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VIBRATION ANALYSIS OF A STEEL FLOOR SYSTEM WITH DRY FLOORS: A NUMERICAL – EXPERIMENTAL STUDY

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Abstract. One of the trends of contemporary architecture is the design of buildings with long spans and increasingly slender structural elements. In addition, the use of dry floors has been common in residential and commercial constructions. Thus, the structural design adopted for current buildings is usually more susceptible to vibrations from human activities, since these structures have lower natural frequencies. However, researches dealing with the study of vibrations in dry slab floors supported by rolled or welded steel beams are scarce. For this reason, this project aimed to study the dynamic behavior of a steel floor system with dry floors. A finite element (FE) numerical model was developed using ANSYS 19.0 software to simulate this as-built floor system. This numerical model was adjusted and validated by the first two natural frequencies of the structure obtained by an experimental modal analysis. In this practical analysis, two accelerometers, an A/D converter and a portable computer were used to acquire the signals in the time domain. With features and routines developed in MATLAB, these signals are processed and transformed into the frequency domain by the FFT algorithm (Fast Fourier Transform). It was observed that the deviation between the numerical and experimental results were close enough to prove the reliability of the models developed.

Keywords: Dynamic analysis, Modal experimental analysis, Dry slabs, Finite element modeling.

1 Introduction

According to Benevolo [1], the Civil Construction, in which handcraft and inaccurate techniques were used in the past, has adopted the mechanization of its production systems. Terms essentially related to industries began to be applied in the process of architecture and engineering designs. For instance, one can cite mechanization, serial production, composition, organization, etc. Additionally, several construction techniques have emerged in the past few decades. One of these new methods is called dry construction technique, which is characterized by the absence of water in most of the in-situ building process. However, researches dealing with structures used in such technique are still uncommon in the literature. Therefore, the present paper focused on a dynamic study of floor systems used in the dry construction technique. The following sections will briefly review some theorical details concerning the dry construction technique, modal testing and FE modal analysis.

1.1 Dry construction technique

In the 1930s, as reported by Bruna [2], the dry construction technique was devised by the architect Prouvé. In this technique, water is only used at the foundation stage. In subsequent phases, water and other elements contained in a traditional construction are dispensed with, such as sand, cement, gravel and mortar, for example. Thus, any construction that follows these preconditions may be considered as a dry construction.

The absence of water during part of a construction stage offers advantages related to the principles of sustainability. In other words, dry construction technique has economic, social and environmental benefits. The main advantages of this technique associated with the above three pillars of sustainability are: the use of prefabricated materials with tightly controlled physicochemical dimensions and characteristics, standardization of structural elements, the systematic manufacturing and assembly methods using repetitive operations, the possibility of multiple assembling and disassembly, the speed of execution, the administrative control of production, the possibility of separating the manufacturing and assembly sites, the rigorous physical and financial control of the work, less waste of materials and labor allocation and the abandonment of traditional construction practices based on the artisanal use of molded pieces in loco (Brandão [3]). Thus, the application of the dry construction system contributes to the economic, social and ecological advancement of Civil Construction.

Nowadays, there are a variety of building processes that are compatible with dry construction. For example, systems known as Light Wood Framing (construction system with structural elements in wood) and Light Steel Framing (construction system with structural elements in cold-formed steel sections) may be cited. In addition, it is possible to use the dry construction technique with structural elements in rolled or welded steel profiles. One of the advantages of this last option is the possibility of reaching large spans.

Moreover, in the market there are several options of industrialized slabs compatible with the structural system of rolled steel profiles. One of them is the sandwich-structured composite panel (SCP), whose application does not involve the use of water and the coating is applied directly to its surface by means of a bonding material. The SCP is usually found in the market as Painel Wall® (Eternit), LP Mezanino® with cement boards (LP Building Products), Masterboard Panels® (Brasilit) or Painel Wall Wood® (Dercolit).

Although the SCP is commercially available, in the academic field it is still little researched. Thus, this paper employs a floor system with a SCP as its object of study. The SCP adopted herein is composed of an Oriented Strand Board (OSB) wooden core, sandwiched by two fiber reinforced cement boards. Figure 1 illustrates a SCP as well as its usual dimensions.

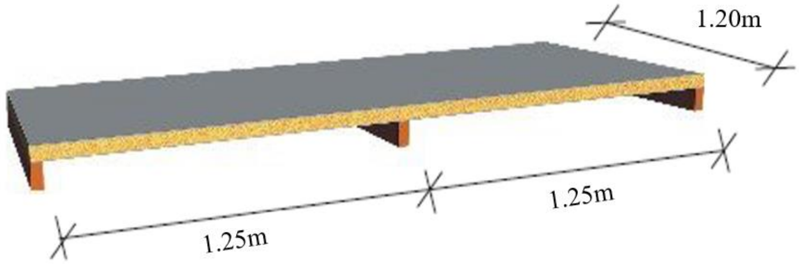


Figure 1. SCP dimensions.

1.2 Experimental modal analysis

The objective of the experimental modal analysis is to obtain a mathematical model of the system under study that relates the output (response) of the system to each unit of input (excitation) applied (Nóbrega, [4]). This mathematical model will allow to describe more precisely the dynamic behavior of the system. Thus, the analysis process consists of the adjustment of the theoretical curves of the adopted model to the experimental curves, through which parameters such as natural frequencies, vibration modes and modal damping are obtained. Ewins [5] states that there are basically two types of vibration measurement: those in which only one parameter is measured (usually the system response) and those in which both the excitation and response parameters are measured.

