Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Characterization of the Dynamic Response for the Structure of Mallorca Cathedral

G. Martínez
UMSNH - Universidad Michoacana de San Nicolás de Hidalgo, Civil Engineering School, México

P. Roca
Technical University of Catalonia, Department of Construction Engineering, Barcelona, Spain

O. Caselles and J. Clapés
Technical University of Catalonia, Department of Geotechnical Engineering and Geo-Sciences, Barcelona, Spain

ABSTRACT: The paper presents an on-going investigation carried out to characterize the seismic response of Mallorca Cathedral, one of the largest and more audacious medieval structures built in Europe. In spite of being located in the Balearic Islands, a moderate seismic region, the seismic performance of the building is of concern due to the large dimensions and slenderness of its structural members. The investigation combines a set of integrated activities, including the dynamic experimental characterization by ambient vibration measurements and the numerical analysis of the building by means of detailed FEM modeling. Preliminary results are presented regarding (1) the application of modal matching to the calibration of a partial model of the building and (2) a seismic performance analysis of a typical nave bay subjected to a seismic demand obtained from hazard analysis. The study referred is part of a more exhaustive research, still in progress, aimed at evaluating the seismic behavior and vulnerability of the building.

1 INTRODUCTION

A large part of the architectural heritage of the world is located in high seismic places. In regions prone to earthquake, the study of the seismic performance of the structure is essential to conclude on the safety and the need for possible strengthening. Seismic assessment is also needed in low or medium seismic locations as a way of assuring the capacity of the structural systems to resist expectable earthquakes occurring in long-return periods. This need is even more obvious in the case of large and slender buildings due to the complexity of their dynamic response. This is the case of Mallorca Cathedral, located in a low-to-medium seismic region (the Balearic Islands). Mallorca Cathedral (Fig. 1) shows an audacious Gothic structure composed of long-span and slender members, such as long-span central nave vaults sustained on very slender piers.

The state of conservation of the building is mostly satisfactory. However, significant deformation and some cracking can be observed in piers, vaults and walls. Fig. 2 shows the existing crack pattern for the cathedral's south façade. The existing cracks and deformation are mainly attributed to local foundation soil conditions or to effects derived from the construction process itself (Roca, 2004). The already existing damage might contribute to weaken the strength response in the even of an earthquake.

According to seismic catalogues, the island of Mallorca has been since then affected by three major earthquakes (with intensity bigger than VI) in the last 400 years: Campos-Palma (1660), Selva (1721) and Palma-Marratxí (1851). The only earthquake that affected the cathedral occurred on May 15th,1851. A maximum VIII intensity in the Palma-Marratxí area was assigned (Mézcua and Martínez-Solares 1983) to this last event; that is why it can be considered as the major earthquake in Mallorca in the last four centuries.

