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Monitoring of long-term damage in Gothic Cathedrals

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Abstract

A discussion of the significant types of material and structural disorders related to long-term damage observed in Gothic structures is presented together with some considerations on possible investigations addressed to better characterise the phenomena involved. Such investigations should integrate numerical modelling, laboratory experiments and monitoring consistently. In particular, the possibility of monitoring deformations and structural lesions, during significant periods, is regarded as the more promising approach for improving knowledge and assessment of long-term damage and its influence on the overall stability of the building.

1 Introduction

Because of their subtle structural design and large dimensions, Gothic Cathedrals are among the historical constructions that eventually may experience important time-dependent phenomena leading to progressive, long-term deterioration. In fact, a significant number of Gothic Cathedrals are today showing severe material and structural disorders even in locations not affected by extraordinary actions such as earthquakes.

Very large deformations can be observed in many Gothic Cathedrals (as well as many other ancient monuments), which are one or more orders of magnitude larger than those which would be expected from the conventional understanding of long-term creep deformation. On the other hand, these large deformations may cause a significant increase in the eccentricity of the load applied at critical points of the building, thus contributing to the gradual intensification of the existing stresses and deterioration. Effects related to the mechanical decay of the material can be observed, such as longitudinal cracking and crushing due to sustained compressive stresses in parts of the construction which, nevertheless, are subject to moderate compression reaching only 30% or an even smaller ratio of the uniaxial compression strength.

All these facts seem affected by elements of a very different nature, although mostly related to the history of the building. Among these effects are the construction sequence, the influence of construction details, the cumulative effect of multiple thermal cycles or multiple low-intensity earthquakes across centuries, and the effect of maintenance and historical repairs.

The present paper reports significant effects (in particular, large deformations, cracks and other possible lesions) observed in various Gothic constructions in Spain (Mallorca, Barcelona, Tarazona Cathedrals, Church of Sta. Maria del Mar, and others). Some considerations are presented on the possible factors generating or influencing such effects and the capacity of up-to-date numerical models to simulate the mechanical processes involved.

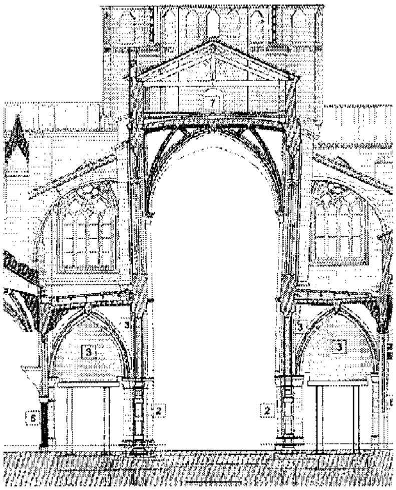
Finally, a discussion is presented on the role of monitoring in the characterisation of long-term damage effects occurring in historical buildings and the requirements to be taken into account in laying out monitoring programmes adequately oriented to the detection of active long-term processes.

2 Observed damage related to historical or long-term processes

The study of some Gothic Cathedrals in Spain, carried out by the authors, has provided evidence for significant historical or long-term phenomena causing different types of material or structural disorders. Among the most significant observed disorders are (1) overall large deformations, (2) cracks in elements subject to compression and (3) large cracks causing separation between different structural components or significant portions of the building (fragmentation). Both types of disorders are briefly discussed in the following paragraphs.

2.1 Large deformation

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 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.



