MORPHOLOGY, STRUCTURE AND HISTORY – THE CASE OF THE UPPER FLYING ARCHES OF MALLORCA CATHEDRAL

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SUMMARY

The structure of Mallorca Cathedral has called the attention of prestigious researchers who have studied it by, at their time, pioneering techniques of analysis. However, there are aspects –as in any historical construction- which cannot be understood from a pure structural approach but demand morphological or historical insights. This is the case of the upper battery of flying arches, which poses paradoxes about its actual role and present condition.

1. INTRODUCTION

The complete understanding of an historical construction can be hardly obtained from the exclusive study of its structural rationale. As defended by so many experts, the analyst must also take history into consideration as a very revealing source of information and comprehension. Historical construction techniques, long-term or accidental actions and historical repairs or alterations are to be investigated, among other aspects. In order to illustrate the above ideas, this paper describes the case of the upper flying arch batteries of Mallorca Cathedral as an example of a construction device which can not be fully understood from pure structural considerations.

Prestigious specialists, as Josep Rubió i Bellver at the beginning of 20th c. and Robert Mark, during he 70's, have dealt with the equilibrium of the structure of Mallorca Cathedral. Both specialists carefully investigated the possible structural role of the upper flying arches and concluded that they did not contribute to the equilibrium. Moreover, Josep Rubió suggested that their thrust effect was unfavourable and required an additional balancing action. This balancing actually existed in the form of significant extra dead-load placed over the crown of the vaults and arches. Not only the role of the upper flying arches, as intended by the original constructors, is not understood today; also, the actual condition of these elements poses a significant paradox to the analyst. The main alteration of these elements consists of a large deflection; so large that, in fact, it can be hardly understood as an actual mechanical long-term deformation. Aiming to a deeper understanding of the above mentioned aspects, the authors describe some hypotheses, not directly based on structural requirements but on historical and morphological considerations, to better understand the reason why the upper flying arches were built and how they attained their very deformed shape.

2 DESCRIPTION OF THE CONSTRUCTION

The nave of Mallorca Cathedral, initiated in 1350, can be placed among the more outstanding Gothic Cathedrals because of its grandiose dimensions and the extreme slenderness of its structural elements. Its 44 m vault keystone height is only exceeded by the choirs of Beauvais and Cologne cathedrals, while the free span of 17,8 m of its main arcade is only surpassed by that 21,8 m wide unique arcade of Girona Cathedral. The main piers supporting the vaults and clerestory walls have octogonal section with diameter of 1.6 or 1.7 m. The slenderness of the piers, reaching a ratio of 13.8 between diameter and highness, constitutes the more unique and audacious aspect of the building and contributes largely to a sense of internal great spaciousness; in the case of other medieval cathedrals, this value stays between 8 and 9 (9.7 in for the piers of the choir of Beauvais Cathedral). These extreme dimensions and slenderness are by all means involved in the today large deformations which are experienced by the piers and in overall by the construction. A certain set of cracks is also observed at the base of some of the piers. Because of those alterations, the structure is deserving careful assessment.

The nave is stabilised by imposing buttresses tied to the main arcade by a double battery of flying arches spanning over the aisle vaults. The flying arches of the lower and upper batteries, spanning about 8 m, share almost equal geometric shape and dimensions; the lower ones end at the level of the springing of the vaults and arches of the main arcade while the upper ones end in a position close to the crown of the clerestory walls (Fig. 2-3). Many of the flying arches –but not all- are propped in small double arches. Some of the original double arches seem to have been removed at some time after the construction of the church. A largely deformed geometry is observed today in most of the flying arches and, particularly, in the upper ones. As already mentioned, the observed deflection is so large that it can be hardly understood as caused by true deformation of mechanical origin.