According to Bilošova [6], the instruments needed to perform an experimental modal analysis consist basically of three or four major items. Firstly, an excitation mechanism by means of electrodynamic vibrators (with harmonic or random signal) or impulsive excitation (hammer impact or an initial displacement in the system). Secondly, a transducer system such as accelerometers and load cells should be used to measure the various parameters of interest. Note that proper attachment of these transducers to the structure may precisely provide its response. Bilošova [6] describes various types of fastening materials, such as screws (stud), special cement, thin double adhesive stud, beeswax and magnet, sorted from the best to the worst. Thirdly, an analog-to-digital (A/D) converter for transforming continuous signals (analog signal) into discrete signals (digital signals). Finally, a computer system for post-processing of measured data, extraction of modal parameters, animation of vibration modes, etc. Figure 2 shows a typical experimental setup exemplifying the items cited.

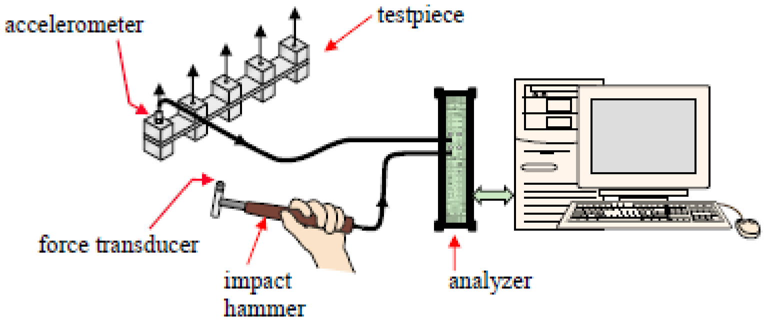


Figure 2. Typical experimental setup for modal testing [6].

Modal parameters, such as natural frequencies of vibration, can be determined from the measured signals. These parameters are determined in the signal processing step, which aims to highlight or extract information contained in a signal where a direct observation could not reveal (Silva and Maia [7]). For the determination of the modal natural frequencies of the system, the time domain signal shall be transformed to the frequency domain. There are different operations in the literature to perform this transformation. One of the most commonly used algorithms is called Fast Fourier Transform (FFT). This expression refers to a family of efficient algorithms for obtaining the Discrete Fourier Transform (Soriano [8]). Currently, this operation is performed simply with programs and features developed in MATLAB. A detailed description of the basic relationships of the Fourier

Transform as well as these algorithms can be found in the books (Ewins [5]), (Chopra [9]), (Clough and Penzien [10]), (Silva and Maia [7]) and (Soriano [8])

1.3 Numerical modal analysis

Modal analysis is used to determine the vibration modes of a system and their respective natural frequencies. In this analysis, the damping is not considered. The non-damped free vibration motion equation of a system with n degrees of freedom can be expressed as follows:

$$\boldsymbol{m\ddot{u}(t)} + \boldsymbol{ku(t)} = \boldsymbol{0} \qquad (1)$$

where $\boldsymbol{m}$ and $\boldsymbol{k}$ are, respectively, the system mass and stiffness matrices, $\ddot{u}$ and u are, respectively, the acceleration and displacement vectors and 0 is a zero vector.

For a linear system, the solution of Eq. (1) may be represented by:

$$\boldsymbol{u(t)} = \boldsymbol{\hat{v} sen(\omega t + \theta)} \qquad (2)$$

where $\boldsymbol{\hat{v}}$ represents the system configuration, ω is the angular frequency and θ is the phase angle.

When Eq. (2) and its second derivative are replaced in Eq. (1), an eigenvalue and eigenvector problem is obtained:

$$\left[\boldsymbol{k} - \boldsymbol{\omega^2 m}\right] \boldsymbol{\hat{v}} = \boldsymbol{0}. \qquad (3)$$

Eq. (3) will have a nontrivial solution if and only if the determinant of the expression in brackets equals zero.

$$\left|\boldsymbol{k} - \boldsymbol{\omega^2 m}\right| = \boldsymbol{0}. \qquad (4)$$

Eq. (4) is called the characteristic equation. From the development of this determinant one can arrive at an equation whose n roots $(\omega_1^2, \omega_2^2, \ldots\ \omega_n^2)$ represent the frequency squares of the n possible vibration modes of the system.

2 Experimental program

2.1 Methodology

The floor system studied belongs to a dance academy located in Vitória-ES, Brazil. The building has two levels, ground floor and first floor, and its floor system uses dry slab supported by rolled steel beams. The slab consists of SCP. Figure 3 presents the first-floor plan of the building.

First step to perform a modal testing is the determination of the excitation and response measurement location. For this, the structure was discretized by a numerical model using ANSYS 17.0. Even though this model is not validated and adjusted yet, it generates good notions of the mode vibrations. In this way it is possible to choose the location of the excitation and measurement points for the modal testing. Figure 4 shows the first two modes of vibration found with the numerical model. The location of the excitation and measurement point are displayed in Fig. 3 as $N1$ for the first vibration mode and $N2$ for the second vibration mode.

Impact excitation technique is used to induce vibrations in the floor system by human jumping. The jumps are placed in the points $N1$ and $N2$ aforementioned. Figure 5 shows one of the jumps performed by a person during measurements to excite the first vibration mode of the structure. Figure 6 shows the simultaneous jump of three people to the induce the second vibration mode of the structure. More people were required to excite the second vibration mode, since the mass of just one person was not enough to cause vibrations with frequencies close to the natural frequency in this mode. In addition, the choice of jump as an impact excitation is justified by the impossibility of using other excitation techniques that could damage the structure or disrupt the functioning of the dance academy for a longer period. Plus, other forms of excitation require sophisticated equipment only available in very specialized laboratories.