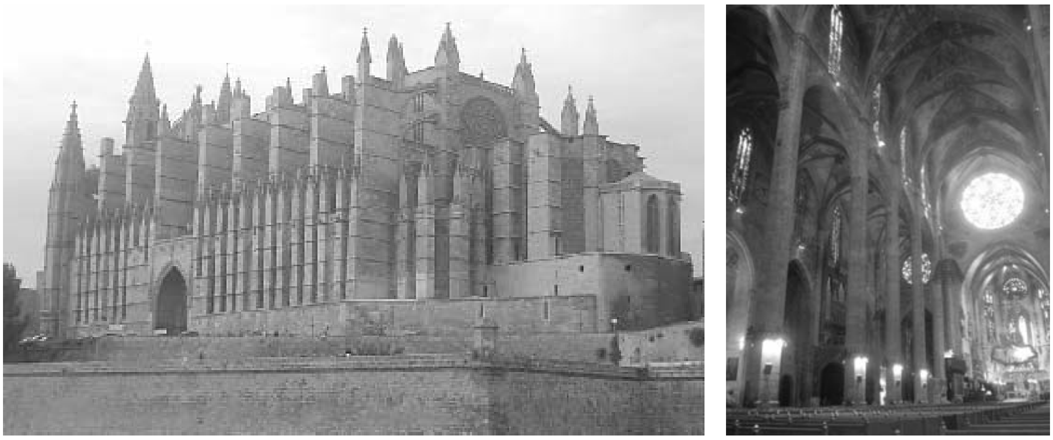


Figure 1 : Mallorca Cathedral

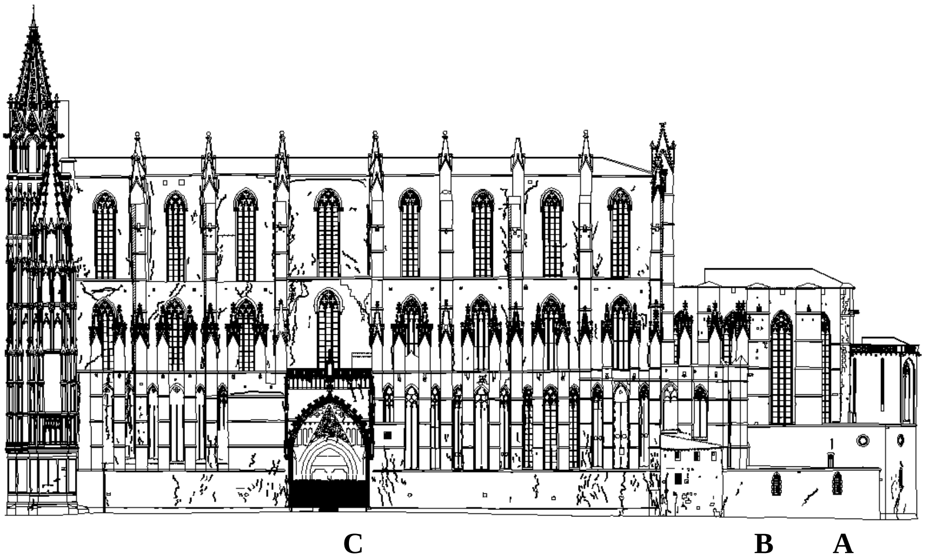


Figure 2 : Crack pattern of southern façade

2 THE STRUCTURE

The building has a total length of 120 m and encompasses three different bodies, including (from the East to West) a small apse (the so-called Trinity Chapel, A), a choir built in the shape of a single nave Gothic construction (the Royal Chapel, B) and the main nave (C, Fig. 2).

The largest body of building consists of the main large nave limited by the west façade and the choir. This main nave is, in turn, composed of a central nave, 44 m high, and two collateral naves surrounded by a series lateral chapel built between the buttresses. The central nave spans 19.9 m and reaches 43.9 m at the vaults keystone. The two collateral naves span 8.72 m each and reach 29.4 m at their vaults keystone. The naves are sustained on octagonal piers with a circumscribed diameter of 1.6 or 1.7 m and a height of 22.7 m to the springing of the vaults.

The central vaults transfer the lateral thrust towards the buttresses by means of a double battery of flying arches (Fig. 3, left). The central nave piers are made of solid masonry and are composed of large stone pentagonal and square blocks. The transverse arches of the central nave are diaphragmatic and are connected to the buttresses by a double battery of flying arches. The building contains a false transept connecting the northern and southern main doors. The bell-tower and cloister are located next to the northern façade. The highest point of the building, with a height of 64 m, is located on the west façade towers.

The building has been subjected important repairs throughout its history; particularly, a significant number of vaults of the central nave were repaired or even reconstructed during the 18th and 19th centuries. The original western façade, build during 15th c., was taken down and rebuilt as a new neo-Gothic construction during the second half of 19th c. The demolition of was motivated by the significant out-of plumb (about 1.3 m) experienced by the façade.

