Construction process, damage and structural analysis. Two case studies

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ABSTRACT: The paper refers to the studies recently carried out on the church of Santa Maria del Mar in Barcelona and Mallorca cathedral, built during the 14th and 15th centuries. Historical research has provided significant insight on the construction processes, which were remarkably different in the two buildings. This information has been considered to investigate the possible link between construction and existing deformation and damage. As shown by these examples, insight on the construction process (and later man-caused alterations) may be important for an accurate structural analysis.

1 INTRODUCTION

The buildings analyzed, namely Mallorca cathedral in the island of Mallorca and the church of Santa Maria del Mar in Barcelona, show common architectural features but also significant dissimilarities which, in turn, have lead to different damage and deformation conditions. As will be later described, one of the main differences is found in the construction processes and their consequences for the latter condition of the structure.

The studies were undertaken in close cooperation between historians, structural engineers, mineralogists, architects, geophysicists and other specialists. Detailed research on available historic documents has permitted the identification of essential issues related to the construction process and later events (architectural alterations, earthquakes, fires) having left their imprint on the structure. Geophysics, carried out by means of seismic tomography, pulse radar and dynamic testing, has been very useful in characterizing essential structural and morphological features. Structural analysis, carried out by means of classical approaches (limit analysis) and advanced non-linear numerical models, has permitted the characterization of the structural performance under gravity, soil settlements and earthquake (Clemente, 2007, Martínez, 2008).

Based on the information provided by historical and geophysical research, a sequential analysis has been developed, in the case of Mallorca cathedral, as an attempt to simulate some aspects of the construction process. An essential issue of the diagnosis lays in the distinction of damage related to active phenomena, still contributing to further deterioration, from that which has resulted from past or already extinguished actions. In some cases, stabilized damage or alterations caused by past actions may be preserved and respected as a sign of identity linked to the historical character of the building. In other cases, repairing this type of damage may be necessary to avoid problems related to durability or functionality, or to improve the capacity of the building under extraordinary actions (as earthquake). If repaired, historical or traditional techniques should be preferred to alternative possibilities in order to avoid unnecessary loss of authenticity of materials and structure.

For obvious reasons, the ISCARSAH Recommendations (2005), state that the intervention must always address the real causes rather than “the symptoms”. When addressing past or extinguished actions, the need for intervention should be carefully appraised and repair and strengthening should be limited to truly indispensable operations.

Possible historical actions which may have contributed to damage, but (in principle) are not expected to happen again, include anthropogenic ones (wars, fires and other types of destruction, lack of maintenance and inadequate restorations) and natural ones (as
stabilized soil settlements). Earthquake does not lay in this group for obvious reasons. Yet another “action” belonging to this group, which by no means should be neglected, is the construction process itself and its related hazards and difficulties.

2 DESCRIPTION OF THE BUILDINGS

Santa Maria del Mar is a rare case of a Gothic church entirely built during a short period of time spanning 53 years. Moreover, the building has not experienced any significant architectural alteration after its construction, resulting in the uniformity and architectural purity for which the building is today acknowledged. The overall arrangement of the structure is very similar to that of Barcelona Cathedral, built during 13th and 14th c., and consists of a three nave structure built on a basilical plan.

In Barcelona Cathedral, the wish for a unitary and diaphanous inner space, reminiscent of that of Roman basilicas, laid to an innovative design. The central vaults were built with longer span in both the transverse and longitudinal directions (12 and 8 m), compared to other contemporary buildings, and were supported in surprisingly slender piers; the lateral vaults spanned as much as one half of the central ones and were built at a height close to that of the central ones; the external walls were built along the external perimeter of the buttresses and these were used as partition walls between lateral chapels. In the case of Barcelona Cathedral, this combination contributed successfully to create the impression of a unique and wide, even magnificent interior space in spite of the limited dimensions of the building. As mentioned, the lateral vaults are almost as high (but not so high) as the central ones; in fact, they are adequately positioned to receive the lateral thrust of the central vaults and carry it to the buttresses, so that structural flying arches are not needed.

