. The beautifully designed sacristy by Gabriel de Casas, possibly finished in 1740, the high choir by Tomás Alonso, and the expansion of the Chapel of Socorro by Fernando de Casas y Novoa should also be highlighted here.

A Brief Description of the Building and the Church

The monumental complex, which occupies a plot of more than 20,000 square metres, is located opposite the north side of the cathedral and is the most extensive architectural collection of historic buildings in the city. It is surrounded by the Costa Vella to the north, the Plaza de la Inmaculada to the south, the Plaza de Moeda Vella and the Plazuela de San Martíño to the east and the Rúa do Val de Dios and the Travesías Dúas Portas to the west. San Martín Pinario consists of two cloisters, the oldest one of which is dedicated for office space, and the other, known as the "Processional cloister"**,** is where the caretaker is based comprising an interior patio, once used for carriages and now home to museum, an extensive exterior patio - known as Las Tullas - located in the complex's northern zone, and a wing to the west, which is now a student residence.

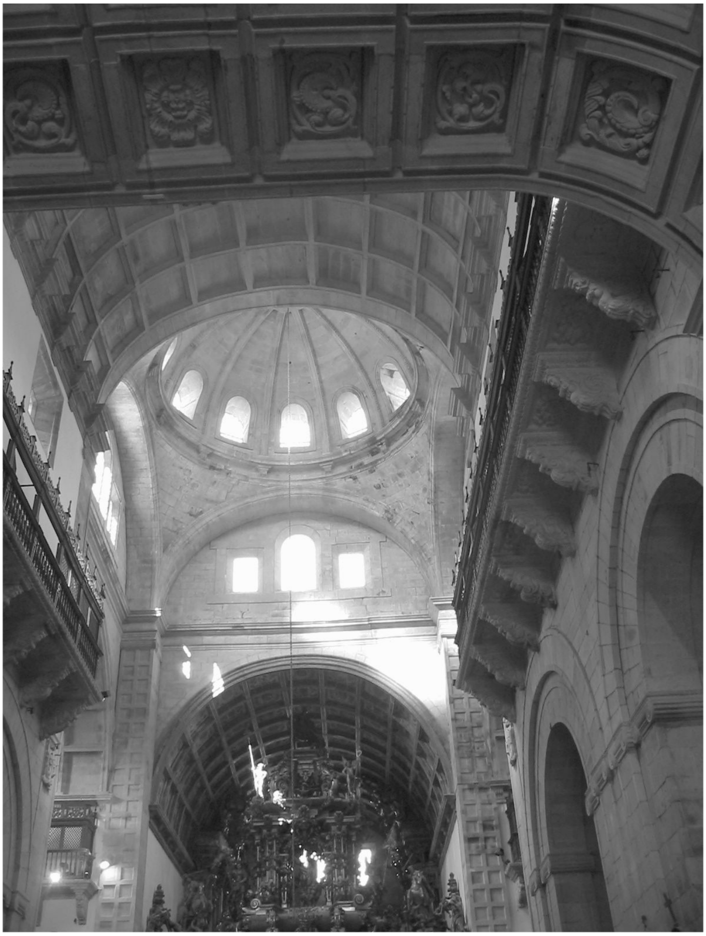

Figure 2. The Church of San Martín Pinario (seen from the entrance). Notice the spatial cadence of the choir vault, the nave vault and the dome.

The church, located in the northern part of the complex, is monastic and has a Latin cross-shaped floor of considerable proportions and expanse. It is covered with a barrel vault of caissons and a dome on pendentives at the intersection of the arms **(fig. 3)**. It also has a second vault of great interest. This is the flat vault that the nave's choir shelters. The front is rectangular and has Baroque choir stalls as well as very valuable Baroque altarpieces. The largest altarpiece was inspired by the canopy of Saint Peter's Basilica in Rome. The church has connected lateral chapels, which include the Chapel of Socorro, covered with a dome and a lantern**,** and the Greek cross-shaped sacristy covered with a coffered dome.

