NUMERICAL CHARACTERIZATION OF BUILDING IN STRUCTURAL MASONRY USING MODAL PARAMETERS

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Abstract. *The objective of this work is to perform the numerical characterization considering its modal parameters (frequencies, damping and modal shapes) of a 16-story concrete block masonry building. The experimental modal parameters of the structure were obtained from the data of the vibrations due to the operational actions observed in 53 pre set points with two hours of measurement each. The final numerical characterization was produced by adjusting the modal parameters of a numerical model based on the Finite Element Method - FEM to the values obtained in the experimental campaign. To confirm the technique, the procedure for obtaining the modal parameters was performed in a second tower similar to the first, considering 18 points and 1 hour each. The comparison of the results of the two towers indicated that the experimental modal parameters obtained approximated the real values. The definitive numerical model presented an acceptable average error for the representation of a structure in masonry.*

Keywords: *Structural masonry, structure dynamics, building vibrations.*

1. INTRODUCTION

The evolution of the use of structural masonry has an exponential growth and many authors, such as OLIVEIRA (2014) and PELETEIRO (2002), have been studying their behavior by analyzing aspects such as constitutive parameters and the work of interfaces between masonry prisms. So many researches are justified because of the variety of blocks and materials of settlement as a variety of traits that accept diverse forms of mooring. These characteristics give masonry structures a unique feature: heterogeneity.

In another aspect, equally challenging, studies were conducted in order to perform a numerical model that best portrays this type of structure, both in the micro modeling aspect to evaluate the behavior of the masonry prism as well as in the macro modeling for the verification of global behavior of the structure as approached by LOURENÇO (1998).

The use of numerical models can help in the observation of the dynamic behavior of the structures considering the effects of the external actions in relation to the time and with this make possible the use of modal parameters (natural frequencies, modal shape and damping rates), thus allowing a new tool in evaluating large structures that undergo dynamic loading requests.

In order to obtain this data, the technique called modal analysis has been shown to be adequate and able to determine modal parameters in civil engineering structures by vibration data presented as responses to external dynamic actions, extracting the signals and treating them through techniques processing. Some studies have already been carried out in works that presented significant dynamic loads such as bridges (LARDIES - 2011), slender chimneys (MINGUINI - 2015), and it is evident that the technique has a great potential to be applied, since the verification of the behavior enabling its structural analysis.

However, some challenges have not yet been overcome, leaving the question of the efficiency of its application of modal analysis to large structures, essentially static, to characterize a numerical model that simulates dynamic behavior with an acceptable precision and allows its use in analyzes more precise civil engineering structures, allowing the construction of more economical and safe projects.

This paper presents the experiments to survey the modal parameters of two large identical buildings and the realization of a numerical model that represents it for use in structural analysis.

2. METHOD

For the development of this study was performed the analysis of the structure to determine the points and data acquisition in two towers for validation of the modal analysis procedure adopted for buildings.

The constitutive properties of the masonry structure and its geometry were also investigated considering the arrangement of the structural elements presented in the projects, making a 3D model in software based on Finite Element Method - FEM to obtain its modal parameters.

Evaluating the data obtained in the building site with those presented in the numerical model, it was verified the need for a calibration of the model to fit the experiment, generating the final numerical model for the representation of the building.

3 EXPERIMENTAL STUDY OF THE DYNAMIC BEHAVIOUR OF THE BUILDING

The objects of study of this work are two buildings in structural masonry located in a residential condominium in the district Planalto in the city of Belo Horizonte in an open region that exposes the buildings with more 44 m of height and the greater face with area superior to 1619 m², to large amounts of wind, being denominated as tower 3 and tower 1, as shown in Fig. 1.

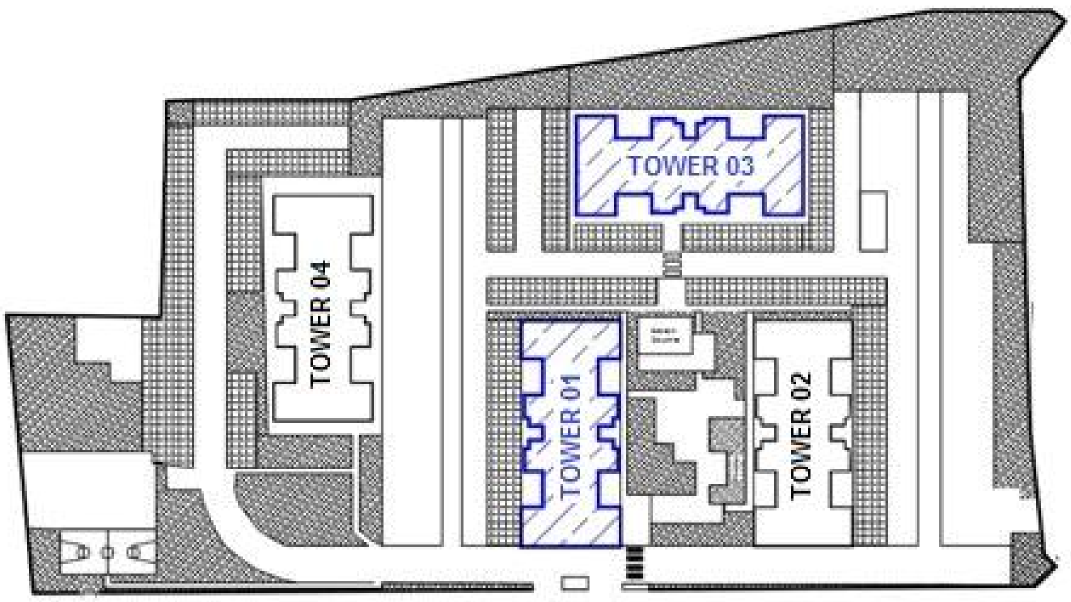

Figure 1 – Position of towers in condo

The towers have the same structure with 14 residential floors with 8 units each, a tank floor and roof slab. The foundation of the building is formed of foundation beams and pile foundation. The project provides for a distribution of variable resistance masonry prisms of concrete blocks as shown in Fig. 2.

