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Medieval Walls System Against Earthquakes Types: Structural Model and Qualitative Aspects

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ABSTRACT : The present survey of the structural skeletons of Spanish Gothic cathedrals found that Medieval builders erected anti-earthquake wall systems that have gone largely unnoticed to date.

The earthquakes that affected Europe during the Middle Ages when Gothic cathedrals were being built obliged master builders to change the French structural and building model to enhance stability. They therefore included anti-earthquake systems in their structures, consisting in a series of orthogonal stone walls and spandrel arches located over the vaults, creating a system of individual cells that behaves like a stiff frame. Taken as a whole, these stone cells tie the entire mass of the cathedral together by inter-connecting all the structural members: columns, piers, buttresses and flying buttresses.

Such anti-earthquake wall systems and all the specifics on their interconnections should be included in the structural models used to analyze cathedrals.

1 SPANDRELED CATHEDRALS

An earlier, unprecedented analysis of Spanish cathedrals led to their classification by structural and construction types (Casinello 2003). Further to that classification, Spanish cathedrals were divided into two main groups: “spandreled” and “non-spandreled”.

Spain’s Gothic legacy, among Europe’s finest, is the only one to exhibit many different kinds of structural skeletons. The reason for this variety is to be found in the differences in the seismic history of its various regions. Indeed, Spain is regarded to be a seismic hazard area, even though seismic activity is lower than in Italy or Greece. In the Middle Ages when Gothic cathedrals were being built, Spain was afflicted by more than 58 major earthquakes and tsunamis. The regions of the country where seismic activity has been historically greatest are Catalonia in the northeast and Andalusia in the south. The city of Almeria, for instance, nearly vanished under a tidal wave in 1522. By contrast, seismic risk in Galicia in the northwest and Castile in the centre is low. Significantly, spandrels have been found to form an important part of the structures of all Spanish cathedrals built in Andalusia and Catalonia, but in none built in Galicia or Castile.

Similarly, seismic risk is low in France, the birthplace of Gothic cathedrals, with the exception of only one small region, namely the Pyrenees Mountains. Unsurprisingly, then, the country’s most prominent Gothic cathedrals were built in regions where seismic hazard was not a concern. Consequently, Medieval masters building cathedrals in Andalusia and Catalonia were obliged to forsake the French model to ensure that their structures would withstand the dynamic forces unleashed by earthquakes. Indeed, several generations of master builders were eyewitnesses t to the dramatic consequences of earthquakes in Spain. The changes they consequently introduced in what is referred to here as “spandreled” cathedrals affected geometric shape and masonry design as well as the structural skeleton, which was reinforced with an anti-earthquake wall system. These characteristics are an indication that Gothic cathedrals were built to rational seismic criteria.

1.1 Geometric Shape

The first change that Medieval masters introduced to make cathedrals more earthquake-resistant affected their geometric shape. Cruciform structures gave way to rectangular shapes in spandreled cathedrals, which are compact symmetrical boxes with no wings on the sides. This layout is more earthquake-resistant than in buildings with wings, where multidirectional vibrations cause stress to concentrate at the corners. And the fact is that all Spanish cathedrals built in areas where seismic hazard is low such as Leon, Burgos or Palencia in the centre of the peninsula, are cruciform, whereas those in areas where such risk is high are rectangular: Seville, Almeria, Santa María del Mar, Girona and Palma de Majorca.

Moreover, the stability of the box shape is reinforced by the positioning of the buttresses. While in non-spandreled cathedrals the buttresses are essentially located outside the perimeter of the building – in an arrangement reminiscent of the backbone of a fish or a comb – in spandrel temples the buttresses spring from inside the cathedral, increasing the strength and compactness of the stone skeleton as a whole. In some cases the buttresses are found at a higher position on lateral naves or vaulted chapels, but they always spring from inside the cathedral and are thus interconnected by the lateral spandrel vault around the entire perimeter of the structure. Such an arrangement also lowers the risk of buckling and bending by reducing the total height. These significant differences in geometric shape and buttress position are clearly illustrated in the comparison of Burgos and Seville Cathedrals given in Fig. 1.

