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USE OF AMBIENT VIBRATION TESTING FOR MODAL EVALUATION OF A 16 FLOOR REINFORCED CONCRETE BUILDING IN LISBON, PORTUGAL

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SUMMARY

This paper presents a description of the experimental and analytical studies performed on a multi-storey office building in the newly residential and office area of Lisbon, Portugal. The building is located in sensitive alluvium soil, near Tagus river – Lisbon. This city was severely damaged by strong magnitude earthquakes e.g. 153126.01, 1755.11.01 and 1969.02.28.

The selected building is a 16-storeyed reinforced concrete structure consisting of "oval" shaped flat plate slabs with a central rectangular rigid core. The structure has 12 floors above ground and four basement levels. Ambient Vibration testing was conducted in order to determine natural frequencies, mode shapes and damping ratios. Those parameters were obtained using Artemis software. A FEM model of the structure was developed using SAP2000 software. Both the experimental results as well as the analytical results are presented in this paper and compared.

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INTRODUCTION

The instrumental monitoring of engineered structures is an essential tool for mitigating hazard programs. The dynamic characterization is important for the dynamic behavior prediction, finite element modal updating and structural health monitoring, Tamura[1].
The city of Lisbon is located in an area of moderate seismic activity characterized by infrequent strong magnitude events. The city was severely damaged in, 1531(M=7.0), 1755 (M=8.9) and 1969 (M=7.9).

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The work presented in this paper was developed under the framework of the Dynaseis project, funded by the Portuguese Science Foundation. The main objective of this research project was the instrumentation and study of a newly designed and constructed 16 -storey office building, the Portuguese Telecom tower, located at the newly residential area of Lisbon located along Tagus estuary, using ambient vibration tests. Several ambient vibration experiments have been carried out in Portugal for modal identification in cable-stayed bridges, Cunha [2] a mansory aqueduct aqueduct, Drei [3] and public buildings, Ferreira [4]. The study, presented here is a pioneer full-scale experiment carried out on a reinforced concrete office building in Lisbon, Portugal.

The dynamic parameters of a structure can be obtained by artificially excitation of the structure and measurement of responses and input forces Ren [5]. Ambient vibration tests have several advantages: they are non destructive; they do not require expensive devices for artificial excitation, so the cost of the overall experiment is fairly reduced and finally they can be performed during the normal operation of the structure.

Modal identification is the determination of modal parameters of 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 (civil, space and mechanical). In these cases the loads are unknown, and the identification process is carried out based on the responses only. Normally the identification process is based on ambient vibration tests, and presuppose that a structure can be adequately excited by natural ways like wind, human activities and the resulting motions can be readily measured with highly sensitive instruments. Applications on civil engineering structures can be found in Ventura [6], Brincker [7], Cunha [8], etc.

The building is particularly interesting to structural engineers for many reasons: a) the floor slabs are waffle slabs; b) its oval shape plan is fairly unusual; c) the building has the foundations in a alluvionar soil and high water level. The building has a reinforced concrete shear with two cores at the extremities, which concentrates most lateral and torsional resisting elements. The torsional response of such kind of structure is of great interest to structural engineers dealing with earthquake excitations.

The finite element model (FEM) of the building is explained in see section 3. Dynamic analysis results are compared with experimental data such as fundamental frequencies and mode shapes, are tabulated and discussed. The FEM was then updated based on the results obtained experimentally.

Ambient vibrations tests were conducted on May 16, 2003 by the “Dynaseis” team of “Instituto Superior de Engenharia de Lisboa”. The results of tests are presented in this paper. The modal parameters, lateral and torsional, fundamental frequencies and the corresponding mode shapes and damping ratios were obtained using frequency domain decomposition (FDD) and stochastic subspace identification (SSI) techniques.