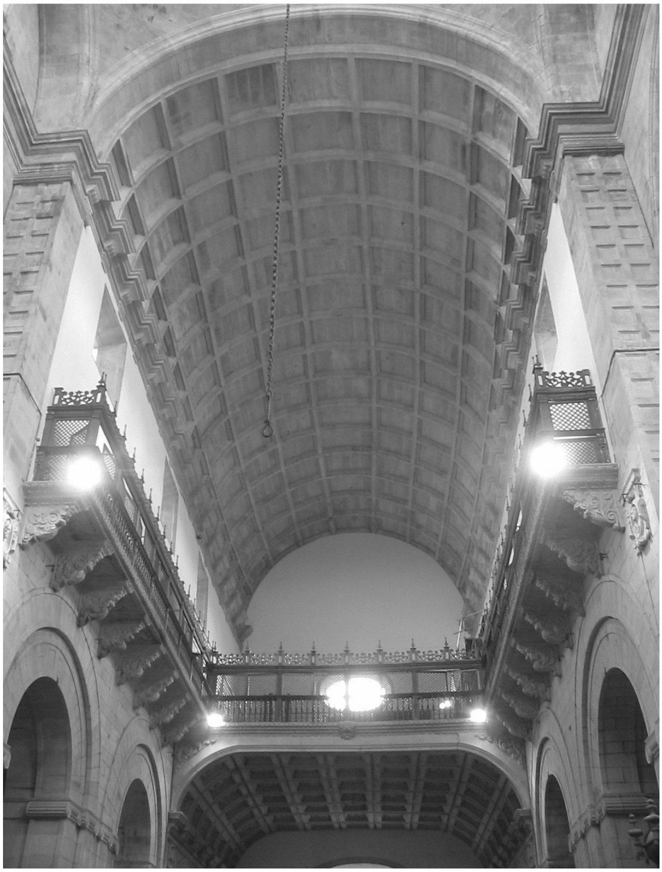

Figure 3. The Church of San Martín Pinario (seen from the altar).

THE GRAPHIC SURVEY

The basic cartography for this complex of historic buildings was the result of a project that came about through an agreement between the Compostelan Seminary (*Seminario Mayor Compostelano*) and the Department of Architectural Theory and Design at the University of A Coruña.

For the elaboration of the graphic documentation, a perimeter base topographic network was first set up. It was completed with a second topographic network of points in the construction's interior (the church, the cloisters, the patios and the reference wooden floors). A Leica TPS 300 laser telemeter was used. The network was defined so that it was possible to geo-reference any point within the set and the stations with their respective local coordinates positioned along the plane. A photographic archive with files was made. This included:

- Photos
- A point set to measure topographically
- A redrawing of unclear areas
- A positioning of the area on the plane
- A specification on the photos for the area to be measured

Afterwards the data found for each point (coordinates x, y, z) were filled out for all the files. Then, these were distributed among work groups, who helped collect data and carry out the final graphic survey.

The buildings in the monastery were divided into five work zones: the church, the cloister with the caretaker's office, the exterior patio, the museum, the cloister devoted to offices and the area for the student residence. In the survey, the following partial data can be highlighted:

- The church's façade: 505 support points.
- The church's nave: 707 support points.
- The cloister of the caretaker's office: 1004 support points.
- The southern façade: 161 support points.

To obtain a higher degree of accuracy and greater detail for the basic graphic documentation to be used in the study of the choir's flat vault, a cluster of points was generated by means of a 3D laser. Afterwards, representations of the ground plan, the elevation, cross-section, as well as the corresponding sections with longitudinal and transverse ribs and their volumetry, were done using the data from the initial graphic survey so that complementary graphic documents could be produced. These documents were necessary to carry out the structural analyses **(fig. 4)**.

A 3D CYRAX-2500 scanner-laser along with the CyraCiclone, Cyra Cloudworx and AutoCAD programs were used. According to the planning, sixteen shots were taken with an average viewing angle of 40°. The number of scanned points was variable, basically due to the distance between the vault and the scanner positions, oscillating between 250 000 and a million points per shot. The point cluster, in which we have managed to approximate the distance among the network's points to a centimetre, has been defined by a total of seventeen scannings.

This paper presents the graphic survey of the flat vault in detail. By studying this survey, one can confirm the vault's ideal geometry and its current deformed geometry.