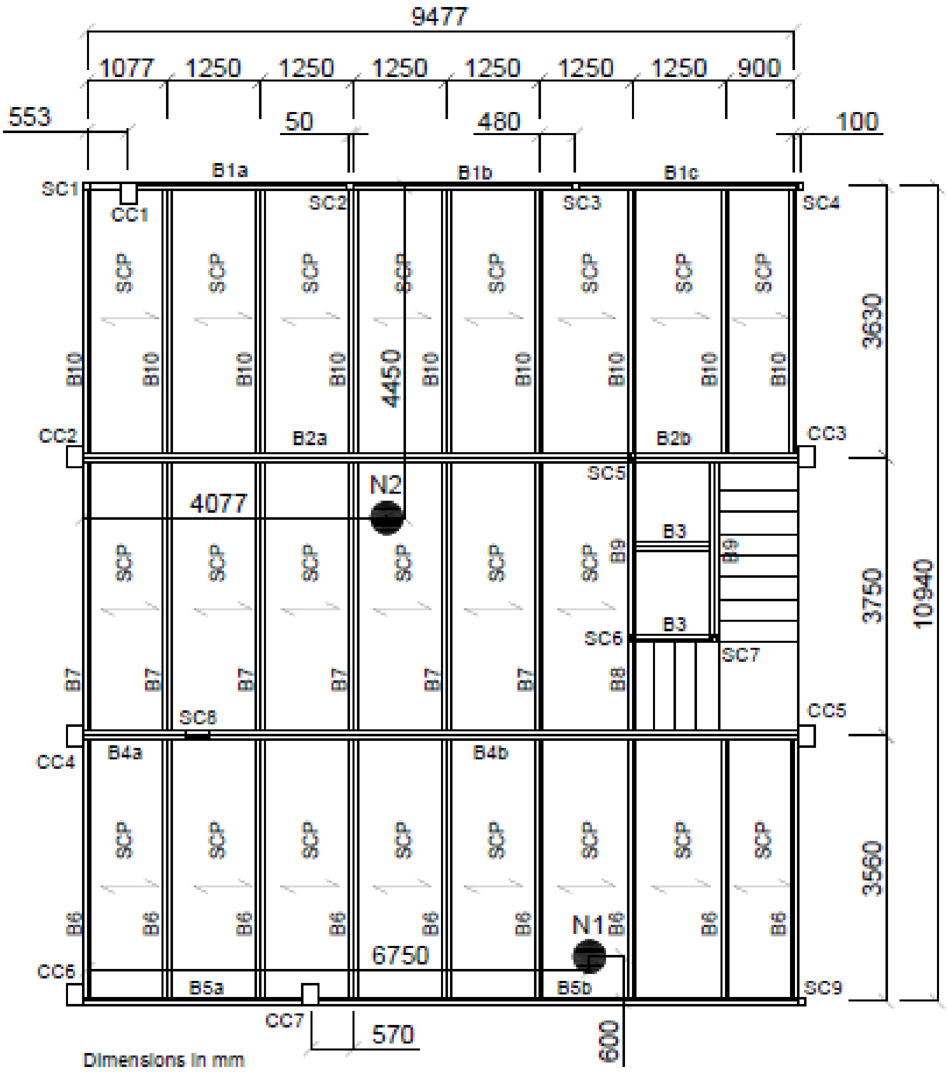
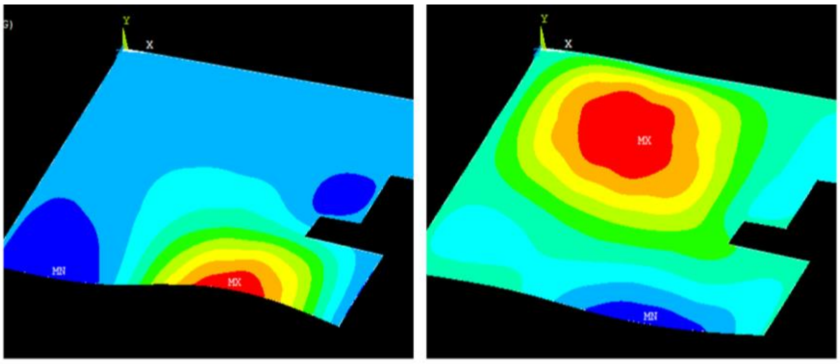


Figure 3. First-floor plan of the building under analysis.



(a)

(b)

Figure 4. Mode shape of the (a) first and (b) second vibration modes of the floor system.

Figure 5. Excitation to induce the first vibration mode of the floor system.

Figure 6. Excitation to induce the second vibration mode of the floor system.

The equipment used to perform the modal testing are an A/D converter, two accelerometers and a laptop computer. Figure 7 shows the arrangement of the data acquisition system during the test. The mechanisms used to attach the accelerometer to the structure are double sided adhesive tapes and clamping devices, as shown in Fig. 8. Clamping devices can attach the accelerometer to the structure similarly to an attachment provided by screws. For the measurements at point $N1$, only the adhesive tape could be used, because a false ceiling prevents access to the beams. At point $N2$, both attachment types could be used. Figure 8a shows the accelerometer attached to the beam bottom flange by the clamping device at point $N2$; Fig. 8b displays the other accelerometer at point $N2$ attached by double sided adhesive tape instead; and, Fig. 8c shows the accelerometer attached on the floor at point $N1$ by adhesive tape.

Figure 7. Data acquisition system.

(a) (b) (c)

Figure 8. Accelerometers attachment.

Finally, the last step before performing the tests is to establish the analog and digital data sampling parameters – basically, the sampling frequency and filters frequency. The sampling frequency is 400 Hz at point $N1$ measurements and 20000 Hz at point $N2$. Different sampling frequencies are applied in order to assess the results sensibility to this parameter. However, both values satisfy the Nyquist sampling criterion as they are higher than the Nyquist rate – twice the maximum component frequency of the system being sampled, which is around 10 Hz according to the numerical model developed. Additionally, a low pass filter with a cut-off frequency of 30 Hz is used to enhance the signals acquisition.