The structure of the building provides stretches of masonry in concrete blocks with stretches reinforced with grout and steel frame. Columns and slabs were built in reinforced concrete to increase the rigidity of the structure and an expansion joint is located in the line of symmetry of the largest dimension. This distribution of these structural elements can be seen in Fig. 3 which shows the structure of a residencial floor.

For the field measurements, no record was found in the literature that established the duration, acquisition rate and distribution of points in a large structure with essentially static characteristics, and for this reason was defined a method based on experience on previous studies, usually bridges, where the dynamic loads are larger and thus more likely to be registered. However because it is a building in structural masonry, the vibration coming from these loads, mainly due to the winds, is smaller and for this reason more difficult to be perceived.

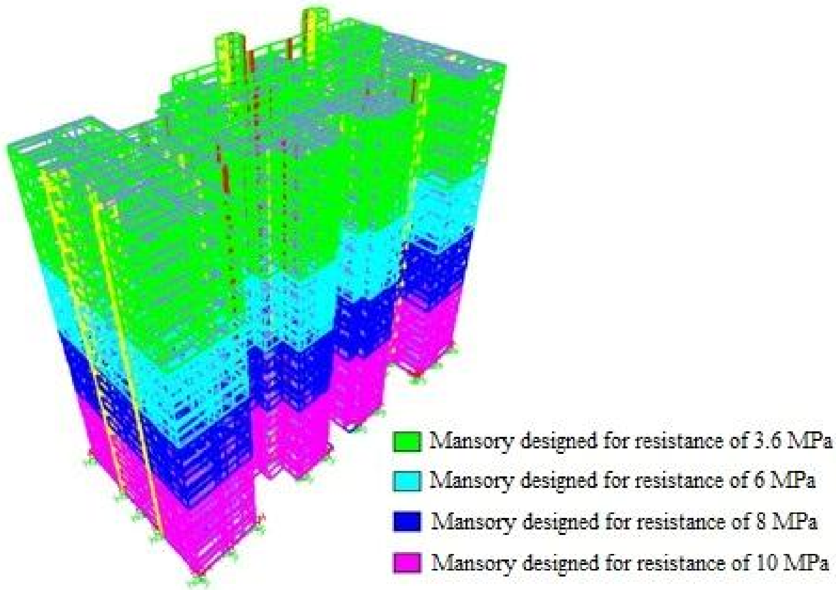

Figure 2 – Distribution of block strength per floor

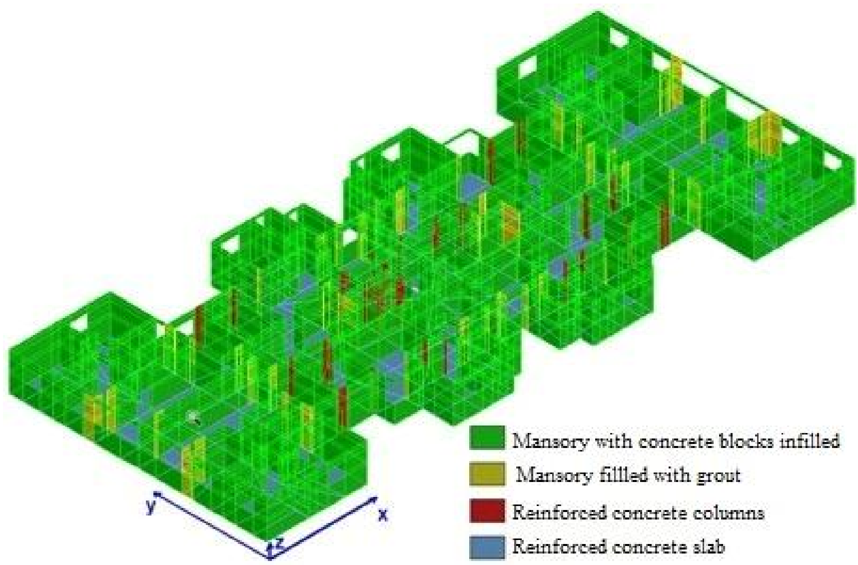

Figure 3 – Structural elements on each floor.

In this context, a more conservative survey was devised in the first experiment carried out in tower 3 to ensure significant registration in both qualitative and quantitative aspects, with 53 points for data acquisition, distributed vertically as shown in Fig. 4 and horizontally according to Fig. 5, with a period of 2 hours for each point, for a total of 106 hours analyzed.

