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ONE CENTURY OF STUDIES FOR THE PRESERVATION OF ONE OF THE LARGEST CATHEDRALS WORLDWIDE: A REVIEW

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ABSTRACT

Mallorca cathedral is one of the largest ever built cathedrals in the world. When compared with all other Gothic cathedrals in the world, it is found that its columns have the highest slenderness ratio, its main nave span is the second longest after Girona cathedral, and its main nave is the third highest after those of Beauvais and Milan cathedrals. The preservation of the cathedral was always of concern due to its audacious dimensions and slender structural members. About one century ago, a pioneering structural assessment was carried out by Rubió. Since then, and up to date, a relevant number of studies have been carried out on this cathedral and covered many aspects such as the history of construction, the characterization of the construction materials, the seismic assessment, the static and the dynamic monitoring, and the investigation of the foundation soil, among others. The objective of this article is to review these studies making focus on their main conclusions that are relevant for future studies on the cathedral and other similar historical structures.

KEYWORDS: Mallorca cathedral, Inspection, Dynamic Identification, Dynamic monitoring, Static monitoring, Structural assessment, Geophysical techniques, Seismic assessment.

1. INTRODUCTION

Mallorca cathedral is considered the crown of the Gothic architecture. The studies oriented to understand its construction, structural behavior and seismic safety started about one century ago. In 1912, Rubio, a famous Catalan architect, carried out a structural assessment using the graphic-static method to understand the path of gravity loads from the dead weights over the vaults to the columns and buttresses foundations. This was a pioneering study at that time because of the application of such technique to a large challenging structure like Mallorca cathedral.

The studies continued since that time until today. A very detailed historical study was carried out and revealed a lot of details regarding the construction process by Domenge (1995a, 1995b, 1997). This helped in investigating many other aspects related to the cathedral, Figure 1. The studies can be classified into inspection, structural assessment and monitoring. The inspection included the visual inspection and documentation of cracking and deformations. The vertical supporting elements of the columns, the walls and the buttresses were inspected using geophysical techniques. Samples from stone and mortar were chemically analyzed to reveal its composition. In 2005 and 2010 dynamic identification tests were carried out to obtain the modal parameters of the cathedral. The foundation soil was subjected to a detailed inspection by boreholes and near-surface geophysical techniques.

In the structural assessment studies, several techniques were employed including simple ones like graphic-static and limit analysis and more advanced ones like nonlinear static (pushover) analysis on 2D and 3D models of the cathedral.

Monitoring was also exploited. Static monitoring of cracks, inclinations, environmental actions (temperature, humidity and wind) was carried out. Dynamic monitoring was carried out and the effects of captured earthquakes on the behavior of the cathedral were investigated.

It can be said that it is extremely rare to find a historical structure that has been subjected to these large number of studies. Therefore, this paper aims at presenting a review of all these studies.

2. CONSTRUCTION, FAILURES AND RECONSTRUCTION

Mallorca cathedral is a Gothic construction built during XIV to XVI century, Figure 2. It is in the island of Mallorca, Spain. Since 1931, the cathedral is classified as Cultural Heritage of National Interest. Comprehensive historical research has been already carried out based on the analysis of ancient docu-

ments available in the files of the cathedral's Chapter and can be referred at Domenge (1995a, 1995b, 1997) which is the base of the following information. Along the three centuries of construction, the cathedral structure passed by a number of distinctive phases. The construction history of Mallorca cathedral can be divided into five phases: (a) from 1300 to 1370; (b) from 1370 to 1601; (c) from 1601 to 1851; (d) from 1851 to 1888 and (e) from 1888 to today.

About the year 1300 the construction of the cathedral started. The financial support was given by the king Jaume II who left an important legacy in his testament for the construction of the Trinity chapel, part 1 in Figure 3. From 1311 to 1330, the works of the following body of the apse named the Real chapel, was concluded, part 2 in Figure 3. By the end of the year 1370, six lateral chapels were built; three on the south side and three on the north side of the cathedral, part 3 in Figure 3.

The second period extended from 1370 to 1601. In this period the full construction of the cathedral was carried out. The cathedral Chapter was the one who decided to build the main nave with its magnificent dimensions (Llompart, 1995). In the year 1374, the first bay of the nave was constructed, part 4 in Figure 3. The second bay of the nave was concluded by the year 1385 in addition to the construction of two lateral chapels, part 5 in Figure 3. By the end of the XIV century, the work concentrated in the construction of the west entrance and the adjacent chapel, part 6 in Figure 3. Around 1406, the third bay and two lateral chapels at the north side were built, part 7 in Figure 3. The fourth bay was finalized by the mid of the XV century, part 8 in Figure 3. The fifth bay had some difficulties during its construction due to the increase in the span and was concluded around 1560. By that year also, three chapels on each side were built, part 9 in Figure 3. In the next thirty years, the remaining three bays of the nave (part 10 in Figure 3) were rapidly concluded. The full construction of the cathedral was concluded by the construction of the west façade, part 11 in Figure 3, around the year 1601. It can be noticed from the construction sequence that the lateral chapels' construction was always in advance to the naves' construction because of the funding provided by noble families or corporations willing them as pantheons or gremial chapels. Also the long period of interruption in the construction from 1450 to 1560 is noticeable.

The third period can be called the reconstruction period. The first structural problem started in 1639 and the last important dismantlement was for the west façade in 1851. Thereby, this period lasted from 1639 to 1851. In this period, many parts of the cathedral failed or manifested critical cracking so that it was decided to dismantle and rebuilt it again. In the

17th century, some of the vaults and arches collapsed and were reconstructed. The earthquake of March 18th, 1660 resulted directly in the failure of two arches and initiated the out-of-plumb overturning of the west façade. In the 18th century, some vaults suffered from severe cracking and large deformations, furthermore some of them collapsed, therefore, they were reconstructed. In addition, six flying arches were propped. In Roca and González (2001) a discussion is given about possible reasons of this intervention and the real necessity of it. Till the mid of the 19th century, the main concern was about the west façade only and other structural elements didn't show any collapses. The out-of-plumb of the west façade increased from 80 cm near the mid of the 17th century to 90 cm at the beginning of the 19th and reached a very alarming value of 130 cm and it

was essential to demolish it. The earthquake of 1851 affected the already deteriorated west façade.

The fourth period extended from 1851 to 1888 and was mainly focused in the dismantling and reconstructing the west façade. The new façade had a flamboyant neo-Gothic style and was very different from the old façade and also from the rest of the cathedral, Figure 4. The buttresses' sections were significantly increased with respect to the former ones. The reconstruction works finished in 1888.

The fifth period from 1888 till today included a series of interventions. During the last decades, Mallorca cathedral has been subjected to continuous repair and maintenance works. The west and south façades were restored about ten years ago (CPA, 2003a; CPA, 2003b), and recently Herráez (2012) carried out visual inspection and documentation to the current state of these two façades.

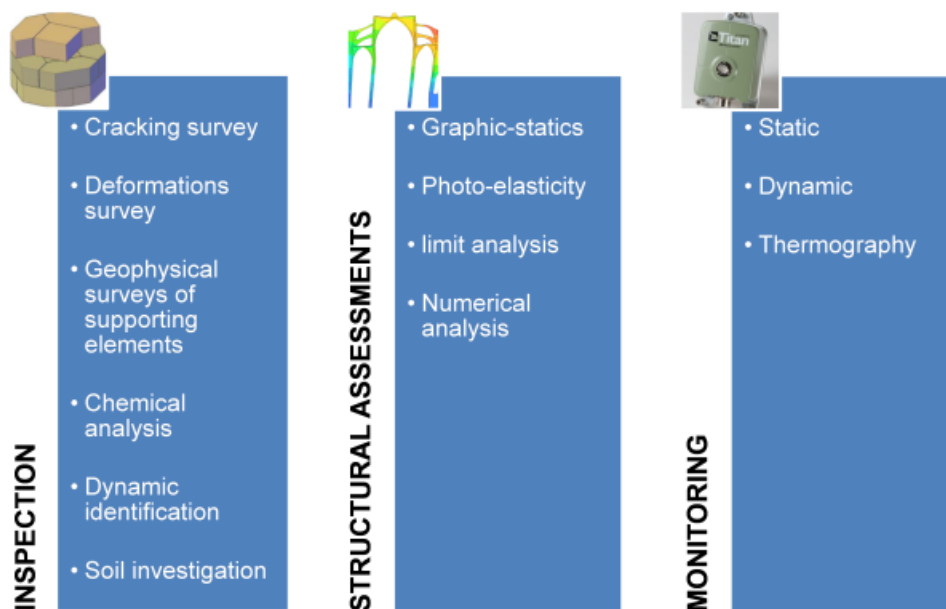


Figure 1. Studies carried out on Mallorca Cathedral.



Figure 2. Mallorca Cathedral: external view showing the apse area and the south façade.

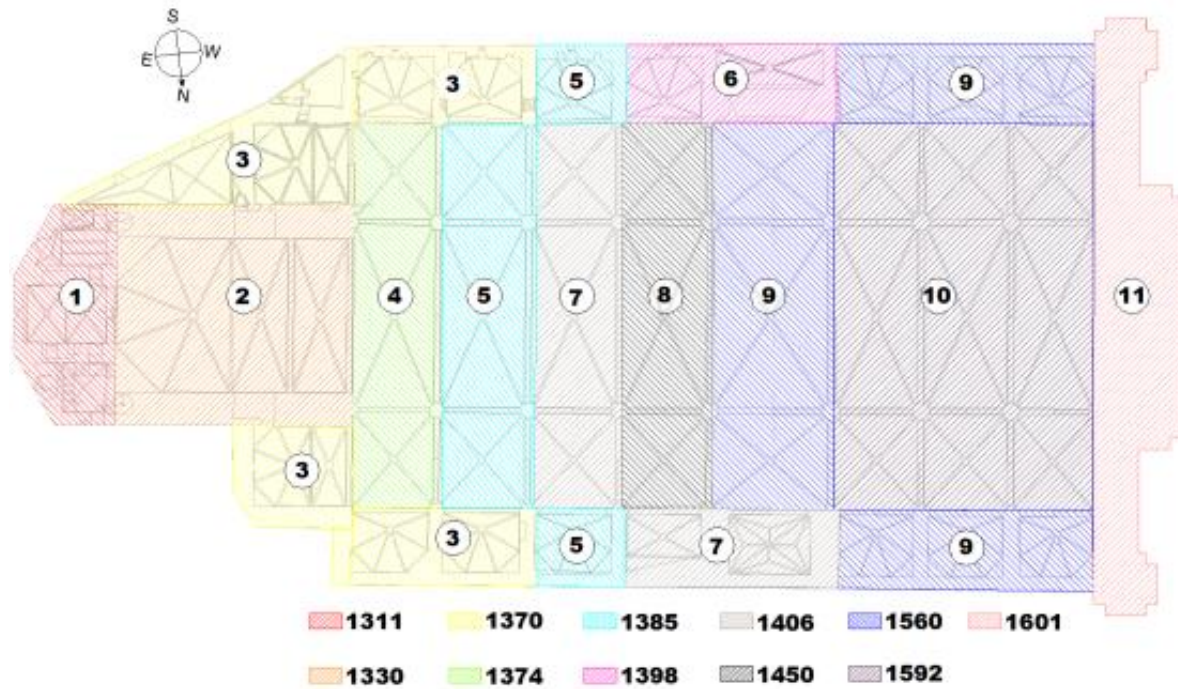


Figure 3. Plan showing the progress of Mallorca cathedral construction from 1306 to 1601. The indicated years are for the approximate end of the construction of each part (Elyamani, 2015).