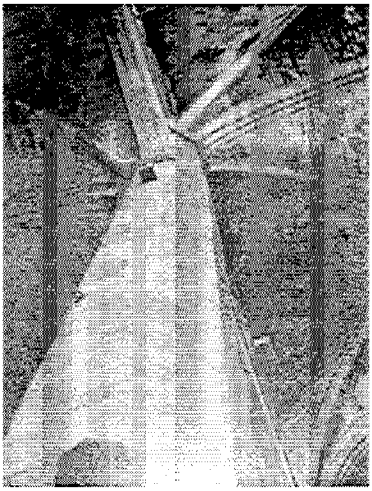


Fig. 1. Deformation of the piers and walls of the nave of Tarazona Cathedral

Fig. 2. Deformation of a pier in Mallorca Cathedral

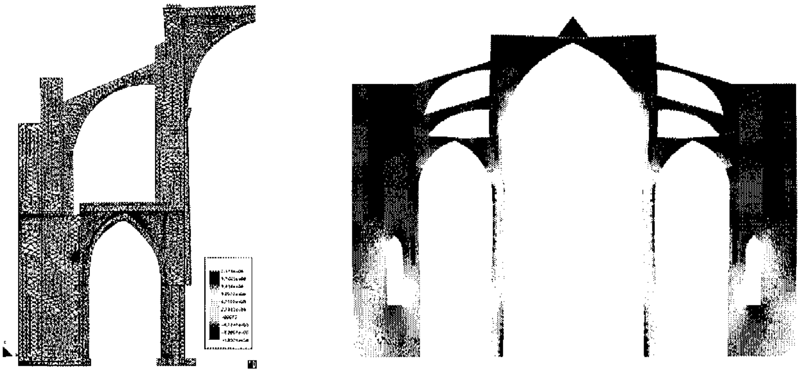


Fig. 3. Numerically predicted deformed shapes of the transverse sections of Tarazona (left) and Mallorca (right) cathedrals subject to gravity load (amplified by 100).

Obviously, these actual deformed shapes have been also determined by many different actions and phenomena occurring during the construction process and also during the long-term, historical life of the building.

It must be noted that, in spite of the quantitative disagreement between the observed and numerically predicted deformations, the corresponding overall shapes are very similar qualitatively (Fig 3); it can be said that part of the historic or long-term actions experienced by the construction produced a certain amplification of the initial deformation caused by gravity load.

Important effects related to deformation can be attributed to construction. On the one hand, construction of historical structures took large periods of time which, in turn, included long stages during which the structure was subject to provisory support conditions; during these intermediate phases, the structure was forced to develop resisting mechanisms not entirely consistent with its final 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.

Even after the completion of the structure, later creep may be partially determined by the initial stress state and initial deformation acquired during intermediate construction phases. Thus, completing the structure may induce a certain constrain on the already initiated creep, causing, in turn, a gradual redistribution of stresses and possible long-term cracking. This late cracking - derived from the construction process- will provide by itself increasing deformability in the long-term.

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. 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.

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2.2 Damage of compressed members

The authors have observed vertical cracking in some of the piers in almost all studied Cathedrals. Vertical cracks and related lesions in piers are particularly significant in Tarazona Cathedral (before the restoration, Fig. 4), Mallorca Cathedral (Fig. 5) and the Basilica of Santa Maria del Mar in Barcelona. In all the above-mentioned buildings, severe cracking appeared in spite of the moderate average compressive stress caused by gravity load.

Fig. 4. Stacked stone blocks from a dismantled pier of Tarazona Cathedral.

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. In tests carried out in the Laboratory of Structural Technology of Universitat Politècnica de Catalunya on specimens made of stacked sandstone blocks with 1 cm mortar joints [1], longitudinal cracks appeared for an applied stress ranging from 30% to 60% of the compression strength of the specimen. As expected, specimens made of larger units showed more tendency to crack under moderate compression. The lesser values of the ratio between the cracking stresses and the compression strength (30%) were obtained for specimens made of large blocks (40×20×20cm), while the larger ratios (60%) were obtained for the specimens with the smaller units (20×10×10 cm, in both cases placed in a horizontal position).

Numerical analyses carried out for gravity load in the cases of naves of Tarazona and Mallorca Cathedral (Fig. 3) did not permit immediate explanation of these cracks, even if the possibility of cracking at reasonably low stress levels was considered. It must be noted that these calculations were carried out on the actual deformed shape of the transverse sections.

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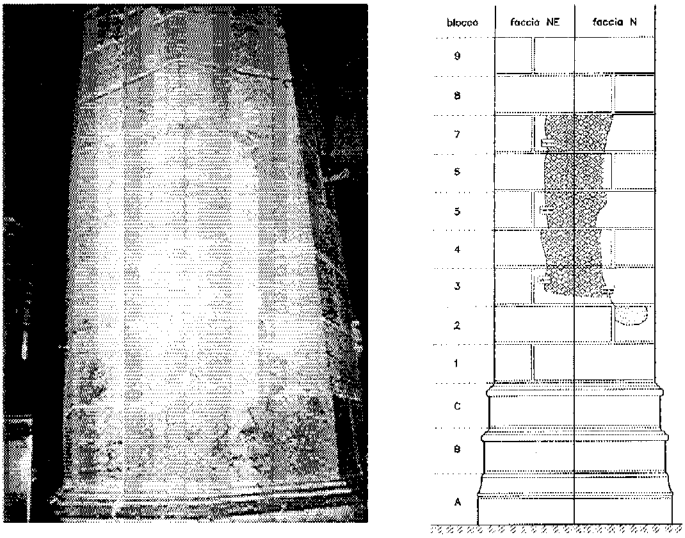