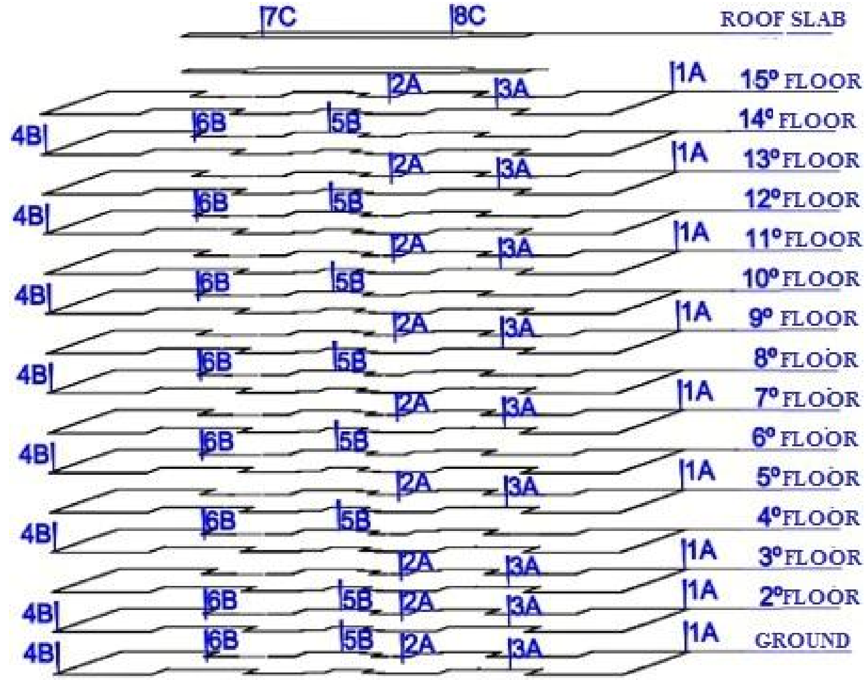

Figure 4 – Distribution of data acquisition points in tower 3

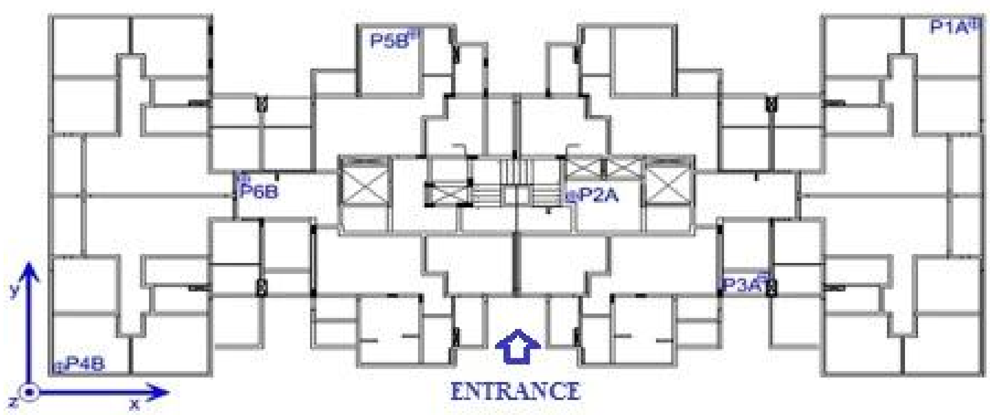

Figure 5 – Distribution of data acquisition points on each floor

In order to carry out the measurements, a set consisting of two data acquisition systems with 3 accelerometers each, model MRC 2000C from the manufacturer Syscom Instruments was used, adopting sample rate of 100 Hz, thus guaranteeing a good record of the spectrum of vibrations present in the structure.

For the analysis of the field surveys, the signals go through a treatment flow as shown in Fig. 6, starting with a preprocessing with analog filters, followed by transformation of the analog (continuous) signals into digital (discrete), through a converter Analogue/Digital

(A/D), providing the data for digital signal processing in order to obtain the modal parameters.

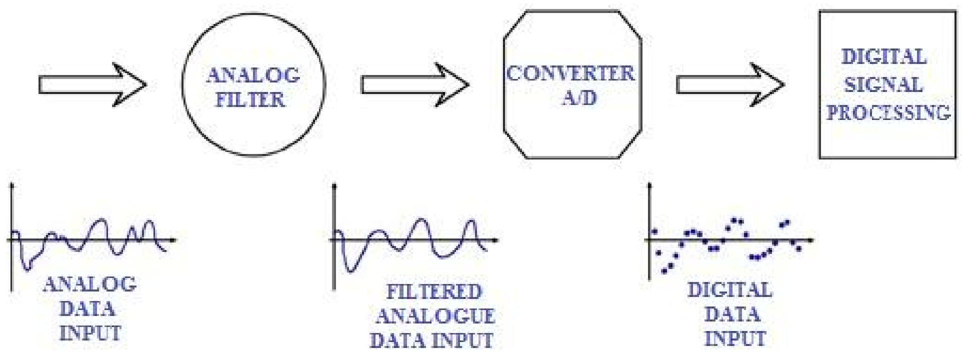

Figure 6 – Signal processing steps

The signal processing and analysis were performed using the ARTeMIS Extractor software, using FFT (Frequency Fourier Transform) methods in the frequency domain that perform the decomposition of the signal in time series, being this a faster method in defining the main frequency of the structure shown in Fig.7 and the SSI (Stochastic Subspace Identification) in the time domain where random actions are identified that represent the transient phase of the impulsive load and establish a stochastic pattern, allowing the dissociation of frequencies very close to each other demonstrated in the Fig.8.

