Approach to Seismic Behavior of Mallorca Cathedral

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SUMMARY:
The paper presents the current state of an on-going research aimed at characterizing the seismic response of Mallorca cathedral. Mallorca cathedral is an audacious Gothic structure built in the island of Mallorca during 14th-16th centuries, characterized for its large dimensions and slender structural members. So far, experimental and numerical modal analysis, in addition to tentative model updating and seismic analysis, have been performed. The dynamic identification tests have been carried out by ambient vibration testing, while the frequency domain decomposition (FDD) technique has been used to obtain the modal parameters. A 3D Finite Element (FE) model has been used to determine the vibration modes. The model has been updated by modifying some structural parameters to improve the matching between experimental and numerical modal parameters. Once updated, the model has been utilized to study the seismic response of the cathedral using non-linear static pushover analysis. Conclusions on the possible collapse mechanisms and the seismic performance of the structure are presented.

Keywords: dynamic identification, model updating, seismic analysis

1. INTRODUCTION

Historical masonry construction can generally sustain vertical loads in a stable and safe manner while showing certain vulnerability to seismic loads. In case of a complex structure like Mallorca cathedral, located in a low-to-moderate seismic zone, the vulnerability arises from its daring structural features, as in particular the very slender columns, the long-span arches and vaults, and the high central nave vaults. Mallorca Island has experienced at least three moderate earthquakes with intensity bigger than VI during the last centuries: Campos-Palma in 1660; Selva in 1721 and Palma-Marratxi in 1851. This last event had intensity of VIII, and is considered as the major seismic event in the island in the last four centuries (Martínez et al., 2006).

Dynamic identification tests are useful to characterize the main modal parameters (natural frequencies, mode shapes and damping ratios). These data represent the structure's dynamic behaviour as a result of physical or mechanical properties (as the elastic modulus of the masonries) that may be difficult to obtain. The real response of the structure under specified or unknown excitations can be used to calibrate FE models (Ramos et al., 2011). In the current research, still in progress, the dynamic identification tests were carried out as one of the tasks planned to assess the seismic performance of Mallorca cathedral. The extracted modal parameters were then used to tune a FE model. The tuned model was then used for the seismic assessment by means of nonlinear static pushover analysis.

2. THE STRUCTURE

The building is composed by three different bodies (Figs. 1 and 2): a small apse (the so-called Trinity Chapel, part A in Fig. 1); a choir built in the shape of a single nave Gothic construction (the Royal Chapel, part B in Fig. 1) and the main nave (part C in Fig. 1) which constitutes the main body of building.

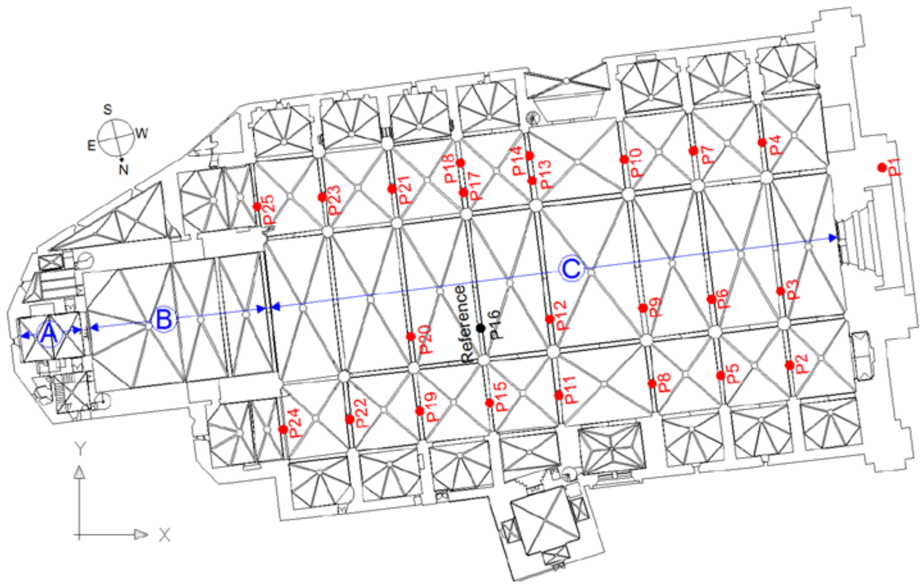

Figure 1: Plan of the cathedral indicating the main parts and the measured points in the dynamic identifications tests

