The nave vault of the Hieronymites Monastery Church in Lisbon

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ABSTRACT: This paper presents a research work of the nave vault of the Hieronymites’s church. Its author was identified, through the historical study by comparing the vaults of the monastery. The observations in the place itself and the architectonic and photogrammetric survey, revealed constructive details and the structural behavior of the vault. The geometric analysis allowed us to understand the conception process - the project. A hypothesis is formulated for the constructive evolution of the vault. Last, we obtain pertinent data to be considered for the safeguard of the monument.

1 INTRODUCTION

The Monastery of Saint Mary of Bethlehem (Santa Maria de Belém), better known as Monastery of Hieronymites, is one of the most notable Portuguese examples of the Manueline architectural style. This Late Gothic Portuguese style, usually considered as ornamental, tends to be valued by its architectural and structural quality in the History of Art.

Mário Tavares Chicó (1954), was the first to notice the originality of the Manueline, namely the clear fusion of the naves in the Church of Belém. The barrel vault form, is an exceptional example of the space unit of the latest Gothic, which was the main purpose throughout all Europe, see Fig. 1 and 2.

Later, Mendes Atanázio (1984), developed the subject and expressed the idea that the Manueline has a conception of its own in that "the spider's web pattern produced by the ribs had as main purpose to maintain the soffit at the same level and to distribute the forces in a balanced way on the walls. This is why the walls were left strong and thick". This author used to appeal to the architectural research, in particular of the vaults of the Monastery of Hieronymites, for which reason this study has been developed, focusing specially in the nave vault.
2 HISTORICAL ANALYSIS

The Monastery of Saint Mary of Bethlehem, built by the will of king D. Manuel I’s, occupies the place of an old church donated to the hermits of Saint Jerome in 1499. A first phase of works was executed by the French master Diogo Boytaca, presumably the person responsible for the initial plan. From 1517 on, a great development took place under the responsibility of João de Castilho: in the span of three years the south door, the cloister, the sacristy and the refectory were built; in 1522 he was entrusted the construction of the columns and the vault of the transept. His work capacity was notable - between 1515 and 1528 he worked simultaneously in three more important construction sites of the time, the convent of Christ in Tomar, the monastery of Alcobaça and the monastery of Hieronymites. This master of Spanish origin was responsible for the introduction of the curvilinear rib in Portugal, in 1511, in the vault of the high altar of the cathedral of Braga.

Figure 2: The barrel form of the vault making the clear fusion of the chief nave and side-aisles.

Figure 3: The monastery of Hieronymites: plan and figure at the end of the XVIIIth century.
In the absence of any evidence about the author of the vault of the nave, a comparative analysis of the vaults of the Monastery of Hieronymites was made. The similarities between the vault of the nave and the vaults of the sacristy, the cloister and of the transept, attributed to João de Castilho, are evident: ribs with similar profiles present the same detail at the tass-de-charge; at the top and in intersectional zones with the haunches, curvilinear ribs are used; the space unit between the several bays is obtained by the continuity of the form either at the haunches or at the top of the vault.

Around 1920/1930, the General Department of National Buildings and Monuments (DGEMN) made a campaign of restoration of the vaults of the church. Precious documentation about this restoration and the evolution of the state of conservation of the vaults to the present time was found in the archives. Photographs and texts make reference to the materials and techniques used in the restoration of the ribs, filling of joints and replacement of arch stones. Some drawings presented with accuracy plans and cross-sections of the nave and transept vaults. Several texts testify the stone deterioration and the fall of fragments even after the restoration works, which could be confirmed in the place itself.

Figure 4: Photographs of the transept vault; the details (from the restoration works about 1930) documents the profile of the ribs serving to the arch-stones laying, and the presence of iron cramps between the voussoirs.

3 ARCHITECTURAL AND STRUCTURAL SURVEY

The topographic and photogrammetric survey of the nave vault, were fundamental for the structural understanding. The walls presented minor horizontal and vertical deformations; on the contrary, the columns leaning towards the longitudinal walls, with deviations between 5cm and 18 cm, show the behavior of a typically Gothic structure due to the larger span of the chief nave, not of a barrel vault structure, its apparent form, see Fig. 5.

The deviation of the buttresses of the south wall in relation to the axis of the columns was confirmed, proving the late conception of the vault and the pre-existence of the wall. The presence of corbels in its interior, possibly served as support to the platform for the construction of the vault. In the north wall geometric plans are observed to the real scale, where they were possibly made, see Fig. 6.

Research with ultrasound was made in three columns of the church. It was verified that the layers of the columns are monolithic or formed by two blocks, and four juxtaposed blocks compose the ones of the transept. In two sections low speeds were obtained: in the base of the south
column of the transept (column 1), due to the presence of fissures, and to 6.35m of height in one of the columns of the nave (column 6), for undetected reasons.