DESCRIPTION OF THE BUILDING

As already referred, the building has 12 floors above ground and 4 basement levels, and is responsible for the entire telecommunications network in “Parque das Nações” complex. The geometry has an oval development in plant with two main reinforced concrete cores in the extremes. Concerning structural behavior they give the structure the adequate stiffness for a good response to the horizontal loads. Both cores contain stairways but one has the elevator shafts. The two cores are connected by waffle slabs and embroidery beams. The waffle slabs are typically 0.25 m, and the core walls are typically 0.30 m thick. The waffle slabs discharge the loads directly on the columns.

Fig.1 : View of tested building.

FINITE ELEMENT MODEL

The use of identification techniques in structures implies the choice of an "*a priori*" model that is adjusted previously to the defined objectives. That fact implies the validation "*a posteriori*", of the model previously chosen.

The Finite Element Model (FEM) was developed using the computer program SAP 2000 version 7.10. The program can be used for linear and non-linear analysis, static and dynamic analysis of three-dimensional structural modeling, Computers [9]. In this study the program was used to determine the fundamental frequencies and the corresponding mode shapes of structure, based on it physical properties.

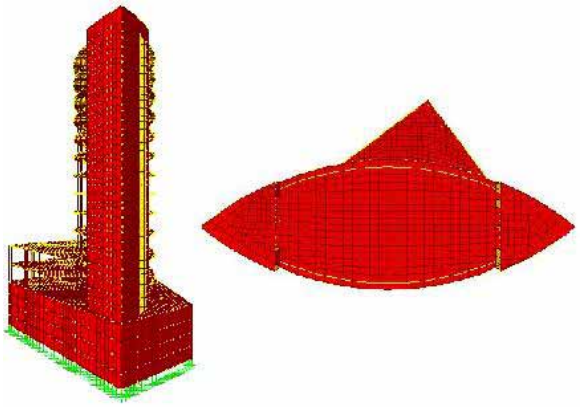

Fig. 2: 3D view and top view of finite element model.

The FEM, includes 14533 shell elements and 957 frame elements. It is assumed that the reinforced concrete structure has the following characteristics: i) the material is homogeneous and isotropic; ii) modulus of Elasticity, E = 36.5 GPa (determined with base in the initial conditions of design; and admitting the increase of 25% based on the Portuguese code (REBAP), iii) Poisson's ratio 0.2; iv) linear elastic behavior is admitted. The connection between the contention walls and the foundations soil it is simulated by an elastic restriction.

The results obtained with FEM were used to choose the adequate sensor location for ambient vibration tests. Experimental results were used to update the FEM, introducing a slight variation of the elasticity modulus, in order to match analytical and experimental results (see Table 1).

N.º	Mode shape	Updated Model
1	1st NW-SE	1,05 Hz
2	1st NE-SW	1,19 Hz
3	1st torsion	1,89 Hz
4	2nd NW-SE	4,22 Hz
5	2nd NE-SW	5,21 Hz

Table 1: Comparison between the two models

The mode shapes and corresponding frequencies of the updated model are presented in Fig. 3, for the five first modes.