Figure 2: General view of Mallorca cathedral showing south facade and apse

The construction started around the year 1300. The Trinity Chapel and the Royal Chapel were completed around the years 1311 and 1370, respectively. The imposing main large nave and the west facade were completed by the year 1601 (Domenge, 1999). The main nave is composed of a central nave and two lateral naves surrounded by a series of lateral chapels constructed between the buttresses. The central nave spans 19.9 m and reaches a height of 43.9 m at the vaults' keystone. The two lateral naves span 8.72 m each and reach 29.4 m at the vaults' keystone. The naves are supported on octagonal piers with a circumscribed diameter of 1.6 and 1.7 m and a height of 22.7 m to the springing of the vaults.

3. DYNAMIC IDENTIFICATION AND MODEL UPDATING

3.1 Description of Tests

Three tri-axial force balance accelerometers were used to carry out the ambient vibration dynamic tests. Two of them correspond to the CMG-5T model with dynamic range of 140 dB for 0.005 to 0.05 Hz and 127 dB for 3 to 30 Hz, bandwidth ranging from DC to 100 Hz, full scale from 0.1 to 4g, and weight of 2.7 Kg. The other one is Titan model with dynamic range of 166 dB for 1 Hz and 155 dB for 3 to 30 Hz, bandwidth ranging from DC to 430 Hz, full scale from 5 V/g to 80 V/g, and weight of 960 gm. Acceleration records were measured in 25 points in 15 different setups. In all tests one accelerometer (P16 in Fig. 1) was kept immovable. The test time was chosen to be approximately 1000 times the fundamental period of the cathedral (Ramos, 2007) which was previously found analytically and experimentally by (Martínez et al., 2006). The recording time for each setup was 15 minutes with 100 samples per second. A 9-channel Digital to Analogue Converter was used for data acquiring.

3.2 Results of Tests

The Frequency Domain Decomposition (FDD) technique (Brincker, Zhang and Andersen 2000, 2001) was used for determining the modal parameters (natural frequencies and mode shapes). In this technique the Power Spectrum Density (PSD) matrix is firstly evaluated then decomposed with the Singular Value Decomposition (SVD) method. The recorded signals were processed by a decimation of 1 (Nyquist frequency of 50 Hz), the number of lines between 0 Hz and the Nyquist frequency is 4096, and the Hanning window overlap is 66,67%. The peaks related to resonant frequencies were picked (Fig. 3), and then the corresponding mode shapes were defined.

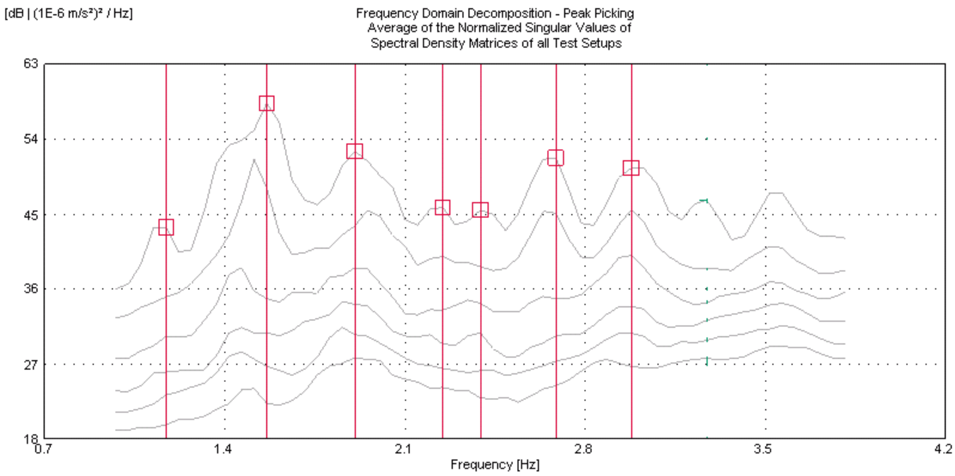

Figure 3: Frequency decomposition of all setups processed together and picked peaks

It was not possible to identify all the modes. The identified modes in each individual setup and in all setups processed together were investigated. Based on that, it was concluded that the fourth, fifth, sixth, seventh and eighth modes were reasonably identified. Those modes were considered for the modal matching and the updating process of the FE model, discussed later. It is noteworthy that the identified frequencies were confirmed by the long term monitoring of the cathedral, performed for nine continuous months just after the dynamic identification tests (Elyamani et al., 2012).