2.2 Modal testing results

After signal acquisition, the measurement data is processed by the algorithms developed in MATLAB. Figure 9 shows the graph of a typical floor acceleration measured at point $N1$. The transient part of the signal is truncated from the original signal and repeated multiple times. This procedure attempts to remove the noise captured in the signal and to improve the resolution of the frequency spectrum, which is inversely proportional to the total signal time. The Hanning window is then applied to this signal prior to the FFT operation. Figure 10 shows the power spectral density (PSD) of the signal obtained with the FFT operation. The first peak happened at a frequency of 6.787 Hz, considered the first natural frequency of the structure.

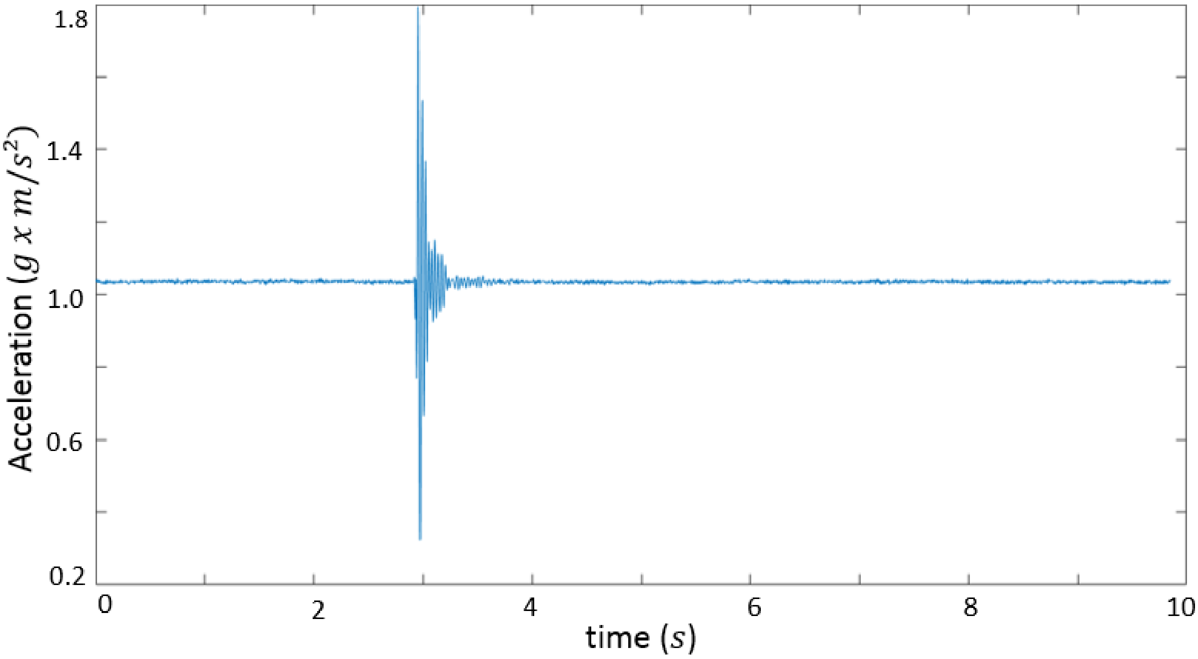


Figure 9. Typical acceleration response of the first vibration mode excitation.

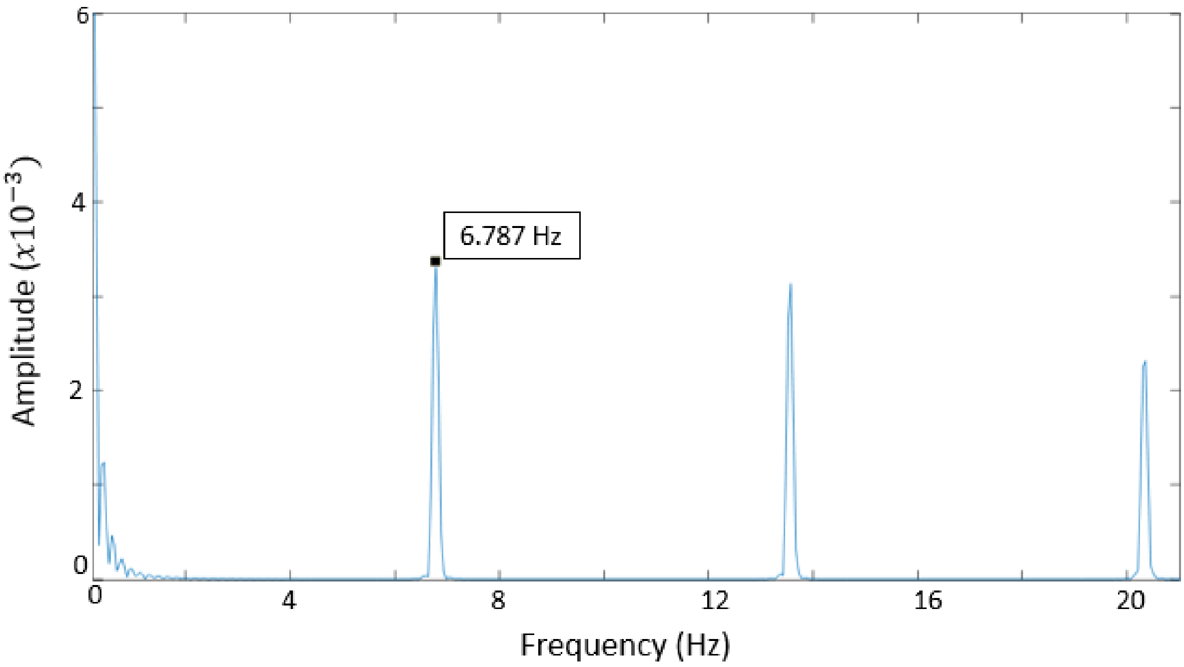


Figure 10. Power spectrum density for the signal of the first vibration mode excitation.