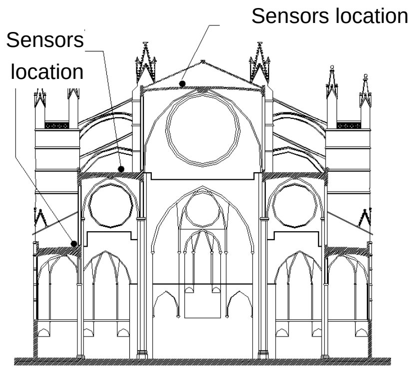
3 DYNAMIC PROPERTIES

3.1 Experimental investigations

Modal properties were estimated using ambient vibration (e.g. human activity at or near the surface of the earth, surf, running water, etc.) measurements on several points of the façade, chapels, lateral naves and main nave. Fig. 3 indicates the points where the measures were taken.

On each single point, a set of three minute acceleration records, utilizing 225 s.p.s., was performed. Using the well know *Peak Picking* technique (Bendat and Piersol 1993), and assuming low damping and well separated modes, several modal frequencies were determined.

Fig. 4 shows an acceleration record interval and its corresponding acceleration autospectrum obtained for sensors located over the main nave vaults. A fundamental frequency of 1.28 Hz can be noticed.



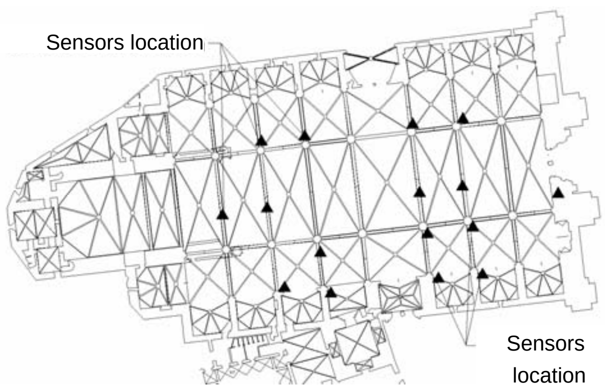
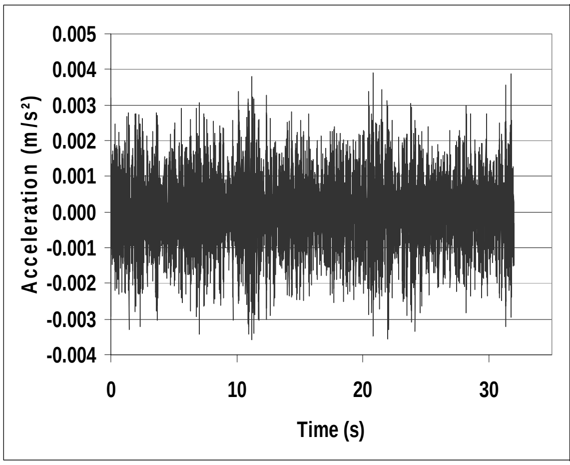


Figure 3 : Sensor location on a transversal section (left), and plan view sensors location (right)



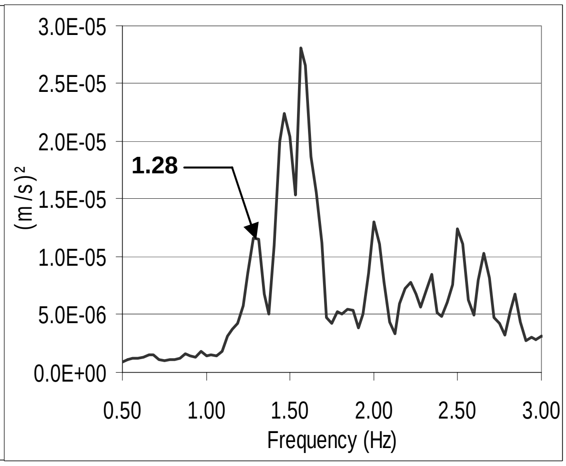


Figure 4 : Acceleration time record (left) and acceleration autospectrum (right)

3.2 Finite element model

A preliminary FEM model, including the structure of the main nave has been developed. The model includes 71335 nodes and 228134 elements (Fig. 5); the elements are four-node isoparametric solid tetrahedral ones. The meshing was performed using GID software (CIMNE 2006). An elastic eigenvalue analysis was performed using DIANA code (TNO DIANA 2005), in order to estimate the model natural frequencies and modal shapes.