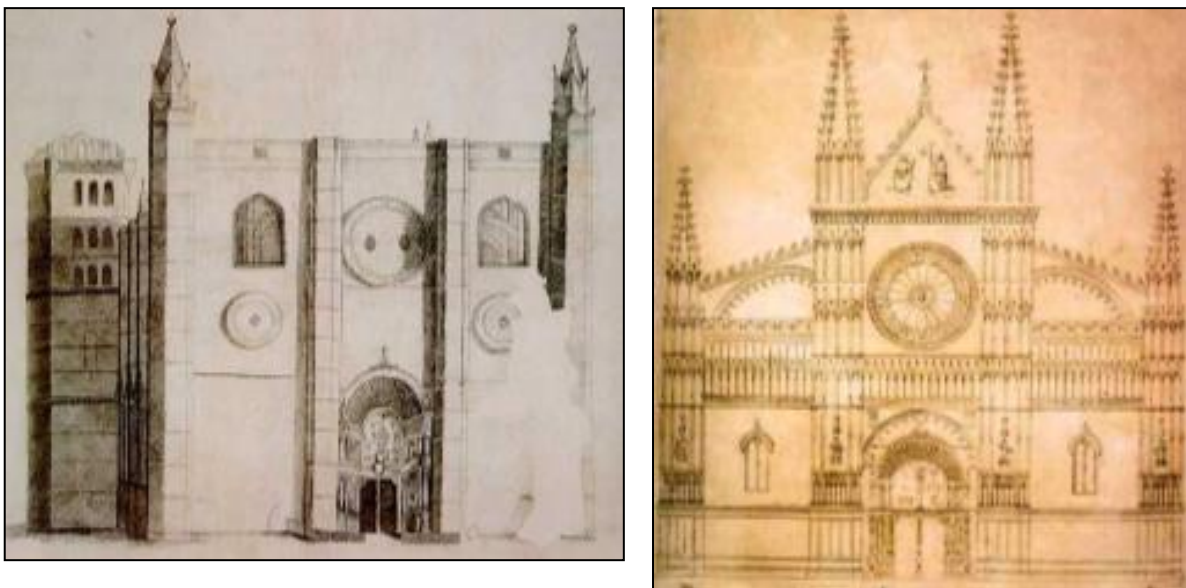


Figure 4. The west façade: comparison between the original façade (left) and the new façade of Baptist (right).

3. DESCRIPTION

This part is based on Roca (2001; 2004) and Roca and Lodos (2001). To a large extent, the cathedral of Mallorca is a Gothic cathedral. Nonetheless, it has some Renaissance characteristic, because the works began in the XIV century and finalized in the heat of the Renaissance period. The plan and the longitudinal section (Figure 5) show two distinct bodies. The first body is formed by the main nave and the second body includes the choir and the surrounding

chapels. The first body includes a central and two lateral naves. This body is flanked by eight powerful buttresses lodging between the lateral chapels. The second body includes the Royal chapel, a single nave imposing Gothic construction by itself, and the smaller Trinity Chapel. The length of the nave of the main body is of 77m and is distributed across seven bays. The width covered by the naves is of 35.3 m, of which 8.75x2 m are spanned by the two lateral naves and 17.8 m by the central nave.

The lateral naves are covered by pointed vaults of simple square plan; whereas, in the central nave they are of double square plan. This scheme is repeated both in all the bays of the naves except in the 5th one (from the choir), due to the presence of lateral doors. In this bay, the longitudinal span of the vaults is slightly longer. The height reached by the vaults in their highest point (the key of the transverse arches) is of 43.95 m.

The cathedral of Mallorca is also unique in being the Gothic cathedral with the highest lateral naves (29.4m). All of the octagonal columns have a circumscribed diameter of 1.7m except those of the first three bays from the east façade that have a slightly lesser value of 1.6m. The singularity of the building becomes more patent when its cross section is compared with the ones of other Gothic cathedrals, Table 1. Some internal views are shown in Figure 6 for naves, vaults and clerestory.

The transverse arches of both the lateral and central naves are diaphragmatic, meaning that they are provided with masonry spandrels wall filling all the space to the key height. The vaults are filled just

with a light structure composed of slender stone wallets and slabs. The structure of the cross section is complemented with significant additional weight, in the shape of triangular masonry masses placed upon the transverse arches and the keys of the vaults of the central nave, Figure 7. On the transverse arches, Figure 7-a, a symmetrical triangular wall exists reaching its maximum depth at the key of the arch. On the keys of the vaults, the overload appears as a pyramid of square base, Figure 7-b. According to Rubió (1912), these overloads are necessary to assure the stability of the cathedral.

The slenderness of the piers, reaching a ratio of 14.6 between diameter and height, constitutes the more unique and audacious aspect of the building and contributes largely to a sense of internal great spaciousness. The diaphanous interior space is made possible, in fact, by the very robust external buttressing system provided to the construction. The base of the main buttresses is 7.7m long and 1.5m wide; its maximum dimension represents a 44% of the span of the central nave.

Table 1. Comparing main dimensions of some of the largest Gothic cathedrals in the world (Salas, 2002).

Cathedral name	Central nave		Lateral nave		Columns
	Span	Height	Span	Height	Height/Diameter
Mallorca	17,8	43,95	8,75	29,4	14,6
Girona	21,8	34,20	Single nave cathedral		No columns
Milán	16,4	44,0	7,0	29,0	9,0
Beauvais	13,4	46,3	5,0	21,0	7,1
Amiens	12,4	41,5	6,4	18,7	7,5
Reims	12,0	36,4	5,3	16,0	5,0
París	11,85	31,4	4,6	10,2	4,5
Salamanca	11,0	34,0	7,3	22,4	3,5
Barcelona	11,0	25,6	5,5	20,5	8,5

4. INSPECTION

4.1. Cracking survey

Cracking survey revealed that some of the structural elements of the cathedral have the following types of cracks (González et al., 2008; Roca, 2001; Roca et al., 2013; Abacilar, 2010). For columns, vertical or oblique cracks exist in some of the columns and tend to concentrate close to the less confined parts of the section, i.e., the corners, Figure 8. In some cases, the cracks cross several rows and shape full wedges partially or totally detached from the core of the column. For vaults, two types of cracks

can be found, Figure 9. The first are the separation crack along the contact line between a vault of the central nave and the supporting transverse arch. The second are cracks inside the vault masonry. For walls, cracks in clerestory walls are mostly developed along the mortar joints. Some of these cracks are related to the out-of-plumbing experienced by the west façade, even after the reconstruction previously discussed. For other structural elements, cracks also exist such as in the buttresses and lateral nave vaults.

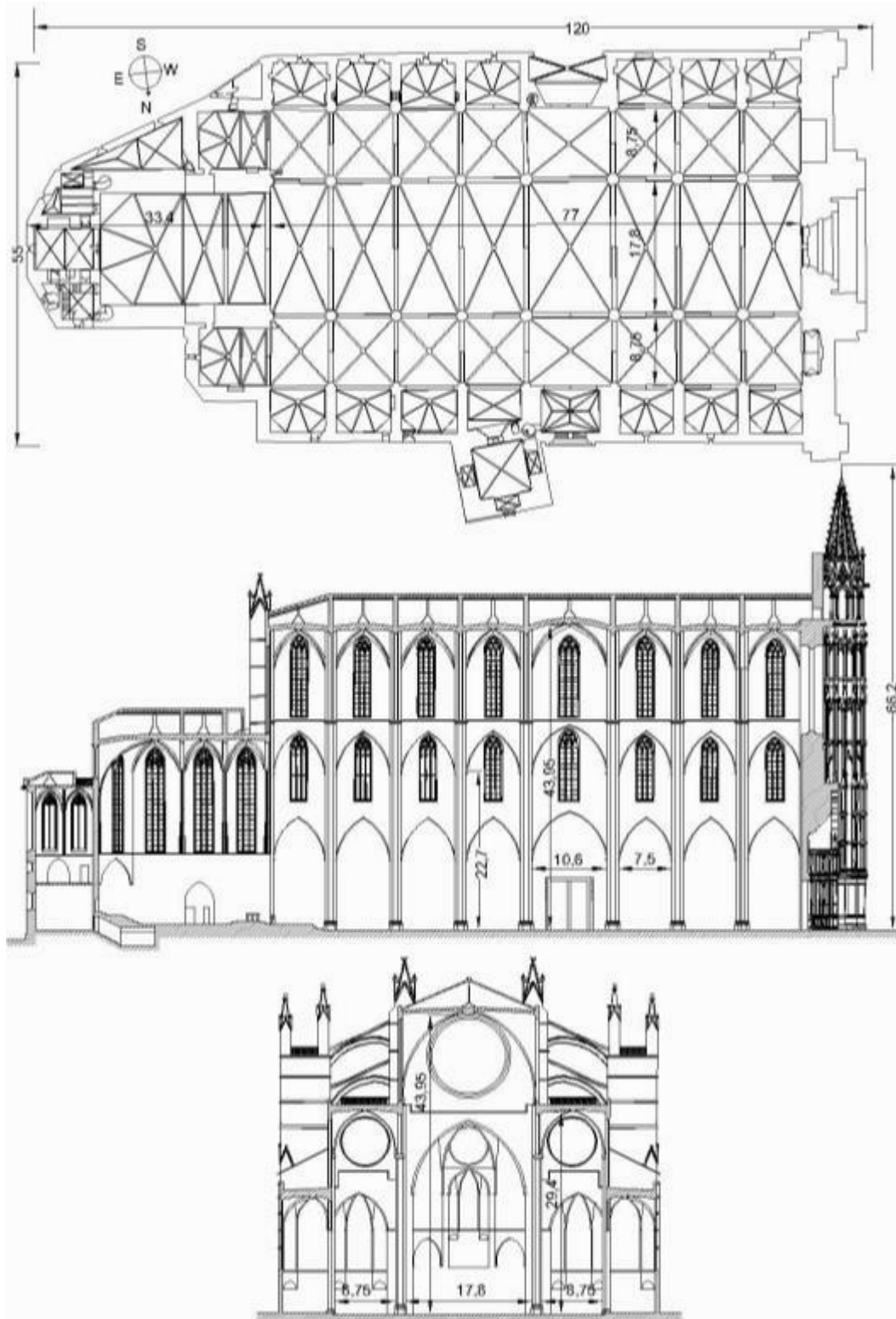


Figure 5. Mallorca cathedral: plan (top); longitudinal section (center); and transversal section (bottom) (from Director Plan of Mallorca Cathedral).



Figure 6. Internal views of Mallorca cathedral: looking at west façade and north nave, note the slenderness of columns and the upper and lower clerestories (left), and main nave vaults (right).



Figure 7. Additional weights: over the transversal arches keys (left); and over the vaults keys (right).

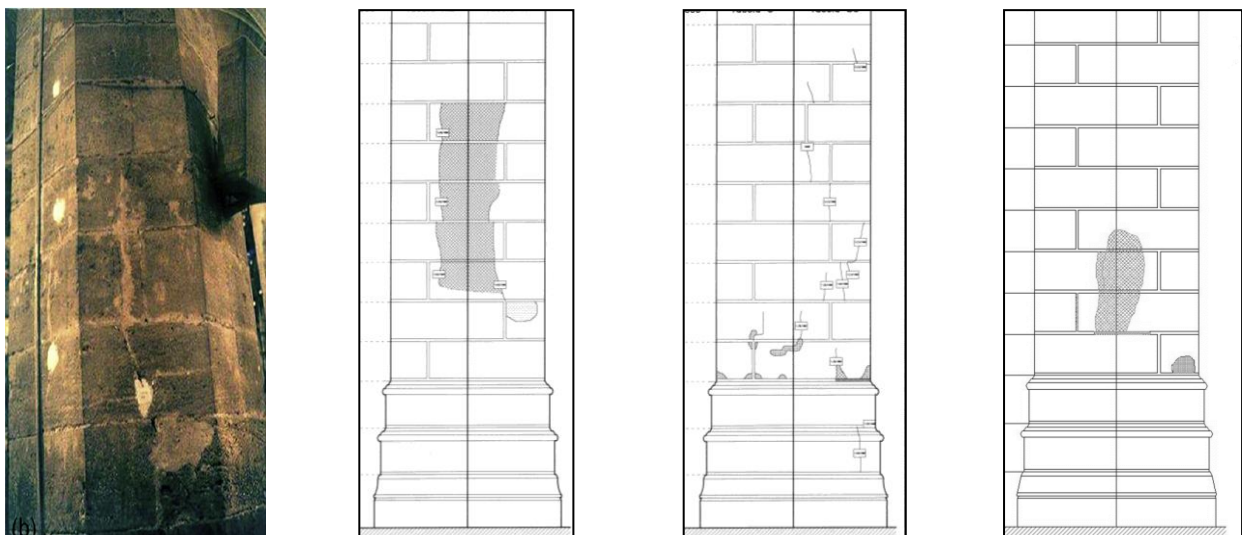


Figure 8. Cracking in columns: a cracked wedge near to the column corner (most left); and documentation of the cracked faces (three drawings).

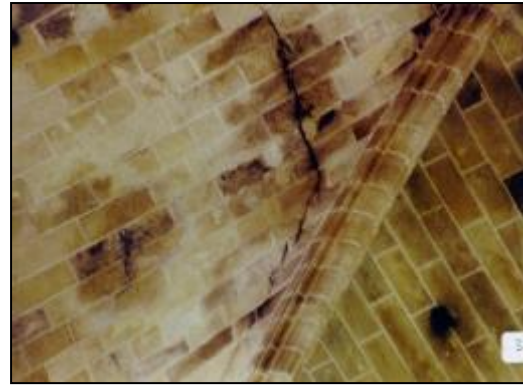


Figure 9. Separation between a vault and supporting arch (left); developed crack in a vault (right).