Figure 11 shows the graph of the floor acceleration when excited by multiple jumps at point $N2$. Analogous to the procedure applied in the first vibration mode signals, a transient part of the signal is truncated from the original signal and repeated multiple times. Then, Hanning window is applied to this signal prior to the FFT operation. Figure 12 shows the PSD of the signal obtained with the FFT algorithm using MATLAB. The spectrum of frequency amplitudes showed numerous peaks. The first peak of the spectrum occurred at a frequency of 10.12 Hz, established as the frequency of the second experimentally obtained structure vibration mode. Note that the spectrum is spread over several lines, indicating an error occurred which may be related to the setup parameters applied or the procedures employed in the post-process analyses. Even though the spectrum does not indicate a single frequency, a smooth curve could be drawn through the lines and the peak amplitudes could be estimated.

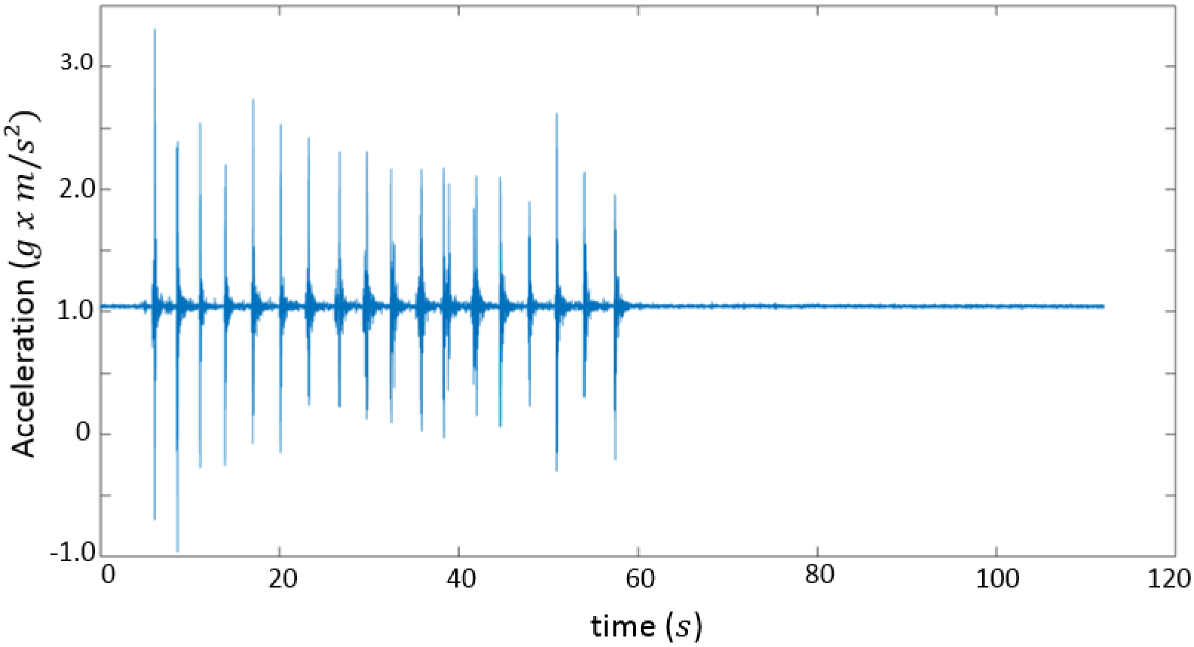


Figure 11. Acceleration response of the second vibration mode excitation.

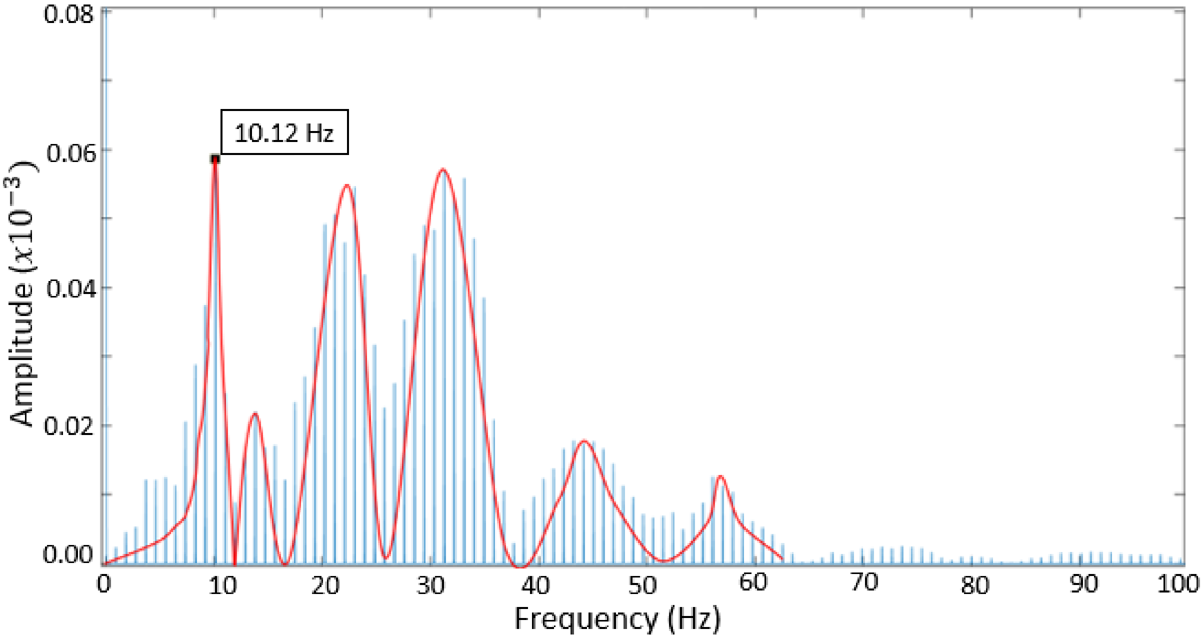


Figure 12. Power spectrum density for the signal of the second vibration mode excitation.

