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DYNAMIC CHARACTERIZATION OF THE FUNCHAL'S CATHEDRAL BELL TOWER

Carla M. Jardim[1], *Luís A.M. Mendes*[2] *and Amílcar M.L. Gonçalves*[3]

ABSTRACT

This paper describes the experimental campaign and the numerical analyses made to assess the dynamic behaviour of the Funchal's cathedral bell tower. Ambient vibrations tests were used to perform an output-only modal analysis. The test campaign included five test setups using piezoelectric high sensitivity accelerometers and high performance data acquisition boards. The main features of the tests and the results obtained from the operational modal analysis are presented. The experimental results were used to calibrate a numerical modal implemented in finite element software. The results obtained using both approaches are compared and it was possible to observe a good match between the experimental and numerical results, although some differences can be found for the main torsion mode frequency. This work provided valuable information regarding the structural behaviour of the tower, very useful for future works in the cathedral, *e.g.* seismic reinforcement. The paper closes with the main conclusions extracted from this work.

Keywords: *Operational, Modal, Analysis, Ambient, Vibration, Test, Numerical, Modelling*

1. INTRODUCTION

The main objective of the work presented in this paper is to assess the dynamic characteristics of the Funchal's cathedral bell tower. To achieve this, ambient vibration tests were executed to estimate the most significant modal parameters using modal analysis techniques. Simultaneously, a numerical model was created in finite element software using the most usual material parameters and structural simulation techniques for this structure type. At the end, the objective is to compare the results of both approaches and to calibrate the numerical models in terms of the materials' properties and modelling assumptions, *e.g.* the most realistic boundary conditions.

The Funchal's cathedral, also known as "Sé do Funchal", is a sixteen century masonry church composed by several sub-structures (see Figure 1a). The bell tower is the highest body, reaching more than 52 metres from the base. It presents a square configuration in plan and it includes four clocks in each façade together with a group of seven bells (see Figure 1b).

[1] Civil Engineer, Master Student at Universidade da Madeira, carlajardim@msn.com

[2] Ph.D., Researcher, Fundação para a Ciência e a Tecnologia, LNEC, ICIST, luismendes77@gmail.com

[3] Civil Engineer, Laboratório Regional de Engenharia Civil (Madeira), agoncalves@lrec.pt

a) b)
Figure 1 Funchal's Cathedral: a) Main façade; b) Bell tower

After this introductory section, the paper is structured in three main parts. At first, the experimental campaign is described and the main results obtained are presented. Afterwards, the attention is drawn to the numerical simulation, in particular the modelling techniques adopted and the results of the modal analysis. The paper ends with the main conclusions extracted.

2. EXPERIMENTAL DYNAMIC CHARACTERIZATION

2.1. Framework

The dynamic characteristics of the bell tower were assessed using the so-called *Operational Modal Analysis* (OMA) technique. In this technique, the vibrations generated by the wind, traffic and other sources of uncontrolled *in-situ* forces are used to characterize the dynamic properties of the structure. Measuring only the response of the operating structure subjected to the ambient excitations, it is possible to extract the modal parameters by assuming some hypothesis regarding the excitation properties and using appropriate modal analysis techniques.

This approach presents two very significant advantages regarding the traditional input-output modal analysis techniques. First, this technique does not require imposing significant constraints to the use given to the structure during the tests. Secondly, it is not required to apply controlled and deterministic forces, which for very large structures can become a challenge or even not feasible. In addition, for fragile or historical structures, applying forces on the structure could introduce non-acceptable damage in the structure. This is the case of the Funchal's cathedral. It would require powerful and expensive excitation sources to introduce a controlled and measurable input into the structure. In addition, due to the combination of historical importance of the structure and its fragility, it would be difficult to perform input-output modal identification techniques with the guarantee of not damaging the cathedral.

As mentioned before, the excitation is unknown in the OMA technique and therefore cannot be defined as a deterministic amount and must be considered as stochastic processes, which are defined by a set of statistical parameters, like standard deviation, expected value *etc*. Commonly, the excitation is considered to be a Gaussian white noise process, resulting that all the modes are excited with equal energy. Nevertheless, this assumption is always an approximation as the excitation may present frequency bands with concentrated energy that are directly outputted on the response (*e.g.* as peaks in the spectra), and therefore should be identified as non-structural. This represents a key aspect of the output-only modal analysis techniques.