Santa Maria del Mar is the only other Gothic construction having been built according to this structural arrangement. Other Gothic cathedrals have low aisles (as in French Gothic) or have them as high as the central nave (as in German late Gothic churches). Furthermore, the builders succeed in improving the possibilities of the concept in terms of structural economy, unity, diaphanousness and aesthetics, the latter soundly emanating from the geometrical proportions. This was attained by designing the central vaults as almost perfectly square in plan, by giving them some extra height (up to 32 m) and by supporting them on austere but extremely slender octagonal piers (Fig. 1, above). The resulting construction includes four large vaults, spanning 13.5 m in both directions, supported on 8 piers with circumscribed diameter of 1.6 m. As in Barcelona Cathedral, the span of the lateral vaults is half of that of the central ones, while the buttresses are used to separate the lateral chapels. The building is completed with the choir and the façade, whose structure conforms to the uniform arrangement given to the perimeter of the naves. In particular, the façade is built with two large buttresses which are, in fact, needed to counteract the longitudinal thrust produced by the first square vault.

As opposite to Santa Maria del Mar, Mallorca Cathedral was built over a large period, spanning for 300 years (from 1306 to 1600), and was later subjected to significant repairs and reconstructions. To some extent, the structural design of Mallorca Cathedral seems inspired by Santa Maria del Mar and shares with it major features, such as the search for spaciousness, the high lateral naves (although not so high as to take the role of flying arches), the lateral chapels between buttresses and the extremely slender, solid octagonal piers. However, and because of the large dimensions intended to the nave, the builders also resourced to structural devices commonly used in large Gothic buildings, such as the double battery of true flying arches spanning over the aisles. In a way,
Figure 2. Arrangement of stone blocks in octagonal piers.

Figure 3. Diaphragmatic arches and dead weight over vaults in Mallorca Cathedral.

Figure 4. Pottery filling over the central vaults of Santa Maria del Mar.

to adequately counteract the horizontal thrust of the central nave.

3 HISTORICAL INFORMATION

Construction of Santa Maria del Mar church began on March 25, 1329. It involved, in the first place, the formation of the full perimeter, including the buttresses, chapels, lateral walls, choir and façade (Fig. 5), which were fully completed by 1350. There is evidence suggesting that this phase was followed by the construction of the arches, both the longitudinal (or clerestory) and transverse ones, and both at the lateral and central naves (Vendrell et al.). At this stage, a normal use of the building would have been possible thanks to a provisory wooden roof supported on the transverse arches. The construction was completed by building the vaulted roof on the already existing arches, starting, in each bay, with the lateral vault membranes and then the central one. The last stone was placed on November 3, 1383. Remarkably, this procedure does not agree with the construction plan (supposedly) developed in most Gothic Cathedrals, which involved a gradual extension in the longitudinal direction starting from the choir and finishing with the main façade. In fact, Barcelona and Mallorca Cathedrals are known to have been built according to this latter plan.

In 1379, when the last bay was almost completed, a fire destroyed the scaffoldings and caused some damage to the stone. Another fire, provoked in 1936, caused significant damage to the piers, arches and vault keystones. Earthquakes are known to have occurred in several occasions, as in 1373, causing the collapse of the upper body of one of the façade clock-towers, and 1428, when the collapse of the rose window killed a number of people (Fontseré, 1971).

The building has also experienced damage during bombardments against the city in 1714, (during the
Succession War) and the Spanish Civil War (1936–1939), among other episodes.

The architectural unity and the consistency of the construction process suggest that a fully developed project should have been well established before 1329, when the construction began. At this moment, not even the choir of Barcelona Cathedral, frequently regarded as the immediate precedent, was finished.

Construction of Mallorca Cathedral began by year 1300 starting with the presbytery (which comprises the so-called Trinity and Royal Chapels). According to the most widely accepted interpretation, by 1330 it was decided to build the remaining construction according to a three-nave plan and yet, by the mid of 14th c., it was decided to increase the height of the vaults. The construction of the main nave developed during the rest of 14th and 15th c (with a major interruption from 1460 to 1570). The main façade, of noticeable Renaissance style, was built from 1594 to 1601, when the cathedral was consecrated.