The structural model was updated using experimentally measured frequencies. To match the experimental frequencies, it was necessary to globally increase 25% the Young modulus in piers, vaults and buttresses. The resulting values are presented in Table 1. Before updating, the value of the Young modulus used was set up to 1000 times the masonry compressive strength.

The stiffening action of the façade, the bell-tower and the choir (the Royal chapel) on the structural response of the nave was simulated by introducing appropriate boundary conditions. In particular, the modal matching allowed the identification of the following effects: (1) The façade provides very significant stiffness on the nave structure in the transverse direction; (2) The choir causes large displacement restriction in the longitudinal direction of the building (i.e. it provides large stiffness in the longitudinal direction); and (3) The bell-tower produces a longitudinal and transversal displacement restriction up to the chapels' highest level. The bell-tower is disconnected from the principal building over the chapels' highest level.

Based on the aforementioned observations, longitudinal displacement restriction (free transversal displacements) in the nave bay close to the choir and longitudinal free displacement (restricted transversal displacements) in the bay close to the façade end were defined in the analysis. Using the previously mentioned constraints, a satisfactory match between analytical and experimental modal frequencies was obtained (Table 2).

Notwithstanding, it is envisaged to improve the model by including a detailed and realistic description of façade, choir and bell-tower structural systems. This will permit the appraisal of the results obtained using the above preliminary model.

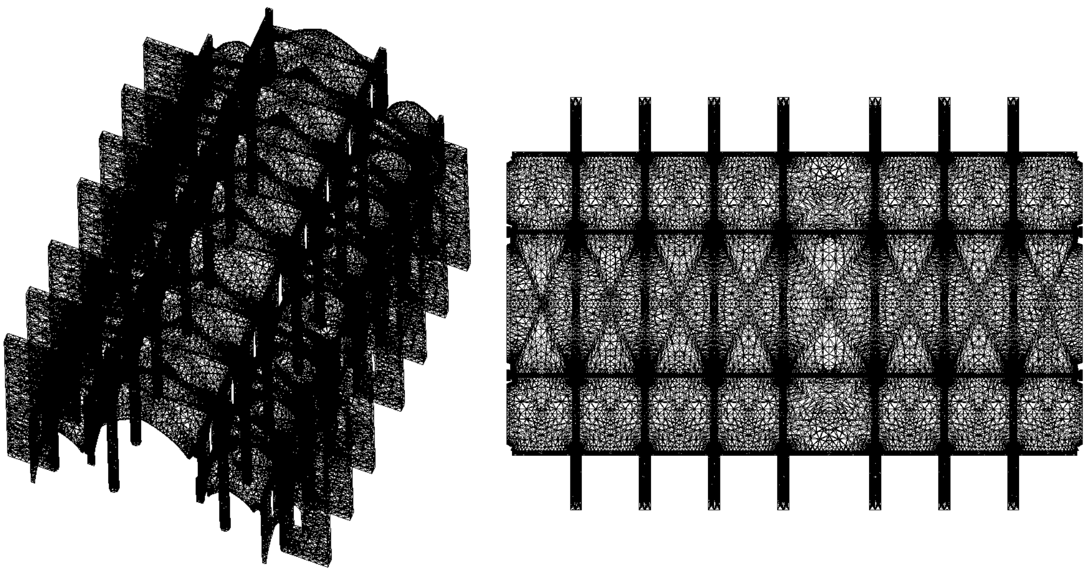


Figure 5 : Perspective of the FEM model (left) and plan view of the FEM model (right)

Table 1 : Model updated mechanical properties

	Young modulus Pa	Poisson coefficient -	Density Kg/m^3
Piers and flying arches	1.0E10	0.20	2400
Vaults, walls and buttresses	2.5E9	0.20	2100
Fill material	1.25E9	0.20	2000

Table 2 : Comparison between measured modal frequencies and analytical modal frequencies

Mode	Measured frequency Hz	Analytical frequency Hz	Difference %
1	1.28	1.22	4.92
2	1.47	1.51	2.72
3	1.63	1.59	2.52
4	1.84	1.86	1.09
5	2.03	2.08	2.46