2.2. Description of the experimental campaign

The response measurements are typically concentrated at a set of positions, chosen to reveal the relevant dynamic properties like the mode shape configurations, and located at zones where the vibration modes present larger amplitudes. The sensors available for the measurements were not enough to make all the desired measurements in single setup. Consequently, it was necessary to move sensors using multiple setups to cover all points targeted to be measured. Reference sensors rested in specific positions in order to adjust the phase of the vibrations of all the points measured, and thus, resulting in mode shapes with synchronized amplitudes evolutions.

The measurement campaigns took place in a single day (May 30th, 2012) and a total of five test setups were carried out using non-moveable reference sensors as presented in Figure 2. The measurements included a total of sixteen measurement points in both horizontal directions. The Pimento acquisition system was used to acquire the data (see Figure 3-a) and eight high-sensitivity ICP accelerometers were used for the measurements (PCB model 393B12, 10 V/g). The sensors were fixed to the walls from the inside of the tower using a steel cube and mechanical connectors (see Figure 3-b).

The data acquisition and the position of the reference sensors were chosen to be located at the terrace to avoid the second mode inversion points and in order to have larger vibration amplitudes. Nevertheless, due to constraints related with the hardware available and with the power supply, the reference sensors and data acquisition had to be set at the third storey (see Figure 2).

2.3. Modal analysis and results

Two modal analysis codes were used for modal extraction (LNEC-SPA [1] and the LMS PolyMAX [2]). The first one was developed at LNEC and has been used as the dynamic test analyser for shaking table and in-situ vibrations tests. The second software referenced was used to confirm the results obtained. All the data and visualizations presented in this paper were obtained with the LNEC-SPA software.

Frequency-based modal analysis techniques were used for the modal parameter estimation, in particular the well-known *Frequency Domain Decomposition* (FDD) [3] and the *Enhanced Frequency Domain Decomposition* (EFDD) proposed by Brincker *et al.* [4]. The theoretical background of these methods is well-known and out of the scope of this paper. Nevertheless, the EFDD is based in the same singular value decomposition of power spectrum density matrices perform in the FDD procedure, and it improves the accuracy of the modal frequencies and damping estimations using curve fitting techniques.

Three modes were clearly identified from the test results: the main translational modes and the first torsion mode. The mode frequencies and damping ratios are listed in Table 1. It can be observed that the two first modes present close frequencies (1.82Hz *vs.* 1.95Hz) meaning that they are separated by only 0.13Hz. This was expected because the tower presents similar plan configurations, *e.g.* dimensions, wall thickness, material distributions, *etc*.

The experimental mode shapes configurations are presented in Figure 4. These mode shapes confirm that the first two modes are translational modes and that the third is essentially a torsion mode. In what concerns the translational modes, the mode shapes revealed interesting and not expected plan diagonal mode shape configurations. Although the plan configurations are practically symmetrical, apart from the stairway located near a corner of the tower and some openings and inside space arrangement, this can only be explain by the tower boundary condition, *i.e.* the interaction with the cathedral's main body. The damping levels estimated by the EFDD technique were relatively uniform and low (about 1.2%). This was expected taking into consideration the low vibration amplitudes generated by the ambient vibrations.

This information revealed to be extremely useful for adjusting the modelling techniques used in the numerical simulations presented in the following section.

