ABSTRACT: The city of Lagos (Algarve, Portugal) is located in an area of moderate seismic risk. In recent years particular attention has been devoted to the historical centre of the city. The focus of this study is the evaluation of the seismic vulnerability of one of the most important historical monuments of the city: the church of N. Sra. do Carmo, built in the 16th century, destroyed by the 1755 Lisbon earthquake was partially rebuilt afterwards. To characterize the dynamic behaviour of this structure we developed a Finite Element Model (FEM) and performed a set of ambient vibration tests. In this paper we present a preliminary FEM of the structure and its comparison with experimental data. This work was developed in the framework of project CARAVELA – Instituto Politécnico de Lisboa.

1 INTRODUCTION

The city of Lagos (SW Portugal) is located in an area of moderate seismic risk. In historic times the city was severely damaged by large earthquakes and, for the well known 1755.11.01 Lisbon event, the macro seismic intensity in Lagos was estimated as IX-X, similar to what was observed in the city of Lisbon. Historical documents report earthquakes in Lagos at 382 BC, 1356, 1504, 1719, 1722. More recently, the 1969.02.28 event, located south of the Gorringe Bank, with a magnitude near 7.9, caused considerable damage to this city.

Instrumental seismicity close to Lagos is not yet well characterized, in spite of the significant development of the Portuguese seismic network in Algarve, which is now able to locate a large number of small magnitude events in the southern Portuguese shelf.

Recently the local authorities devoted particular attention to preserve and rebuild the main historical buildings of the town centre. In this study we present the preliminary results on dynamic characterization of the church of Nª Srª do Carmo or “Igreja das Freiras” (“nuns church”, see Figure 1). The church was built in the 16th century and was partially destroyed by the catastrophic earthquake of 1755.11.01 – known as the Lisbon earthquake. It was partially rebuilt after that event but since then no significant retrofit was performed.

The municipality of Lagos approved recently a major rehabilitation project for this monument. The works will take 18 months, divided in 3 stages: repair
and rehabilitation of structural elements (walls, arches, roof, vault); restoration of the interior architectonic elements; restoration of the glazed tile panels and guild woodwork.

2 THE STRUCTURE

Stone masonry churches are particularly vulnerable to earthquakes due to their configuration: open spaces, presence of thin walls, poor connections among the structural elements, and also due to the fact that the materials used have low or no tension strength.

The central nave is covered with a barrel vault, a structural form quite common in religious European heritage; a spherical dome is located over the high-chapel (Figure 4). The external walls discharge directly on the soil.

The structure has a rectangular plan and its dimensions are approximately 30 m by 7 m; its height varies from 9 m to 11 m. The highest point of the structure is the bell tower with 2 m by 2 m and 12.15 m height.

The interior of the church keeps some remarkable architectonic details: the arch of the High Chapel, the glazed tile panels, the throne, the tabernacle and, in the floor of the central nave, a considerable number of grave stones.

In the central nave we may observe a large fissure that runs along the barrel vault (cf. Figure 5). This crack may compromise safety of the structure in case of moderate or strong seismic activity.

3 AMBIENT VIBRATION TESTS

Dynamic analysis based on ambient vibration tests is a methodology used to characterize the dynamic behaviour of a structure excited by low amplitude vibrations. The information obtained can be useful to calibrate and update finite element models of the structure, or can be used for the health monitoring of the building.

Modal identification is the determination of modal parameters of existing built structures from experimental data. Output-only modal identification of structures is normally used to identify modal parameters from the natural responses of many structures. In these cases the loads are unknown, and the identification process is carried out, based on the responses only. Many Applications on modern civil engineering structures can be found in literature (Ventura, 1996; Brincker, 2002). In Portugal several experiments were carried out, e.g. Ferreira (2001), Baptista (2004). An example of ambient vibration testing on historical structures can be found in Shelley (2000).

The response of the structure must be recorded at specific locations in order to maximize the information content with respect to the parameter identification. At this stage, the conditions inside the church do not permit a correct sensor location so the ambient vibration tests performed were rather simple. A preliminary test was performed in order to obtain the first natural frequency for FEM updating (Figure 6).