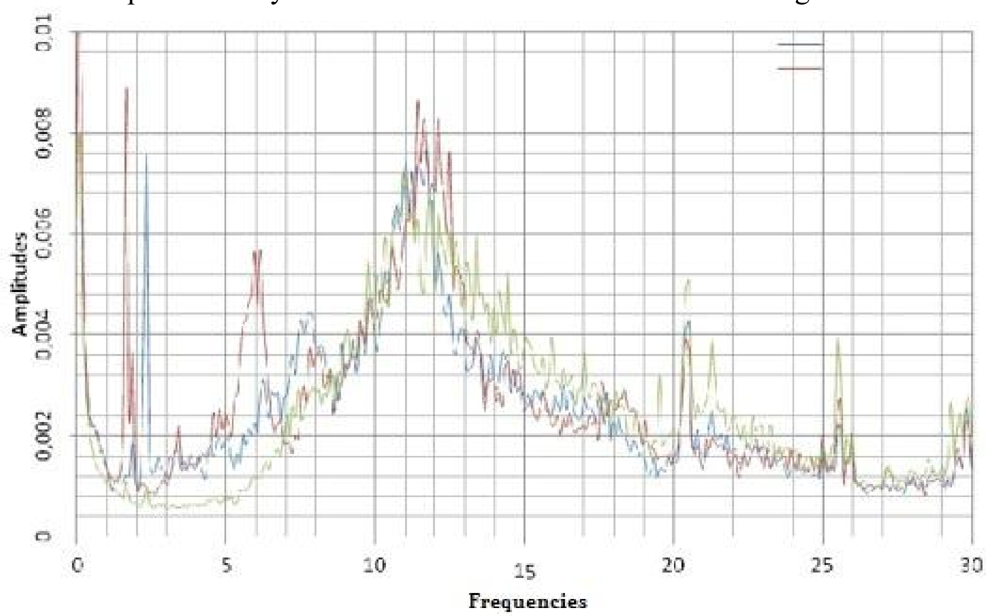

Figure 7 – Spectrum obtained by analysis using the FFT method for tower 3

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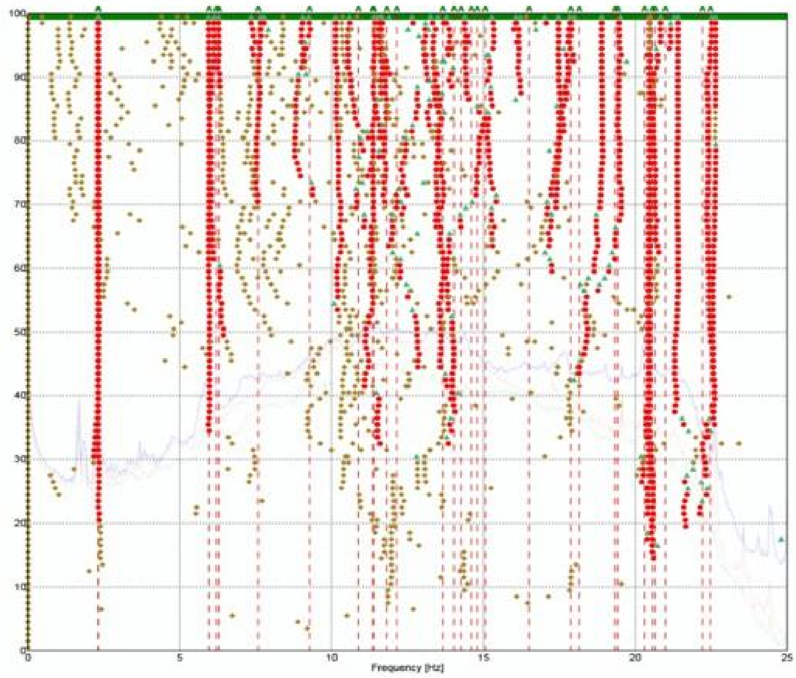

Figure 8 - Result of signal processing obtained through SSI analysis for the tower 3

After analyzing the results obtained for tower 3, a new vertical distribution of the points was proposed - Fig. 9, to evaluate both the efficiency of the method and the need for points to be analyzed, reconfiguring to 18 points, distributed according to figure 9, however concentrating the sites in the upper floors and recording time at each point for 1 hour, thus totaling 18 hours spent in tower 1.

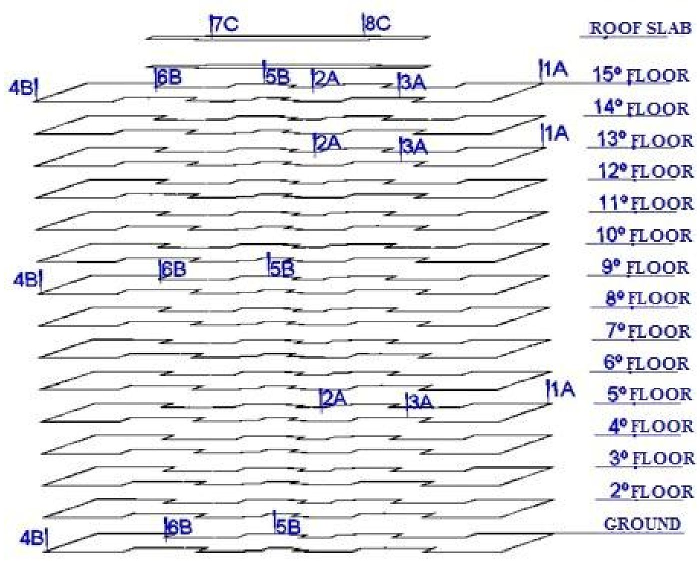

Figure 9 – Distribution of data acquisition points in tower 1

Using the same data acquisition and processing procedures performed for tower 3, the results of tower 1 were obtained Fig. 10 for FFT analysis and Fig. 11 for SSI.

