STUDIES ON THE ORIGIN OF DEFORMATION AND DAMAGE IN LONG-SPAN HISTORICAL STRUCTURES

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ABSTRACT

The paper presents some remarks on the origin of damage in long-span masonry constructions stemming from the study of a set of medieval building in Spain which included several Gothic Cathedrals. The studies allowed the identification of frequent forms of damage related to long-term phenomena which can be roughly classified into the following categories (1) large deformations affecting the entire construction; (2) longitudinal cracks and other effects related to compression stresses, and (3) cracking due to shear or tensile stresses leading to the separation of parts or the fragmentation of individual structural members.

Long-term processes leading to the decay of the structural performance (such as long-term damage due to creep related phenomena) are by all means involved in the generation of the described alterations. However, the studies carried out illustrate that lasting effects due to historical events (such as, in particular, the construction process itself) have also influence on the final condition of the building.

Valuable information on these constructions is now available thanks to the studies currently undertaken, which involve historical research, structural analysis and monitoring. In particular, the influence of the construction process on the deformed condition of the building has been illustrated though the structural modeling and analysis of a hypothetical intermediate construction stage suggested by the historical research.

1 INTRODUCTION. FORMS OF DAMAGE

The analysis of a set of medieval buildings (among which the Cathedrals of Mallorca, Barcelona, Girona and Tarazona, in Spain) has provided evidence on the significance of certain forms of damage related to long term processes, which, to a larger or lesser extend, are common in historical buildings. These forms of damage can be classified –in a non-comprehensive way- into the following categories: (1) overall large deformations, (2) longitudinal cracks and crushing in elements subjected to compression and (3) large cracks, due to shear or tension stresses, causing separation between different structural components or significant portions of the building (fragmentation). As mentioned in the following paragraphs, the development of such types of damage can be hardly understood from the mere consideration of purely mechanical and instantaneous phenomena; long-term physical phenomena (as long-term damage processes related to creep) and lasting effects of historical facts (as the construction itself) are also to be considered.

1- Large deformations affecting piers, buttresses and other structural components are commonly observed in ancient constructions. In many cases, such large deformations are one or more orders of magnitude superior to those predicted by instantaneous or short-term numerical analysis, even if non-linear material or geometrical effects, or even a conventional

Figure 1: Pier of Tarazona Cathedral affected by damage in compression

Figure 2: Crack between transverse arch and cross vault in the nave of Mallorca Cathedral

treatment of primary creep at short or mid-term, are considered. This phenomenon is clearly observed in Tarazona and Mallorca Cathedrals, where the existing lateral deformation of piers is at least 100 times larger than the numerical prediction obtained for the non-linear instantaneous analyses carried out for the building subject to gravity load.

2- As is well known, cracks parallel to the direction of applied compression may appear in materials such as concrete or stone even for stresses significantly lower than the compressive strength. Longitudinal cracking is not rare in vertical masonry components subject to moderate compressive stresses, below 30-60% of the estimated compressive strength of the masonry. The authors have observed vertical cracking and other effects related to compression (such as crushing and disappearance of nervures or material) in some of the piers of almost all the studied Cathedrals. Vertical cracks and related lesions in piers are particularly significant in Mallorca Cathedral and the Basilica of Santa Maria del Mar in Barcelona. Even more apparent effects (such as crushing and loss of material) could be seen in Tarazona Cathedral before its recent restoration (Fig. 1; see in Roca and Gonzalez [1] for a more detailed discussion).

3-Division (fragmentation) by large cracks affecting the entire contact between structural members or parts of the construction is not uncommon in historical constructions. In many cases, these large cracks are caused by soil settlements. Similar effects may be caused or influenced by thermal environmental actions; large cracks affecting walls or vaults are observed which, because of their location and geometry, strongly suggest an acquired role of expansion joints. Examples are found in Girona and Barcelona Cathedrals, with cracks appearing along construction joints, and Mallorca Cathedral, where wide discontinuities are observed between some of the transverse arches and the vaults of the nave (Fig. 2).

2 MECHANICAL DECAY AT THE LONG TERM

Long-term phenomena leading to progress deterioration during historical periods must be accounted for in order to understand the actually existing damage. As observed a propos of the study of recent collapses (Papa and Taliercio [2], Binda, et al. [3],[4]), the effect of creep under constant stress, at the long term, may induce significant, cumulative damage in rock-like materials. As mentioned by Binda et al. [3], accumulation of damage (eventually leading to collapse) may occur for stress values significantly lower than the normal strength obtained by standard monotonic compression tests. The same authors found that such phenomena could start at 40%-50% of the normal strength value.

Effects due to historical actions may have also contributed very significantly to the continuous increase of deformation. Extraordinary actions such as large earthquakes may produce important lesions and irreversible deformations (Fig. 3). Low-intensity earthquakes or repeated occurrences of hurricane-force wind may act cumulatively to cause ever increasing damage and deformation. Daily or annual thermal cycles individually have a minimal effect; however, a certain, irreversible increment of deformation may be produced after each cycle, thus contributing over very long periods of time to a meaningful increase in overall deformation. It must be noted that the effects cyclic actions do not dissipate with time, but may increase in an accelerate way as the construction becomes more and more damaged.