3 PREVIOUS STUDIES

At the beginning of 20th c., architect Josep Rubió i Bellver engaged in the study of the structure of the nave of Mallorca Cathedral based on a detailed static analysis [1]. His study was carried out apropos of the (controversial) restoration works undertaken by Antoni Gaudí. (Fig. 1). As can be understood from his own writings, Rubió began his analysis by assigning certain initial values to the thrusts caused by the central and aisle vaults and lower and upper flying arches and then iterating until reaching an adequate solution.

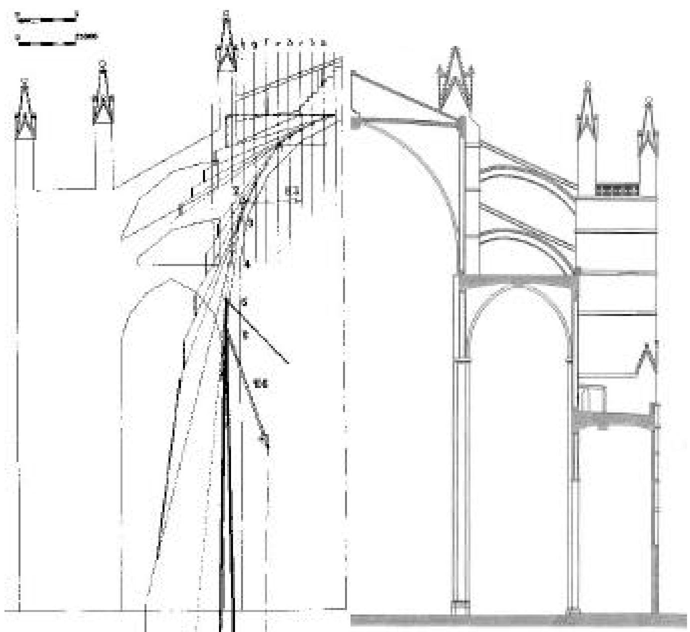
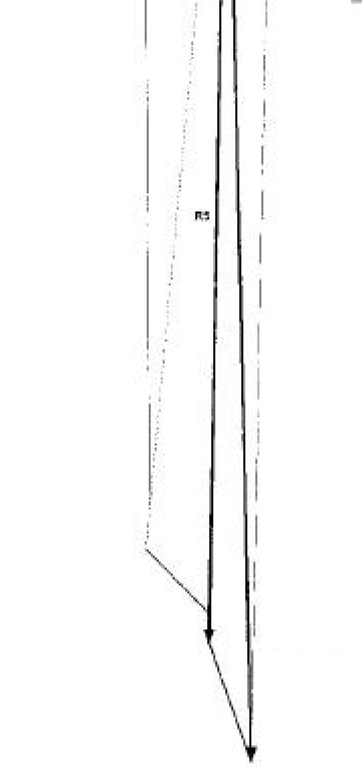


Fig. 1 – Section of the nave of Mallorca Cathedral (right) and reconstruction of the analysis by Rubió (left).



The initial value given to these thrusts was taken, in a first attempt, as an intermediate between its minimum and maximum possible values. As is well know, these limits correspond to the active and passive thrust –the minimum trust for which the arches are stable and maximum one for which the arches are estable as well. Successive attempts to find the equilibrium solution led Rubió to modify these initial values until foreseeing an equilibrium solution with the thrust fully contained within the volume of the elements. As explained by the author, fitting the descending thrust within the volume of the pier revealed very difficult and demanded very specific values for the thrusts estimated in arches and vaults (Fig. 1). The obtained solution yielded an unexpected distribution of forces: a high value of the thrust had to be assumed for the vaults and arches of the central nave while a low value, close to the active one, was found for the ones in the aisles.

This result is contradictory with the distribution of forces which one would expect in a Gothic Cathedral, with minimum thrust in the central vaults counteracted by extra-developed thrusts in the aisle vaults and flying arches. The cause of that alteration is found in the action of the upper battery of flying arches. Their location far above the springing of the arcade arches is not convenient since it can not be counteracted by the vaults of the central nave. According to Rubió, this led to the inclusion (either during the construction or later) of the diaphragmatic walls which exist over the nave arches and the pyramidal dead weights placed over the nave arches and vault crowns. On the contrary, the lower battery of flying arches is adequately located and contributes neatly to stabilise the nave vaults. Rubió concludes that it would have been better not building the upper battery of flying arches.