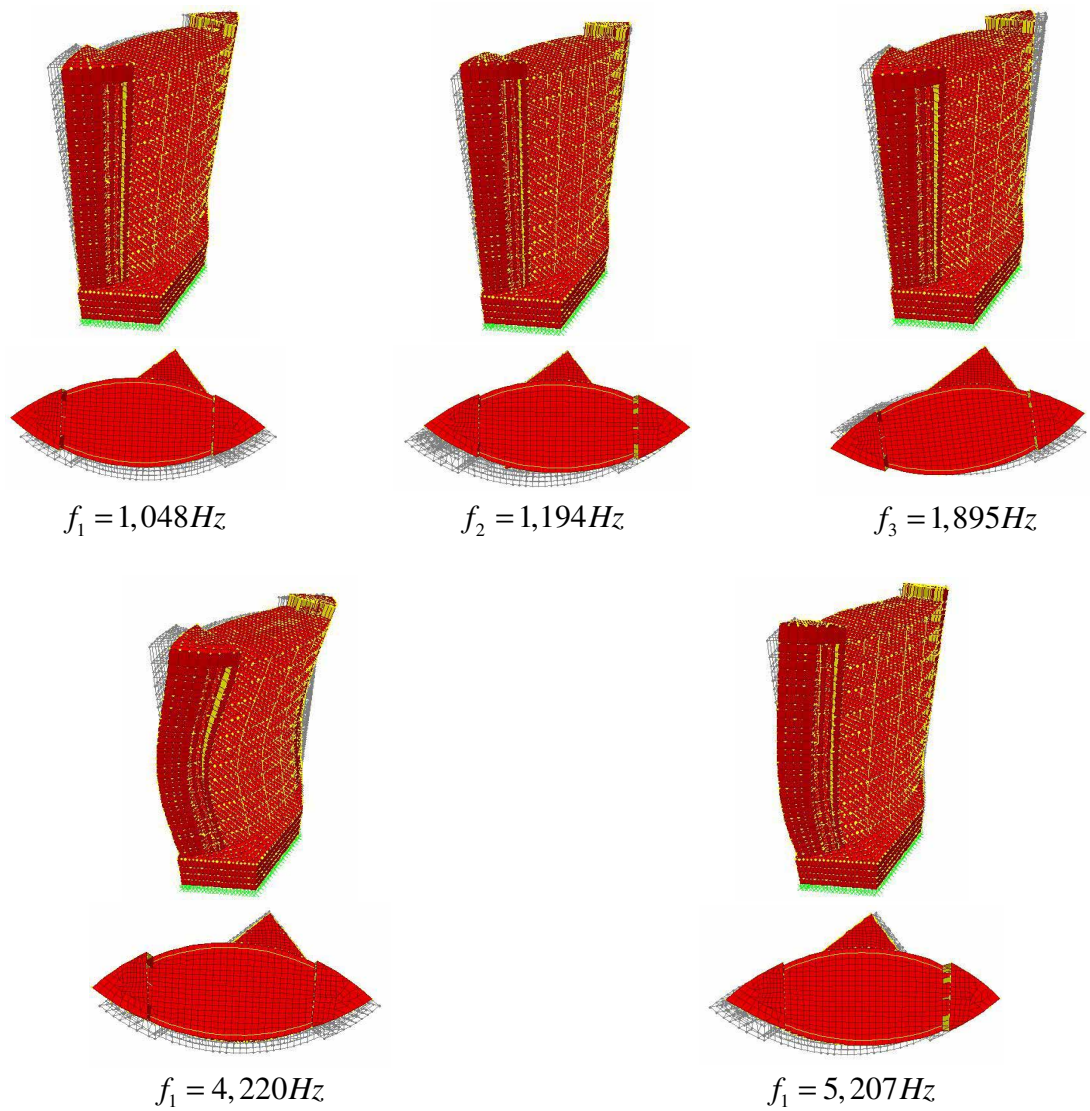

Fig. 3: Mode Shapes obtained from the finite element model.

AMBIENT VIBRATION TESTING

Analysis based on ambient vibrations test is a methodology used to characterize the dynamic behavior of a structure excited by low amplitude vibrations. The information obtained can be useful to calibrate and update finite element models of the building, or can be used for the health monitoring of the building. The procedures and main results obtained for ambient vibration tests are described below.

Instrumentation

The instrumental network includes force balance aceleromoters from Kinemetrics: one three-component acelerometer - Model FBA ES-T and three unidirectional model Model FBA ES-U, cables, a 12-channel data acquisition system signal conditioner and A/D converter (Kinemetrics, Altus K2), and a laptop.