The damage affecting the construction, which in normal conditions always increases due to the mentioned and other possible causes, will, in turn, enlarge the sensitivity of the construction towards a variety of actions. This situation contributes to constantly increasing (never-mitigating) deformation at the long-term or even accelerated long-term deformation which, in the worst case, can lead to the collapse of the construction. Since the more persistent action is gravity, it is not strange that such constant increase of deformation may manifest as a monotonic, non-assimptotic amplification of the initial deformed shape due to dead load.

3 INFLUENCE OF CONSTRUCTION AND HISTORICAL EVENTS

Important effects related to deformation can be attributed to construction process. The construction of historical structures lasted during large periods amounting to several decades or centuries. The construction included long intermediate stages during which the structure was stabilized by means of provisory supports or was forced to develop resisting mechanisms not entirely consistent with its structural arrangement and design. It is likely that the structure showed larger mobility during these intermediate phases due to the flexibility of the provisory supports and the more limited lateral confinement, so that significant initial deformations were produced. This phenomenon was amplified by the early settlement of mortar in joints and the initial creep of compressed members.

Historical research on Mallorca Cathedral (built during 13th to 15th c. [5]) has proven that the construction of each bay followed the same process, consisting on, fist, the erection of the lateral chapels (with their vaulting) and buttresses, and, second, the construction of the collateral and then the central vaults. Momentarily, the construction experienced an

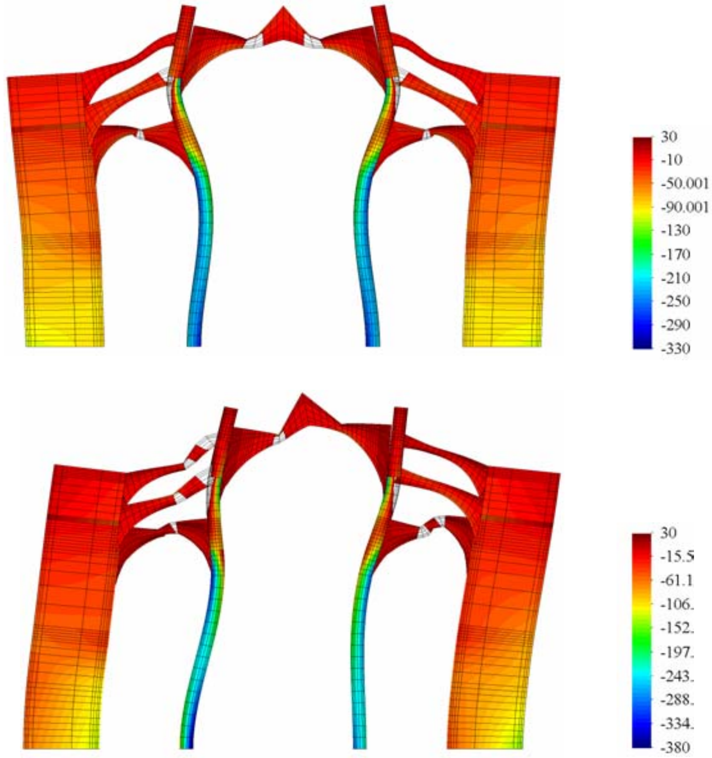

Figure 3: Analysis of the transverse section of Mallorca Cathedral. Above: deformation (×2000) and distribution of normal stresses (10×kN/m^2) in chromatic scale (white used for cracking) for dead load. Below: deformation (×1000) and distribution of stresses caused by a major earthquake (a_c/g=0.12).

intermediate stage consisting of the partial structures shown in Fig. 5 (left). It is not clear, from the historical documents, whether the centering of the lateral vaults was removed prior to the construction of the central vault, or whether it was maintained during the entire operation. Removing the centering of the lateral naves would have caused a very significant inward thrust on the partial structure (Fig. 4) producing large lateral deformation. Given the characteristics of the wooden centering frames used at the time (with no foreseeable effective transverse ties to prevent from causing lateral forces against the capitals of the piers, Fig. 4), it is likely that keeping them during the construction of the central nave would not have saved the piers from receiving a significant unbalanced lateral thrusts.

The numerical simulation of this stage, carried out by means of a FEM continuum damage model (see in [6] for more information on the calculation technique used) has shown that equilibrium is possible for this particular condition at the cost of a very important deformation; however, no significant damage is experienced by the partial structures. The obtained lateral deformation is one order of magnitude larger than that predicted by an instantaneous analysis on the entire structure. Consistently, the subsequent completion of the central clerestory walls and vaults in the sequential analysis (Fig. 5, right) does not cause significant additional deformation.