Research on the historical books has provided significant hints on the construction process. As shown in Fig. 6, the construction of the nave progressed, bay after bay, from the presbytery towards the façade (the last part to be built). Construction of the chapels was ahead because of the funding provided by noble families or corporations willing them as pantheons or gremial chapels (Domenge, 1997).

Figure 5. Construction of Santa Maria del Mar. 1: foundation; 2: perimeter; 3: arches and vaults.

Figure 6. Construction stages of Mallorca Cathedral.
It has been possible, at least for one of the bays (the 4th one), to identify the process leading to its complete construction (Fig. 7). Once again, it started with the lateral chapels, followed by the piers, then one lateral vault, then the other and finally the central one. In the case of this bay, the construction of the vaults lasted 7 years. It should be noted that during a period of about 5 years, the lateral vaults were already pushing against the pier while the lateral vault was not yet there to counteract their thrust.

The building has experienced significant problems and repairs. The 4th vault (previously discussed) partially collapsed 30 years after its construction. A significant number of vaults were repaired or reconstructed during the 17th, 18th and 19th centuries. Due to the concerning out-of-plumb (about 1.3 m), the original façade was taken down replaced by a new one during the second half of 19th c. Demolition was decided in March 1851 and hence was not connected to the earthquake occurring in May the same year.

4 EXISTING DAMAGE

Four different types of alterations, visible in both buildings, are here highlighted and discussed:

1- Cracking in piers. Cracks exist in a few piers of Mallorca Cathedral and most piers of Santa Maria del Mar (Fig. 8). Vertical or oblique cracks have developed across the stone extending, in some cases, to several rows. They tend to concentrate close to the corners of the octagonal section (the less confined parts) and, in some cases, shape full wedges partially or totally detached from the core of the pier. In the case of Santa Maria del Mar, the cracks are related to additional forms of damage (black patina and crusting, superficial loss of stone and mortar at joints) which can be clearly associated with the severe fires experienced. The reason for similar cracks in a few piers of Mallorca, randomly distributed, is less clear.

2- Cracking in arches and vaults. In the lateral naves of Santa Maria del Mar, a longitudinal crack has developed following the keystones of the transverse arches (Fig. 8, right). The longitudinal cracks in the aisles are due to a differential settlement between the pier and the buttress. The arches do actually show the deformation and damage which should be expected from this type of settlement (Fig. 9, left). In a few cases, initial deformation appeared

Figure 7. Mallorca Cathedral’s 4th bay construction sequence.

Figure 8. Cracking in piers (Mallorca Cathedral, left, and Santa Maria del Mar, repaired, right).
due to an early or accidental removal of centering (Fig. 9, right) related, perhaps, to the fire of 1379.

3. Cracking in walls and facade. Cracking, mostly developed along the mortar joints, can be also recognized in the exterior or clerestory walls. It can be linked to the out-of-plumbing experienced by the facade in the case of Mallorca Cathedral and the facade clock-towers in Santa Maria del Mar.

4. Deformation. The deformation of the overall structure is perceptible in Mallorca Cathedral. The piers show significant lateral deformation reaching, in some cases, up to 30 cm, i.e., 1/100 of height at the springing of the lateral vaults. Remarkably, both the magnitude and the shape of the deformation vary very significantly (almost randomly) among the different bays, or even between the two halves of a single bay (Fig. 10). Conversely, the piers of Santa Maria del Mar show a more regular pattern both in direction and value, with maximum values ranging between 2 and 6 cm (8 cm in a single case), about 1/300 of the height at the springing of lateral vaults.