3 Finite element modal analysis

3.1 Modelling techniques

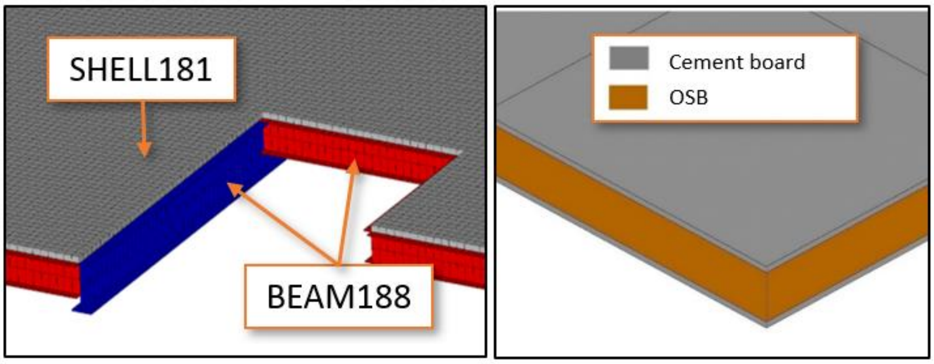
The modeling of the floor system began with the identification of the material properties of the structural elements that compose it. The steel beams are made of ASTM A572-Grade 50 steel and, according to ABNT NBR 8800: 2008, the modulus of elasticity is equal to 200 GPa, the Poisson's ratio is 0.3 and the density is 7850 kg/m³. The material is considered linear, elastic and isotropic. The SCP is 40 mm thick and consists of two 4 mm thick cement boards at each end with a 32 mm thick OSB wood panel in the middle. The cement board is considered isotropic and its mechanical properties values are taken according Campello [11]: 7 GPa for the modulus of elasticity, 0.2 for the Poisson's ratio and 1450 kg/m³ for the density. The mechanical properties of OSB vary according to the three orthogonal directions. The values of longitudinal modulus of elasticity (E), transverse modulus of elasticity (G) and Poisson's ratio (v) are extracted from the experimental study conducted by Morrissey, Dinehart and Dunn [12] and are presented in Table 1. The x, y and z directions indicate, respectively, the transverse, radial and longitudinal directions of the OSB plate. Density is adopted equal to 590 kg/m³. Those values for thickness and density of both materials were provided by Louisiana Pacific Corporation (LP). Elastic-linear behavior is considered for all material models.

Table 1. OSB material properties

Property		Value
Longitudinal modulus of elasticity (N/mm^2)	E_x	3100
	E_y	6200
	E_z	6200
Transversal modulus of elasticity (N/mm^2)	G_{xy}	240
	G_{yz}	1600
	G_{xz}	240
Poisson’s ratio	ν_{xy}	0.3
	ν_{yz}	
	ν_{xz}	

Modeling the mass of the finite elements as realistic as possible plays an important role in numerical modal analysis accuracy. In the FE model developed there is the mass related to the structural elements that compose the floor system and the additional mass from the permanent and accidental loads on the structure. The first mass is calculated by the computer program according to the geometry and volumetric density of each structural element. The additional mass should be estimated and entered after modeling. However, this mass will be used as an adjustment parameter of the numerical model, as it influences the value of the natural frequencies of the system. Moreover, as the building is already built and there is no detailed description of which finishing materials were used, its value cannot be accurately estimated. Therefore, the total value of the added mass corresponding to all items and variable loads present in the structure will be established later during the numerical model adjustment.

Element choice also plays a key role in FE numerical analysis. In this FE model, beams are simulated by 2-noded beam elements (BEAM188), with six degree-of-freedom (DOF) at each node. SCP is represented in the FE model by 4-noded shell elements (SHELL181), with six DOF at each node and three layers reproducing the three different materials of the SCP. Figure 13a shows the elements chosen to represent the floor system; Fig. 13b shows the multi-layer shell element used to represent the SCP; and, Fig. 14 shows an isometric bottom view of the FE model developed using ANSYS 19.0. In those images primary beams are represented in blue, secondary beams in red and the SCP in gray.



(a) (b)

Figure 13. (a) Elements implemented in the FE model and (b) the multi-layer shell element used to represent the SCP.

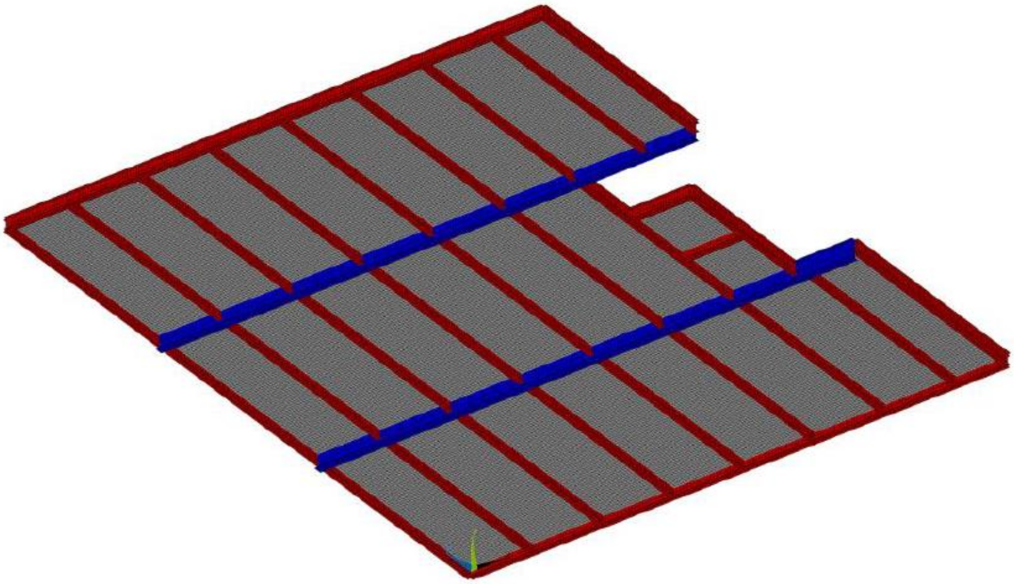


Figure 14 – 3D Isometric bottom view of the FE model developed.