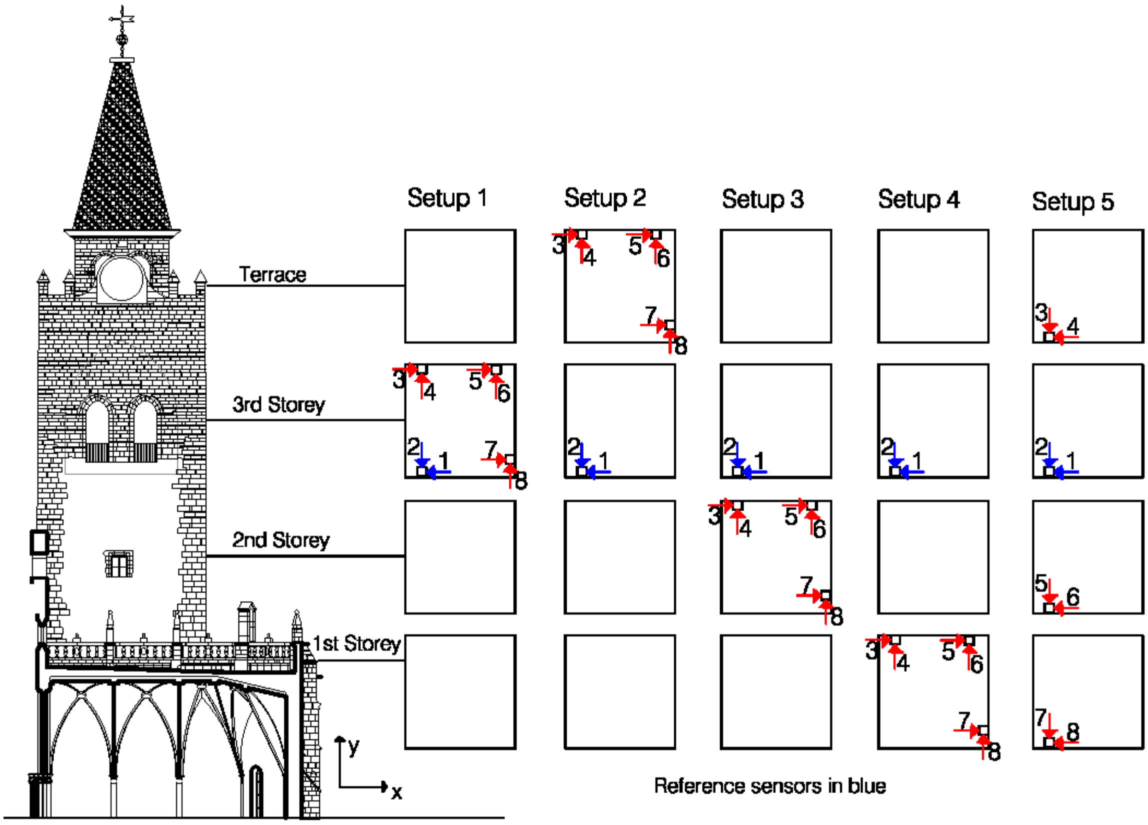


Figure 2 Experimental Test Setups

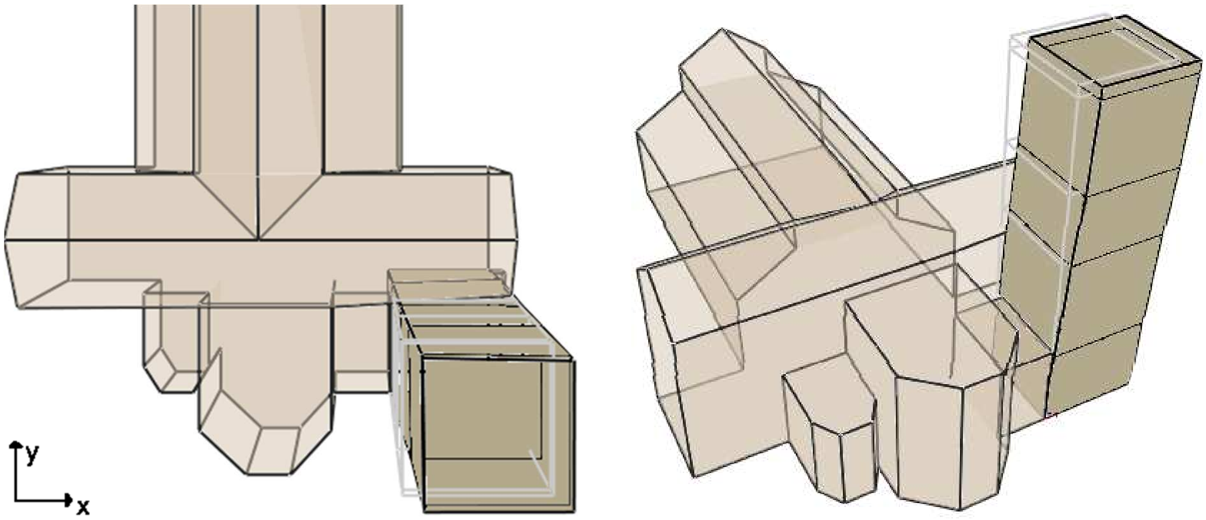
a)