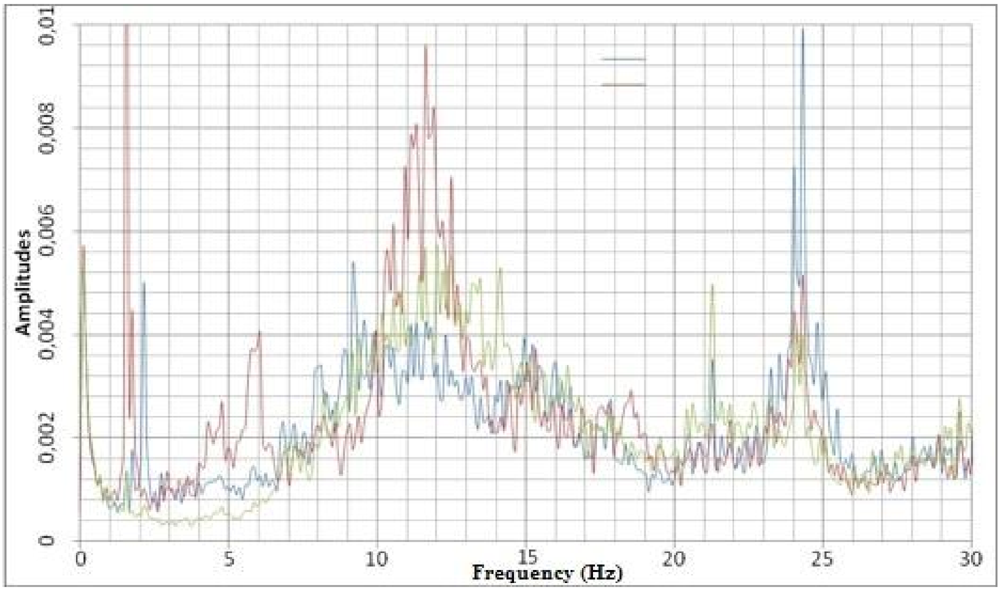

Figure 10 - Spectrum obtained by analysis using the FFT method for tower 1

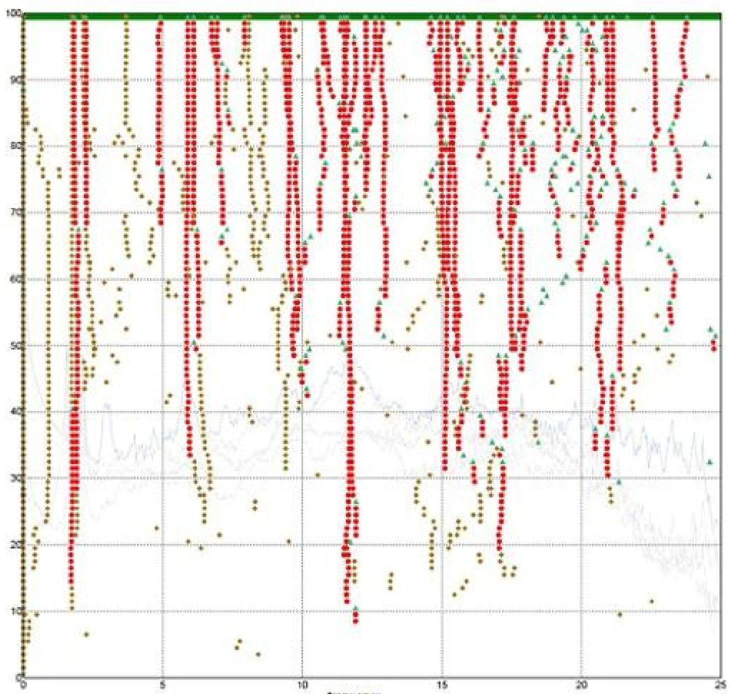

Figure 11 - Result of signal processing obtained through SSI analysis for the tower 1

Analyzing the campaigns carried out for towers 1 and 3, a correlation of 99.82% between the experimental natural frequencies was verified (Fig. 12), thus indicating that the concern to obtain all the main modal shapes was attended by the two events.

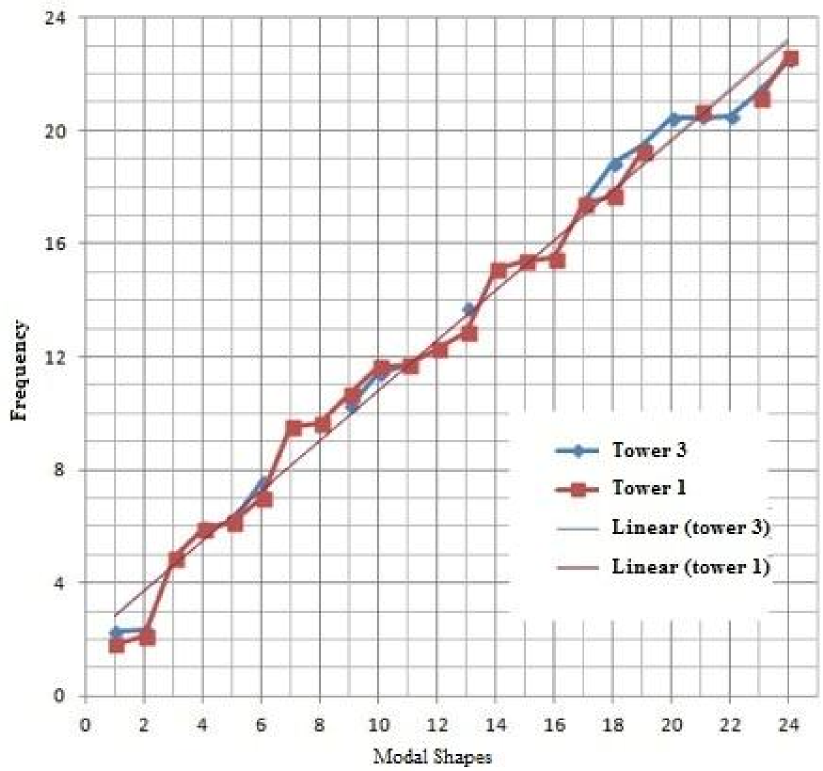

Figure 12 – Comparison of the experiments Tower 3 X Tower 1

Another important aspect verified in the study is the possible decrease of points to be measured and the duration of abstractions, significantly reducing the time for analysis of the structure in both the measurement and the treatment of the data without loss of quality in obtaining the modal parameters.