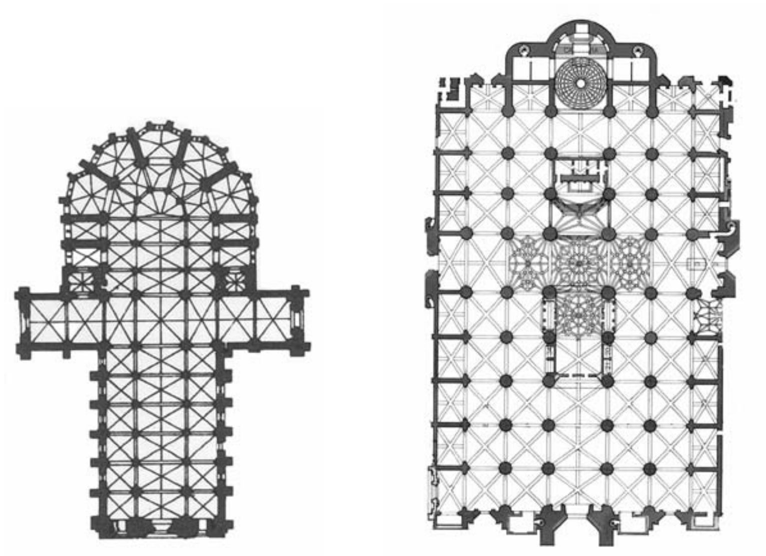

Figure 1 : Left: cruciform, non-spandreled Burgos Cathedral. Right: rectangular, spandreled Seville Cathedral

1.2 Masonry design

The second major difference between the two approaches is to be found in the masonry design.

The high sloping roofs of the French model were replaced either by flat roofs resting directly on the vault extrados or no roof per se at all, but simply a course of stone or fired clay material (10 to 12 cm thick) laid over the stone vault, such as in the central nave on Seville Cathedral. Such solutions – flat or non-existing roofs – are more earthquake-resistant than slanted roofs for they eliminate the enormous thrust transmitted by the latter to the top of the walls. Significantly, every single spandrel cathedral in northeastern and southern Spain has a flat roof, despite the substantial differences in climate, particularly as regards rainfall. What the two regions do have in common, however, is their high seismic risk. These flat roofs were built in different ways and there may very possibly be some that have gone unidentified because they are concealed beneath the deck tile. In most of the cases studied to date, they consist of an outer course of tile laid on a fill of several layers of lime mortar containing fragments of hollow earthenware. This fill rests on the extrados and was laid in various ways, usually over the entire vault. But on occasion, as in the first lateral nave of Seville Cathedral, it was – very skilfully – built over four cone-shaped brick vaults previously erected on the four corners and along the diagonal rib of the extrados of a stone fan vault which is visible from inside the Cathedral. These secondary structures rest directly on the main vault itself and support part of the flat roof, leaving a hollow space over the haunches of the stone vault. This ingenious arrangement concentrated more weight on the keystone, the most effective manner of stabilizing ogival stone vaults (Cassinello 1998).

Elongated stone blocks ranging from 15 to 20 cm thick and a 3- to 6-cm layer of lime mortar were used to build Gothic vaults in both spandreled and non-spandreled cathedrals. Nonetheless, as discussed above, in spandreled temples the structural behaviour of such vaults is very different due to the masonry design for the flat roof and the mortar cover over the stone vault. In other words, structural modelling that fails to take these specific arrangements and their distinctly different structural behaviour into account would lead to erroneous results. The vaults in spandreled cathedrals, being much heavier, generate much greater thrust. The total weight borne by the spandrel vaults with flat roofs in Almería, Santa María del Mar and Seville Cathedrals comes to 10 - 18 kN/m2, whereas in non-spandreled cathedrals such as in Leon, Burgos and Salamanca in central Spain, these vaults bear from 6 to 9 kN/m2 (Fig. 2).

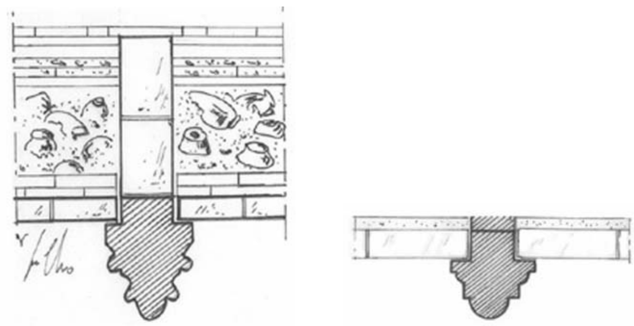

Figure 2 : Cross-sections of spandrel and non-spandrel Gothic vaults.