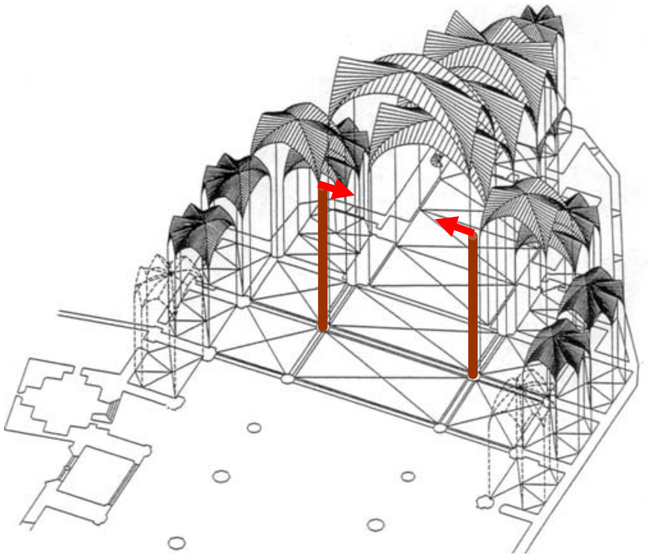

Figure 4: Construction process and momentary unbalanced forces

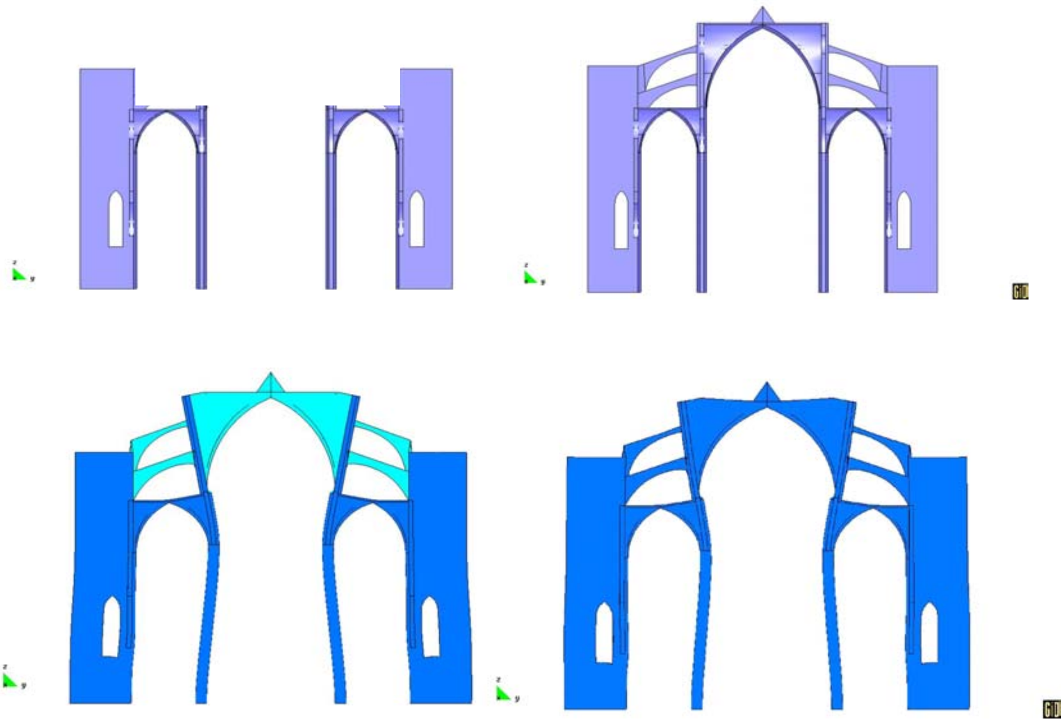

Figure 5: Simulation of the construction process. Intermediate (left) and final (right) configuration and accumulated deformation

4 CONCLUSIONS

Historical constructions may show a variety of structural alterations (such as large deformation, cracking or related damage in compression, and fragmentation due to cracking in tension or shear) caused by phenomena or actions developed during historical stages and long periods of time. In many buildings, such forms of damage do manifest in a very severe and apparent way.

Conventional instantaneous analyses are not adequate for the study and the simulation of such effects. More accurate studies may require the simulation of (1) the subsequent historical stages of the building (in particular, the construction process) through a sequential analysis, (2) actions occurring in historical periods, such as major earthquakes or the repeated effect of minor earthquakes or thermal cycles, and (3) long-term rheologycal or damage processes (such as those related to creep) which may have developed through its life. It must be noted, however, that a realistic simulation of historical actions or long-term damage processes is still requiring for additional experimental studies and numerical developments. Furthermore, historical information providing useful insight on the construction process and latter architectural alterations (or other historical events) is often unavailable.

Nevertheless, a correct interpretation of the existing deformation and damage requires an accurate analysis. In turn, only a correct understanding of damage can lead to an accurate assessment of the real condition of the building.

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