The system used is composed by a set of three roving sensors (FBA ES-U) and one sensor of three component (FBA ES-T) used as reference sensor. The sensors are connected to the data acquisition system (DAS) with dynamic range greater than 114 dB, and output data format with 24 bits. The high dynamic range and superior resolution offer significant advantages for applications where signal fidelity and data integrity are vital. It allows to get a maximum sensitivity of ±2,5 Volt/mg; placing the level of saturation of the system of acquisition in ±10 Volt.

The response of the structure was recorded at several locations in the building; however the location of the sensors should maximize the information content with respect to the parameter identification. The 3 component accelerometer was used as reference sensor and thus should be located in points that are antinodes of the vibrational motion. The reference sensor was placed on top of the building, at 12th floor.

Setups were performed on every floors. In order to capture the translational modes in the NW-SE and NE-SW, and the torsional modes of the structure, two uni-directional accelerometers were oriented in the NE-SW direction, and one uni-directional accelerometer was oriented in the NW-SE direction (Fig. 4). In order to avoid movement during testing the sensors were firmly attached to the structure and to assure good quality control on the data acquisition we kept the same sensor layout at every floor for the roving sensors.

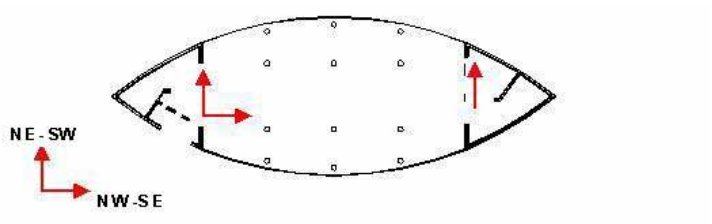

Fig. 4: Positioning of sensors in a typical floor plant.

Experimental Setups

Acceleration data was recorded 30 minutes, to ensure that all modes of interest are excited. The sampling frequency is 250 Hz. The results presented here were obtained using a decimation factor of 10 for the sampling frequency of 250 Hz and make the average of samples of 1024 points put upon for 2/3. That

value corresponds to eliminate in the spectra all frequencies above 12.5 Hz. Frequencies above 12.5 Hz show considerable associated noise and were discarded in the present study.

SPECTRAL ANALYSIS

Modal identification is used to identify modal parameters of a structure using experimental data measurements. The building is subjected to ambient vibrations generated by "unknown" loads, like wind, human activity, ventilation, etc. It is assumed, that the all system is driven by white noise Cunha [2]. In these cases structural modes are identified as well as what are called operational modes. The main focus of output only analysis is to be able to distinguish the structural modes from the operational modes, in the modal identification process.

The computer program ARTeMIS Extractor, release 3.2, was used to perform the modal identification of the structure, SVBs [10]. Two diferents techniques were used for modal identification: the Frequency Domain Decomposition (FDD) and the Stochastic Subspace Identification (SSI). These two modal identification techniques are used to cross-validate the results.

The roving sensors were placed, in every floor in the same positions (see fig. 4). In order to simulate the modal configurations it is assumed rigid body motion of the floor slabs and the recorded motions were translated to the equivalent motion of the four points used to simulate the oval shape of the structure, as diamond in ARTeMIS.

The FDD technique decomposes approximately the spectral density matrix of the system response into a set of SDOF systems using the Singular value Decomposition (SVD). The singular values are estimates of the spectral density of the SDOF systems, and the singular vectors are estimates of the mode shapes. This technique is usually designated in literature as Peak Picking Ventura [11].

The SSI technique consists of fitting a parametric model to the raw time data series collected by the sensors. Using a specific representation of the transfer function, all the modal parameters are exposed. Therefore, the natural frequencies damping ratios, and mode shapes can be extracted. The Unweighted Principal Component (UPC) algorithm was used to analyze the data Ventura [11].

Experimental Results

Results of FDD peak picking method are presented in Fig. 5. It is clear the identification of five peaks: they are structural modes and represent natural frequencies of the building. The first three modes have too small damping.