4.2. Deformations survey

A complete survey of the deformations of the cathedral was carried out by González and Roca (2003-2008). It was found that the deformations of the overall structure are perceptible. The columns show significant lateral deformations, Figure 10. In some cases, it reaches up to 30 cm, near to 1/100 of the height at the springing of the lateral vaults. Moreover, all the bays of the cathedral are showing clear deformations. In Figure 11, the deformed shape of each of the seven bays of the cathedral is shown and the values of the measured deformations at some selected key points are reported for each bay. Those points are the keys and the springing of the central and the lateral arches and the top of columns. It can be noticed that both the magnitude and the direction of the deformation vary significantly and show almost random trend among the different bays. Maximum lateral displacement in columns ranges from 2 cm up to, in a single case, 26 cm, with an average of 13 cm corresponding to a ratio of 1/175 with respect to the height and 1/137 with respect to the free span (Roca et al., 2013; González et al., 2008).

The construction process can be considered the main reason for such deformation. It has been possible to identify the process leading to the complete construction of the fourth bay as shown in Figure 12 (Domenge, 1997). It started with the lateral chapels, followed by the columns, then one lateral vault, then the other and finally the central one. It can be observed that during a period of about 5 years (from 1453 to 1458), the lateral vaults were already pushing against the columns while the central vault was not yet there to counteract their thrust. The lateral vaults were built 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 (Figure 12 (c)). Bourgeois (2013) and Pela et al. (2014) showed that they could have been stabilized by means of auxiliary devices, in specific, iron ties

across the lateral arches and struts across the central one (Figure 13).

4.3. Geophysical surveys of columns, buttresses and walls

The two geophysical techniques of the ground penetrating radar (GPR) and the seismic tomography were carried out to characterize the inner structure, the properties of the columns, the buttresses and the clerestory walls. They were used also to identify low quality zones and internal cracks. A summary is given here and the full details about the methodology followed and the obtained results can be consulted at Pérez-Gracia et al. (2013); Roca et al. (2008), Martínez (2007); Caselles et al. (2006); Caselles et al. (2005) and Caselles et al. (2004).

For walls, the obtained radargrams showed that they were composed of a single 45cm layer of stone masonry with no inner filling, Figure 14 (left). There was no important reflector inside the block stones meaning that no significant internal cracks affect the walls. For buttresses, it was found that they were constructed using one external stone masonry leaf about 35cm wide at both sides with an internal layer of a poorer stone block masonry, Figure 14 (right). A single core perforated in a buttress showed that the inner material consists of blocks of a poor and easy workable type of local limestone. For columns, GPR images indicated that they were built with five stone blocks, four external stones and one internal block (Figure 15). No important anomalies associated to voids or important internal cracks were found. Three of the cracked columns were selected for inspection using seismic tomography. The seismic tomography images confirmed the results of the GPR that the columns have an inner sector built with a stone similar to the outer limestone ashlars and no voids or filling materials exist. The tomography images showed good quality unions between block stones using low quantity of mortar.



Figure 10. Deformed columns: internal column (left); and column at triumphal arch (right).

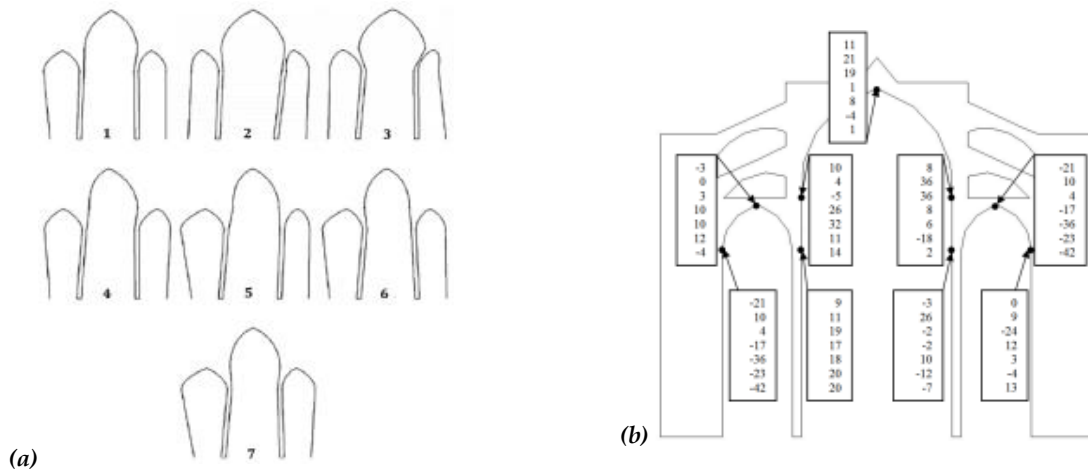


Figure 11. Deformation survey: (a) bays' deformed shapes (numbering from east to west); and (b) values of deformations (cm) at each of the seven bays in the same order of (a) (from Clemente, 2006).

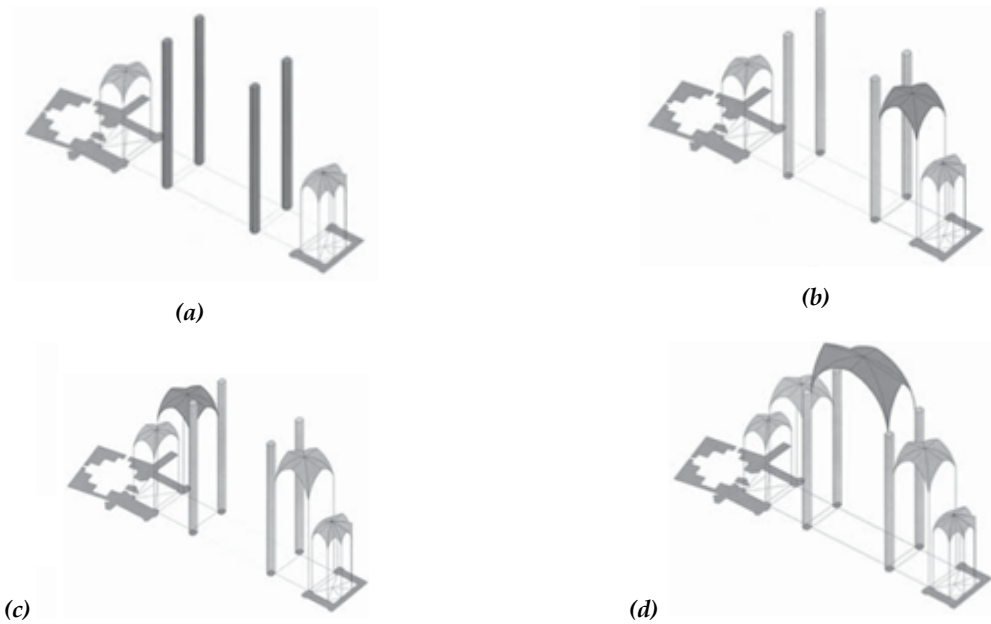


Figure 12. Fourth bay construction: (a) lateral chapel (1391-1406) then columns (1406-1426); (b) lateral vault (1453-1454); (c) lateral vault (1458); and (d) central vault (1459-1460) (Domenge, 1997).

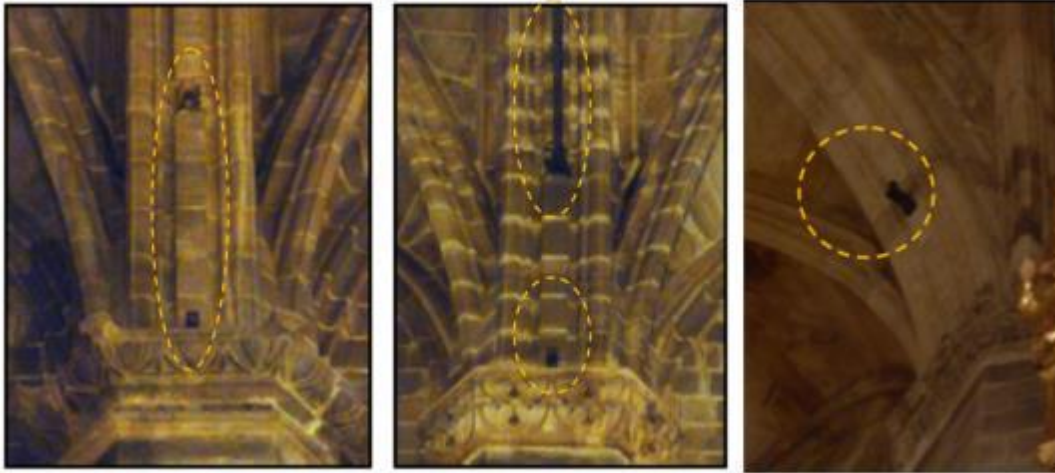


Figure 13. Evidences of using of ties in Mallorca cathedral construction: northern nave of 7th bay (left); northern nave of 6th bay (center); and southern nave of 4th bay (right) (Bourgeois, 2013).

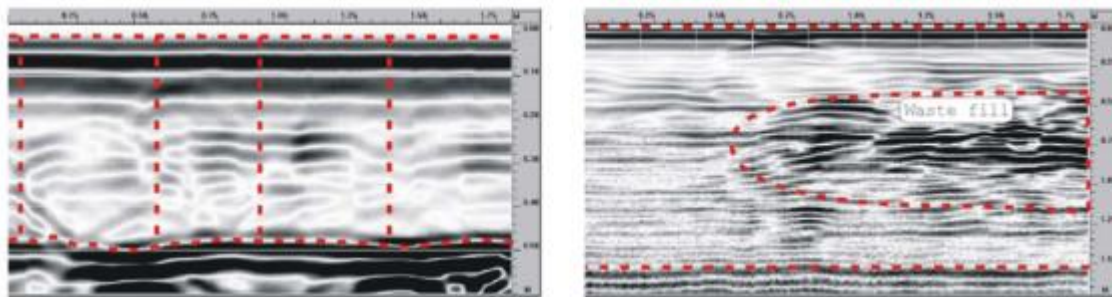


Figure 14. GPR inspection: radargram of clerestory wall with red lines showing possible distribution of stones (left); and radargram of a buttress with inner filling surrounded by a red closed shape (right) (Roca et al., 2008).

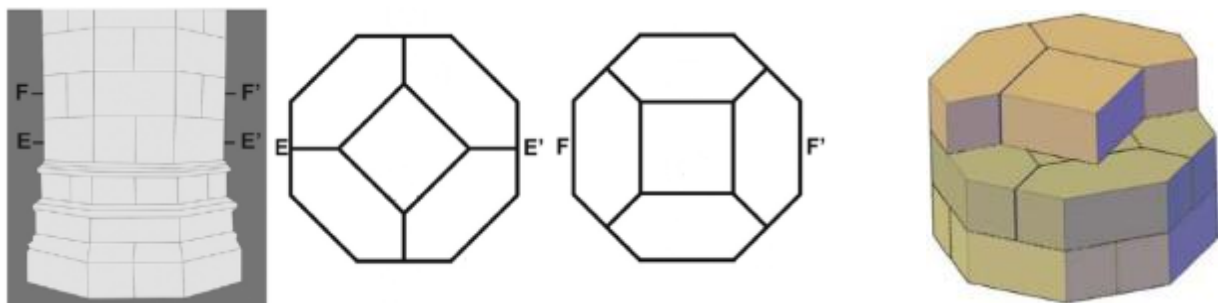


Figure 15. Reconstruction of columns internal structure using GPR inspection: distribution of blocks in elevation (most left); two cross sections (center); and 3D reconstruction of columns (most right) (Pérez-Gracia et al., 2013; González et al., 2008).

4.4. Chemical analysis

Samples from the stone were taken over the building and analyzed using scanning electron microscope (SEM), and Energy-dispersive X-ray spectroscopy (EDX). The analysis showed that the cathedral was built with four types of carbonate rock from the Miocene. The main structure of the cathedral is of white dolomite and white limestone. A grained

limestone was used to close up some large windows, while oolitic limestone was used at the west and the south façades (Alonso et al., 1996). A clear correlation was found between construction stages and different stone varieties. The chemical analysis allowed confirmation of the hypothesis on the construction process as suggested by the historical research. The substitution of all flying arches during the XVIII century is also recognizable in that of them are built

with the same variety of local sandstone that is not present in the rest of the building. Information has been also been gained on the extent of the repairs historical repairs and particularly joint repointing. The deterioration of the facades' stone due to air pollution and sea sprays was also investigated (Roca et al., 2008; Alonso et al., 1996). In a similar investigation, on Amfissa cathedral (Greece), Liritzis et al. (2015) investigated the mortar used in wall painting using XRD and SEM analyses and the compressive strength of this mortar.