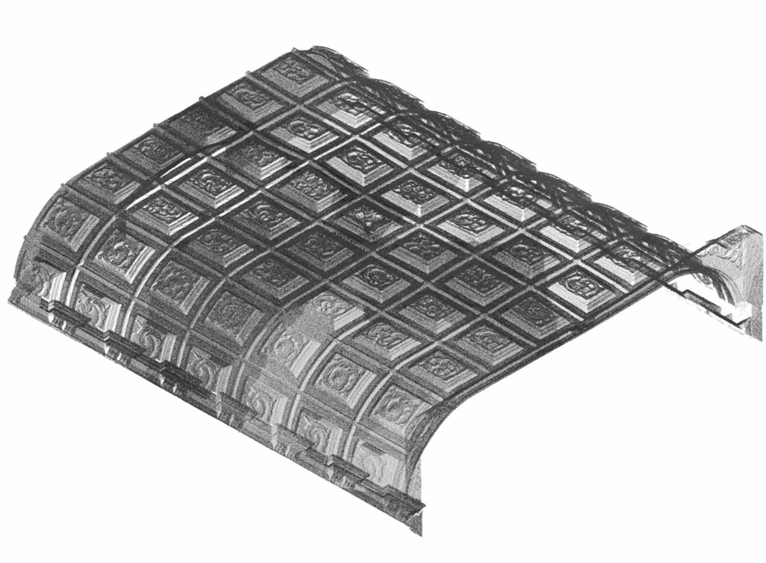

Figure 4. The survey of San Martín Pinario The axonometry of the intrados of the choir vault (scanner).

San Martín Pinario's Constructive Solutions

From a constructive point of view, stonework solutions within the building that reveal great workmanship coexist alongside those that do not. This situation can be explained by the different interventions that took place. At one stage, the constructive criterion seems to have been modified, going from solutions of strength in form, which were basically turned to because of compression, to architrave solutions in which the stonework pieces, like large ashlars, often a kind of stone slab, are arranged at flexure, as if they were wooden structures. Could it, perhaps be a technical regression?

By walking around the outside of the building, one can see that it is correctly built and well made. An analysis of the development of the spaces in which redundant lintel solutions are used confirms this impression. The first resistant element in the shape of a lintel is placed in the space and the wall is rigged to the lintel as if it were from a flat arch's sectioning.

The following projecting parts found in San Martín should be mentioned:

Vaults

- The church choir's flat vault, which is the topic of this paper **(fig. 5)**.

- The church's lattice barrel vault: Palacios (2005, p.105) points out that it is a vault 'with square crosspieces' given that the longitudinal ribs have equal sections and lead towards the vault's centre. Since this vault is made according to a system of transepts and crosspieces, it represents a classic model built according to Gothic constructive methods. This system is much simpler and much more economic than continuous Renaissance stereotomy.

- A polychrome presbytery vault: Without having yet studied this vault in more detail, it seems to be the previous polychrome solution.

- A ribbed dome on pendentives with twelve Roman arches designed on a spherical surface.

- Masonry groined vaults in the Baroque cloister: The stereotomic solution satisfies the orthodoxy found in Renaissance Spanish treatises.

Two different stereotomic traditions coexist in the building's adjacent main areas: the late development of Gothic ashlar work and Renaissance stereotomy.

Figure 5. The choir vault. (Courtesy of A. Parga.)

Singular splayed arches

- A splayed arch defined by a Roman arch as a big portal and an elliptical arch as a small portal. Both have the same span and are located in the entrance to the staircase from the sacristy **(fig. 6)**.

- A trumpet-shaped splayed arch defined by a Roman arch that fits in a flat arch at a kneeler on one side. It is located in the entrance to the small room with lintels of the sacristy's entrance.

According to Palacios (2003), the solution of splayed arches with a Roman arch in a big portal is not very common in Spain, where the Roman arch is usually placed as a small portal. In France, however, the use of big portals seems to be widespread.

Figure 6. Splayed arches in the sacristy.

On the other hand, other solutions exist. The constructive (structural) quality of these solutions seems "reversed", since one can choose less refined organisational systems for whose functioning flexure is an essential mechanism. These solutions remind us of those used in carpentry:

- The staircase's steps are formed with ashlar under flexure (built into the wall).
- The landings of this staircase are achieved exclusively with pieces under flexure and attached at half wood.
- The presbytery's perimeter rooms are based on a solution that entailed placing stone slabs between every two arches at the base of a series of flat arches. In this area we found that one of the arches has a free span of more than seven metres, which evidently suggests a certain degree of expertise that contrasts with the plan's simplicity.
- The roof of the small room at the chapel's entrance is made with stone slabs under flexure.