The 4th and 5th peaks are not as well defined as the first three modes. The existence of only one singular value for each frequency shows that those modes are also structural modes.

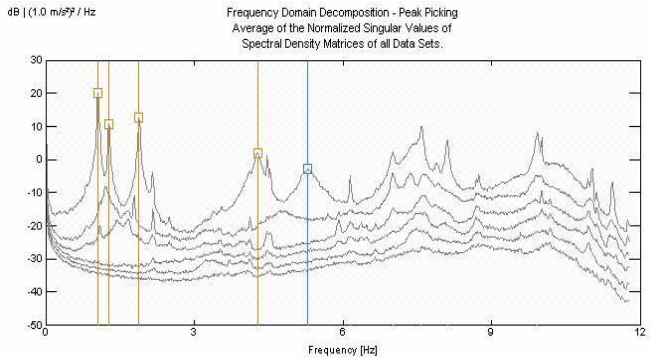

Fig. 5: Singular values of the spectral density matrices.

The analysis of Figure 6 presents the stabilization diagram of SSI technique, this diagram is helpful for selection of the structural modes by poles stabilization. In Table 2 we present the comparison between the experimental and FEM results.

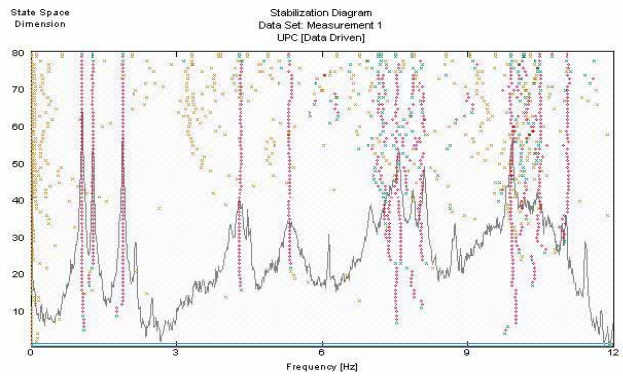

Fig. 6: Stabilization Diagram from the SSI technique.

The analysis of Fig.6 enables the clear identification of the first five modes, in the stabilization diagram. The results presented in Table 2 confirm a good cross validation of the results obtained using the two modal identification techniques. Damping ratios estimates are also presented in Table 2, although it is worth to point out that when dealing with ambient vibration testing the modal characteristics obtained correspond to low amplitude vibrations which may be different for higher levels of excitation Ventura, [12].

N.º	Mode shape	Numerical results	EFDD	Damping Ratio [%]	Std. Damp. Ratio [%]	SSI	Damping Ratio [%]	Std. Damp. Ratio [%]
1	1st NW-SE	1,05 Hz	1,05 Hz	1,05	0,25	1,05 Hz	0,69	0,21
2	1st NE-SW	1,19 Hz	1,28 Hz	0,97	0,24	1,28 Hz	0,94	0,24
3	1st torsion	1,89 Hz	1,89 Hz	0,58	0,12	1,89 Hz	0,53	0,10
4	2nd NW-SE	4,22 Hz	4,27 Hz	2,64	0,61	4,28 Hz	2,08	0,31
5	2nd NE-SW	5,21 Hz	5,25 Hz	4,16	0,58	5,26 Hz	3,73	0,60

Table 2: Comparison of the fundamental frequencies and damping ratios.

In Figures 7 and 8 we present isometric views of the mode shapes of the first five vibration modes. The first mode corresponds to the lateral direction according NW-SE, the second mode represents the second lateral direction between NE-SW. However this does not correspond to a pure translation mode due to the

influence of the lowest two floors, that induces a small associated deformability, in the other direction. The third mode is clearly a torsional mode.