As it is well known, and according to the limit theorems of plasticity, the fact of obtaining a single equilibrated solution does demonstrate that the structure is in equilibrium; however, the solution found does not necessarily represent the actual condition of equilibrium. In the case of Rubió's application, all attempts to find an alternate solution different to the one above presented failed; this fact, still, does not mean that his solution is the only possible. As stated by himself, "the solution obtained, even if satisfactory, does not fully content the spirit nor it is unquestionable" (translated from [1]) .

The pioneering studies on the structure of Gothic Cathedrals carried out in the 70's by Robert Mark [2.3] included the analysis by photoelastic modelling of emblematic Gothic constructions such as Amiens, Bourges, Beauvais and Chartres Cathedrals. Given its extreme dimensions and structural interest, the case of Mallorca Cathedral was also considered and analysed using the same technique. The analysis permitted to draw interesting conclusions about its structural features and response subject to subject to gravity loading and wind. Although some of the conclusions reached by Mark are not in agreement with those drawn by Rubió, both researches coincided in some relevant aspects. With regard to the upper flying arches, Mark demonstrated that they do not contribute in a significant way to the overall equilibrium; furthermore, the ends of the upper flying arches do experience appreciable tension. This result was consistent with the fact that a number of upper flying arches needed to be propped by infill walls or columns built over the lower ones (Fig. 3). Following Mark [2,3], the form of the flying buttresses is related to such distress; the flying arches are long and are not appreciably sloped to help contain relatively high bending moments. Moreover, since the Cathedral of Mallorca does not exhibit the typical, northern Gothic high-pitched roof, its upper flying arches serve little purpose. The absence of appreciable compression force in them –as obtained by the photoelastic analysis - can only contribute to its malfunction. According to Mark, a far more effective buttressing system would employ a single battery of more highly sloped flying arches.

4 ABOUT THE ROLE OF THE UPPER FLYING ARCHES

The work of the mentioned authors suggests that the second, higher battery of flying arches lacks of evident structural role and even causes some undesired effects which, following Rubió, require additional artifices (such as the dead weights over the arches and vaults) to compensate for them. The inclusion of this upper battery could thus be observed as a flaw in the structural understanding of the ancient constructors who, apparently, transposed to Mallorca Cathedral a design of the largest High Gothic cathedrals (as in Amiens, Beauvais and

Cologne) which, in fact, was unsuitable for it. Upper flying arches would only reach full structural sense if vaults had been covered with a high pitched roof, which has never been the case of Mallorca Cathedral. However, structural requirements were not the only need that the ancient builders encountered in their laying out of the morphology of a large construction.

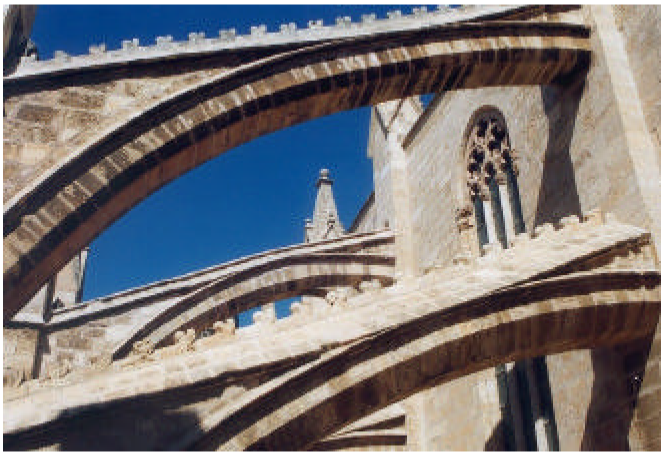


Fig 2.- Apparent deformation of flying arches

Beyond other aspects related to liturgical service and symbolism, morphology resulted also from functional requirements related, for example, to illumination, drainage and other. In particular, draining the large roof surface of the central nave of Mallorca Cathedral, covering more than 1200 m^2 , is not a minor problem at all.