The Choir Vault

The flat vault of the choir in the Monastery of San Martín Pinario is formed by a series of seven sections made up of stone arches that are supported on both sides of the nave with a free span of almost 12 metres. Its directrix corresponds to two fourths of a circle with an interior radius of 2.12 metres connected by a straight section. The solution of both walls is unique. They have a front arch that forms the elevation towards the altar, and intersects with the façade's wall through a projecting impost, which is equal to half a rib. A series of transverse ribs (eight in all) with a section identical to the transverse arches gives the vault its coffered aspect. The vault is enclosed by a set of stone slabs that rest on the transverse arches. The slabs have a length of approximately 1.4 metres and are beautifully carved.

The cross-section of the central part of the transverse arches falls within a square measuring 70 x 70 centimetres and uses some 10 centimetres on each side as a support for the stone slabs. As a result, the useable cross-section of the central part is reduced to about 50 x 70 centimetres. However, the arch's extrados maintains its horizontal height. In fact, it increases slightly towards the supports and it reaches about 2.8 metres of depth, which forces the level of the lateral arches' impost to change. These lateral arches enclose the nave under the vault **(fig. 7)**.

The support of the stone slabs defining the vault is produced at a distance constant to the lower face of the vault, giving it the appearance of a continuous surface. The base of the ribs is filled in such a way that the horizontal height, which is defined by the slabs forming the central part, is kept constant.

Figure 7. The extrados of the choir vault. Test pits. (Courtesy of R. Saez y A. Parga.)

At first glance, the set is seen as a whole. Only a detailed analysis and the contribution of photographs allow us to appreciate the solution used. Although the arches are constructed of stonework, the six supposed longitudinal ribs located in the centre are made of wood with an apparently identical section like the arches on which they are supported. Only the ribs located in the middle of the curved area on both bases are also made of stone. Photographs allow us to see this. The central ribs show visible traces of the presence of insects, which are apparently large woodworms, while those made of stone are found untouched. The damage is primarily concentrated on the ribs where the curved and straight sections of the directrix meet as well as on the surrounding areas of the keystone, which corresponds to the area of the caissons. Overall, this seems to suggest some kind of structural collaboration.

The vault plan described is also applied to the stereotomy of the elements. Thus, the main arches are broken up in voussoirs that correspond to the design of the transverse ribs. One voussoir forms the junction between the ribs and the next one is used for the part corresponding to the caisson. While the former has rebates for inserting wooden elements, the latter is much more simply cut. The sectioning of the curved part is not influenced by this rule. Perhaps, it is due to the arch's depth in this part, which is subdivided into three voussoirs. This solution is the base's section of all the ribs and in the middle of the second section. Nevertheless, the front arch is not influenced by this criterion and likewise has one-piece voussoirs on the curved part.

The design described clearly seems to be derived from the Gothic criteria of ribbed construction and infill. However, in this case, the infill may have a marked lintelled character, although its design was adapted to the aesthetic norms prevailing at the time of its construction. It would, therefore, be another example of the survival of the criteria of medieval construction. The measurements and the design of this vault do not allow for comparison with other flat arches in the city, like the arches in the entrance to the Cathedral's Communion Chapel and the one in the main staircase of the University, which today is known as the Faculty of Geography and History. The latter was made by Miguel Ferro Caaveiro in 1774 and has measurements of 3.4 x 8.00 square metres. These arches are simply flat roofs made of stone. For these roofs, a course sectioning parallel to its larger side is used. Although the floor of the vaults is markedly rectangular in both cases, their measurements are much smaller.