The cconfirmation of results was obtained in the experimental study of the dynamic behaviour of the building, these are now used as reference for the verification of the functionality of the numerical model that will be performed.

4. DEVELOPMENT OF THE NUMERICAL MODEL

Considering the complexity of the structural aspects involving a masonry building, a numerical model (figure 13) was designed for tower 3 with 3D geometry that allowed the presence of high and low windows, doors, masonry walls, columns, masonry prisms, grout filled masonry and slabs.

The thin shell element was adopted for all the elements that make up the building, since it represents both the plate and membrane behavior with good precision, when used in linear dynamic analysis.

According to the SAP 2000 (1998) manual, the shell element has its own local coordinate system, where axes 1 and 2 are in the plane of the element and axis 3 is normal to this plane. It has 24 degrees of freedom, being 6 per node, comprising 3 degrees of freedom of translation Ux, Uy, Uz and 3 degrees of rotation- Rx, Ry, Rz, thus allowing to analyze as many displacements as the rotations in each node.

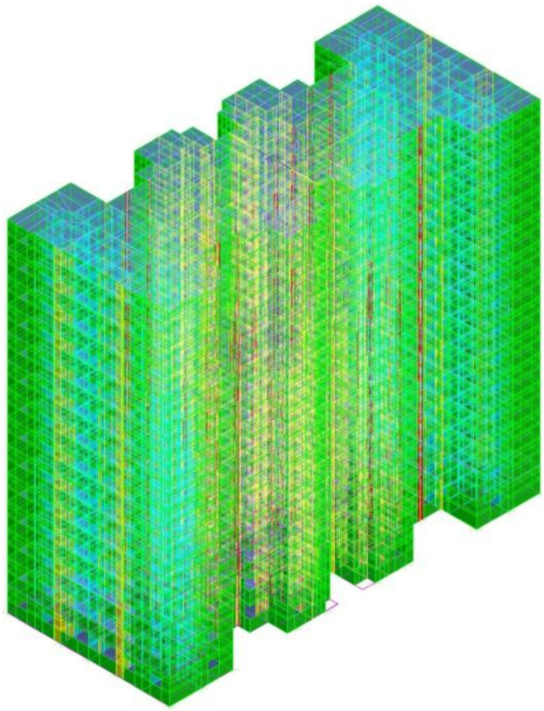

Figura 13 – Numerical model of the building in structural masonry

For the representation of the foundations was chosen the spring element that works similar to a spring where the linear behavior was specified. This element has 6 degrees of freedom where it is allowed to assign six spring stiffness constants, one for each degree of freedom, to simulate the support of a structure.

In order to assign the properties of the elements that compose the model, the data of the masonry prisms were used by studies carried out in Brazil that already present the data of the homogenized prisms for macro modeling as proposed by Lourenço (1996), which reports the steps that consider the arrangement of the together, vertical and horizontal, to find an "equivalent material" (Figure 14).

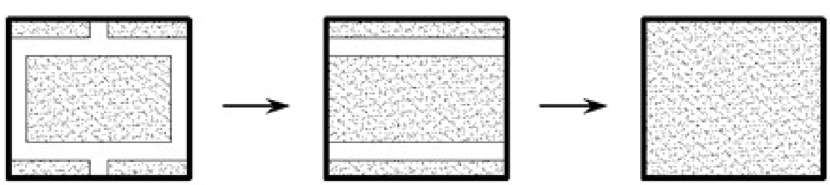

Figure 14 - Method of homogenization of masonry

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The resistances of the structural elements that make up the building were extracted from the executive projects. For the modulus of elasticity of the prisms of unfilled blocks, we use eq. (1) provided for in the norm NBR 15961-1 / 2011, and for sections filled with grout applied the eq. (2) of norm NBR 6118/2014 for the average resistance of project.

$$E_{alv} = 800\ f_{pk}, \tag{1}$$

where f_{pk} is the characteristic strength of the masonry prism expressed in MPa and E_{alv} the masonry modulus expressed in GPa.

$$E = \alpha E \cdot 5600\sqrt{\cdot f_{ck}} \quad \text{for } f_{ck} <= 50 \text{ MPa} \tag{2}$$

where αE is the parameter as a function of the nature of the aggregate and f_{ck} is the characteristic compressive strength of the concrete.

The specific weight and Poisson coefficient properties of the masonry were taken from NBR 15961-1 / 2011 while the properties of the concrete elements were obtained from NBR 6118/2014. Table 1 presents all the data that characterize the structural elements that constitute the building in the initial numerical model.

Table 1 - Values assigned to represent the materials in the initial numerical model

	Resistance of prisms MPa	Modulus of elasticity GPa	weight density kN/m³	Coefficient of Poisson
Mansory - 10 MPa	10	8	14	0.2
Mansory - 8 MPa	8	6,4	14	0.2
Mansory - 6 MPa	6	4.8	14	0.2
Mansory – 3.6 MPa	3.6	2.9	14	0.2
Block filled with grout	17.5	19.9	24	0.2
Columns	30	31	25	0.2
Slabs	30	31	25	0.2
Foundation beams and piles	30	31	25	0.2

After the numerical model was elaborated the modal analysis was performed through SAP2000 software to obtain natural frequencies and modal shape. The model presented a total of 45297 nodes, 84 with string restriction for simulation of the piles, 767 linear elements that represent the foundation beams and 47846 shell elements representing masonry, slabs and columns analyzed, 271.782 equilibrium equations were generated and the first twenty-five modal shape were extracted from the numerical model.