b)

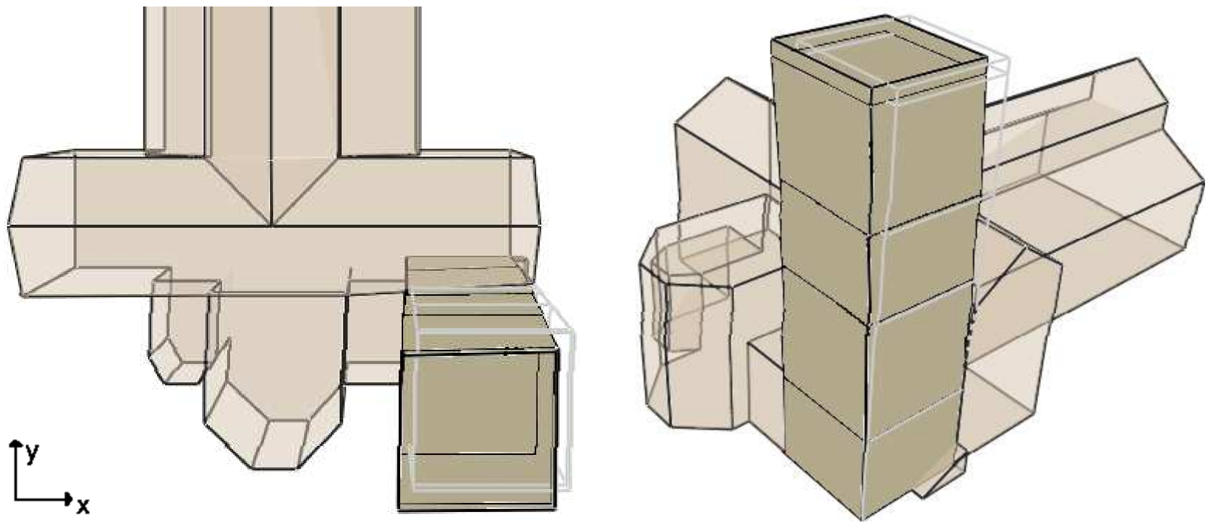
Figure 3 Measurement system: a) Pimento data acquisition system; b) Typical accelerometer setup

Table 1 Modal Identification results

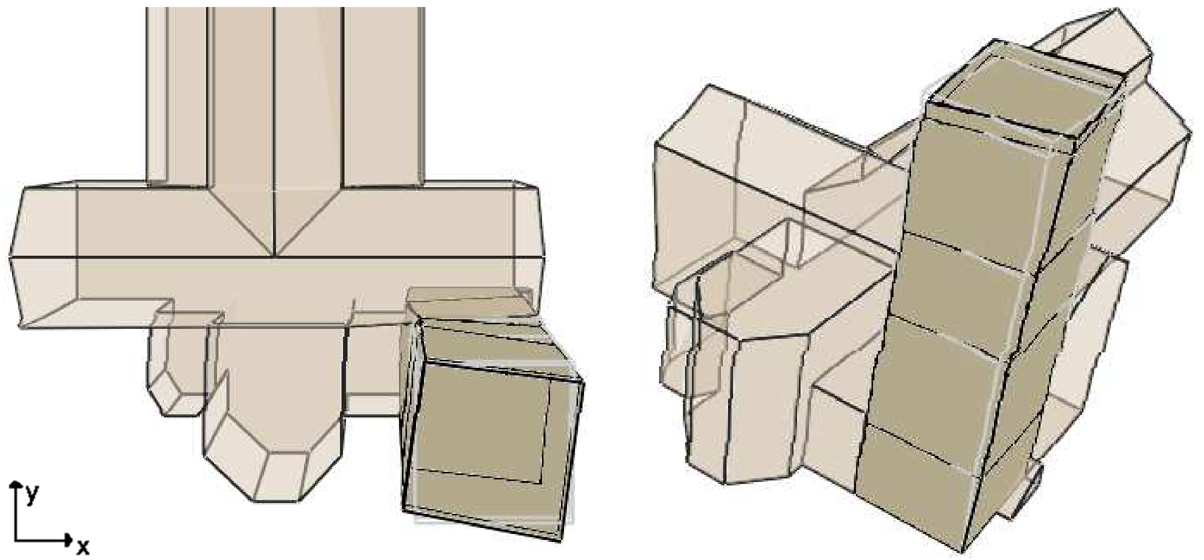
Mode ID	Frequency [Hz]	Damping [%]
Mode #1	1.82	1.20
Mode #2	1.95	1.16
Mode #3	4.39	1.20