Another singular flat vault is found in the sacristy of the Monastery of San Lorenzo de Trasouto. A study on this vault can be found in Freire (2005). The sacristy is a quadrangular space with some 7.4 metres from side to side. It is covered with a vault that seems to be made from four identical groined vaults, which is the result of the floor's division in four equal parts. The vault's central square - which includes a fourth of each one of the groined vaults' bases - is taken up by a flat vault. Taking advantage of the fact that the height of the groined vaults' key is, in any case, the same and constant for the intersecting shafts, a fourth of each vault is substituted by a flat part. Thus, it is a vault with a noticeably flat square-shaped central area and a measurement of 3.7x3.7 metres. Its transverse section is made up of two fourths of the circumference of the same radius connected with a long straight section of diameter. In this way, the two transverse sections passing through the axes of this vault have a similar design to that of the vault that interests us here. Nevertheless, San Martín Pinario's vault has much larger measurements and its functioning seems to respond more to a series of flat arches than to a spatial system. At least, this is what the corbelled cornice supporting the nave's vault implies.

Mechanical Studies on the Vault

The Outline of the Choir Vault

The vault's transverse section – two fourths of the circumference of an equal radius connected with a straight line of diameter – recalls the design of a modified catenary. This is the pressure curve of a cable subjected to a filling that reaches a constant horizontal height corresponding to a negligible filling thickness. Obtaining the equation of a modified catenary comes from Inglis (1951). Its graphic representation is found in Huerta (2003) and its formulation was taken from J. Heyman ([1969] 1995, pp 95 96) for this work.

In this case, the curve corresponding to a state of weight loads was shown. It tries to represent idealistically the weight load to which the vault is subjected. To do this, the arch's span (11.92

metres) is taken as the arch's free span increased in the value of its depth (0.70 metres). The thickness of the keystone's filling represents the repercussion of the flagstone pavement on the ribs on which it is supported (0.60 metres), while this filling increases the arch's real height (210+70=280) on the support.

The resulting curve has a design very close to the arch's profile, although it does not completely fit inside the arch. The critical points appear in the junction's rib between the curved part and the straight one. In any case, taking into account a greater span would permit us, without any doubt, to inscribe the graph completely. However, since it is somewhat illustrative, it has not been considered relevant.

Observable Damage

Due to some repair work that was not carefully done, the damage that the right side of the vault's first arch (if we are looking at it from the altar) shows is very visible. It would seemingly correspond to a characteristic situation forming the collapse mechanism with hinge joints formed at the key and the arch's haunches in agreement with the postulates of plastic theory, and complying with the findings mentioned in the previous paragraph, although the damage only is visible from one side of the arch.

The scanner allowed us to confirm the front arch's deformation **(fig.8)**. A difference of 17 millimetres between the levels of the arch's base and a difference of 30 millimetres between the joints of the straight part with the circle's quarters were found. The deflection with respect to the line that unites the aforementioned points reached 30 millimetres. In any case, the profiles for different planes obtained with the scanner demonstrate that the problem is limited and only found on this arch. Apart from the damage here and the limited damage seen in the wooden part, there are no other damaged parts visible on the vault.

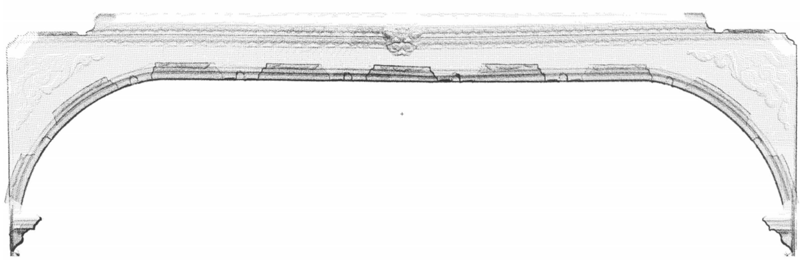

Figure 8. The survey (scanner) of the choir vault. Front. Actual state.

Finite Elements Models

To contrast the rigid elements approach, a 2-D model of a section of the church and a 3D model of the vault were realized. The mechanical characteristics of ashlar work of the internal and external faces of the wall and the vault were defined using the techniques described in Valcarcel (2001).

In the figures one can observe both the model used and the results obtained. **Figure 9** correspond to the traversal section of the nave, with the choir arch and the transversal walls and vaults used as buttresses. It s evident that the behaviour of the choir arches is in fact nearly independent of the other elements.