4.5. *Dynamic identification*

Ambient Vibration Testing (AVT) (Elyamani and Roca, 2018a) was performed during 3rd and 4th May 2005 on several points of the façade, the chapels, the lateral naves and the main nave using one tri-axial accelerometer (Caselles et al., 2015; Boromeo, 2010; Martínez, 2007; Martínez et al., 2007; Martínez et al., 2006). Using the Peak Picking technique several modal frequencies were determined and were used in updating the Finite Element (FE) model of the cathedral.

In 2010, AVT was repeated again (Elyamani et al., 2017a; Elyamani, 2015; Caselles et al., 2012; Bettoni, 2011). Three tri-axial force balance accelerometers were used. AVT configuration was based on a preliminary modal analysis carried out using the FE model of the cathedral. It was noticed that only the modes number 1 (Figure 16-a) and 2 (Figure 17-a) were global ones with considerable mass participation and characterized by predominant movement of the main and lateral naves of the cathedral. Therefore, the sensors were organized so that capturing these two modes would be achievable. The dynamic identification was carried out using multiple methods implemented in the software MACEC (MACEC, 2011). The global modes number 2,3 and 4 were the best estimated ones because from all methods they had very near modal parameters. These modes were global ones with high mass participation, which made their identification more attainable than in the case of more local ones, Figures 16-b and 17-b. For the remaining modes, only their natural frequencies were satisfactory identified and the remaining modal parameters were poorly identified. More information can be consulted at Elyamani (2015).

4.6. *Soil investigation*

A number of boreholes and an integrated near-surface geophysical study was performed to investi-

gate the soil under and around the cathedral (Azuaque, 2012; Pérez-Gracia et al., 2009; Caselles et al., 2009; Martínez, 2007; Caselles et al., 2007; Caselles et al., 2005). 16 boreholes were carried out (S1 to S16 in Figure 18). The boreholes showed that there is a first layer of filling underneath the structure of a depth from 1 to 2.5m followed by a layer of rock has a depth from 3 to 4m and that the majority of the foundations of buttresses, columns and facades rest on this layer of rock, except near the south side of the apse area where the foundations rest on the layer of filling. The existence of the rock layer may be one of the reasons that encouraged the builders to construct such a huge heavy structure without fearing from any geotechnical problems, specifically what regards the bearing capacity.

For the geophysical surveys, the main objective was to determine the shallow geological stratigraphy and the depth and continuity of the soils or rocks underneath the structure. A large number of Ground-penetrating radar (GPR) profiles (from G1 to G37 in Figure 18) and ten profiles using the capacitively coupled resistivity method (ERT) (from R1 to R10 in Figure 18) were used to obtain 2D images of the shallow subsurface. Five profiles using the Refraction microtremor array measurements (ReMi) (from M1 to M5 in Figure 18) were used to characterize the rock and soil properties. These different investigation techniques proved that the stratigraphy consists of five types of soils: (A) filling materials formed by stones, soil and pottery; (B) some layers of sand and silt; (C) a layer of gravel; (D) conglomerate rock and (E) Quaternary limestone.

The measured shear wave velocities at five points (from Point1 to Point5 in Figure 18) in each of these soil types were reported. The investigation results suggested that the soil can be divided into three main zones: Zone 1, Zone 2 and Zone 3, Figure 18. Zones 1 and 2 are in the south side; both present a thick soft sediment layer of filling used during the Roman epoch. Zone 2 is characterized by the thickness of the soft filling layer reaching up to 30 m which shows very low shear wave velocities. Zone 3 is characterized by homogeneous layers with higher shear wave velocities. Finally, an investigation of one of the columns foundation was also carried out using one 2D GPR profile. It suggested that the columns were built over a foundation that took a pyramidal shape, i.e., the width increases with the increase in depth.

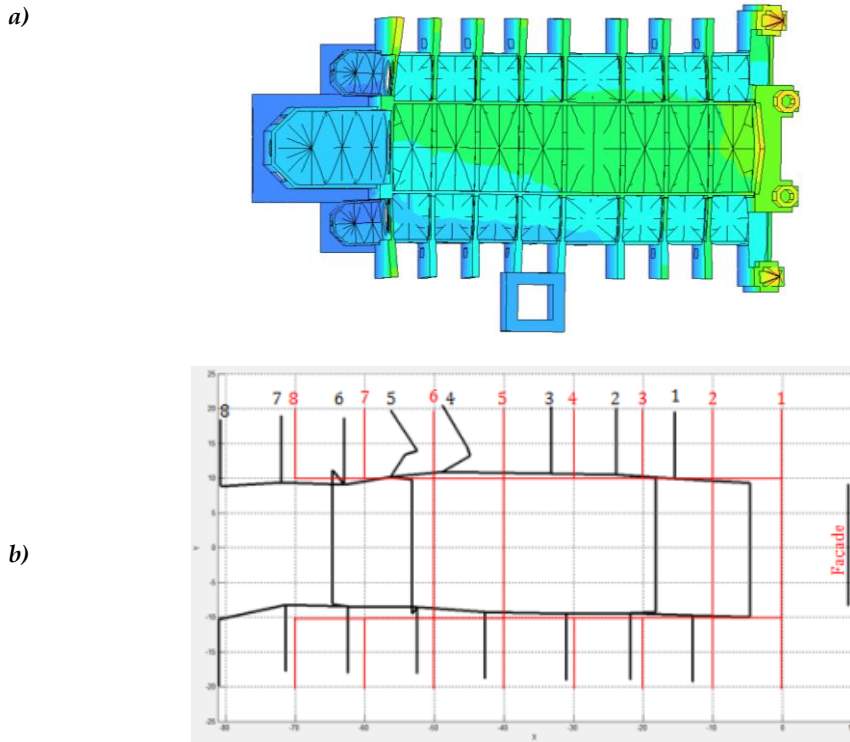


Figure 16. (a) First numerical mode shape, and (b) second experimental mode shape (Elyamani et al., 2017a).

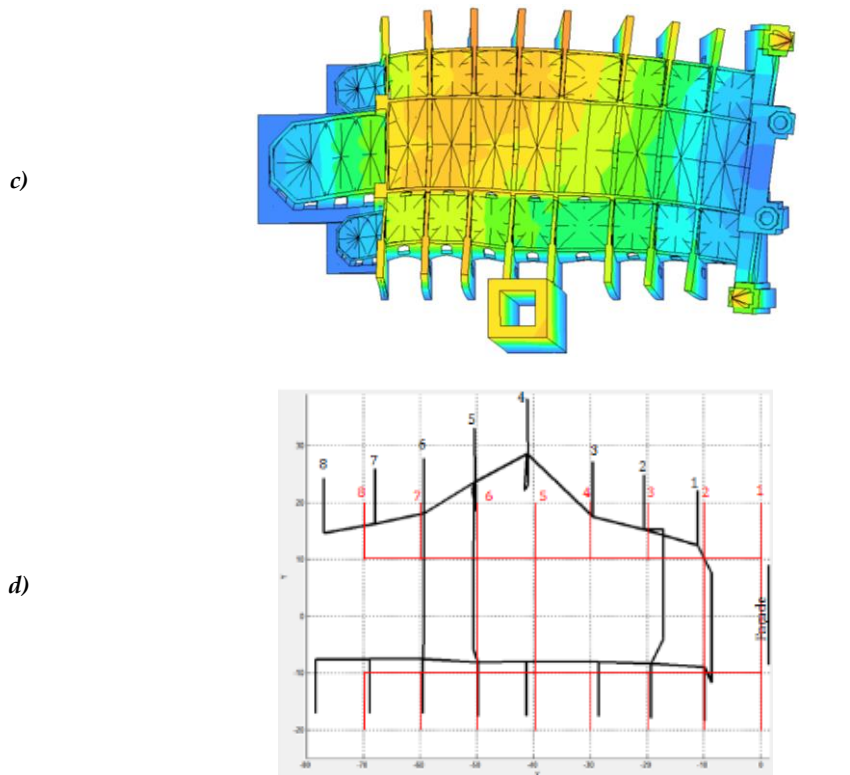


Figure 17. (a) Second numerical mode shape, and (b) fourth experimental mode shape (Elyamani et al., 2017a).

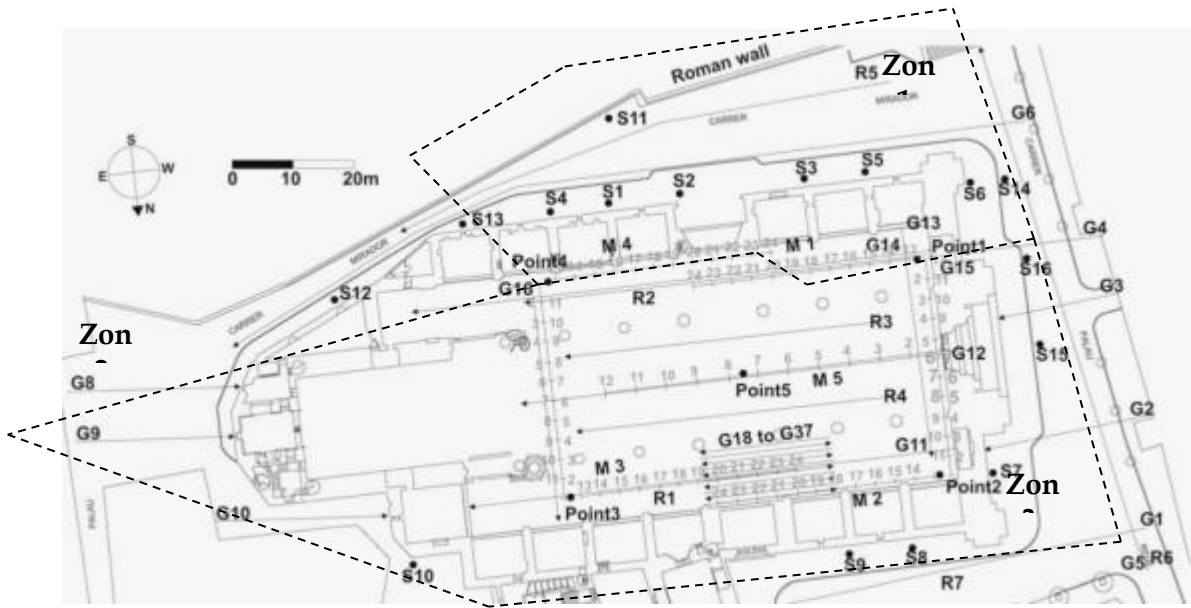
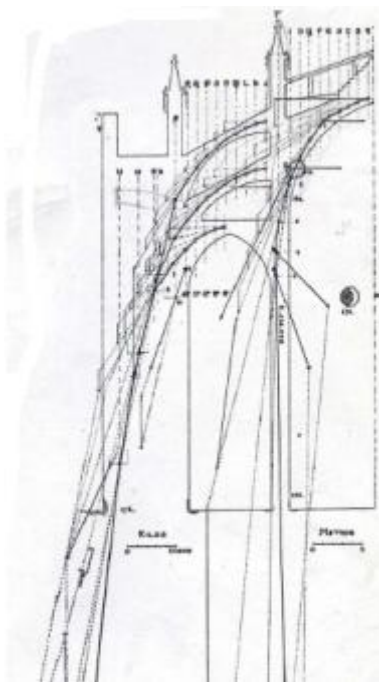
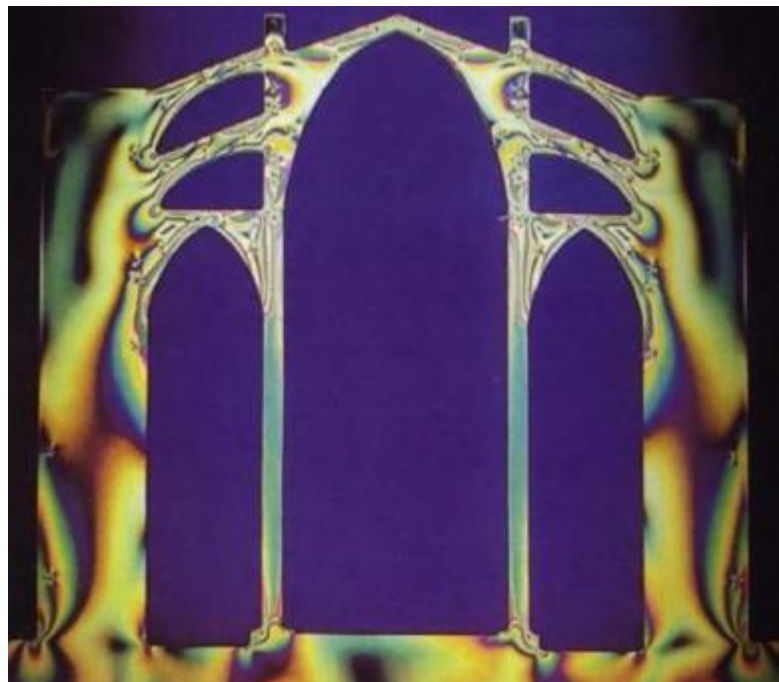


Figure 18. Different profiles and drilling points on plan (Ss: boreholes, Gs: GPR, Rs: ERT, Ms: ReMi profiles) and the division of the soil into three zones (adapted from Pérez-Gracia et al., 2009).