3.3 Comparison of results

Table 2 summarizes the five first modal frequencies obtained from updated structural model and experimental testing showing a maximum 4.92% (mode 1) and a minimum 1.09% (mode 4) difference between reported values

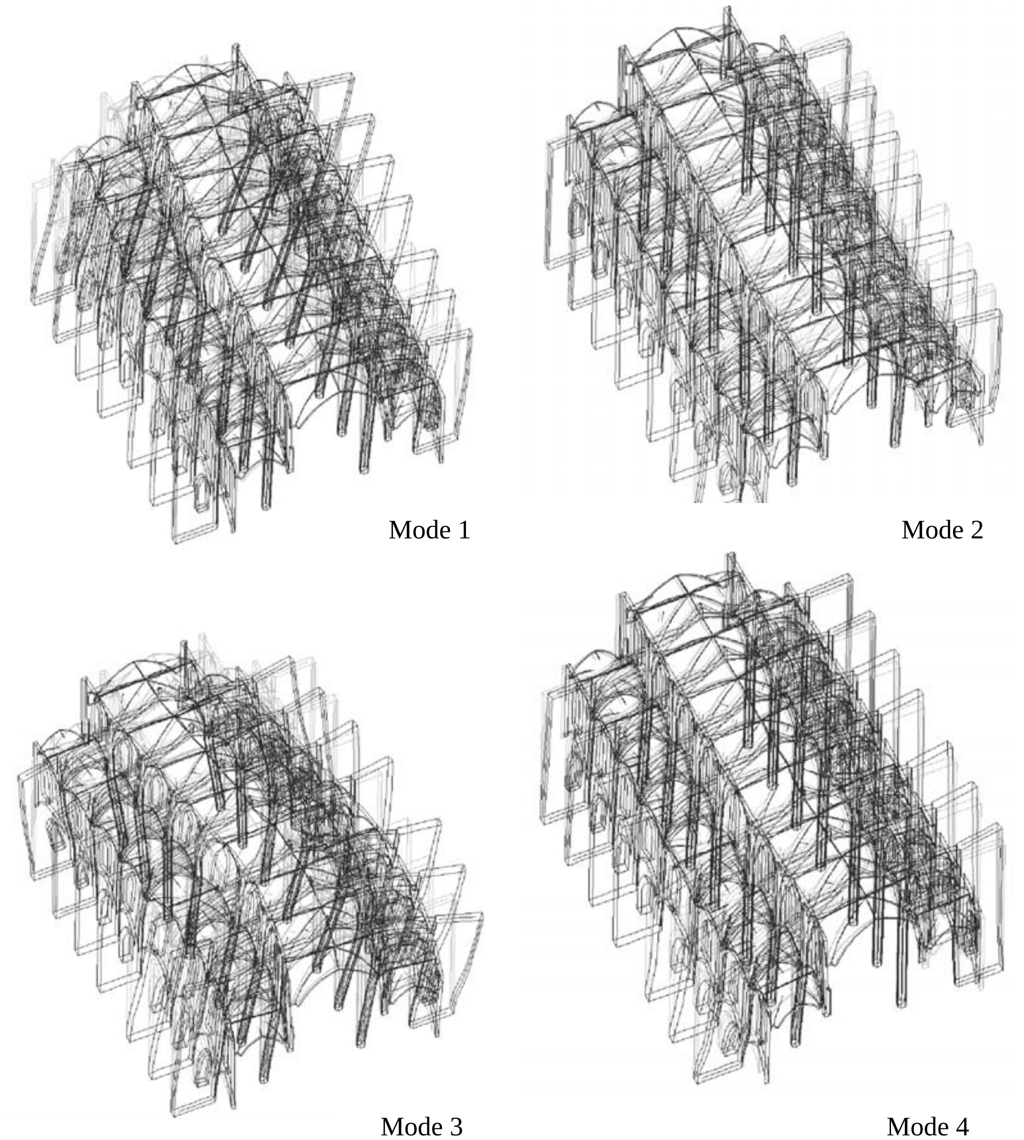


Figure 6 : Vibration modes 1-2-3-4

4 SEISMIC PERFORMANCE

Seismic performance can be measured in terms of damage level experimented by a structural system before a certain seismic hazard level is reached. The previous definition implies the definition of a seismic demand definition and the characterization of a structural seismic capacity (Freeman 1998).