These deformations have been measured with respect to the ideal un-deformed geometry of the structure. For that purpose, the “ideal” profiles are reconstructed based on the information on original geometric parameters (radii, positions) which can be derived (or guessed) from the present geometry. All deviations due to construction defects, positioning errors, deformation of centering and plastic mortar settlement (among other possible effects) are ignored. Because of it, real deformations cannot actually be determined and the above measurements can only be understood as a coarse estimation. The possibility of the deformations mentioned for Mallorca Cathedral being mostly a consequence of errors and hazards experienced during the construction cannot be disregarded. The same applies to possible soil settlements estimated as a

difference between architecturally related vertical references (such as opposite impostes, capitals or arch springings), whose unevenness might be due, at least in part, to construction inaccuracies.

5 CONSTRUCTION PROCESS AND DAMAGE

From a theoretical point of view, structures based on the balance of arch thrusts, as Gothic cathedrals, attain full stability only at their final and complete configuration. Moreover, adequate equilibrium requires (again, theoretically) the simultaneous activation of all the arches and vaults by first building the entire system and then removing all the centering almost at once. This is not obviously the case of the buildings discussed in this paper (as it is not either the case of most similar constructions). Conversely, real construction processes involved intermediate stages were equilibrium was reached only thanks to auxiliary devices or, in a more hazardous way, by relying in the capacity of the incomplete structure. The order in which the structural members were built was essential to make the entire construction viable or to limit the construction difficulties.

The construction process has been, in no few cases, a hazardous phase contributing by itself to initial damage and deformation. Repairing this damage may have been possible during or after the construction. Correcting the deformation is difficult or impossible and, in most cases, it has stayed as a testimony of this initial phase.
Nevertheless, Santa Maria del Mar was built following a procedure which would ascertain, at any moment, an easy balance of forces. First, the construction of the entire perimeter structure (including buttresses, walls, chapels along the choir, sides and façade) would provide a stiff system able to laterally buttress the rest. Then, the construction of all longitudinal and transverse arches (of both central and lateral vaults) would provide the necessary lateral stability to the slender piers. The transverse and longitudinal (or clerestory) arches would also grant full stability during the formation of the entire vaulted roof. In the longitudinal direction, the stability was ultimately provided by the choir and façade buttresses, already built. This is probably the reason why, yet at present, the piers are showing such a limited drift in spite of their slenderness.

The process, however, may have generated an inconvenient side effect. The construction of the vaults took place about 30 years after the perimeter structure had been built. As should be expected, the lateral structure had by then already experienced most part of its possible soil settlement. Due to the settlement of the piers, the new members built across the aisle (arches and vault membranes) experienced a vertical deformation (or differential settlement). The lateral longitudinal crack along the keystones of the transverse arches may have been caused by this effect. In fact, settlements may have been important during the construction because the foundation soil, composed of rubble and loose sand, is certainly deformable. However, a later significant increment of differential settlements between lateral structure and piers seems unlikely because the rubble existing over the vaults (a sort of medieval lime concrete supposedly placed in a later stage but still during the construction) does not show any crack in correspondence to the one seen at the intrados of the vaults. Moreover, the arches appear more damaged than the vault membrane, which does not either accompany their significant deformation (figure 9, left); the only explanation is the later construction of the vaults (after the arches had been built) and the possible development of most the settlement while the material of the vault membranes was gradually placed on the arches, but yet with the possibility of correction or almost free deformation while the mortar had not yet hardened.

As mentioned, the construction of Mallorca Cathedral followed a different path involving the subsequent construction of the bays. The lateral vaults were built (as in Santa Maria del Mar) before the construction of the central ones. In this case, historical research has not provided, so far, any hint on the way the structures were stabilized while the central vault was not yet built (third stage of Fig. 7). Several possibilities, however, may be considered.

First, the lateral vaults could have been stabilized by means of previously built transverse arches, as in Santa Maria del Mar. If so, the almost 20 m span arches would have needed some stabilizing extra weight to resist the thrust of the lateral vaults without experiencing inward deformation or collapse. Extra weight actually exists (Fig. 3), although its original purpose might be different. Second, they could have been stabilized by means of auxiliary devices such as steel or timber ties across the lateral arches or struts across the central one. Third, they could have been built without any stabilizing element, the partial structure being (precariously) stable by itself thanks mainly to available tensile strength.