Modeling realistic boundary conditions is a challenging and important part of developing a simulation. Hence, assumptions are made according to the structure connections. Flexible connections are considered between columns and beams. Then the three translational DOF are restricted at the nodes near to the column's location. Connections between beams and columns are also adopted as flexible. The connections between the secondary and primary beams, in turn, were considered rigid, that is, transmitting the translations and rotations in the three axes. For SCP, they are modeled as a single panel across the length of the slab. This alternative considered the existence of final finishes under the slab, such as elastomeric glue and laminate flooring, providing displacement compatibility between the panels. Finally, total interaction between the panels and beams nodes is assumed, that is, there is a total transfer of the shear stresses between panels and beams nodes. Overall, all assumptions taken attempted to simplify the FE model without missing relevant features of the real structure behavior.

3.2 Adjustment and validation of the numerical model

Adjustment and validation of the numerical model is performed based on the first two natural frequencies of the structure. These frequencies were measured experimentally and are used as parameters for the model calibration. According to section 2.2, the natural frequency of the first vibration mode of the structure is 6.787 Hz and for the second vibration mode 10.12 Hz. Therefore, the numerical model adjustments aim to achieve these frequencies for the first and second vibration modes.

Since natural frequency is related to the mass and stiffness of the system, these are the parameters to be adjusted for numerical model calibration. The stiffness matrix can be changed by varying boundary conditions and/or properties of materials and elements. The geometric properties of the elements cannot be changed as they correspond to the measured data of the as-built structure. The boundary conditions are related to the connections between the elements which were already studied and simplified. Any changes in boundary conditions would increase the natural frequencies values, once most connections were considered flexible. The natural frequencies of original FE model are greater than the measured frequencies. Therefore, the only parameters left to decrease the value of natural frequencies are the added mass and the modulus of elasticity of the materials.

Figure 15 shows a parametric study made to assess the sensitivity of the FE fundamental frequency of the floor to them. The varying parameters are the additional mass and the modulus of elasticity of the slab materials. It was found that the reduction of the material modulus of elasticity have little influence on the determination of the natural frequencies. A reduction below 0.5 Hz for a 60% reduction in elastic modulus was found. The additional mass, on the other hand, had a significant impact on the results. Approximately 1.0 Hz was reduced by adding 40 kg/m² of mass to the system floor. Therefore, it was decided to maintain the material properties and change the added mass so that the first two natural numerical frequencies correspond to those obtained experimentally.

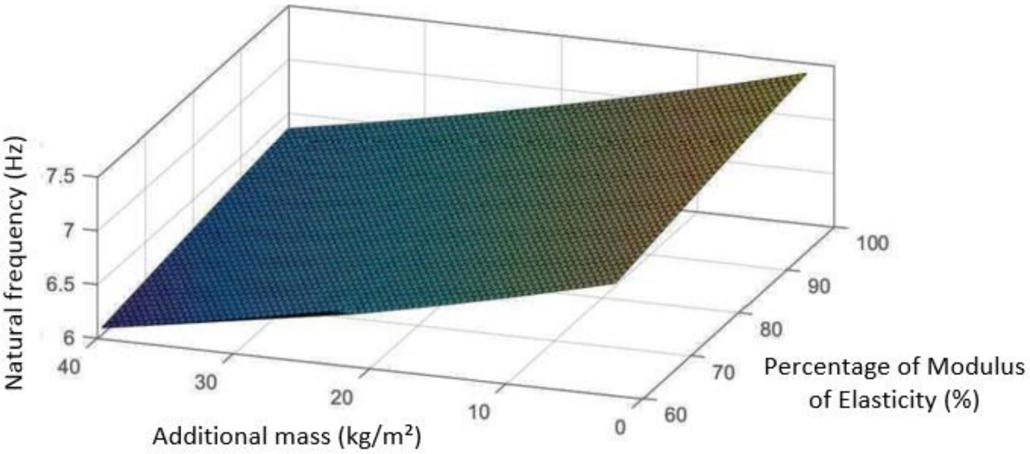


Figure 15. Modulus of elasticity reduction and added mass increase sensitivity study.

Figures 16 and 17 show the natural frequencies of the first and second modes, respectively, obtained by varying the additional mass from 0 kg/m² to 30 kg/m². Plus, a line crosses the curve found indicating which additional mass should be chosen to obtain a numerical frequency equal to the experimental one. Thus, it has been found that the additional mass for the natural frequency of the first structure vibration mode to be 6.787 Hz and that of the second 10.12 Hz must be, respectively, 23.3180 kg/m² and 24.2077 kg/m². Therefore, 23.3180 kg/m² is adopted as additional mass, obtaining a frequency of 10.17 Hz for the second mode. Thus, it is considered that the numerical model is validated according to the experimental modal analysis performed.