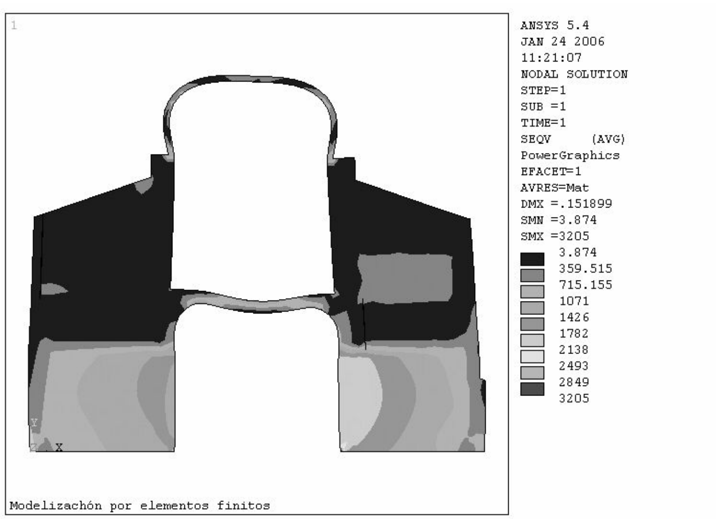

Figure 9. A 2-D model. Equivalent stresses of the transversal section f the church.

Figures 10 and 11 show the results obtained for the 3-D model of arches. The stresses are reasonably low and confirm the graphical predictions.

CONCLUSIONS

- This paper provides information on the survey of San Martín Pinario and offers complete scientific documentation on the most important historic building, after the Cathedral, in the city of Santiago de Compostela.

- The church choir's flat vault is presented and studied. It is a coffered vault made with transverse arches on which a flagstone pavement rests. The most surprising discovery about this vault is the use of wooden pieces to make the edges of the caissons parallel to the nave's axis.

- The usefulness of the laser scanner in determining the actual geometry of the structure is demonstrated here. The use of this technique allows us to differentiate materials, to detect cracks that provide information on thickness and depth, to obtain actual profiles on the different parts under consideration and to contrast them with the structural models. Through plastic-rigid analysis modelling it is possible to evaluate the stability of the elements. However, deformation analysis leads us to the conclusion that other methods, particularly the Finite Element Method, are probably more suitable.

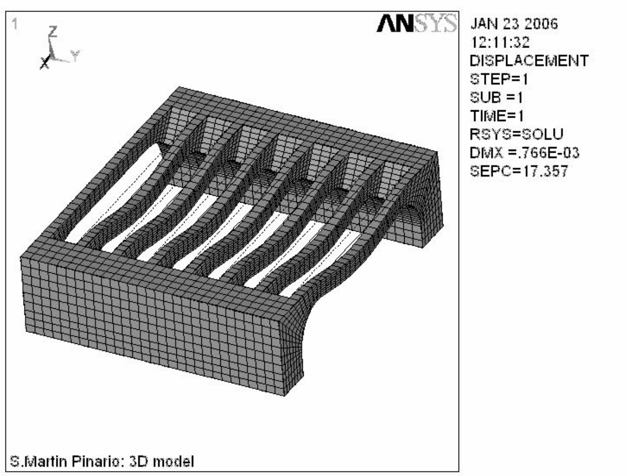

Figure 10. 3-D model. Deformed shape. Choir arches.

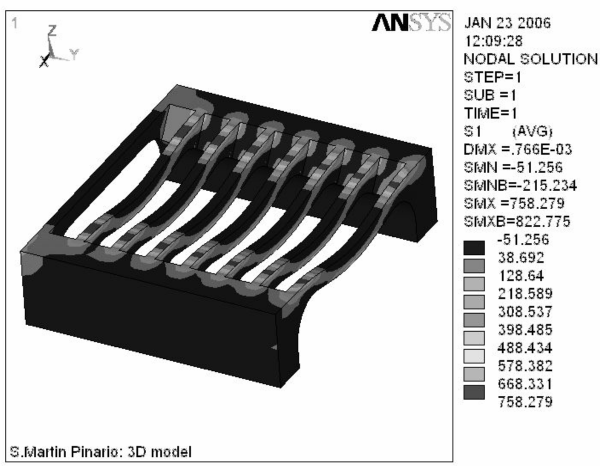

Figure 11. 3-D model. Principal stresses (kN/m^2). Choir arches.

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