3.3 Model Updating

The finite element model previously used by (Martínez et al., 2007) was used for the current study. The same properties of materials were also used as initial values in the updating process. The model was built in Diana code (TNO DIANA, 2005). Vaults were modelled using T15SH elements, three-node triangular isoparametric curved shells. The rest of the cathedral was modelled using TE12L elements, four-node three-side isoparametric solid pyramid. The model includes 149248 nodes and 491851 elements with 490789 degrees of freedom (Fig. 4).

In the model updating process, experimental and numerical frequencies and mode shapes were compared. The mode shapes were compared using the Modal Assurance Criterion (MAC) (Allemang and Brown, 1982; Allemang, 2003), defined as

$$MAC_{e,n} = \frac{\left| \sum_{i=1}^{n} \varphi_i^e \varphi_i^n \right|^2}{\sum_{i=1}^{n} \left(\varphi_i^e\right)^2 \sum_{i=1}^{n} \left(\varphi_i^n\right)^2} \tag{4.1}$$

where φ^e and φ^n are the experimental and numerical mode shape vectors, respectively. A MAC value less than 0,40 is considered a poor match while MAC value greater than 0,80 is considered a good match (Gentile and Saisi, 2004).

So far, two updating steps have been carried out. In the first step, we introduced springs to compensate for un-modelled parts. Those parts include mainly the vaults of lateral chapels, the adjacent building to the tower and the trinity chapel. In the second step, the Young's moduli (E) of different materials were modified. The comparison of modes was carried out taking into account their corresponding shapes. It must be noted that some of the modes obtained numerically were not detected in the experiments. Figure 5 shows the comparison between numerical and experimental mode shape with the highest MAC value. In terms of frequency difference the updating is sufficient, but in terms of MAC values more updating steps are required.

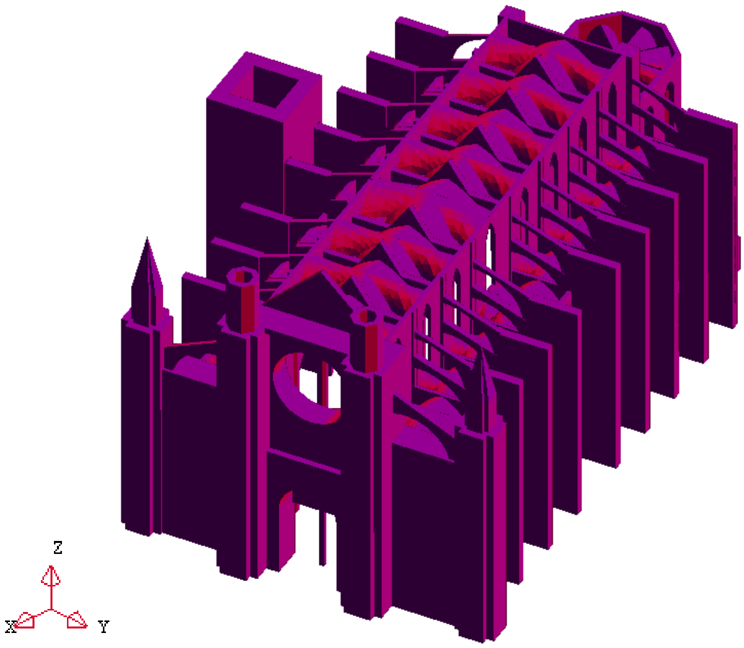

Figure 4: FE model of Mallorca cathedral

Table 1. Model updating results.

Num. mode no.	Exp. mode no.	Exp. mode F (Hz)	Initial model F (Hz)	Initial model Error %	Initial model MAC	Step 1 F (Hz)	Step 1 Error %	Step 1 MAC	Step 2 F (Hz)	Step 2 Error %	Step 2 MAC
2	4	1,563	1,592	1,9	0,697	1,721	10,1	0,713	1,624	3,9	0,713
3	5	1,904	1,694	11,0	0,363	1,980	4,0	0,248	1,868	1,9	0,248
7	6	2,246	2,116	5,8	0,137	2,399	6,8	0,308	2,263	0,8	0,308
9	7	2,393	2,446	2,2	0,326	2,515	5,1	0,378	2,372	0,9	0,378
10	8	2,686	2,638	1,8	0,467	2,730	1,6	0,498	2,576	4,1	0,498
			Aver-age	4,54	0,398	Aver-age	5,52	0,429	Aver-age	2,32	0,429