(a)



(b)

Figure 19. (a) Static-graphic analysis of Rubió (1912), (b) Photo-elasticity analysis of Mark (1982).

5. STRUCTURAL ASSESSMENTS

5.1. Pioneering studies

5.1.1. Graphic-statics (Rubió, 1912)

Rubió (1912) studied the equilibrium of a typical bay of the cathedral using the graphic-statics method. He found, after several trials, a thrust line fully contained within the sections of the main nave arch, the column, the flying arches and the buttress, Figure 19. He found that the fitting of the descending

thrust line inside the column was difficult and it became almost tangent to the column perimeter at the springing of the lateral nave vault. He related the curvature already exist in the column with this finding. He pointed out the necessity of the additional weights above the main nave arches and vaults for the equilibrium. For the upper flying arches and because they push against the main nave vault, not building them at all would be better for the equilibrium of the cathedral typical bay. On the contrary, the lower flying arches are well suited and have op-

timal shapes. He calculated the maximum compressive stresses in the arch and the column sections to be 3,1 and 4,5 MPa, respectively.

5.1.2. Photo-elasticity (Mark, 1982)

Robert Mark (1982) performed pioneering studies using the photo-elasticity method on the structure of some Gothic cathedrals such as Chartres and Bourges. Mallorca Cathedral was also studied. A model for the typical bay of the cathedral was created and then scaled loads equivalent to the gravity and the wind loads were applied. Afterwards, a pattern of light was passed through the model, and using the obtained images, the distribution of internal stresses was qualitatively interpreted, Figure 19. Mark conclusions were in agreement with the ones of Rubió (1912) in that having only the lower battery of flying arches with more inclination towards the buttresses would be better than using two batteries. Mark was not in agreement with Rubió (1912) regarding the state of stress in the columns. The photo-elastic study showed a uniform state of compression in the columns under gravity loads of 2,2 MPa which cannot result in the visible bending of the columns. Even under wind loads, this value could reach 2,7 MPa. He proposed an explanation for the strengthening intervention carried out on the upper battery of the flying arches. He noticed that this battery was subjected to tensile stresses and moreover, its deflection that resulted initially from the self-weight would increase under the effect of wind loads.

5.2. Recent studies

5.2.1. Graphic-statics (Maynou, 2001)

This work represented the modernization of the work of Rubió (1912). Maynou (2001) created a MatLab code for the automatic implementation of the graphic-statics method to a typical bay of the cathedral. While Rubió (1912) found one equilibrium solution after several trials, Maynou found a lot of solutions, Figure 20. He confirmed the necessity of the over-weights above the main nave arches and vaults for the stability of the cathedral. Also, he confirmed the same comment of Rubió about the upper flying arches.

5.2.2. Kinematic limit analysis

5.2.2.1. Coutinho (2010)

This researcher studied 14 possible collapse mechanisms of the cathedral, Figure 21, related to the west façade, the typical bay, and the east façade. He applied first the linear kinematic limit analysis and the safety was checked according to the regulations of the Italian code (Circ. NTC08, 2009). All the

considered mechanisms verified the demands of the Eurocode, the Spanish code and the deterministic scenario. For the probabilistic scenario, two mechanisms didn't verify the demand for the return period of 475 years, and the four mechanisms didn't verify the demand for the return period of 975 years. When the nonlinear kinematic limit analysis was used, these mechanisms were verified.

5.2.2.2. Elyamani (2015, 2017b)

Based on the collapse mechanisms found in the longitudinal direction by the pushover analysis, two collapse mechanisms were studied by the kinematic limit analysis technique. The west and the east façades overturning were considered, the found capacities were 0,144g and 0, 118g, respectively. Those values were near to the capacities obtained by the pushover analysis.

5.2.3. Numerical analysis

5.2.3.1. Salas (2002)

Salas (2002) used the FE method with isotropic damage model and the Generalized Matrix Formulation (GMF) method (Molins, 1996; Molins and Roca, 1998) in studying the structural behavior of a typical bay of the cathedral. Using the FE method, he carried out linear and nonlinear analysis under the effect of the own weight using the theoretical undeformed geometry and the actual deformed geometry of the bay. He compared the maximum compression stress in the bay, the deflection of the main nave arch and the horizontal displacement of the top of the column. The results were found to be very near and no significant differences were found whether considering the actual deformed geometry or the theoretical undeformed geometry. The results of the nonlinear analysis using the GMF method were not different from the FE method. In a following stage of the study, he increased the own weight up till the complete collapse, the FE and GMF gave a collapse load multiplier of 1,7. Afterwards, the author examined different configurations of the bay by (a) ignoring the overweight on the main nave arch, (b) ignoring the upper battery of flying arches and (c) ignoring the overweight and the upper battery of flying arches. It was found that ignoring the overweight reduced the collapse load multiplier to 0,9 only, i.e., the structure was not able to bear its self-weight. Thus, it was assured the necessity of the overweight for the stability as was concluded before by Rubió (1912) and Maynou (2001). The collapse load multiplier was reduced to 0,7 when neglecting the upper flying arches. Interestingly, when ignoring both of the overweight and the upper flying arches, the collapse load multiplier reached 1,6. Wind and earth-

quake analyses were also carried out according to the Spanish codes NBE-AE/88 (NBE-AE/88, 1988) and NCSE-94 (NCSE-94, 1994), respectively. The

analyses showed that the cathedral would resist a wind pressure of 1,45 kN/m² and a base shear of 0,12g.

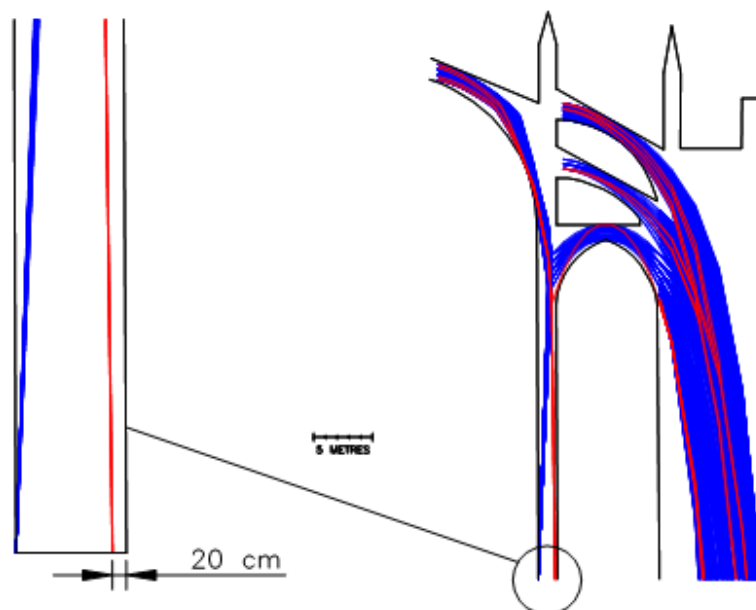


Figure 20. Automatic static-graphics of Maynou (2001): thrust lines (in red) giving the maximum eccentricities at the base of the column.

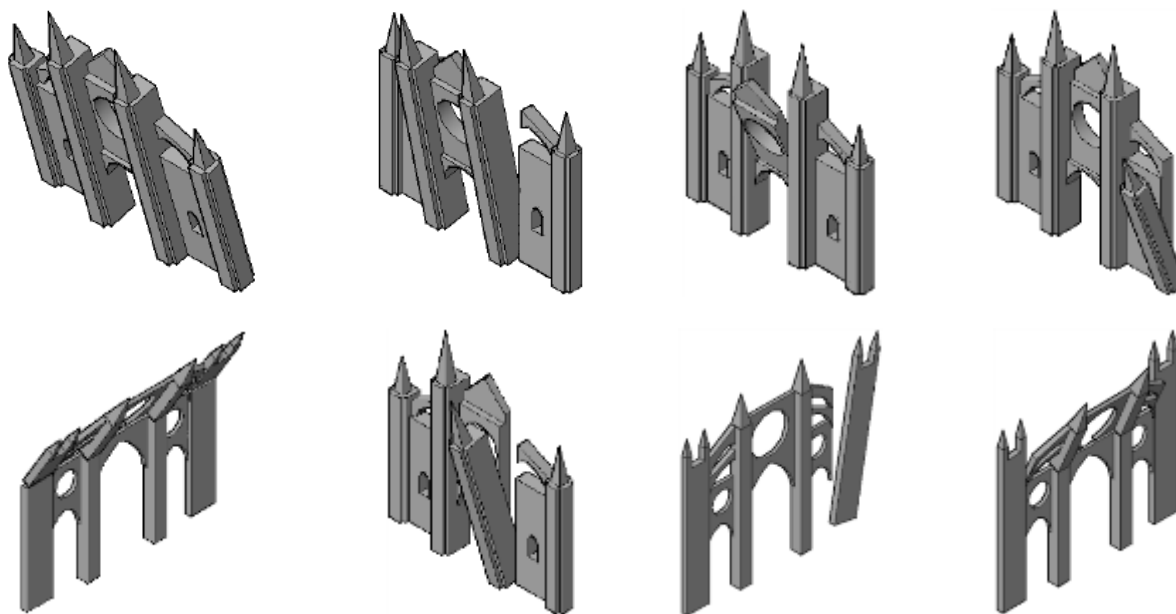


Figure 21. Some of the collapse mechanisms studied by Coutinho (2010).

5.2.3.2. Roca et al. (2012a, 2012b, 2012c, 2013);
Clemente (2006); Clemente et al. (2006);
Pelá et al. (2011)

A number of analyses were carried out using the distributed damage model and the localized damage model (Clemente, 2006 and Pelá, 2009) using 2D and 3D models of the typical bay of the cathedral. A number of analyses were carried out under the effect

of (1) the self-weight, with and without considering the construction process and a sensitivity analysis was also carried out (2) creep loads and (3) the seismic loads. The collapse load factor under the self-weight using the distributed damage model was 2 and using the localized damage model increased slightly and reached 2,15. The collapse mechanism obtained from the two models was similar and occurred due to a combination of compressive and ten-

sile damage, Figure 22. The compressive damage was observed at the base of the buttress and the tensile damage was observed at the flying arches, the naves' vaults, the main nave arch and around the window opening of the buttress. In Figure 23 a comparison is made between the damage when applying the full self-weight (load factor of 1) without considering the construction process and with considering the construction process. It was found that the horizontal displacement of the top of the column increased from 0,75 cm to 1,84 cm when considering the construction process. According to the authors, this result suggested that the deformations of the piers were mostly due to the construction process. It was also observed larger areas affected by damage in the top of the column, the flying arches and the vaults when considering the construction process. Another analysis was carried out to investigate the effect of masonry creep using viscoelasticity model and considering the geometric nonlinearity. It was found that the horizontal displacement of the top of the column reached a value of about 12 cm which is comparable to the actual displacement existing in the cathedral. This value was only 0,75 cm in case of instantaneous analysis without considering creep. No change in the collapse mechanism was noticed.

The found collapse load factors under the effect of self-weight were checked via a sensitivity analysis on the tensile strength, the compressive strength and the tensile fracture energy. The localized damage model was found to be less sensitive to the tensile strength than the distributed damage model. For both models, the collapse load factor decreased with the reduction in the tensile strength. A linear relation was noticed between the compressive strength and the attained load factor for both used models. A clear effect of the tensile fracture energy on the capacity was found for both used models. When this material parameter is very low, the structure is not able to bear its self-weight and after a certain value, stabilization in the attained capacity was noticed.