Figure 5: Transverse deformation of the columns, showing the behavior of a typically Gothic structure.

Figure 6: Survey of the nave: cross-sections showing the a) west wall b) north wall c) south wall d) plan
4 THE CONCEPTION – GEOMETRIC STUDY

Based upon the plan of the restoration works, the geometry was analysed:

− The central key-stones of the chief nave and the bays define symmetry axes. In the chief nave we found a square figure, in the side-aisle, diagonals at 60° define equilateral triangles; circumference arches on the diagonals, define the levels of the central key-stones: it is the geometric rule, characteristically Gothic, see Fig. 7.

− The ribs at the haunches correspond to curves of circumferences with different rays. If the vertical projection of the ribs is made in a same plan and the tops are linked, the arch that defines the cross section of the vault is obtained. The conception process would have been the inverse: first the curve that generates the required form was defined, and this determined the level of each key-stone and rib established in plan, see Fig. 8.

Figure 7 : The geometry of the side-aisle and chief nave are typically Gothic

Figure 8 : Top) the circumference arches of the ribs; bottom) vertical projection of the ribs
The analysis of the ribs in the plan, Fig. 9, shows that:

- The fine and curvilinear ribs, define the octagons, squares and lozenges at the top of the vault.
- The thickest ribs, defined by straight lines, make the connection between the supports, avoiding parallelisms to the axes, through a net of opposite triangles.
- The traditional transverse and longitudinal arches are substituted by pairs of triangles. The result is star-like forms, quite used in Spain.
- The diagonals are equally substituted by pairs of triangles, resulting the octagonal form in the chief nave.
- The relationship between the nave and the transept is confirmed, as well as João de Castilho’s authorship: the same starry form of the nave is repeated in the transept, being the squares substituted by circular figures. It must be noticed that the planimetrical similarity does not imply the altimetric likeness and the same vault form.

![Figure 9: Analysis of the ribs in plan and relationship between the nave and the transept vaults.](image)

Using Viollet-le-Duc’s method (1854-1868), the plan of the tas-de-charge is understood, see Fig. 10. On the pilasters, the ribs tend to define a parallel plan to the wall. On the columns, the springing level of the ribs is made at a superior level in the chief nave that in the side-aisles. The fusion of the ribs allowed for the resistance to the pressure of the filling of the haunches and the thinning of the columns.

![Figure 10: Tas-de-charge a) above the pilasters and b) on the columns](image)

In the geometric analysis of the nave cross-section, the same proportions and figures of the plan can be found. The geometric repetition served to facilitate the construction and the verification of the work. In its interior, a circle or a square is inscribed, Renaissance influences.
5 OBSERVATIONS

The stereoscopic vision used for the photogrammetrical restitution, allowed for the analysis of some details: the curvature of the central ribs suggesting the dome form of the squares and octagons; the parallelism between the haunches up on the pilasters and the walls; the double curvature of the arch-stones of the vault.

The constructional function of the ribs is evident, given its profile to serve to the arch-stones laying, placed in concentric way starting from the supports to the top of the vault, see Fig. 12.

Some holes in the intrados, show a vault of fine thickness and the filling of the haunches. The archive file drawings indicate a profile of approximately 10 cm, reaching the thickness in the final Gothic about 7-8 cm, in order to reduce the weight of vaults of great spans. The filling of the haunches was used to load the support points and to prevent the arches to rise, assuring the stability of the vault.

There are two different rib profiles. From its location in plan, the interpretation of the structure was attempted. In the Gothic traditional ribbed vaults, the structural function is likely to be attributed to the ribs, since the thickest ones are located in zones of main concentration of stresses, in intersection lines of the vault - diagonals, transversal and longitudinal. But in Belém, this theory seems to be inapplicable in such an evident way, because there are ribs of thinner dimensions (the curvilinear ones) that occur in intersection zones. Only a study of structural analysis can enlighten the relationship between the stress values and the dimensions of the ribs.

The structure of the vault of the nave reminds the fan vaults. In the English vaults, Heyman (1967) considers the lowering of the top as a stable and useful structure to the balance of the conoids, supplying the necessary weight to reduce the tensile stresses at the superior level of the haunches. At the wall, the fill of the vaulting conoid allows for the vault thrust to act within a range of levels. The continuous and circular form of the conoid and its filling, cause the lowering of the thrust surface at such a low level, that the buttresses are not necessary. This would be the great difference from the Gothic ribbed vault, collecting the thrust into the diagonal ribs, for which the buttresses would have to be very well positioned.