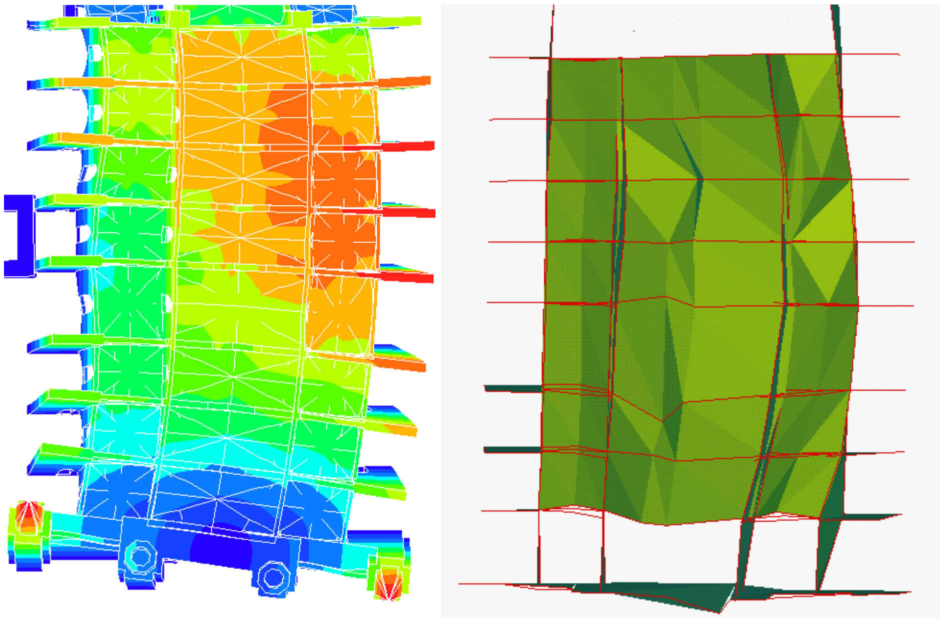

Figure 5: Comparison between 2nd numerical mode (left) and 4th experimental mode (right)

4. SEISMIC ANALYSIS

4.1 Properties of Materials

To simulate nonlinear behaviour of masonry, both cracking (tensile regime) and crashing (compressive regime) were considered in the material model. Tensile regime was modelled using tension cut-off with multi-directional fixed crack model (smeared cracking). The previous model was accompanied by isotropic plastic Drucker-Prager model in compressive regime. The nonlinear properties of materials were guided by the values previously used by Martínez (2007) and Clemente (2006). The updated values of Young's moduli were also used. The tensile strength (f_t) was assumed as 5% of compressive strength (f_c). The cohesion for the used model in compression is calculated from f_c, angle of dilatancy (ψ), and angle of internal friction ($\o$) using Eqn. 4.2. For simplicity associative plasticity was assumed ($\psi = \o$). The materials parameters are specified in table 2.

$$C = f_{c.} \frac{1 - \sin\phi}{2\cos\psi} \tag{4.2}$$

Table 2. Properties of different materials used in nonlinear seismic analysis.

Structural elements	E (GPa)	υ (Poisson's ratio)	γ (Specific weight) N/m^3	f_t (MPa)	ε_u Ultimate strain	C (MPa)	$\psi = \o$
Columns and flying arches	13,6	0,20	2400	0,40	0,1%	3,36	10 º
The rest of the cathedral.	3,4	0,20	2100	0,10	0,4%	0,84	10 º

4.2 Seismic Loads

The seismic analysis was carried out by the static nonlinear pushover method. In this method, a monotonically increasing horizontal load is applied under constant gravity load. The horizontal load distribution adopted was a uniform load proportional to the structural elements' masses. The cathedral was subjected to seismic loads in the longitudinal (X-direction) and transversal (Y-direction) considering both positive and negative sings (see Fig. 4 for axes directions). The procedure is well known and is both proposed by Eurocode 8 and the Spanish seismic code (NCSE-02); it has also been applied previously to similar historical structures, e.g. (Betti and Vignoli 2008, 2011; Elyamani, 2009; Lourenco et al., 2010).