5.2.3.3. Martínez (2007)

The pushover analysis was used to perform the seismic assessment of the cathedral. Not the full model was used but instead five chosen macro elements were used. After obtaining the capacity curves of the macro elements, the capacity spectrum meth-

od was utilized. The seismic demand was characterized using the Spanish code for seismic design (NCSE-02, 2002), the deterministic scenario and the probabilistic scenario. The level of damage was evaluated using the proposed methodology of Lagomarsino et al. (2003). It was found that the macro element of the longitudinal bay would be subjected to the level of damage D3; whereas, all other macro elements would have lesser damage.

5.2.3.4. Murcia et al. (2009); Roca et al. (2009); Das (2008)

In these studies, nonlinear analysis of the typical bay of Mallorca cathedral was carried out under gravity and seismic loads using a tension-compression distributed damage model. The same collapse mechanisms found under the effect of gravity loads and seismic loads found by Clemente (2006) were also found here. For the seismic analysis two load patterns were used, the first was proportional to mass and the second was proportional to the first mode of vibration. The second pattern gave a higher capacity. A sensitivity analysis was performed on the tensile strength and showed, similar to the studied mentioned in section 5.2.3.2, the clear influence of this parameter on the seismic capacity. For performance evaluation, the capacity spectrum method was applied and revealed that the cathedral would show acceptable performance with only limited damage.

5.2.3.5. Pela et al. (2014), Bourgeois (2013)

They studied the effect of the usage of ties during the construction on the structural behavior of a typical bay of the cathedral. The study included also the analysis of the long-term deformation considering the effects of the removal of the ties. Parametric analyses focused on the influence of the section of the ties and the tensile strength of the masonry. Smaller horizontal displacements were found at the top of the column because the ties balanced the deformations caused by the horizontal thrust of the lateral vault and the removal of the ties resulted in an increase in the displacement. The presence of the ties didn't affect the vertical deformation of the cathedral.

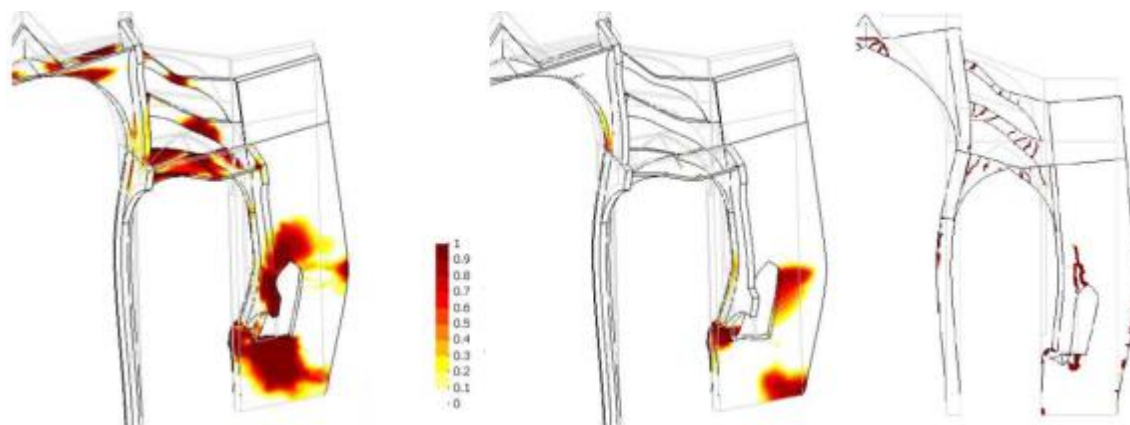


Figure 22. Collapse mechanism of a typical bay under self-weight: distributed damage model: tensile damage (left) and compressive damage (center); localized damage model (right) (Clemente, 2006).

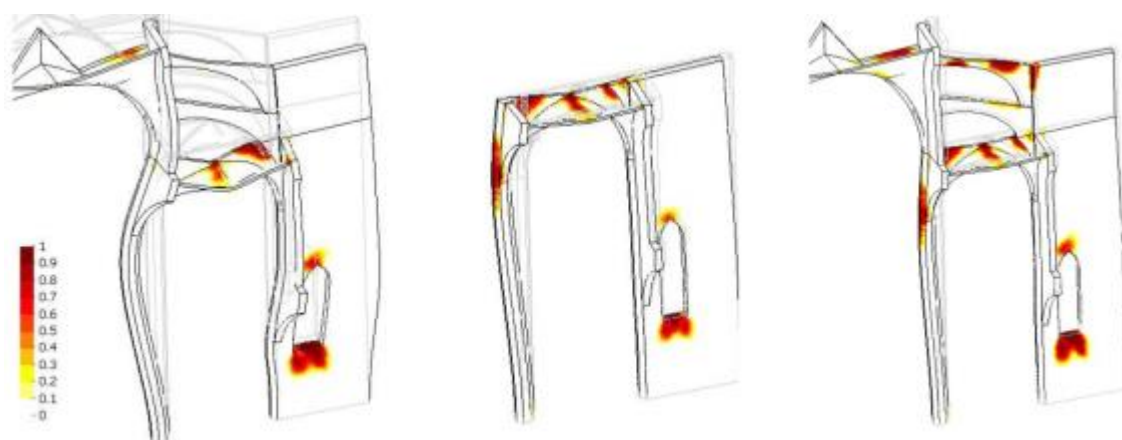


Figure 23. Tensile damage of nonlinear analysis of a typical bay under self-weight without considering the construction process (left); and considering the construction process (center and right) (Clemente, 2006).

5.2.3.6. Elyamani et al. (2017); Elyamani (2015); Caselles et al. (2012)

The seismic behavior of the cathedral was studied using a 3D model updated using the AVT results (Elyamani and Roca, 2018b). The pushover and the nonlinear dynamic analysis were employed. It was found that the seismic resistance of the cathedral in the longitudinal direction is lower than that in the transversal direction. This is due to the fact that in the former case the buttresses (the main earthquake-resisting elements) are loaded by lateral loads acting in their out-of-plan direction, whereas, in the latter case, the buttresses are loaded in their stronger in-plane direction. In the longitudinal direction, the collapse can occur due to the overturning of the facades. The zones that can be severely damaged are those around the large windows of the clerestory walls and the apse walls, the first bay of the central nave vault after the west facade, and the top and bases of the columns. In the transversal direction, the collapse can occur due to the cracks (hinges) appearing in the flying arches, the arches and vaults of the

naves, the top and bases of the columns and the bases of the buttresses.

6. MONITORING

6.1. *Static monitoring (González and Roca, 2003-2008; Godde, 2009)*

A static monitoring system was installed in the cathedral for a period of about five years from 2003 to 2008. The system aimed at measuring the cracks widths, the tilts and the convergences at some critical positions in the cathedral, in addition to measuring the environmental actions of the temperature, the humidity and the wind. In Figure 24 the complete system is shown. As seen, the cracks were monitored at three columns (F1 to F4), two locations at the upper south clerestory wall (F5 and F6) and two vaults (F7 and F8). The convergences were monitored at six positions (C1 to C6), two of them (C5 and C6) gave indication of the movement of the west facade.

The tilts were monitored at two positions (R1 and R2), the second position was aimed at measuring the tilt of the west facade. The temperature and the hu-

midity were monitored at two positions (EC1 and EC2) and the wind was monitored at the position V1. It was concluded that the crack with the highest opening rate was the one between the sixth vault and the supporting arch (F7) that had a trend of about 10 mm/century. This showed that the west

façade perhaps was still tilting out-of-plane. The cumulative trends of the convergences were not considered alarming. It was also observed that both of the cracks and the convergences tended to increase with the temperature raising and decrease with the temperature lowering.

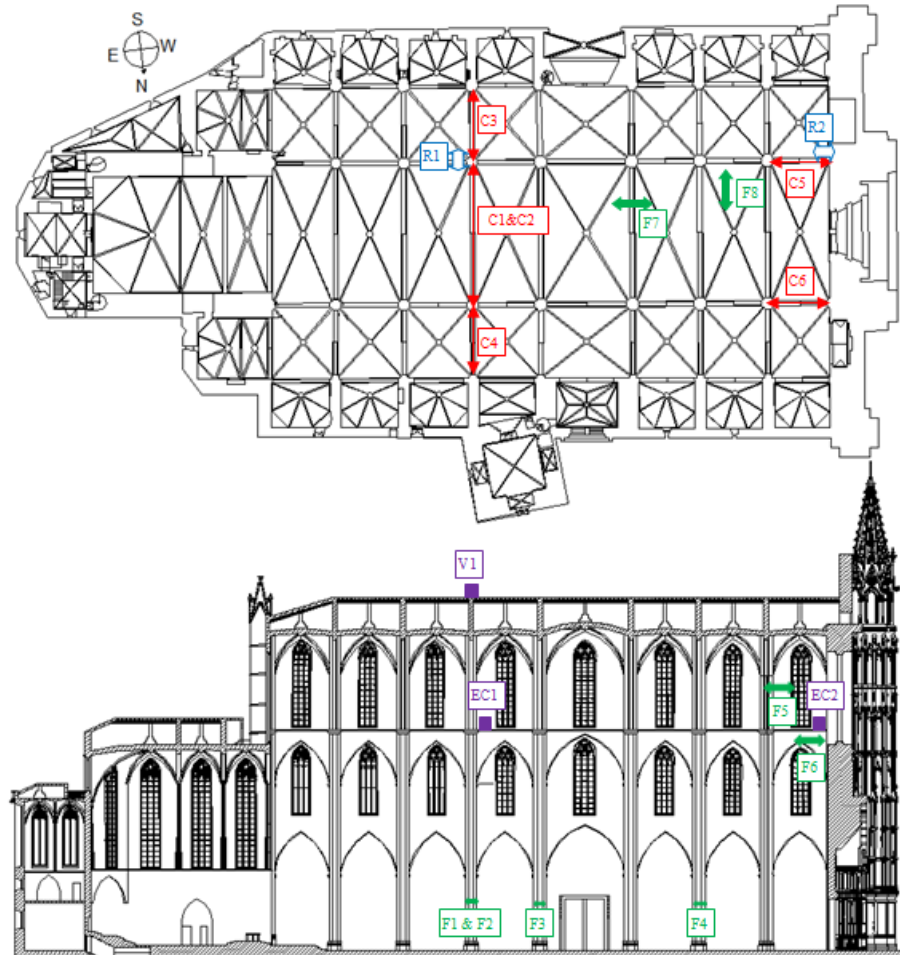


Figure 24. The static monitoring system of Mallorca cathedral (González and Roca, 2003-2008).

6.2. Dynamic monitoring

6.2.1. Boromeo (2010) and Martínez (2007)

A dynamic monitoring system was installed in the cathedral. The objective was to capture any seismic events that would result in a higher level of excitation than that registered during AVT, hence characterizing better the cathedral dynamic behavior. In addition it was aimed to study the effect of the environmental actions on the dynamic behavior, in specific the natural frequencies. The system was composed of two tri-axial force feedback accelerometers, a DAQ system and a GPS antenna. The first accelerometer was installed on the second arch from the west façade and worked alone for about one year starting from 8th June 2005. The second accelerometer was added later on 22nd June 2006 at the ground level of the second north chapel from the west

façade. The two accelerometers worked together for about one year.

Boromeo (2010) processed the recorded signals for a period of about ten continuous months from 15th December 2005 to 24th October 2006. Within this period the daily registered signals between 6 a.m. to 8 am using the peak picking technique was analyzed. A number of modes were detected. The first mode was identified in rare occasions because the accelerometer was installed on a point that was a node in this mode. A clear correlation was observed between the temperature and the natural frequencies. The increase in the temperature resulted in the increase of the natural frequencies and vice versa. For the correlation with the humidity and the wind velocity, the contrary was found. A number of seismic events were captured. All of them were far-field earthquakes. The maximum registered acceleration

was not more than 0,005g. The identified values of the natural frequencies during these seismic events were not different from the average values found during the entire monitoring system.