The major mass mobilizations occurred in the first fourteen modal shapes, however to ensure significant results we selected the initial 25 modes that ensured at least 66% mass mobilization in all directions.

Analyzing the results, we verified the low mass mobilization in the initial modes, which already suggests that the model does not have a good representation of the structure.

Comparing the results with those found in the experimental study of the dynamic behaviour of the building, it is evident the need for a calibration of the model.

5. CALIBRATION OF THE NUMERICAL MODEL

With the results of the processing of the validated experimental survey, we used the data obtained for tower 3 as reference for the continuity of the study. We then verified the results obtained in the initial model to verify the correlation with the experimental values with the results presenting an average error of 41.48% that confirms the need for a calibration of the initial model – Figure 15.

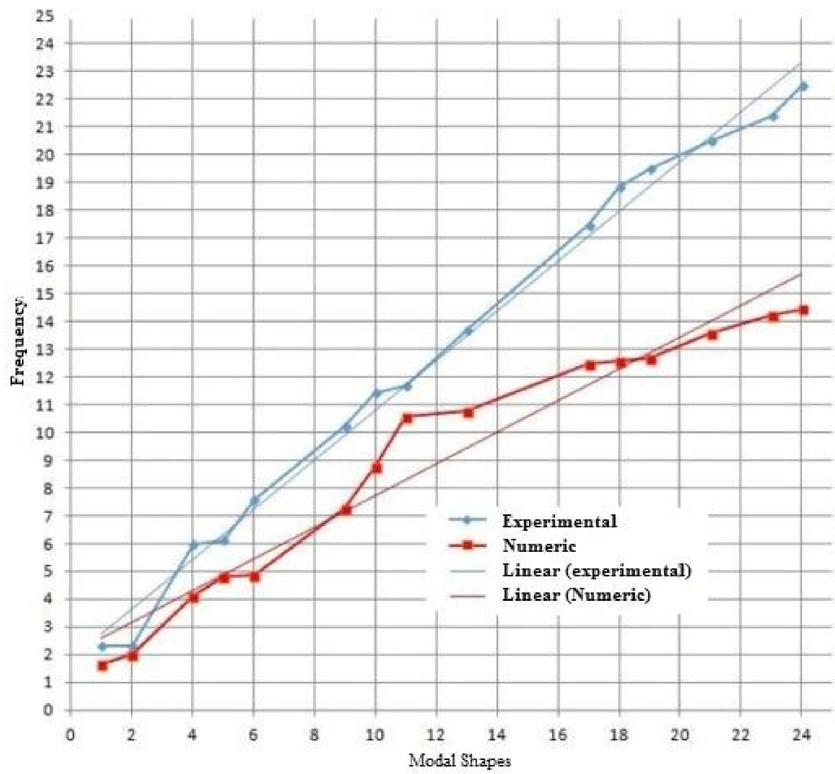

Figure 15 – Comparison of the initial numerical model X the results obtained in the tower 3

For calibration of the initial model, the influences of the modifiable indicators in the SAP2000 software were verified, and their significance was analyzed in the initial, final or specific modes.

After analyzing the parameters of the SAP2000, the calibration process was carried out and the adjustments were made in these indices until the result of the initial model was approached to that obtained in the field experiment.

In order to complete the calibration, 74 calibration steps were necessary according to the flow shown in Fig. 16, with the main changes being: Poisson's coefficient, modulus of elasticity, and especially the stiffness of the foundation, obtaining the configuration presented in the table 2.

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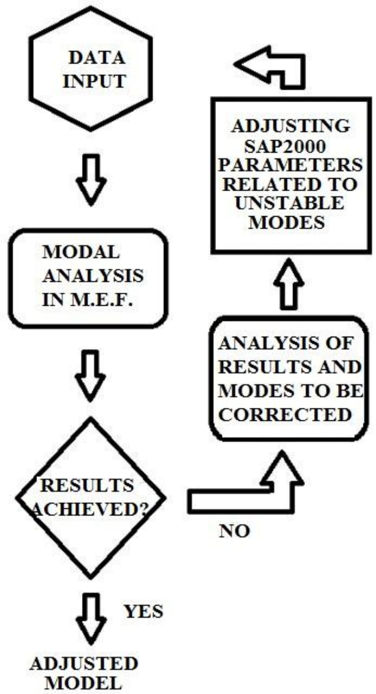

Figure 16 – Calibration flow of the numerical model.

Table 2 – Parameters obtained after calibration of the numerical model

PARÂMETRO	VALOR FINAL
Translation spring coefficient Ux (kN/m)	690000
Translation spring coefficient Uy (kN/m)	575000
Translation spring coefficient Uz (kN/m)	575000
Coefficient of rotation spring Rx (kNm/rad)	575000
Coefficient of rotation spring Ry (kNm/rad)	1150000
Coefficient of rotation spring Rz (kNm/rad)	575000
Modulus of elasticity of masonry (GPa)	13.6
Poisson Coefficient of mansory	0.2
Weight densityof masonry blocks with resistance of 6MPa (kN/m³)	13.8
Weight density of masonry blocks with resistance of 8 MPa (kN/m³)	14
Weight density of masonry blocks with resistance of 10 MPa (kN/m³)	14.2
Weight density of masonry blocks with resistance of 3.6 MPa (kN/m³)	13.6
Weight density of masonry blocks filled with grout (kN/m³)	24
Modulus of elasticity of masonry blocks filled with grout (GPa)	31
Modulus of elasticity of concrete elements (GPa)	31

With the calibration performed, the mean error found was 8.20% for the first 25 modes, with standard deviations of 7.10 for the experiment, and 6.37 for the numerical model with a covariance of 42.44% And with it a correlation between results higher than 93.74% as shown in Fig, 17.