a) Mode #1: 1.82 Hz



b) Mode #2: 1.95 Hz



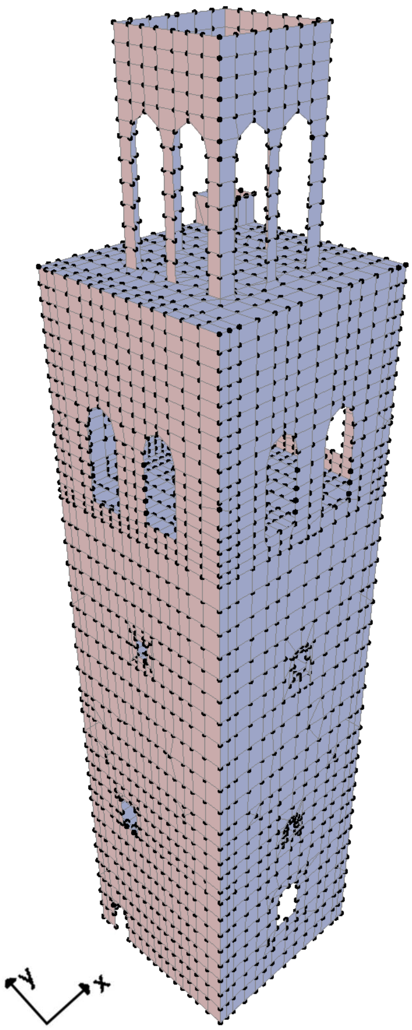
c) Mode #3: 4.39 Hz

Figure 4 Experimental mode shapes

3. NUMERICAL MODAL ANALYSIS

A numerical model was developed in the commercial finite element software SAP2000 [5]. The experimental results were used to calibrate the modelling assumptions and parameters and the final objective is to compare the results obtained using both approaches.

A general view of the finite element discretization is shown in Figure 5. Shell elements with different thicknesses were used to simulate the masonry walls of the tower, which varied between 3.30m at the bottom and 1.50 m at the top of the tower. In addition, truss elements were used to simulate the steel ties connecting the masonry walls. Elastic springs were used to simulate the interaction with the rests of cathedral, in particular in zones that present interconnecting walls or other sources of rigidity.