This technique, known as the *capacity spectrum method*, introduces the Acceleration-Displacement Response Spectrum (ADRS) format, in which spectral accelerations are plotted against spectral displacements. The intersection of the capacity spectrum and the demand spectrum provides an estimate of the inelastic acceleration (strength) and displacement demand (Fajfar 2000).

4.1 Seismic demand definition

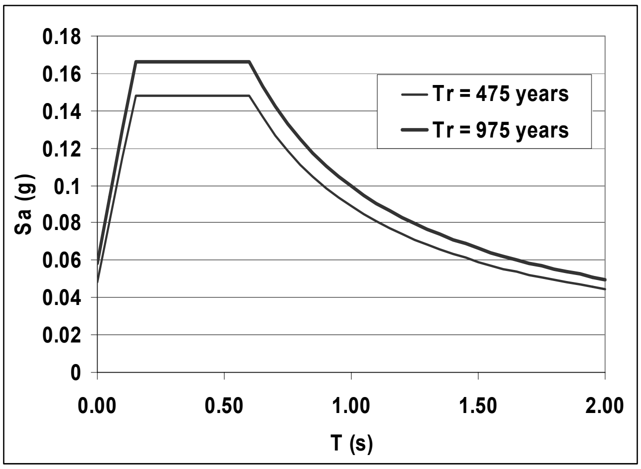
In order to define the elastic demand spectrum, a probabilistic seismic hazard analysis was performed on site using CRISIS 2003 software (Ordaz et al. 2003). Seismicity and geometric source data, proposed by the Global Seismic Hazard Assessment Program (Jiménez 1999), as well as Ambraseys et al. (1996) attenuation relationships, were used in seismic hazard calculations.

Return period (Tr) elastic spectrums of 475 and 975-year on middle soil presenting 5% critical damping, were generated. According to geotechnical studies performed on site, softened elastic spectrums were calculated considering class B soil and Eurocode 8 criteria (Fig. 7a).

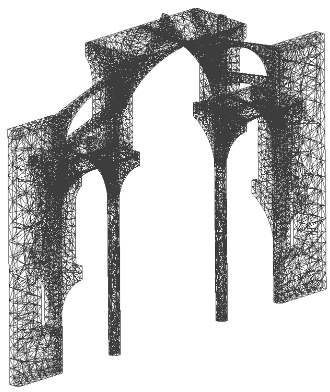
4.2 Structural capacity before seismic transversal demand

A seismic performance study carried out on a model of a single nave typical bay (Fig. 7b) is presented. The model includes 10356 nodes and 29681 four-node isoparametric solid tetrahedral elements. The study is performed to obtain insight on possible damage grade expected in the principal nave, considering an autonomous seismic response according to the macro-element definition (Lagomarsino 1998).

A non linear incremental *pushover analysis* was performed non-linear distributed damage model (Roca 2005). The analysis considered the material properties previously calibrated through modal matching. The resulting capacity spectrum and ultimate damage pattern are plotted in Figs. 8a and 8b.



(a)



(b)