In addition, in Spanish regions such as the Balearic Isles and Catalonia where seismic hazard has been historically high, Medieval masters used a special type of mortar joint. In this type of joint, called "abeurador" in Spanish, narrow channels (1 to 2 cm wide) were carved into the mortar surface of the stone to create a "hidden mortar joint". These channels were cut orthogonally to the direction of the main compression force and frequently used in arches and piers. The *abeurador* was shaped much like the veins in a leaf or a fish bone, i.e., with a main central channel and a number of secondary channels of different lengths branching out symmetrically on both sides. Two different versions of these joints were used in arches and piers. One was carved across the middle of the mortar surface of the stone blocks and the other on the side, like a cramp (Fig. 3). Such hidden joints increase arch and column stability thanks to the friction between stone blocks generated by the channels or cramps, contributing to the ability of the structure to withstand the horizontal dynamic forces unleashed by earthquakes. The Greeks used iron cramps or rods to interconnect stone blocks and thus prevent their dislocation in the event of an earthquake. Similarly, some Medieval masters used hidden carved channels or cramps filled with lime mortar to enhance anti-earthquake resistance, which achieved the same effect without rust-mediated weakening. On the contrary, the strength of such joints grows over time, for lime hardens as carbonation advances.

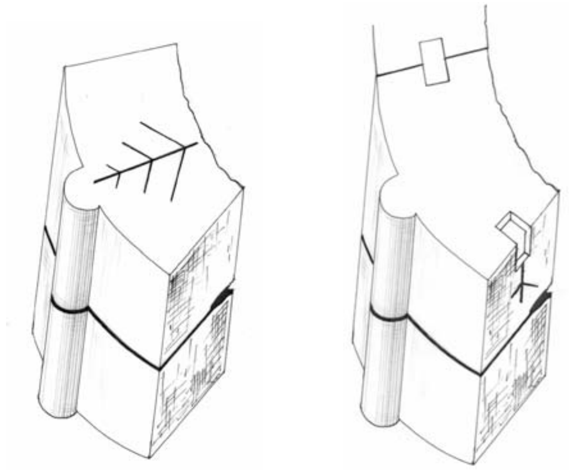

Figure 3 : Types of *abeurador* mortar joints: *abeurador*, cramp-*abeurador*

1.3 Medieval anti-earthquake wall systems

The structural skeleton of spandreled cathedrals is distinctly different from the structure in non-spandreled temples. The large orthogonal walls of the former can absorb the dynamic forces generated by earthquakes, and quite effectively, for they have successfully withstood several seismic events since they were built. This Medieval anti-earthquake system ties the entire stone mass of the cathedral together by inter-connecting its structural members. Nonetheless, all the vaults were built independently, with the space occupied skilfully delimited by a rigid framework consisting in intersecting stone spandrels. Such stone walls or spandrels have often been hidden under flat roofs since they were first built, such as in Almería and Seville Cathedrals. This invisibility, together with the lack of any analysis of the structure as a whole and the absence of contemporary written records on such questions, may explain why Medieval anti-earthquake wall systems have gone largely unnoticed. A second key explanation is that there are no such systems in the most famous French Gothic cathedrals, regarded to be the quintessential model for this style of architecture.

The classifications established to date based on the number of naves, existence or otherwise of flying buttresses and so on, while addressing important issues, do not accurately cover and define all the types of stability models used by Medieval masters in Spain.