4.3 Seismic Response of The Cathedral

The structure shows different seismic capacity depending on the direction of the applied seismic forces (transversal or longitudinal). In the transversal direction the building shows are eight frame-like structures including imposing buttresses. These frames show large capacity when the forces are applied in its more resistant (in plane) direction. The loading of buttresses in a direction perpendicular to their plane and the large windows in the clerestory walls produces a weaker system, and therefore a lower seismic response, in the longitudinal direction. The expected spectral acceleration is of 0.1g according to Martínez (2007).

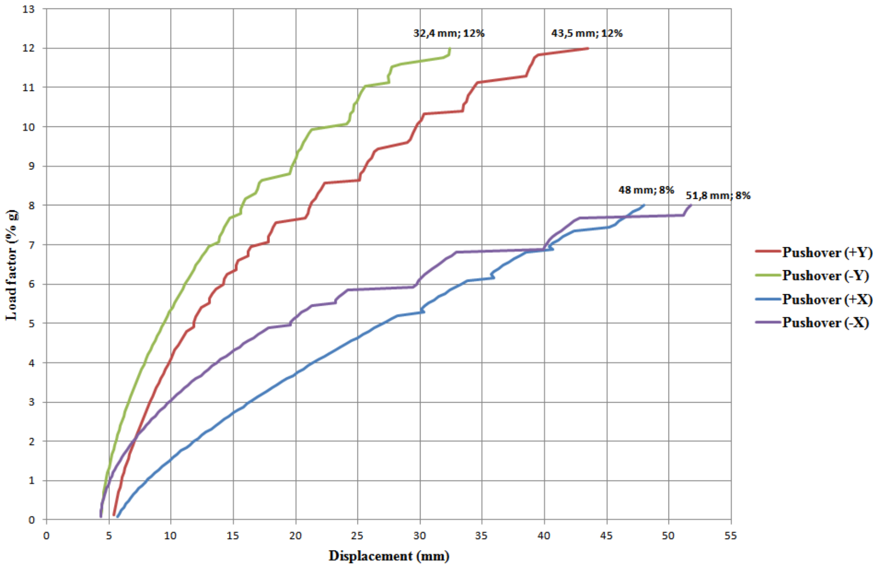

Figure 6: Capacity curves under seismic loads in different directions

Fig. 6 shows the capacity curves obtained. In both X and Y directions (using the axes indicated in Fig. 1), the structure behaves linearly up to seismic load about 0.05g with clear higher stiffness for an earthquake in the Y-direction, which is the stronger direction of the structure. The collapse occurs at seismic load of 0.08g in X-direction and 0.12g in Y-direction. The curves are saw-tooth like. This can be related to the number of insufficient integration points through the thickness (1 point for solids and 3 points for shells were utilized), the usage of relatively coarse mesh in the damaged regions, and the opening of several cracks. This type of saw-tooth curves have also been obtained in other studies (Rots, 2001, Trujillo 2009) on similar structures.

The damage experienced by the structure under seismic forces applied in the transverse +Y direction, at the last step of analysis, is described includes the following aspects:

- Diagonal cracking in southern buttresses, starting from most tensioned zones and passing through windows openings. Compression damage also appears on the other side of the buttresses in the most compressed zone. Northern buttresses are showing also diagonal cracks around windows (Fig. 7).

- The pillars are showing cracks at their bases, at both the compressed and the tensioned sides, and at the springing of arches (Fig. 7).
- Cracking along the full span of flying arches. The cracks are more intensive at the connections with buttresses and clerestory walls (Fig 7).
- Intensive cracks in vaults of lateral and central naves (Fig. 8). This finding is matched with historical documentation of several collapses and reconstruction of vaults.
- There are concentration of cracks at the connection between tower and the two adjacent buttresses, in addition to diagonal cracking in tower (Fig. 9). It is noteworthy that the tower is connected to adjacent buttresses up to approximately one third of its height only.
- The facade is showing diagonal cracks in the walls between towers, and around the rose window. The flying arches of façade are cracked only at the connection with the owers (Fig. 10).