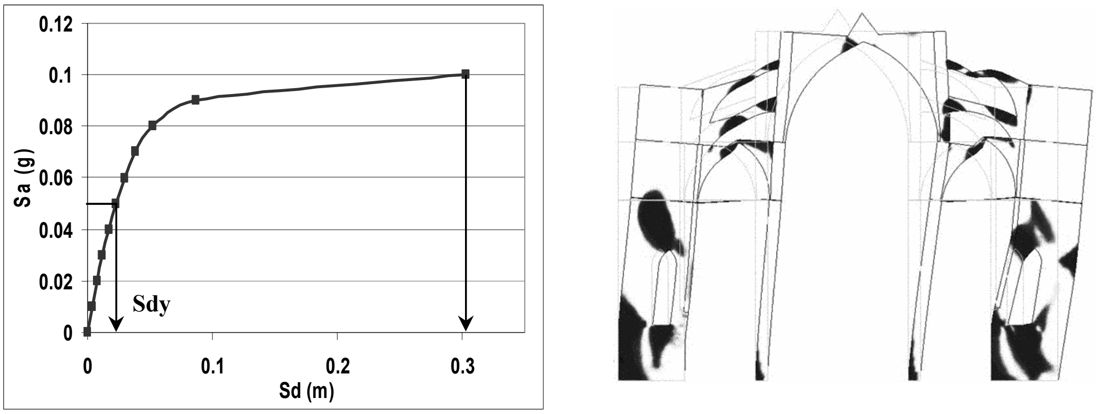
Figure 7 : (a) Elastic demand spectrum for 475 and 975-year return period; (b) FEM model

4.3 Expected damage grade

Fig.s 9a and 9b show the reduced demand spectrum obtained by considering the combination of structural hysteretic behavior and viscous damping effect, together with ADRS format capacity spectrum. The resulting displacement performance point values are 0.028 m for a 475-year return period earthquake and 0.033 m for a 975-year return period earthquake.

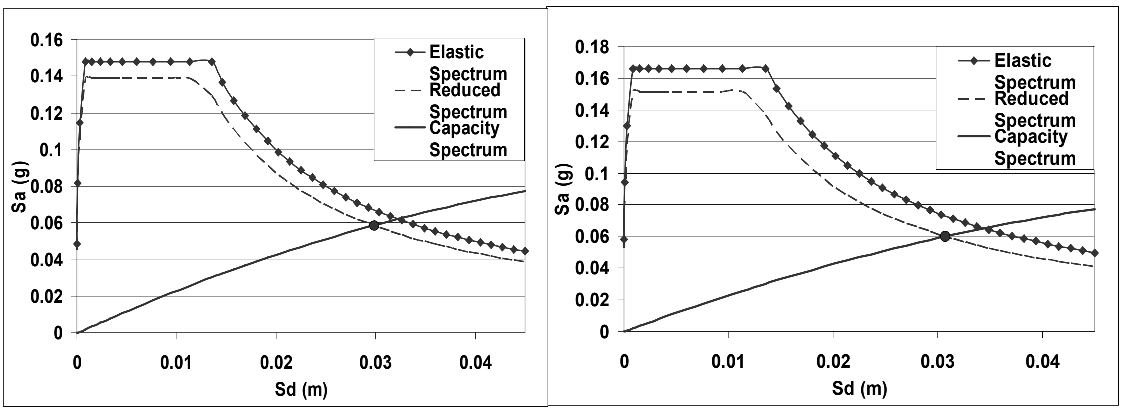
A 0.023 m yield displacement (Sdy), as well as 0.303 m ultimate displacement can be noticed in Fig. 9a. Yield and ultimate structural displacements, together with performance point displacement values, allow the estimation of the expected damage grade.

Damage grade threshold values, based on the Macroseismic European Scale (EMS-98), have been established by Lagomarsino et al. (2003) for different ancient buildings. In this particular case, the consideration of the threshold values leads to the prediction of a moderate damage grade for the seismic design events considered. This prediction can not be straightforwardly applied to large masonry constructions such as a Gothic Cathedral because the methods was calibrated based on masonry small to medium size buildings. Because of it, the prediction is only understood as a first approach to the understanding of the building. A more accurate evaluation will require a non-linear dynamic analysis in the time-domain, to be carried out in the near future.



(a) (b)

Figure 8 : (a) Capacity spectrum; (b) distribution of tensile damage at ultimate condition



(a) (b)

Figura 9 : (a) Tr = 475-year performance point; (b) Tr = 975-year performance point

5 CONCLUSIONS

Experimental model frequencies have been successfully used to calibrate a numerical model of the structure of the main nave of Mallorca Cathedral. Calibrating the model to match the experimental frequencies required the adjustment of the Young modulus of different structural members. It also required the definition of appropriate boundary conditions at the ends of the nave to simulate the contribution to the stiffness of several parts not included in the model (bell tower, façade and choir). With these adjustments, a satisfactory agreement was obtained between the experimental frequencies and the predictions obtained through modal analysis. The study illustrated that modal matching should be carried out on global and detailed structural models, rather than in partial ones, even if the structure can be easily decomposed into marcro-elements or typical parts. A global structural model, including all the structural elements, is now into development and will be used to validate the results obtained by means of the preliminary model.