In the case of Belém, the form of the haunches is different from the fan vaults, because it doesn't have a profile generated by a curve around a central axis. But it is similar because of its continuous apparent form. For this reason, there are no directed stresses and concern about the alignment of the buttresses with the columns and pilasters.
6 THE CONSTRUCTION OF THE VAULT

The construction of the vault reveals complexity, since the ribs are defined by arches of circumference of different rays, not allowing for the standardization in the cutting of the ribs and in the manufacturing of the centering frames.

The work platform would be at the level of the corbels, corresponding to the admitted maximum inclination of 30°, for the voussoirs positioning without the need of the support of the centering. The access would be made through the stairway of the north wall and from the choir, also with access through the south tower. The thickness of the walls will have allowed for the workers' circulation and the positioning of the cranes.

The construction technique would be the one advised by Rodrigo Gil for the Spanish vaults (Palacios 1990): the plan to the real scale was drawn in the work platform, on which the pillars were placed with the required height for each key-stone, determining its position in the vault; then the centering would be placed and the construction of the ribs would begin.

Based upon this construction process, and in the way the centering frames were placed in order to form a stable structure, a hypothesis has been formulated for the constructional evolution, see Fig. 13:

1. Considering the form of the vault, there must have had a span by span construction, the "transverse arches" having been built in the first place (a).
2. The construction of the "longitudinal arches" would have proceeded next (b).
3. With the defined octagonal form, the "dome" would have ended after the location of the central key-stone (c).
4. Last, the ribs of the side-aisles would have been built, for practical reasons that are connected with the need for circulation on the walls, where the cranes for the elevation of the stones would probably be. The wall arch leans on the wall itself.
5. After the conclusion of the ribs, these would serve for the placement of the web stones, from the pilasters and columns, in a symmetrical way, loading uniformly the centering frames and the mortars in the joints. The result is voussoirs of important dimensions on top of the chief nave (e).
6. The haunches were filled with rubble masonry, and the extrados covered with a fine mortar layer, giving stability and solidity to the structure.
7. Some days had to elapse until the mortar dried, before the centering frames could be removed. In the meantime, the decoration of some key-stones, that seem to have been carved in the place itself, would be concluded. The centerings saved for the construction of the next bay were usually maneuvered with strings and removed starting from the extrados; some visible holes in the intrados can be the evidence of this construction process.
Figure 13: Hypothesis for the constructional evolution of the vault: a) the “transverse arches”; b) the “longitudinal arches”; c) the octagon; d) the lozenges; e) the web stones and the rubble fill

7 PERSPECTIVE OF SAFEGUARD

The present study revealed a series of important data that must be considered for the safeguard of the monument.

The main goal should be to respect the original principles: to assure the geometry and proportions and the construction technique used, guaranteeing the form and the stability of the vault.

Due to the presence of fissures in the columns of the transept, it is necessary to calculate the stresses in the two columns and to verify if they meet inside the structure.

The deviation of the columns towards the exterior is usually the result of the removal of the frames and it will be stabilized; however, this fact can be confirmed by periodic surveys.

The fall of stone fragments of the vault, a documented fact that was verified on location, is no doubt, the most alarming aspect. The causes suggested, as the infiltration of the rain water, the corrosion of iron cramps that link the voussoirs, the deterioration of the mortars or the bad quality of the stone, should be investigated with a view to the resolution of the problem. The desegre-
gation of the stone, besides representing danger for the church-goers, can cause the loss of balance in the distribution of the stresses and consequent structural implications.

8 CONCLUSIONS

This study led to the following conclusions:
- The author of the vault of the nave is the master João de Castilho;
- The construction of the vault occurs presumably between 1519 - date of the construction of the columns - and about 1522 - date of the contract for the conclusion of the columns and the vault of the transept;
- The constructional details are Gothic: the profile of the ribs is suitable for the placement of the web stones; these have double curvature, giving resistance and rigidity to the vault; the ribs fuse at the tas-de-charge, in order to reduce the thickness of the columns and to support the weight caused by the filling of the haunches; the rubble fill serves to maintain the form and to guarantee the stability;
- The structural behavior is typical of a traditional church of three naves, due to the inclination of the columns towards the exterior. Because of the continuity of the form of the vault and the filling of the haunches, the stresses are uniformly distributed along the walls, dispensing with the alignment of the buttresses
- The conception of the vault is based upon Gothic geometric principles, but without conditioning the form. The multiplication of triangles formed by the ribs allowed for the spatial unification and the intended form. We stand before an architect trained in the Gothic style, who fully uses the possibilities of the ribs, getting free from the traditional constructional paradigms, in order to imagine a "new" form.

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