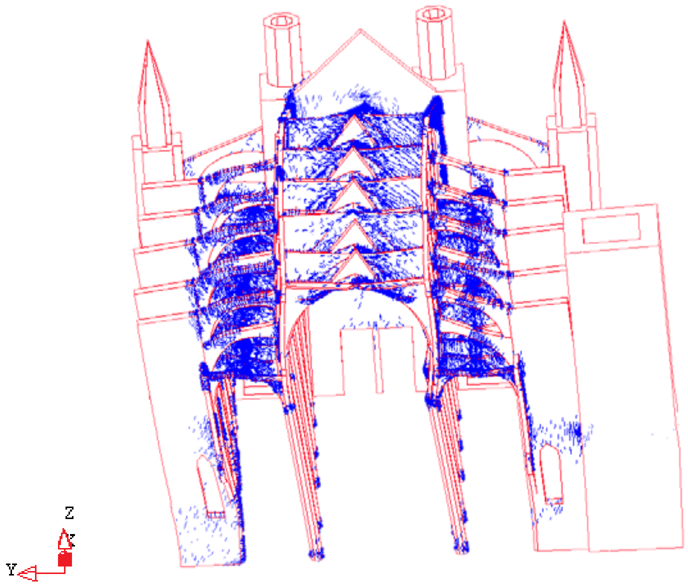

Figure 7: Crack patterns (in blue) in buttresses, pillars and flying arches after an earthquake in +Y direction

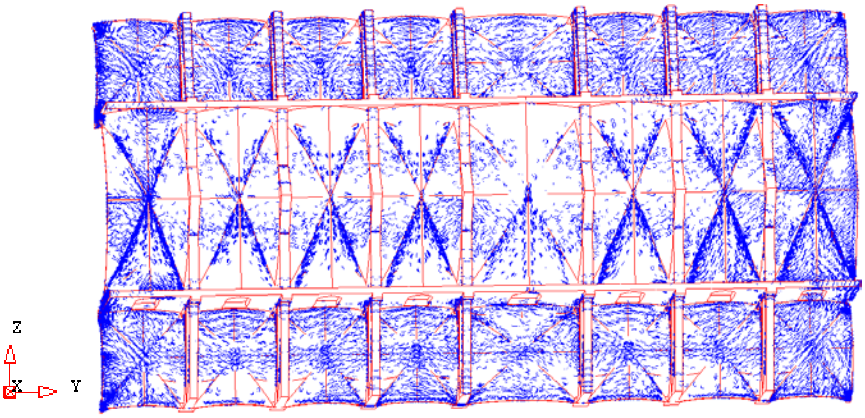

Figure 8: Intensive cracks (in blue) in vaults

For the case of seismic load in +X-direction, and at the last step of analysis, the damage is characterized by:

- Diagonal cracks passing around windows' openings in upper clerestory walls connected to pillars, and lower clerestory walls connected to buttress (Figs. 11 and 12).
- Cracks at pillars bases and at its connection with clerestory wall (Fig. 11).
- Diagonal cracking in apse walls (Fig. 12).
- Symmetrical cracking in facade (Fig. 13).
- There are intensive cracks in vaults like the earthquake in +Y direction.

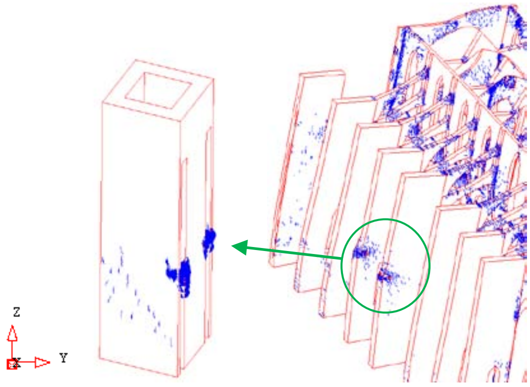

Figure 9: Concentration of cracks (in blue) at connection of tower and cathedral after an earthquake in +Y direction