The procedures for ambient vibration tests are described below.

The instruments used in this preliminary experiment were Kinemetrics force balance accelerometers (FBA ES-U); the sensors are connected to a 12 channel
data acquisition system (DAS) with dynamic range of 114 dB, and output data format with 24 bits.

To obtain the fundamental frequency of the church, a preliminary test was made: acceleration data was recorded for 30 minutes and a sampling frequency of 250 Hz was used.

Figure 7 presents an acceleration record where we can see the amplitude of vibrations inside the church in ambient vibration conditions.

Data processing was performed using Artemis Extractor version 3.4, SVBs (2002). The power spectral densities matrices are obtained using the Frequency Domain Decomposition. This technique decomposes approximately the spectral density matrix of the system response into a set of SDOF systems using Singular Value Decomposition; the singular values are estimates of the spectral density of the SDOF systems, and the singular vectors are estimates of the mode shapes Ventura (2001).

Analysis of the Figure 8 enables the clear identification of the first frequency (fundamental) of 3.3 Hz.

4 THE FINITE ELEMENT MODEL

In order to obtain a finite element model of the structure it is necessary to use idealisations of material behaviour and geometry. Geometry of ancient historical structures may be rather complex as often there is no clear distinction between decorative and structural elements (Lourenço, 2001).

The FEM has been developed using the computer program SAP 2000 version 7.10 (Computers & Structures, 1998). This program can be used for linear and
non-linear, static and dynamic analyses of a threedimensional model of the structure. In our study the program has been used to determine the fundamental frequencies and the corresponding mode shapes of structure, based on its physical and mechanical properties.

In the preliminary phase, it is assumed that all the materials of the structure have the following characteristics: (i) they are homogeneous and isotropic; (ii) modulus of Elasticity, $E=0.7$ GPa (based on a preliminary ambient vibration test); (iii) Poisson's ratio 0.2; iv) linear elastic behaviour is assumed. The geometry of the structure is idealised considering the structure to be made of shell elements.

Figure 10 shows the 1st mode shape, obtained by the finite element modelling; it corresponds to a translation in the transversal direction, with a frequency of 3.3 Hz. The modulus of elasticity has been tuned in order to identify the model from the experimental result.

The second mode shape, obtained from the FEM, involves mainly the bell tower (see Figure 11).

5 FINAL CONSIDERATIONS

In order to obtain an accurate estimate of natural frequencies and mode shapes the sensors should be placed at the base of the vault see Figure 12. Those tests are scheduled for July 2004 as they require the availability of an auxiliary structure that will be used during rehabilitation works.

From the structural point of view, the main concern of the rehabilitation process is the presence of longitudinal cracking along the vault. In order to study this effect, one possibility is the simulation of the crack, by considering a reduction of the modulus of Elasticity in the vertical direction. This hypothesis will be verified experimentally with a new sensors location (see Figure 12).

Procedures to evaluate dynamic behavior, of historical structures, under seismic load are not yet quite well established so any quantitative information on
Figure 12. Future sensors location, in order to obtain mode shapes: (a) transversal section; (b) plan section.

In order to evaluate the seismic performance of a masonry structure, identified by ambient vibrations, a proper non linear constitutive model is necessary for the masonry material. The one developed by Lagomarsino and Calderini (2004) will be adopted; it considers the masonry as a composite material, made by blocks and mortar joints, in which various micromechanical failure mechanisms (openings, sliding with friction, crushing, etc.) are homogenized in a continuum damage model, suitable for the finite element procedure.

Pushover static non linear incremental analyses will be performed, in order to evaluate the capacity of the church in terms of total base shear and displacements. The seismic analysis uses the capacity spectrum method (Fajfar, 2000).

ACKNOWLEDGMENTS

The authors wish to thank Instituto Politécnico de Lisboa for financial support of project Caravela (50-2003) and Architect Frederico Paula for his collaboration.

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