The first and most important structural characteristic that differentiates the stone skeleton of spandreled from non-spandreled cathedrals is that the former were built with spandrel arches. In other words, in such temples the only non-spandrel arches are the diagonal arches in the vaults, which form single units across their respective intersections. Conversely, there are many arches without spandrels in non-spandreled cathedrals: examples can be found in the central naves of all the cathedrals in low seismic regions, such as Leon and Burgos Cathedrals in central Spain. The vaults of spandreled cathedrals were built on the four stone spandrel arches of the vault – formerets and transverses – forming a stiff orthogonal frame. Such structural members – like a rigid stone cell – form an orthogonal wall system that ties the entire cathedral together. This makes each vault independent inside its stone cell, while its spandrel arches – stone walls – are continuous in two perpendicular directions, interconnecting all the other structural members: columns, piers, buttresses and flying buttresses. The use of independent vaults delimited by a rigid framework is an ingenious way to accommodate deformation on their rigid ribs without transmitting the thrust from dynamic forces (earthquakes) to the other vaults of the Cathedral. This structural design is very different from the design of non-spandreled structures such as Leon Cathedral (Fig. 4). There, inasmuch as the central nave vaults are continuous because they were built with non-spandrel arches, only the central transept was built with spandrels.

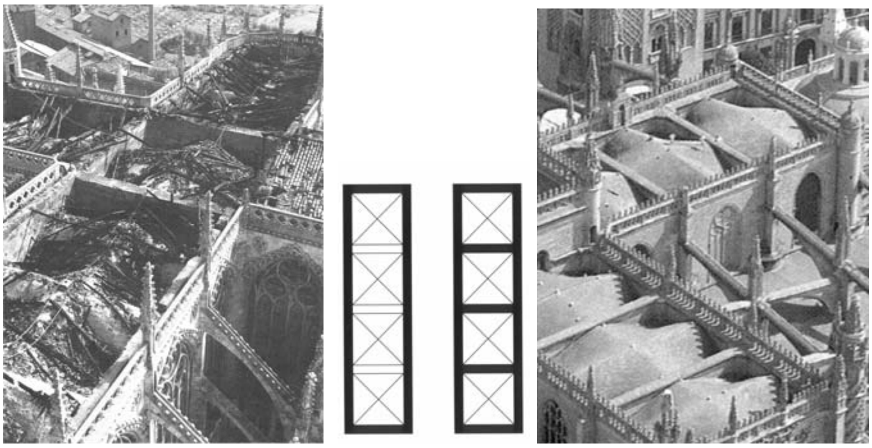

Figure 4 : Central nave vaults with and without spandrels in Leon (left) and Seville (right) Cathedrals

The anti-earthquake stone wall system that ties the entire mass of a spandrel cathedral together intersects at the piers (Fig. 5).

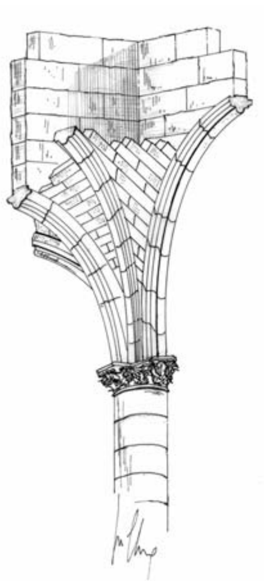

Figure 5 : Vault spandrel arches on the pier

Finally, since the mechanical behaviour of Gothic cathedrals is based on how thrust is generated and offset, six different types of Medieval anti-earthquake wall system components can be defined on the basis of the different ways these structural members are interconnected (Fig. 6). Type I, which can be found in single nave cathedrals, such as in Girona, is based on the spatial unity between the buttress and the spandrel over the transverse arch in the vault. All the stone rib walls, B, extend across the entire width of the cathedral. Type II can be seen in the central nave of cathedrals with three or five naves of different heights, such as in Palma de Majorca, Barcelona and Seville. The flying buttresses, integrated into the rigid framework delimiting the vaults, acquire a new structural function. Type III is found in the intersection between the lateral naves and the flying buttresses, such as in Seville Cathedral, where the enormous weight of the pinnacle increases the stability of the spandrel-bearing pier by compressing only the only the joint in the transverse stone block at the abutment between four flying buttresses. Type IV is a stone rib wall that does not extend across the entire width of the cathedral, but is connected to the pier of the next lateral nave by the spandrel arch.