Barcelona Cathedral and the Basilica de Sta. Maria del Mar, in Barcelona, both built during the 14^{th} c., have been regarded as precursors of many of the design features of Mallorca Cathedral. Some of these common features are obvious, like the prismatic octogonal design of the piers of the main arcade of Mallorca, taken from Sta. María del Mar. Another common feature shared by these buildings (and other Cathedrals built in the Kigdom of Aragon) results as an adaptation of the northern designs to the Mediterranean pluviometry. Thus, not high pitch roofs but flat ones were preferred and really shaped over the vaults. The vaults were left free, with no roof covering them but just a tile pavement built on their top surface to prevent water filtration. It must be said that although the climate can be considered dry in terms of average pluviometry, rain can manifest with intensity during short whiles thus demanding significant drainage capacity. The natural slopes of the vaults act in this case as draining paths until water is finally delivered to the drains and gargoyles. In the case of Barcelona Cathedral, the water falling on the roof of the central nave is channelled over the aisle naves by means of very thin flying arches which definitely cannot develop any structural purpose; then water is channelled across the buttresses and expelled beyond the external perimeter of the building.

As an alternative explanation of the reason why the upper flying arches were built, it can be suggested that the builders of Mallorca Cathedral just adapted the draining solution developed for the Cathedral of Barcelona and Sta. Maria del Mar, to solve a similar, but largely magnified problem. In fact, it is very difficult to envisage a satisfactory alternate solution. Thus, they built the upper flying arches as channels springing from the natural draining, low points of the vaulted roof. Since they had to span more than 8 m, these arches needed to be robust and were built similar to the fully structural lower ones. However, in adopting that solution, secondary mechanical effects were induced which actually disrupted the equilibrium and required additional and artificial balancing devices. The effect generated is to be found in the thrust that the flying arch generates against the upper clerestory wall over the vaults. In fact, this wall shows a prominent inward deformation which can only be understood as caused by the flying arch. This effect was counterbalanced by building the already mentioned diaphragmatic walls and prismatic weights on the arch and vault keystones.

5 ON THE DEFORMATION OF FLYING ARCHES

As already said, most of the flying arches of the building show today a remarkable deformed shape. This alteration becomes very apparent in the downward curvature acquired by the cornices (Figs. 2-3). The deflection of the cornices reaches 1/40 of the arch span in some cases. This dramatic deformation may have created deep concern at certain (historical) time and led to propping some of the upper flying arches on masonry columns built over the lower ones. Three different flying arches, at least, were propped that way and remain so. On the other hand, the arches (under the cornices) do not show the important damage that should be expected to accompany a true large deformation.

Fig. 3 – Flying arch propped on a masonry column

Again, some insight can be obtained from non-structural considerations. To adequately comply with the drainage function, the upper end of the cornice had to be placed so to collect water from a specific point –the low points of the roof of the main arcade- and the lower end had to be placed so to deliver water to another specific point- to the drains built across the buttresses. Instead of shaping a straight line between these two points and fill the remaining gap between this line and the arch, the channel-cornice seems having been built as a free curve which begins and ends at the mentioned points and keeps tangent to the arch about its mid-span. This alternative is more easy to construct; moreover, it does not affect the aesthetics of the structure since the flying arches, hidden by the curtain of buttresses, are hardly visible from the external perimeter of the building. Efficiency may have been preferred to geometrical perfection.

If so, the apparently deformed shape of the cornice of the flying arches should be understood as an original construction treat. Further short-term or long-term deformation may have added real deflection, but still the main component of the apparent deflection should be found in the construction process.

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