6.2.2. Caselles et al (2018); Elyamani et al. (2017a); Elyamani (2015); Elyamani et al. (2012); Bettoni (2011)

A continuous monitoring system was used. It consisted of a system adequately equipped and programmed to continuously measure, record, and wirelessly transfer the records of the accelerations during a long period of time, on a 24h basis, without having to set up an activating threshold. The system was composed of a digitizer, a Data Acquisition system (DAQ), a Global Positioning System (GPS) antenna, an internet router and three tri-axial accelerometers. The monitoring campaign was installed for a period of more than 15 months during the years 2010, 2011 and 2012. The obtained results allowed for a detailed observation of the dynamic properties with time under environmental actions and some captured seismic events. The conclusions drawn from the dynamic monitoring were: 1) the obtained frequencies for the identified eight modes under low level of excitation during the AVT (Elyamani, 2015) were confirmed by the dynamic monitoring campaign under higher levels of excitation in the vicinity of higher wind speeds and some captured seismic events; 2) the global modes of the cathedral were more detectable than the local ones because of their higher mass participation; 3) for the modes from 2 to 8, temperature was a more influential environmental parameter than humidity and wind; 4) the first longitudinal mode correlated well with wind and was detectable only when wind was acting according to a certain direction and velocity; 5) the usage of a higher cost continuous dynamic monitoring system was useful in capturing very low intensity seismic events. These events would not be detected with the usage of a lower cost triggered system. Therefore, this type of monitoring seems interesting for the dynamic identification of large buildings in low seismic zones; 6) for the recorded earthquakes; it was observed a doubling of some frequency peaks, Figure 25. This was probably due to the breathing crack effect, i.e. the opening of the cracks that resulted in decreasing the stiffness, and therefore in; lower value of the natural frequency.

6.3. Thermography monitoring (Elyamani et al, 2018; Elyamani, 2015; Grande, 2013)

An infrared (IR) camera of type "Thermo GEAR G120" produced by NEC Company was used. Its main characteristics were: 1) measuring range from -40° C to 500° C with accuracy of $\pm 2^{\circ}\text{C}$ or $\pm 2\%$ of reading, whichever is greater; 2) thermal image of 320 pixels (horizontal) X 240 pixels (vertical); 3) spectral range from 8 to 14 μm ; 4) frame rate of 60 frames/sec; 5) automatic focusing with focal distance from 10 cm to infinity; and 6) automatic recording of images with interval from 3s to 60 min.

It worked at the same location in two periods: 1) in the winter of 2011 for 14 days from 27/1 (at 11:15) to 9/2 (at 23:45), and 2) in the summer of the same year for 16 days from 28/6 (at 8:16) to 13/7 (at 22:46).

The IR camera was located inside the north pulpit and directed to the arches, the vaults, the upper clerestory and the columns of the main nave. This place allowed the IR camera to cover a large portion of the first five bays of the main nave.

The IR camera recorded one photo each half an hour. For each day of the two monitoring periods, four IR photos were processed and the stone surface temperature was determined for the considered structural element (the columns, the clerestory walls, the arches and the vaults). A comparison was made between the external temperature, the internal temperature and the stone surface temperature of the considered structural elements for the summer period and the winter period, Figure 26. It was noticed that the stone surface temperatures of the different structural elements were in phase and very near to each other for the two monitoring periods. For the summer period, the internal and the external temperatures were in phase, whereas, the stone surface temperature was sometimes delayed with respect to the external and the internal temperatures. In the winter period, the stone surface temperature was in phase with the external temperature. The thermography monitoring revealed an acceptable correlation between the stone internal surface temperature and the cathedral frequencies. In the winter period higher correlation coefficients than in the summer period were found. It was observed also that the natural frequencies were more correlated with the external temperature than the internal temperature and finally with the internal stone surface temperature.

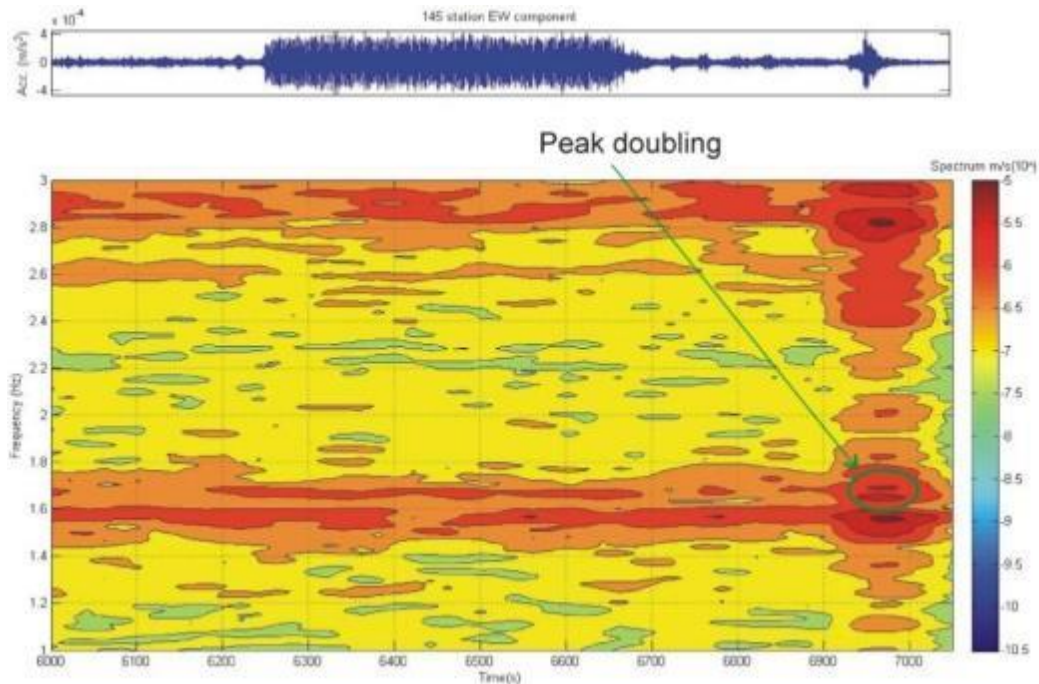


Figure 25. Spectrogram of the EW component at 145 Station for Menorca earthquake (Elyamani et al., 2017a).

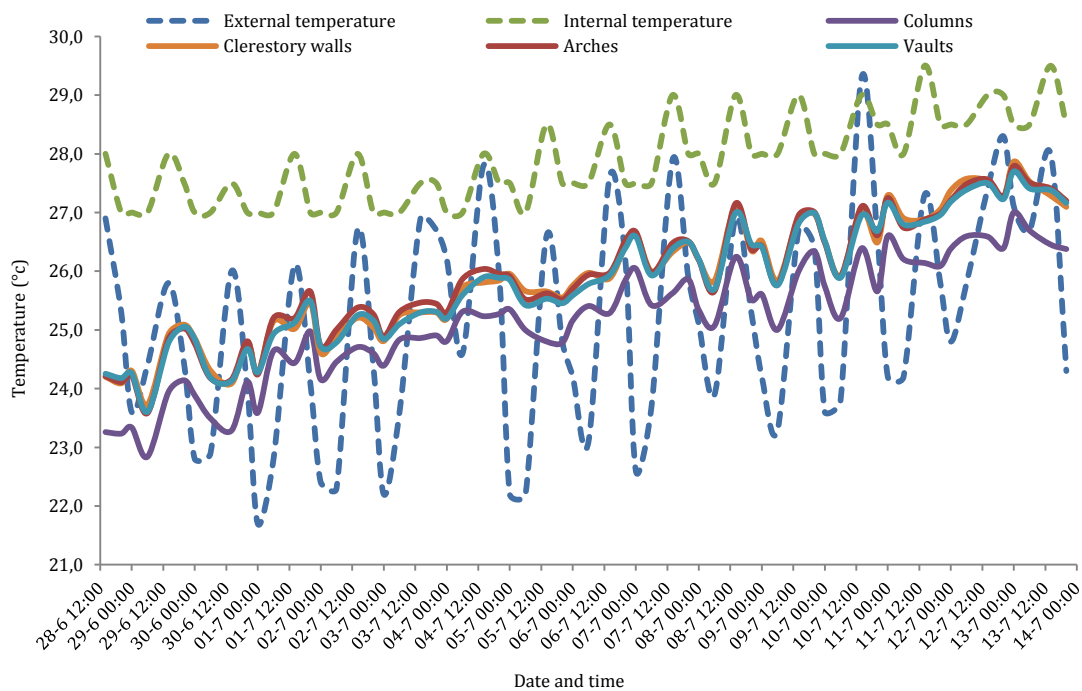


Figure 26. Comparison between external, internal and stone surface temperatures in the summer period from 28/6/2011 to 13/7/2011.

7. CONCLUSIONS

- Many studies have been carried out on Mallorca cathedral. These studies included the historical research on its construction process, the inspection of its structural elements and the underneath soil, the structural assessments using simple and complex techniques and monitoring.
- The construction process lasted for three centuries. This long process resulted in the perceptible deformations seen nowadays. The long span arches and vaults of the cathedral suffered from partial collapses, for different reasons, and were reconstructed. The west façade was totally demolished and rebuilt due to the progressing out-of-plumbing that reached 130 cm.

- Cracks exist in almost all the structural elements of the cathedral including the columns, the vaults and the clerestory walls. The static monitoring revealed that the crack existing between the sixth vault and the supporting arch is the one with the highest progress rate of about 10mm/century.
- The columns have internal solid composition; whereas, the buttresses and the clerestory walls have an internal layer of a regular block stone masonry with a lower strength than the external layers.
- The soil underneath the cathedral can be divided into three different zones with different properties. Almost all of the cathedral foundations rest on rock except a small part on the south east part that rest on filling material.
- The studies carried out using the capacity spectrum method on many possible collapse mechanisms employing many different seismic demands showed the cathedral would resist the expected earthquakes, although experiencing some damage.
- The seismic analysis of the typical bay of the cathedral showed that the collapse could be due to the tensile damage at the flying arches, the main nave vault and around the buttresses opening.
- The detailed studies of the effect of masonry creep showed deformations values that are comparable with the actually measured values in the cathedral.
- The dynamic monitoring system showed the clear dependency of the environmental actions on the natural frequencies of the cathedral.

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REFERENCES

- Abacilar, P. (2010). Damage survey and collapse mechanisms due to seismicity in Gothic churches around Catalonia region and Mallorca. MSc Thesis, Technical University of Catalonia, Spain.
- Alonso, F. J., Ordaz, J. & Esbert, R. M. (1996). *Deterioro selectivo de la piedra de construcción de la catedral de Palma de Mallorca*. Geogaceta, 20 (5): 1228-1231.
- Azuaje, M. M. (2012). Estudio del subsuelo de la catedral de Santa María de Palma de Mallorca mediante El método de refracción de microtemores. MSc Thesis, Technical University of Catalonia, Spain.
- Bettoni, M. F. (2011) Dynamic monitoring of Mallorca catedral. MSc thesis, Technical University of Catalonia, Spain.
- Boromeo, L. (2010) Dynamic monitoring analysis of Mallorca cathedra. MSc thesis, Technical University of Catalonia, Spain.
- Bourgeois, J. (2013). Simulation of the effect of auxiliary ties used in the construction of Mallorca Cathedral. MSc Thesis, Technical University of Catalonia, Spain.
- Caselles, O., Clapés, J., Osorio, R., Canas, J. A. Pujades, Ll. G. & Pérez-Gracia, V. (2004). Tomografía sísmica de las columnas de la catedral de Mallorca. *4ª Asamblea Hispano-Portuguesa de Geodesia y Geofísica*, 3-7 February, Figueira de Foz, Portugal.
- Caselles, J. O. , Clapés, J. , Osorio, R. , Canas , J. A. , Pujades , L. G. & Pérez-Garcia, V. (2005). Integrated geophysical survey applied to the Mallorca cathedral. *67th EAGE Conference & Exhibition*, Madrid, Spain, 13-16 June.
- Caselles, O., Martínez, G., Clapés, J, Roca, P. & Canas, J. A. (2006). Non-destructive geophysical surveys for dynamic characterization of Mallorca cathedral. *1st European Conference on Earthquake Engineering and Seismology*, 3-8 September, Geneva, Switzerland.
- Caselles, J. O., Clapes, J., Osorio, R., Martínez, G., Canas, J. A., Pujades, L. G. & Pérez-Gracia, V. (2007). Integrated geophysical survey for prospecting Mallorca cathedral soil. *Geophysical Research Abstracts*, Vol. 9, 03513, 2007.
- Caselles, O., Clapés, J., Martínez, G., Roca, P. & Pérez-Gracia, V. (2009). Caracterización dinámica del terreno de cimentación de la catedral de Mallorca, España. *17th National Congress of seismic engineering*, La Ciudad de Puebla, Mexico, 11-14 November.
- Caselles, J. O., J. Clapes, P. Roca, and A. Elyamani (2012), "Approach to Seismic Behavior of Mallorca Cathedral", *15th World Conference of Earthquake Engineering*, Lisbon, Portugal, 24-28 September , 2012.