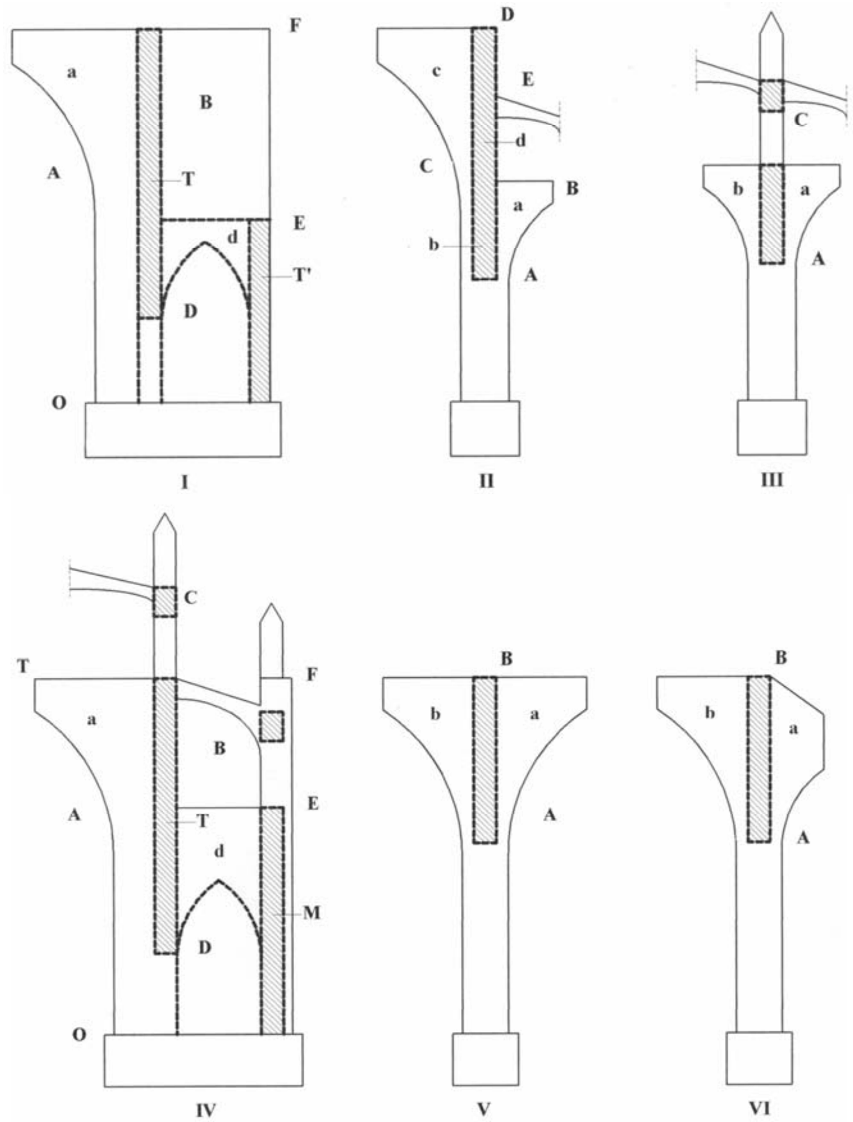

Figure 6 : Types of Medieval anti-earthquake wall systems

Type V is found at the intersections of naves of the same height, such as in Almeria Cathedral. This is the most rigid and simplest type of Medieval anti-earthquake wall system, consisting merely of the intersection of orthogonal spandrels at the same elevation that connect buttresses and piers. In Type VI, a variation on Type V, the spandrels are triangular in shape and notched to angle around the roof, for they extend above it. Such members are found in Santa María del Mar Church. Each type of anti-earthquake wall system is tied to a different degree, but the key characteristic common to them all is that they are joined in two orthogonal directions generated by the intersection of the spandrel arches in their vaults. Spandreled cathedrals were built by combining such types of wall systems and ties. Although more than 100 metres long in some cases (Seville Cathedral), since they never used expansion joints, structural members such as columns, piers, spandrels, and buttresses never had to be duplicated. The masonry design sufficed.

2 STRUCTURAL MODEL

Many important structural aspects of Gothic cathedrals, most of which are associated with the Medieval anti-earthquake wall system, have up to now been omitted from the structural model for these temples. First, there is the existence itself of such systems. Second, spandreled cathedrals were built with spandrel arches; third, there is the evidence provided by differential joints such as the *abeurador*; and last but not least Medieval masters built anti-earthquake systems similar to what we now know as “strong column, weak beam” design, but using a strong buttress, spandrel and pier / weak vault severy approach, in which the vault ribs constitute rigid and independent ties for each vault.