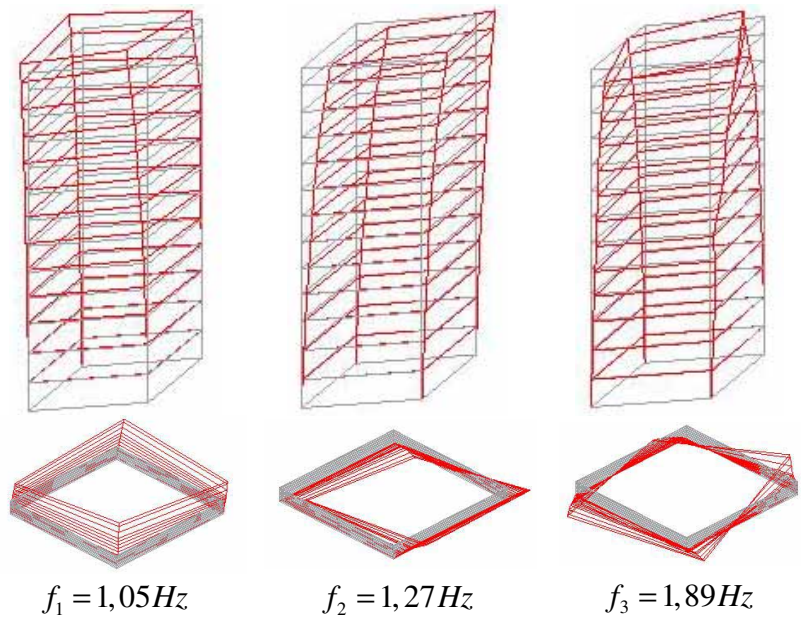

Fig. 7: Mode shapes of the first tree modes.

The 4th and 5th modes are lateral modes in 2nd NW-SE and 2nd NE-SW respectively, that comparatively with the 1st and 2nd modes differ for the fact of they present intermediate nodes.

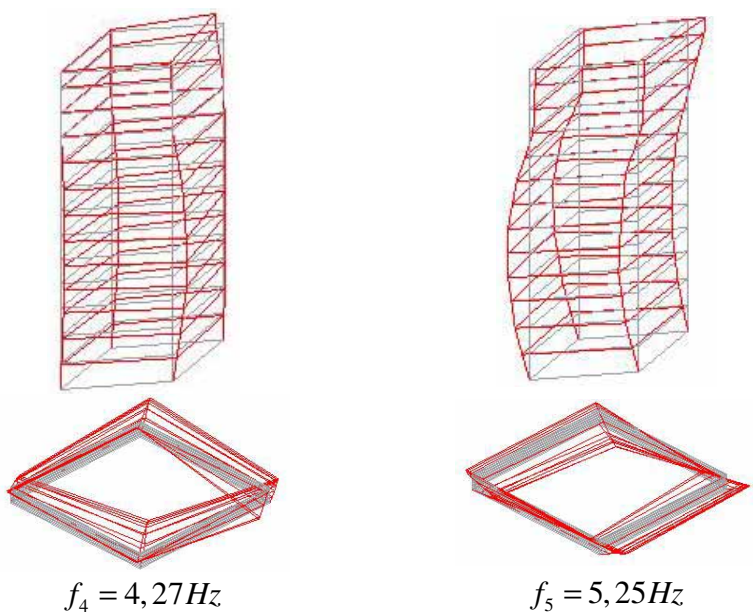

Fig. 8: Mode Shapes of 4th and 5th modes.

CONCLUSIONS

The ambient vibration testing provide an accurate estimate of modal parameters. A good agreement in identified natural frequencies has been found with FDD based on peak picking method and the time domain based stochastic subspace identification SSI.

A good correlation was achieved between results obtained by ambient vibration tests and the FEM. Experimental results were used to update the FEM. Modal parameters obtained in this study, may be used in the future for the health monitoring of the building.

It is particularly important to note the fact that the first five modes obtained experimentally, are in the same sequence of the obtained in the analytical study. The maximal difference between experimental results and numerical results is 6,87% for the 2nd mode; for the other modes the differences are less then 1%.

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