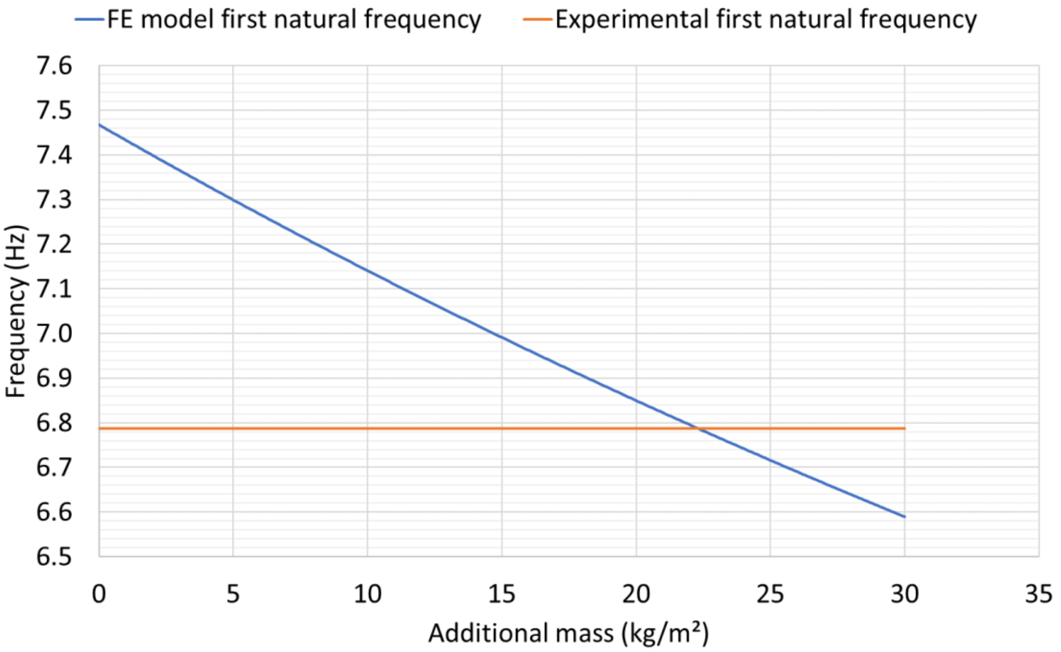


Figure 16. FE adjustment: additional mass *versus* first natural frequency.

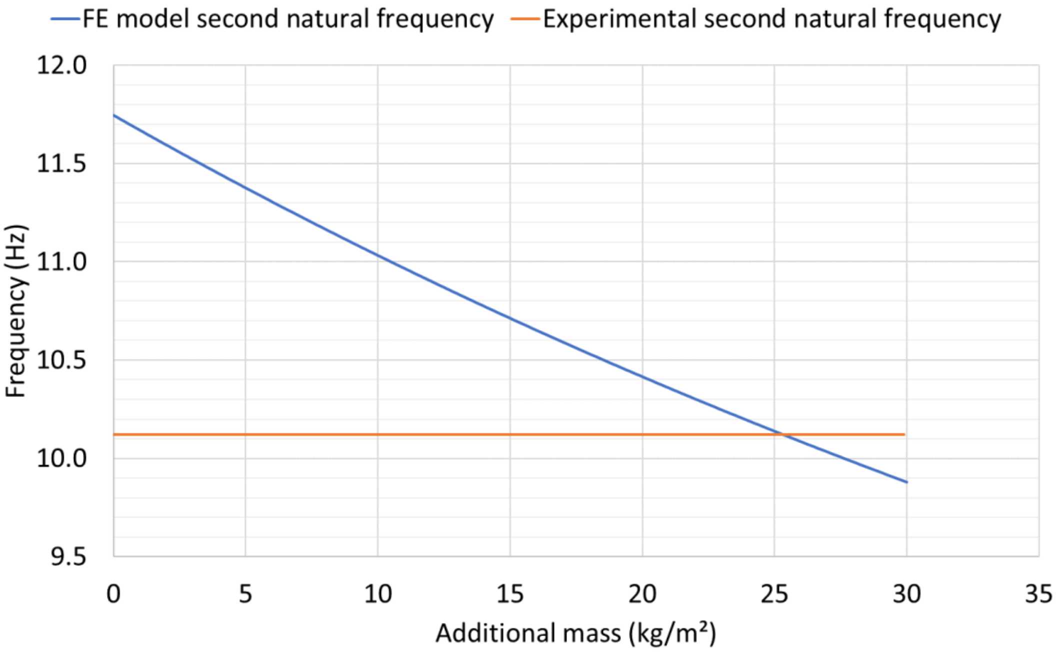


Figure 17. FE adjustment: additional mass *versus* second natural frequency.

4 Conclusions

In this paper, a FE model was developed and validated by measured data for a dance academy. The first two natural frequencies of the floor system were used to adjust and validate the FE model developed. Percentage errors between experimental and numerical results of 0.39% and 1.07% for the first and second vibration mode, respectively, were found. Therefore, is was concluded that the FE model developed could accurately predict natural frequencies for the structure under analysis.

Moreover, conclusions regarding the experimental program methodology employed and the FE model adjustment performed can be drawn from the analyses. Firstly, best experimental results were obtained for the first vibration mode excitation. The main differences between both tests were the accelerometer attachment location, the number of people inducing the vibrations on the structure and their sampling frequency. Hence, it was demonstrated that modal testing results are very sensitivity to those parameters. Secondly, a parametric study was conducted to assess the FE model natural frequency sensitivity to changes of material properties and additional mass. It was found that the added mass has more impact on the numerical modal analysis. To sum up, good quality of experimental modal analysis results relies on properly planned tests grounded on theoretical basis of vibration and signal analysis. Plus, simulating an as-built structure free vibration motion using FE modeling depends on a qualified evaluation of the structure boundary conditions as well as on the estimation and distribution of its mass and material properties.

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