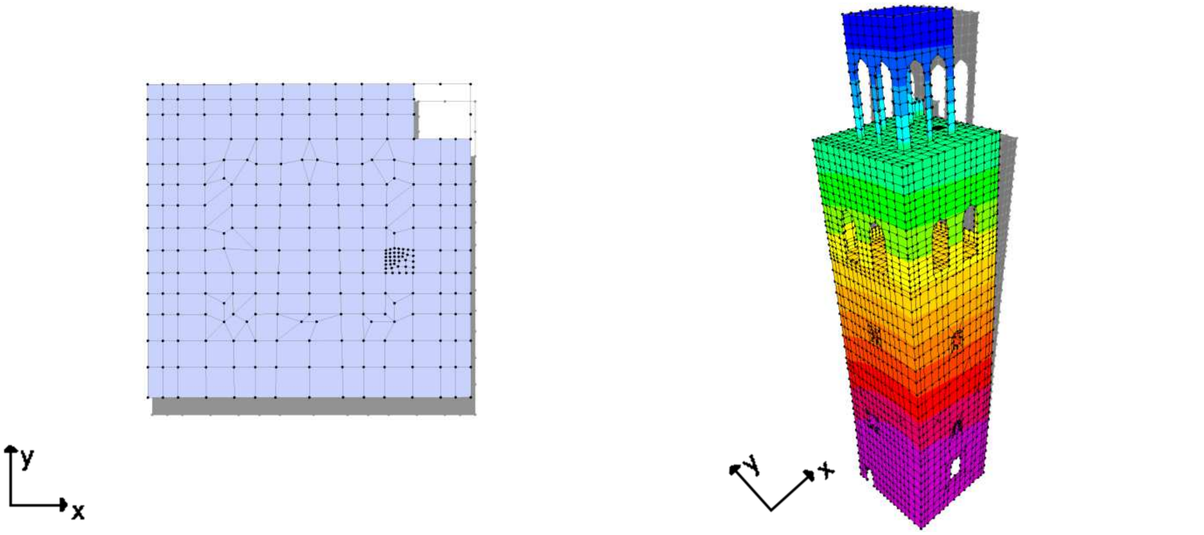
Mesh characteristics:
103 truss elements
3650 Shell elements
21894 DOFs
4952 tonnes of mass assembled (d_x,d_y,d_z)

Material properties:
Masonry: E = 3.5 GPa
Steel: E = 210 GPa

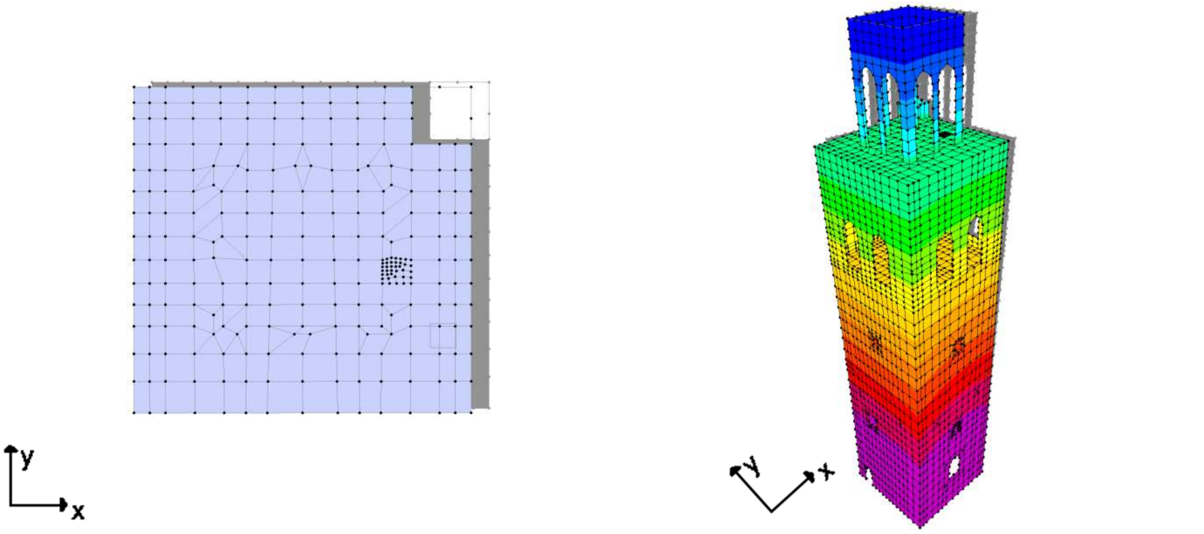
Figure 5 Numerical model characteristics