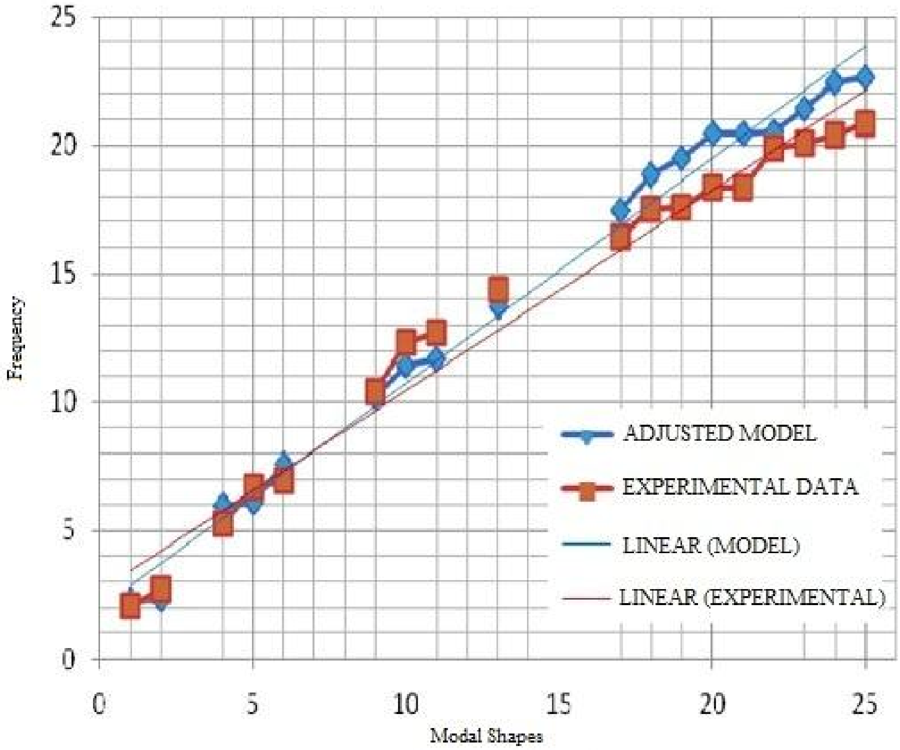

Figure 17 – Comparison between the numerical model calibrated X data obtained in tower 3

6. CONCLUSIONS

As already described in the development of this work, it was a challenge to perform the modal analysis of a large structure, considered as essentially static and with a very heterogeneous constitution.

With the initial capture of the signals, it can be verified that the data obtained were sufficient to obtain the modal parameters, overcoming the questioning if the dynamic loads that impact a large structure, mainly through the winds, would generate data of good quality for the analysis. Then the planning of the way of distribution of points was done, being first (tower 3) executed in a conservative way and later in the second (tower 1) with reduction of points and time of recording. It was verified the efficiency of the method comparing the results in the survey of the towers 3 and 1 with good precision, which validated the form of survey carried out for the structure. Another relevant fact is that the experiment done for tower 1 was more adequate, since it considerably reduced the data acquisition time by practically one-third (from 106 to 18 hours). In addition, it made the signal processing more agile with less redundant data to be processed, and consequently noise reduction allowing robust analysis as it was necessary in the processing that used the time domain techniques, as was the case with SSI.

Another aspect, the representation of the numerical structure from the geometric point of view required a great effort in detailing and describing the elements, both to ensure a good coupling of the elements, and in determining the values of the constitutive indices that faithfully represented the structural behavior of the elements.

Some limitations during the process may have contributed to the failure to achieve a more perfect approximation of the model, among which we can highlight:

1. The limitation of SAP 2000 software that does not have an element that allows the assignment of parameters that represent the behavior of the masonry even if homogenized, this could be solved with more discrete elements at the level of the block, however the computational cost could become very high or even impracticable.

2. The structure in masonry has more than one form of mooring and this means that numerically the couplings of the elements representing the masonry should allow the treatment in such a way that the degrees of freedom at these intersections could portray these differences.

3. Likewise, the presence of elements of pre-shaped parts such as ladder support, rods among others that alter the stiffness and mass of a significant amount of masonry, can not be represented due to the possibility of compromising the processing due to robustness that the model would achieve;

4. And finally, all the signals obtained pass through an operator that interprets them and performs a series of treatments and processes that accumulate approximations, and in the end is assigned by the software a result with a standard deviation for each obtained value that in turn can cover a mode of vibration that is very close and therefore does not appear (coupled modes).

Known some of the main limitations of this process and recalling the dimension of the structure under analysis, it can be affirmed that there are good indications that the model is well representative, given the results found.

Another fact that must be registered is the efficiency of the calibration process of the model, which contributed with an average decrease of 66.81% of the error in relation to the initial model, reaching indexes above 90% in some modes.

In view of this scenario it can be verified that the method can be used to characterize a large building in structural masonry, and with knowledge of the behavior of the structure and the use of other research methods, this technique can contribute significantly, both preventively in the delivery of the work and in the evaluation of secular works, being able to be applied with monitoring or corrective in the aid in the identification of the damages.

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