The application of the capacity spectrum method on the typical nave way leaded to the prediction of a moderate damage grade. This result should be appraised by means of a more detailed analysis in the non-linear range. A more complete model, including a larger part of the structure or even the global construction, should be considered; the damage estimated at the naves could increase due to torsion effects induced by the façade, choir and bell-tower.

Experimental soil dynamic investigations aiming at evaluating possible soil-structure interaction are still in progress. Earthquake instrumentation has been implemented in the building, comprising two high-resolution seismographic equipments located at the highest (vaults extrados) and lowest (ground) levels of the nave. These additional studies are expected to provide larger insight on the dynamic structural response of the building subjected to earthquakes characterized by different energetic and frequency contents.

AKNOWLEDGEMENTS

This research has been carried out within the project "Improving the Seismic Resistance of Cultural Heritage Buildings" funded the European Commission through the Heritage Buildings EU-INDIA Economic Cross Cultural Programme (contract ALA/95/23/2003/077-122), whose assistance is gratefully acknowledged.

REFERENCES

Ambraseys N.N., Simpson, K.A., and Bommer, J.J. 1996. Prediction of horizontal response spectra in Europe. *Earthquake Engineering and Structural Dynamics, (24), p. 371-400.*

Bendat, J.S. & Piersol, A.G. 1993. *Engineering Applications of correlation and spectral analysis*, 2nd Ed., Wiley Interscience.

Fajfar, P. 1999. Capacity spectrum method based on inelastic demand spectra. *Eaethquake Engineering and Structural Dynamics, (28), p. 979-993.*

Fajfar, P. 2000. A Nonlinear Analysis Method for Performance-Based Seismic Design. *Earthquake Spectra*, 16 (3), p. 573-592.

Intenational Center for Numerical Methods in Engineering 2006. GID *The personal pre and postprocessor*, Barcelona, Spain.

Jiménez, M.J., García-Fernández, M., and the GSHAP Ibero-Maghreb working group 1999. Seismic Hazard Assessment in the Ibero-Maghreb Region. *Annali di Geofisica*, 42 (6), p. 1057-1066.

Lagomarsino, S. 1998. A new methodology for the post-earthquake investigation of ancient churches. *Proc. XI European Conference on Earthquake Engineering*. Paris, A.A. Balkema (Abstract Volume and CD-ROM), p. 67.

Lagomarsino, S., Giovinazzi, S., Podestà, S., and Resemini S. 2003. *Wp5 – Vulnerability of historical and monumental buildings Handbook*. Risk- UE: An advanced approach to earthquake risk scenarios with applications to different European towns. Contract No. EVK4-CT-2000-00014. 90

Mezcua, J. and Martínez Solares, J.M. 1983. "Sismicidad del área Ibero-Magrebí." *Presidencia del Gobierno, IGN*, Publicación 203, 299 pp.

Ordaz, M. Aguilar, A. and Arboleda, J. 2003. *Program for computing seismic hazard, CRISIS 2003*. UNAM, México.

Roca, P. 2004. Considerations on the significance of history for the structural analysis of ancient constructions. *Structural Analysis of Historical Constructions IV*, Padova: University of Padova.

Roca, P. and Clemente, R. 2005. Studies on the origin of deformation and damage in long-span historical structures. *11th. International Conference on Fracture.* Turin, Italy (Abstract Book and CD-ROM), p. 642.

S. A. Freeman, 1998. Development and use of capacity spectrum method, *Proc. 6th U.S. National Conf. Earthquake Engng.*, Seattle, CD-ROM, EERI, Oakland, 1998.

TNO DIANA BV 2005. *DIANA-Finite Element Analysis*, The Netherlands.