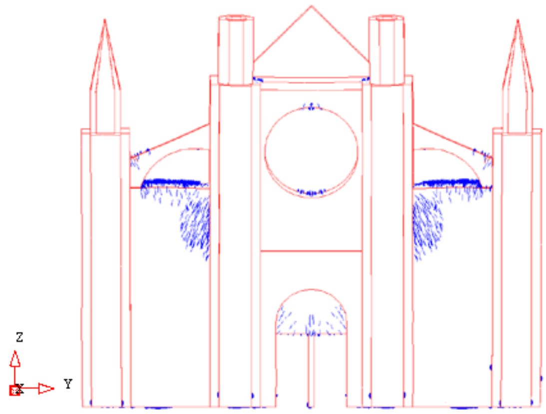

Figure 10: Crack pattern (in blue) in facade after an earthquake in +Y direction

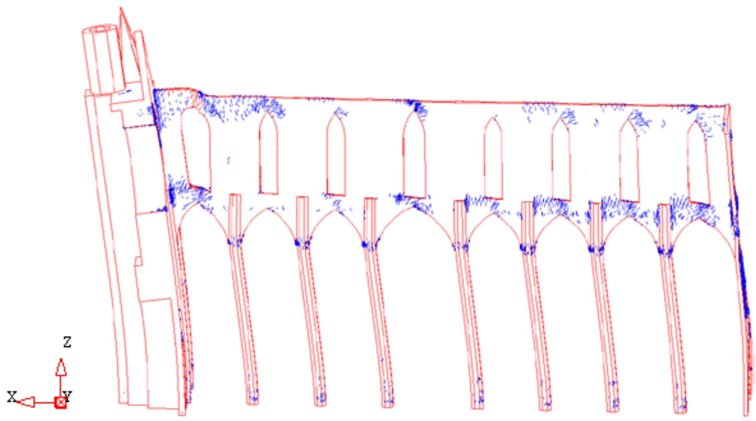

Figure 11: Crack patterns (in blue) after an earthquake in +X direction at frame of pillars and upper clerestory wall

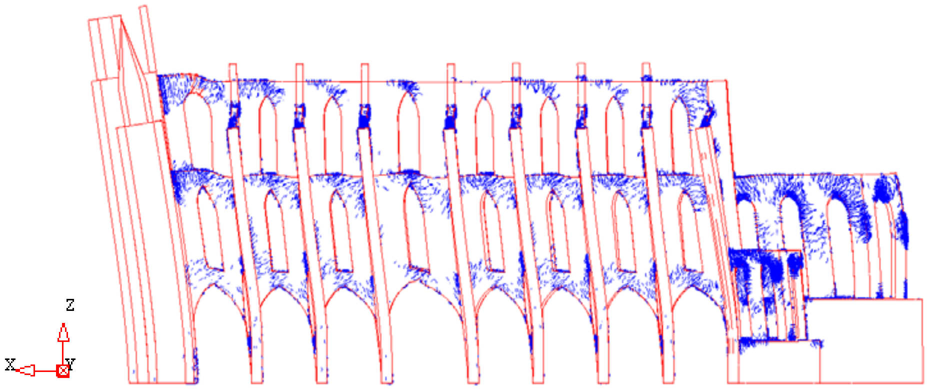

Figure 12: Crack patterns (in blue) after an earthquake in +X direction at apse walls and frame of buttresses and lower clerestory wall

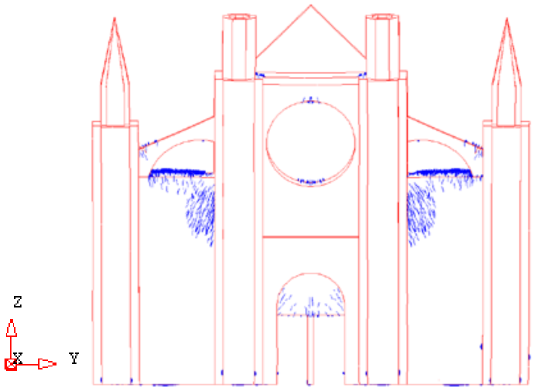

Figure 13: Crack patterns (in blue) after an earthquake in +X direction at facade

5. CONCLUSIONS

The paper presents an application of ambient vibration dynamic identification tests on a complex structure. Only well identified mode shapes and frequencies were used for the purpose of updating the global FE. The modal shape of each associated pair of experimental and numerical modes was visually compared to assure an adequate correspondence. In terms of frequencies, the updating process was sufficient and satisfactory. In terms of MAC values, it can be considered only acceptable. Many effects may be affecting the obtained MAC values, among which the soil-structure interaction, not considered so far in the modal, and the existing cracks. In addition to include the influence of the soil, it is intended to improve the model by simulating the main existing cracks as discontinuities in the FE mesh.

The tuned model was subjected to seismic loads in both the transversal and longitudinal directions using nonlinear static pushover analysis. The curves showed that the cathedral has higher resistance in transversal direction than in longitudinal one. The resisted acceleration in transversal direction is a little higher than the expected spectral one, whereas in the longitudinal direction it is slightly lower.

The pillars' bases and their connections with the clerestory walls showed important cracks, which reveal that those places are vulnerable when subjected to earthquakes in either transversal or longitudinal directions, and should be considered carefully in any future intervention plans. The severe crack patterns found in vaults are consistent with the historical documentation of several collapses of those structural elements.

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