Fig. 5. Cracks shaping a loose wedge along a vertical edge of a pier in Mallorca Cathedral

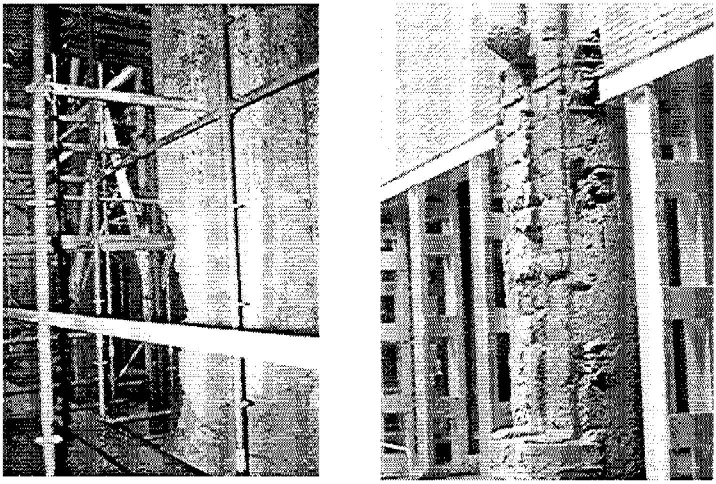

Fig. 6. Physico-chemical deterioration (left) and "thinning" of the section of the piers of Tarazona Cathedral

Table 1 shows the average and maximum compression stresses numerically predicted at the base of the piers. This table also provides the average compression strength of the stone, measured experimentally, and the compression strength of the masonry, estimated by means of empirical criteria (such as the formulae provided by Eurocode 6) These values should be considered only as a first approach given the large heterogeneity of the existing materials.

Table 1 – Values of compression stress compared to strength limits (N/mm^2)

	Tarazona[2]	Mallorca[3]
Compression strength (stone unit)	20	30[4]
Compression strength, estimated (masonry)	6	10
Average compression stress	1,5	2,4
Maximum compression strength	1,8	4,2

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 propose of the study of recent collapses (Papa and Taliercio [5], Binda, et al. [6]), 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., 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. Actions other than dead load may also contribute to long-term damage and couple sinergically with the effect of creep.

As already mentioned, the construction process (and the construction techniques used) may induce mid-term or long-term effects. Aspects such as the construction sequence, the duration of the construction, or the use and removal of scaffoldings and other auxiliary elements, may influence on the later behaviour of the overall building and even cause deferred lesions or other structural disorders. A specific aspect may be found in the use of small wooden wedges as a device to sustain the stone units in their position while the mortar had not yet hardened, which, in some cases (as, again, in Mallorca Cathedral) produced high concentration of stresses leading to the deterioration of the external face of the stone (Fig. 7, center).

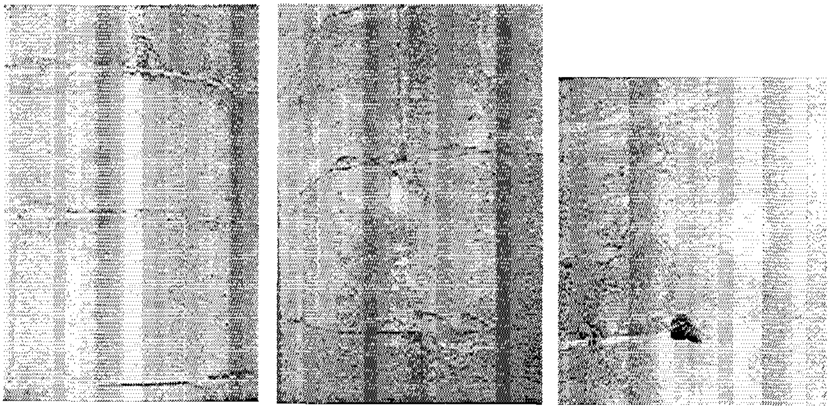

Fig. 7. Causes of deterioration of stone in piers (Mallorca Cathedral): cracks due to local disappearance of mortar (left); deterioration of stone edges due to embedded wooden wedges used in construction (centre); crack caused by a rigid insertion (right).

Repeated occurrences of extraordinary actions such as earthquakes or hurricane-force wind, even if moderate in intensity, also contribute with irreversible, cumulative effects. Such actions may cause dramatic, increases of the eccentricity of the applied vertical forces at the base of the piers; in turn, this will cause additional vertical cracking or other effects associated to the increased maximum compression stresses.