Table 2 Numerical modal analysis results

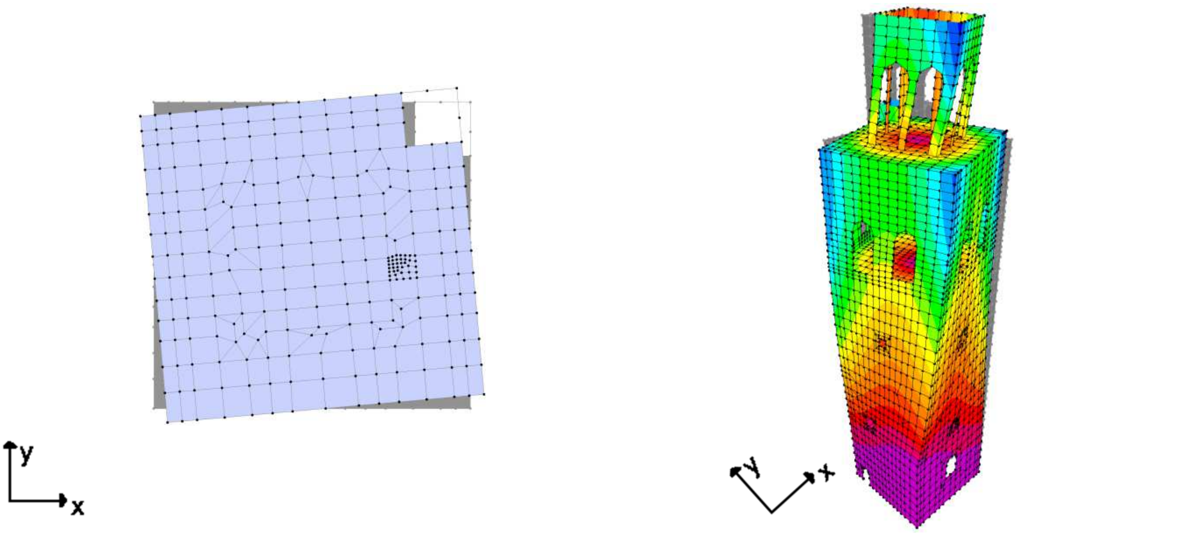
Mode ID	Frequency [Hz]	Relative Error [%]
Mode #1	1.76	-3%
Mode #2	1.81	-7%
Mode #3	6.14	+40%



a) Mode #1: 1.76 Hz



b) Mode #2: 1.81 Hz



c) Mode #3: 6.14 Hz

Figure 6 Numerical mode shapes

The numerical modal analysis results presented were obtained adopting 3.5 GPa for the masonry elasticity modulus and 210 GPa for the steel ties. A total of 4952 tonnes of mass were automatically added by the software for the translational directions.

The mode frequencies and mode shapes obtained are presented in Table 2 and in Figure 6, respectively. It can be observed a good match for the frequencies values of translational modes, as revealed by the relative error values between numerical and experimental results presented in Table 2. Nevertheless, a larger difference was found in the torsion mode. This difference is considered to be high and for the time being, it was not possible to obtain a better match for the frequency values of the three vibration modes simultaneously.

For what concerns the mode shapes, the same diagonal pattern observed in the experimental results for the translational modes was also obtained in the numerical results. This configuration is mainly caused by some asymmetries in the structure (*e.g.* stairway location) and by the interactions with the rest of the cathedral, which were simulated by the boundary conditions in the numerical model.

4. CONCLUSIONS

The ambient vibration experimental campaign made it possible to identity the main three modes of the Funchal's Cathedral Bell Tower. Using a numerical model implemented in a finite element program, it was possible to obtain a good match between the first two modes, although some differences are still obtained for the first torsion mode. Nevertheless, this work is not concluded and further efforts will be made to improve the numerical model in order to better reproduce the experimental results.

A relatively large value for the masonry elasticity modulus was used in the simulations (E=3.5 GPa). This value can be feasible because the vibrations caused by the ambient vibration present very low amplitudes, which are expected to be associated with a stiffer response and lower damping values. The values adopted in the bibliography for this material are usually lower because they are commonly associated with strength or vulnerability assessments, which imply larger deformations, and consequently, less stiff responses (*e.g.* secant elasticity modulus).

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