Whatever the method, there was some hazard and chance for damage and deformation. This is consistent with the fact that the lateral deformations at the piers, as already mentioned, are very variable (almost "random") although large in average, and suggests that the outcome was very sensitive to the skills and methods used by the different builders. Moreover, different approaches (as the three ones mentioned) may have been used during the certainly long and irregular construction process.

The longitudinal stability at intermediate stages is even more challenging as the piers had to face the unbalanced longitudinal thrust of both the lateral and central vaults. According to the historical information available, a previous construction of all the clerestory arches (as a way to stabilize the bays at intermediate stages) should be clearly disregarded. The use of possible temporary devices (temporary ties or buttressing walls) appears as a likely possibility.

6 STRUCTURAL ANALYSIS

Structural analysis has been carried out using limit analysis and non-linear FEM calculations. Previous results concerning dead loading and seismic performance of Mallorca Cathedral have been already presented (Clemente et al., 2006, Martinez et al, 2006, Martinez, 2008). The present discussion focuses on the performance of the structures subjected to dead loading and the possible influence of the construction process. The non-linear FEM analyses have been carried out using a continuous damage constitutive model (Clemente et al. 2006). The material properties have been estimated based on laboratory tests on cores taken from the buildings or the original quarries. The overall stiffness (value and distribution) was assessed by comparing experimental and numerical natural frequencies, the obtained from ambient vibration measurements (Martinez et al. 2006).

In the case of Santa Maria del Mar, the hole drilling test was used to measure the average compression stress at the base of two piers. The obtained value,
of 3.0 MPa, agreed very well with the corresponding numerical prediction (2.9 MPa).

In order to take into consideration the construction process, a sequential analysis can be carried out in which the changes experienced by the construction are subsequently simulated and adequately superposed. In the case of Mallorca Cathedral, a tentative simulation of the construction process has been undertaken using model of the typical nave bay (Clemente, 2007, and Fig. 11). The third possibility mentioned in section 5 (the partial structure being stable by itself) has been analyzed in detail by means of a sequential analysis involving the following steps: (1) Construction of the lateral nave (buttresses and lateral vaults) and (2) construction of the central vault. According to the FEM analysis (in which a small tensile strength is assumed), the stability of the partial structure generated in step (1) is possible, but at the cost of significant deformation and certain damage. Compared to instantaneous analysis, the final lateral deformation attained by the piers increases by a factor of 2.5. In turn, additional damage appears in the upper part of the piers, lateral vaults and upper flying arches. This damage might be connected to some cracks and deformation still visible today (as in the upper flying-arches), although most of it may have been probably repaired during the construction itself. The constitutive model describes this damage as a scalar whose values range between “0” for intact and “1” for totally damaged material.

7 CONCLUSIONS

As shown by the two cases investigated, the construction process may have significant influence on the initial condition of the structure. Some of the alterations (large deformation, damage) which can be observed in historical buildings might be attributed, at least in some cases, to the hazards and difficulties linked to intermediate construction phases.

As in the two examples presented, historical documents may provide, in some cases, meaningful information on the construction process. A detailed inspection may also provide important clues on the way the structure was constructed and the possible hazards encountered by the builders. In turn, structural analysis may contribute with a better understanding of the structural significance and risks involved by the intermediate stages associated to incomplete or provisional configurations of the structure. For this purpose, a sequential analysis (in which the different stages are subsequently simulated) is preferable to a more conventional instantaneous analysis.

Later anthropogenic actions (accidental or intentional fires, architectural alterations, repairs) should also deserve attention and should be always included as part of the historical investigation. In fact, a significant part of the alterations which have been recognized in the buildings discussed in this paper are linked to the construction process or to this second type of actions (as the fires experienced by the structure of Santa Maria del mar).

It turns out that some insight on the construction process may be needed for an accurate structural analysis, while structural analysis itself constitutes a powerful tool to better understand the construction process.

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