Historical anthropic actions may be very significant at causing additional damage. In some cases, large operations undertaken during the life of the construction for purposes not related to the structure may cause a significant alteration of the geometry of the piers or other structural members (as the "thinning" of the piers of Tarazona Cathedral to gain space for a timber choir, Fig. 6, right); in other cases, small, apparently inoffensive actions, may reveal potentially damaging after some time (as the insertion of iron or wooden devices in compressed members, for ornamental or liturgical purposes, Fig. 7, right). On the other hand, lack of maintenance or inadequate historical repairs may contribute as well to the accelerate deterioration of the building.

Decay of stone or mortar due to chemical attack (as observed at the base of the piers of Tarazona Cathedral, Fig. 6, left), may couple sinergically with mechanical effects related to sustained compression forces and thus cause accelerated deterioration.

Initial minor construction or material defects –as the loss of a portion of mortar, in Fig. 7, left- may cause the initiation of cracks in zones subject to significant compression.

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2.3 Fragmentation

Division 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. Such settlements may induce the separation of parts, the enlargement of existing cracks or the opening of construction joints.

Similar effects may be caused by thermal environmental actions. Large cracks affecting walls or roof elements 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 (Fig. 8, right), and Mallorca Cathedral, whether wide discontinuities are observed between some of the transverse arches and the vaults of the nave (Fig. 8, left). Unlike soil settlements, which tend to mitigate with time as the soil consolidates, temperature cycles are always acting and my cause indefinitely cumulating damage through their multiple repetition.

3 The role of monitoring

Characterising long-term damage is, by any means, a challenging task due to the slowness of the processes involved and the fact that they may be masked by more apparent, short-term variations caused by present actions. Characterising it is also difficult due to the multitude of very different actions (as mentioned in the above paragraphs) which may contribute to its initiation and propagation throughout the history of the building.

Fig. 8. Cracks developed in the junction between arch and vault (Mallorca Catehdral, left.) and in a construction joint (Girona Cathedral, right)

Any attempt to assess increasing, long-term damage should be based on a comprehensive approach integrating historical information, detailed inspection,

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laboratory and in-situ experiments, detailed monitoring and accurate structural analysis. In particular, monitoring may allow for the recognition of incremental processes in a term reasonable for engineering purposes and thus provide information useful for the study and restoration of ancient constructions.

In order to characterise incremental, long-term processes, monitoring must be designed to allow a clear distinction between the reversible or cyclic components of the parameters measured, on the one hand, and their irreversible, cumulative components, on the other hand. In turn, the possibility of recognising both types of components demands the following requirements:

Monitoring must be extended to a period long enough to cover the entire duration of acting cyclic actions; since annual variations of temperature must be considered in any case, the minimum acceptable period is a complete year. Additional years will be of value to confirm the tendencies observed and appraise their possible evolution in the long term.

Monitoring must afford the characterisation of the environmental actions occurring during the studied period. This is particularly so in the case of the climate environmental actions; parameters such as the temperature and the humidity are to be measured at different stations in both the interior and the exterior of the building. Wind velocity and direction may be characterised by means of conventional measuring devices. Similarly, valuable information can be obtained if the effect of occurring low-intensity earthquakes or environmental vibrations is recorded by means of accelerometers placed at critical points across the structure.

An accurate numerical model must be available to interpret the results and correlate the causes identified (the measures related to the actions) with their effects (the deformations or displacements measured at different critical points of the building) in light of some hypotheses on the configuration and condition of the structure. A identification process can then be carried out by adequately modifying such hypotheses until attaining a satisfactory coincidence between the numerical predictions and the measurements.

Ideally, the numerical model used should be able to simulate most of the present or historical actions having affected the construction; it should also permit sequential analysis to simulate the construction process and the latter possible structural alterations or repairs. Having specific constitutive equations available for long-term creep of masonry or stone-like materials, such as the one proposed by Papa and Taliercio [5], is of utmost importance for the purpose here referred.

4 Final remarks

Historical constructions frequently show a variety of structural alterations developing gradually throughout historical periods of time. These alterations – including large deformation and cracking of compressed members subject to moderate compression- are caused by the combined effect of the long-term creep of the materials, cyclic environmental actions, repeated extraordinary actions, and are influenced by historical facts related to construction, utilisation and maintenance.

Monitoring can be used to detect possible active processes causing cumulative damage or deformation after a certain period of time. However, characterising long-term damage requires a more comprehensive approach based also on history, inspection, experiments and structural analysis. A more accurate understanding of the phenomena involved, stemming from analytical and experimental research, is also needed.

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