- Caselles, O., Martínez, G., Clapes, J., Roca, P. & Pérez, M. (2015). Application of Particle Motion Technique to Structural Modal Identification of Heritage Buildings. *International Journal of Architectural Heritage*, 9.3 (2015): 310-323.
- Caselles, O., Clapes, J., Elyamani, A., Lana, J., Seguí, C., Martín, A. and Roca, P. (2018). Damage detection using Principal Component Analysis applied to temporal variation of natural frequencies. 16th European Conference on Earthquake Engineering (16ECEE), Thessaloniki, Greece, June 18-21, 2018.
- Circ. NTC08 (2009). Circolare, n.617, 2 febbraio 2009, del Ministero delle Infrastrutture e dei trasporti approvata dal Consiglio Superiore dei Lavori Pubblici "Istruzioni per l'applicazione delle nuove norme tecniche per le costruzioni di cui al D.M. 14 gennaio 2008".
- Clemente, R. (2006). Análisis estructural de edificios históricos mediante modelos localizados de fisuración. PhD Thesis, Technical University of Catalonia, Spain, (in Spanish).
- Clemente, R., Roca, P. & Cervera, M. (2006). Damage model with crack localization – application to historical buildings. In Lourenço, P. B., Roca, P., Modena, C. & Agrawal, S. (Eds.) *Structural analysis of historical constructions*, pp. 1125 – 1133.
- CPA (2003a). Restauración de la portada principal de la catedral de Palma de Mallorca. Memoria final. Report, available at: http://catedraldemallorca.info/principal/images/catedral/media/folletos/Memoria_Portada_Principal_Palma.pdf.
- CPA (2003b). Restauración de la portada del Mirador de la catedral de Palma de Mallorca. Report available at: http://catedraldemallorca.info/principal/images/catedral/media/folletos/Informe_visita_12_13_07_2012.pdf
- Coutinho, D. (2010) Seismic analysis and strengthening of Mallorca cathedral. MSc thesis, Technical University of Catalonia, Barcelona, Spain.
- Cuello, S. I. (2007). Dynamic analysis of Mallorca cathedral. Graduation Thesis, Technical University of Catalonia, Spain, (in Spanish).
- Das, A. K. (2008). Safety assessment of Mallorca cathedral. MSc Thesis, Technical University of Catalonia, Spain.
- Domenge, J. (1995a). *Traces d'una fortuna historiogràfica*.
- Domenge, J. (1995b). *Tres segles d'obras a la seu*.
- Domenge, J. (1997). *L'obra de la Seu. El procés de construcció de la catedral de Mallorca en el tres-cents*. Palma: Institut d'Estudis Baleàrics.
- Elyamani, A., Caselles, J. O., Clapes, J., & Roca, P. (2012). Assessment of dynamic behavior of Mallorca Cathedral. In *Structural Analysis of Historical Constructions. Proceedings of the International Conference on Structural Analysis of Historical Constructions, SAHC 2012* (pp. 2376-2384).
- Elyamani, A. (2015). Integrated monitoring and structural analysis strategies for the study of large historical construction. Application to Mallorca cathedral, PhD thesis, Technical University of Catalonia, Spain.
- Elyamani, A., Caselles, J.O., Roca, P and Clape, J (2017a) Dynamic investigation of a large historical cathedral. *Structural Control and Health Monitoring*, 24.3 (2017).
- Elyamani, A., Roca, P, Caselles, J.O., and Clape, J. (2017b) Seismic Safety Assessment of Historical Structures Using Updated Numerical Models: the Case of Mallorca Cathedral in Spain, *Engineering Failure Analysis* 74 (2017): 54-79.
- Elyamani, A, Caselles, O, Roca, P, and Clapes, J (2018) Integrated dynamic and thermography investigation of Mallorca Cathedral. *Mediterranean Archaeology & Archaeometry*, Vol.18, No.1, p. 221-236.
- Elyamani, A. and Roca, P. (2018a). A review on the study of historical structures using integrated investigation activities for seismic safety assessment. Part I: dynamic investigation, *Scientific Culture*, Vol. 4, No. 1, pp. 1-27. DOI: 10.5281/zenodo.1048241.
- Elyamani, A. and Roca, P. (2018b). A review on the study of historical structures using integrated investigation activities for seismic safety assessment. Part II: model updating and seismic analysis, *Scientific Culture*, Vol. 4, No. 1, pp. 29-51. DOI: 10.5281/zenodo.1048243.
- Godde, E. (2009). Static monitoring analysis of Mallorca cathedral. MSc thesis, Technical University of Catalonia, Barcelona, Spain.
- González, J. L. and Roca, P. (2003-2008). Study of structural-constructive behavior of Saint Mary cathedral in the city of Palma, Mallorca Island (Balears). First Phase: Part I. (2003), Part II (2003), Part III (2004),

- Part IV (2004). Second Phase: Part V. (2008), Part VI (2008), Technical University of Catalonia, Spain, (In Spanish)
- González, R., Caballé, F., Domenge, J., Vendrell, M., Giráldez, P., Roca, P., & González J. L. (2008). Construction process, damage and structural analysis. Two case studies. In D'Ayala, D. and Fodde, E. (Eds.) *Structural Analysis of Historical Construction*. CRC Press Balkema, pp. 643–651.
- Grande, C. (2013). Correlation between weather conditions, heating of structural elements, and the dynamic behavior of Mallorca Cathedral. MSc Thesis, Technical University of Catalonia, Spain.
- Herráez, J., A. (2012). Inspección técnica portadas de la catedral de Palma de Mallorca. Report, available at: <http://www.catedraldemallorca.info/principal/images/catedral/media/folletos/CP1218.pdf>.
- Lagomarsino, S., Giovinazzi, S., Podestà, S., Resemini, S. (2003). Vulnerability assessment of historical and monumental buildings handbook, Report in WP5, RISK-EU project: An advanced approach to earthquake risk scenarios with application to different European towns, contract no. EVK4-CT-2000-00014.
- Liritzis, I., Al-Otaibi, F., Kilikoglou, V., Perdikatsis, V., Polychroniadou, E., Drivaliari, A. (2015). Mortar analysis of wall painting at Amfissa cathedral for conservation – restoration purposes. *Mediterranean Archaeology and Archaeometry*, Vol. 15, No 3,(2015), pp. 301-311.
- Llompарт, G. (1995). El Coro, *La catedral de Mallorca*. Pascual, A. (coord.), Palma.
- MACEC 3.2 a MATLAB Toolbox for Experimental and Operational Modal Analysis, 2011. Developed by Reynders E, De Roeck G, Copyright © KU Leuven, Belgium.
- Mark, R. (1982). *Experiments in Gothic structure*. 1st ed. Cambridge, Mass.: MIT Press.
- Martínez, G., Roca P., Caselles O. and Clapés J. (2006). Characterization of the Dynamic Response for the Structure of Mallorca Cathedral. *Structural Analysis of Historical Constructions*. Vol I: 601-608.
- Martínez, G. (2007). Seismic vulnerability for middle and long span masonry historical buildings (in Spanish). PhD thesis, Technical University of Catalonia, Barcelona, Spain.
- Martínez, G., Roca, P., Caselles, O., Clapés, J. and Barbat, A.H. (2007) Determinación experimental y analítica de las propiedades dinámicas para la Catedral de Mallorca. *Structural Engineering (Intersections/Interseccïi)*, 4(2), Article No.4.
- Maynou, J. (2001). Estudi estructural del pòrtic tipus de la catedral de Mallorca mitjançan l'estàtica gràfica. Graduation Thesis, Technical University of Catalonia, Spain (in Catalan).
- Molins, C. (1996). Un modelo para el análisis del comportamiento resistente de construcciones de obra de fábrica. PhD Thesis, Technical University of Catalonia, Spain.
- Molins, C. & Roca, P. (1998). Capacity of masonry arches and spatial frames. *ASCE Journal of Structural Engineering*, 124(6): 653-663.
- Murcia, J., Das, A. K., Roca, P., & Cervera, M. (2009). Seismic safety analysis of historical masonry structures using a damage constitutive model. *2nd International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, COMPDYN09*, 22-24 June, Rhodes, Greece.
- NBE-AE/88 (1988). *La norma básica de edificación: acciones en la edificación*. (In Spanish).
- NCSE-02 (2002). *Norma de construcción sismo resistente – Parte general y edificación*. (In Spanish).
- Pelà, L. (2009). Continuum damage model for nonlinear analysis of masonry structures, PhD thesis, Università degli studi di Ferrara, Italy.
- Pelà, L., Cervera, M. & Roca, P. (2011). Continuum model for inelastic behaviour of masonry. *Congresso dell'Associazione Italiana di Meccanica Teorica e Applicata*, 12-15 September, Bologna, Italy.
- Pelà, L., Bourgeois, J., Roca, P., Cervera, M., & Chiumenti, M. (2016). Analysis of the Effect of Provisional Ties on the Construction and Current Deformation of Mallorca Cathedral. *International Journal of Architectural Heritage*, 10(4), 418-437.
- Pelà, L., Bourgeois, J., Roca, P., Cervera, M., Chiumenti, M. (2016) Analysis of the effect of provisional ties on the construction and current deformation of Mallorca cathedral. "*International journal of architectural heritage*", vol. 10, núm. 4, p. 418-437.
- Pérez-Gracia, V.; Caselles J.O.; Clapes, J.; Osorio, R.; Martínez, G.; Canas, J.A. (2009). Integrated near-surface geophysical survey of the Cathedral of Mallorca. *Journal of Archaeological Science*, Vol. 36:7, 1289-1299.
- Pérez-Gracia, V., Caselles, J., Clapés, J., Martínez, G. & Osorio, R. (2013). Non-destructive analysis in cultural heritage buildings: Evaluating the Mallorca cathedral supporting structures. *NDT and E International*, 59, pp.40-47.
- Roca, P. & González, J. L. (2001). Structure, history and morphology: The case study of the upper flying arches of Mallorca Cathedral. *UNESCO Millenium Conference*, Paris, France.

- Roca, P. (2001). Studies on the structure of Gothic cathedrals. In: Lourenço, P.B. and Roca, P. (Eds.) *Historical Constructions*, University of Minho, Guimarães, pp. 71-90.
- Roca, P., & Lodos, J. C. (2001). Análisis estructural de catedrales góticas. *OP Ingeniería y Territorio*, (56), 38-47.
- Roca, P. (2004). Detailed description of Mallorca cathedral. Report in the project Improving the seismic resistance of cultural heritage buildings, funded by EU-INDIA Economic Cross Cultural Programme, contract n. ALA/95/23/2003/077-122.
- Roca, P., Clapés, J., Caselles, O., Vendrell, M., Giráldez, P. & Sánchez-Beitia, S. (2008). Contribution of inspection techniques to the assessment of historical structures. *International RILEM Conference*, 1-2 September, Como Lake, Italy.
- Roca, P., Vacas, A., Cuzzila, R., Murcia-Delso, J., & Das, A. K. (2009). Response of Gothic churches in moderate seismic Mediterranean regions. *ISCARSAH Symposium on Assessment and Strengthening of Historical Stone Masonry Constructions Subjected to Seismic Action*, Mostar, Bosnia and Herzegovina, 12th July.
- Roca, P., Cervera, M., Pelà, L., Clemente, R., Chiumenti, M (2012a). Structural assessment of Mallorca cathedral. *8th International Conference on Structural Analysis of Historical Construction*. 15-17 October 2012, Wrocław, Poland.
- Roca, P., Cervera, M., Pelà, L., Clemente, R. (2012b). Construction process numerical simulation and seismic assessment of Mallorca Cathedral. *15th International Brick and Block Masonry Conference*, 3-6 June, Florianópolis, Brazil.
- Roca, P., Cervera, M., Pelà, L., Clemente, R. and Chiumenti, M. (2012c). Viscoelasticity and damage model for creep behavior of historical masonry structures. *Open Civil Engineering Journal*, 6, pp.188-199.
- Roca, P., Cervera, M., Pelà, L., Clemente, R., & Chiumenti, M. (2013). Continuum FE models for the analysis of Mallorca Cathedral. *Engineering Structures*, 46, 653-670.
- Rubió, J. (1912). Lecture on the organic, mechanical and construction concepts of Mallorca Cathedral, *Anuario de la Asociación de Arquitectos de Cataluña, Barcelona*, (in Spanish).
- Salas, A. (2002). Structural study of the typical bays of Mallorca cathedral. Graduation Thesis, Technical University of Catalonia, Spain. (in Spanish)