The spandrel arch is the key to understanding the difference in mechanical behaviour patterns between these cathedrals and the temples built in low seismic risk areas. In spandreled cathedrals the orthogonal spandrel arches are prevented from bending along their planes by stone walls (spandrels) and as there is no possible crack mechanism, the thrust on the spandrel arches may be increased to the ultimate strength of the stone. This means that spandreled cathedrals are much more stable than those without spandrels, with respect not only to supporting their own weight but also to withstanding dynamic wind and earthquake forces.

In another vein, the adaptation of plastic theory to masonry architecture is presently a well known approach to structural analysis. Pursuant to Coulomb’s theory, where equilibrium is reached, the structural skeleton can be regarded to be safe. Since stone masonry strength is low in terms of self-weight, the stability of Gothic cathedrals depends on their geometry. Moreover, in light of the importance of retaining geometric shape over time, stability depends on the unions between the stone blocks. In other words, the retention or otherwise of cathedral shape and the establishment of equilibrium in the event of an earthquake depends on the masonry design. The inference is that the distinctive type of mortar joint and the system of interconnections built into spandreled cathedrals must be included in the structural model.

Medieval masters built stone members more or less rigidly depending on their structural role in the cathedral as a whole and the prevailing seismic hazard. This was achieved with different mortar thicknesses in cathedral joints, using thin layers of joint mortar in the masonry of the structural members that formed a part of the anti-earthquake wall system, while other structural members such as the vault severies had thick layers of mortar. This was the basis for what may be referred to as a “strong buttress, spandrel and pier / weak vault severy” anti-earthquake system. In the absence of data, an experimental test programme was conducted at the INTEMAC Central Laboratory to determine the possible range of variability in Medieval masonry deformability based on the variability of the mortar thickness in structural members in Spanish Gothic cathedrals. The aim was to verify whether such anti-earthquake structural behaviour actually existed, qualitatively speaking. The results obtained showed that it actually did and, as Eduardo Torroja (Torroja 1960) noted, joint mortar thickness has a decisive effect on the structural behaviour of masonry. Modulus of deformation values ranged from 169.7 to 5,632.7 N/mm2 at joint mortar thicknesses of from 17.00 to 5.50 mm. A more rigorous understanding of cathedral structural behaviour depends on the inclusion of this pattern of structural behaviour in the structural model by means of parametric sensitivity analysis.

As noted above, Coulomb’s rupture analysis applied by Heyman over the last few decades (Heyman 1966) is the most suitable method for analyzing the stability of heritage masonry structures. The structural model must, however, also reproduce the geometric shape and masonry design. Moreover, the ongoing deterioration of the stone in cathedrals and heritage masonry monuments in general is indicative of a growing need for a better understanding of the stress to which the material is subjected. Stability analyses must always be conducted. Moreover, inasmuch as the finite element method – FEM –, which has been developing rapidly in recent years (Macchi 1993, Brencich 1998, Casolo 2004), can now be implemented with anisotropic, three-dimensional, non-linear elements of deformation and crack modelling, sensitivity studies can be conducted for highly determinant parameters such as the modulus of deformation. This makes it an effective tool for gaining greater insight into structural behaviour and stress distribution, providing the results are rigorously compared with the realities observed in the masonry structure (Melli 2005).

3 CONCLUSIONS

All the various methods presently in place for analyzing the structure of historical constructions are seeking ways to improve. The structural model for masonry heritage would appear to be in need of a more rigorous definition to make the most of these analytical methods.

To date, spandreled Gothic cathedrals have been analyzed without considering their anti-earthquake wall system or the range of deformability based on the differences in mortar thicknesses in their joints. Such cathedrals follow a specific "strong buttress, weak vault severy" structural pattern which must be included in the structural model. It may be reasonably assumed that many unknown construction characteristics and jointing systems, such as discovered in this type of cathedral, exist in other masonry heritage monuments. Structural models must, then, be exhaustively defined before proceeding to analysis.

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