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COMFORT IN VIBRATIONS FOR THE STEEL-CONCRETE COMPOSITE FLOORS: AN APPRAISAL FOR REVIEW OF ABNT NBR 8800:2008

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Abstract. Steel-concrete composite floors often have human comfort for excessive vibrations as the most critical Service Limit State, in which vibration-sensitive floor systems must be designed so as to avoid the unacceptable transient oscillations due to the walking of people or due to other sources. According to ABNT NBR 8800:2008 [1], this limit state is designed by controlling the natural frequency of the floor under service loads, keeping it above a certain threshold, generally from 3.0Hz to 4.0Hz for the most common cases according to its Annex "L". The main objective of this article is to propose a bibliographic review on the evaluation of comfort for floors, based on their dynamic characteristics, such as natural frequency (f), modal mass (M_{mod}) and damping (D) to obtain speed values (OS-RMS90) and acceleration (peak), when applying dynamic loads as predicted by Sedlacek [2]. The object of study is a steel-concrete composite slab of a steel construction at the Federal University of *Espírito Santo* (UFES, Brazil). After analytical calculations and numerical modeling with dynamic loads, the floor is instrumented and kinematic results (velocity and acceleration) are compared between model and experiment. By means of spectral analyzes of vibration energy, stiffness gains by concrete ageing are observed for calibration of the model, accordingly to Ji Young Kim [3]. Finally, the answers of a questionnaire about comfort answered by the occupants are discussed and compared with international publications to integrate new comfort thresholds and analysis methodology in the new related chapter of ABNT NBR 8800:2008, currently under review.

Keywords: Vibrations; Human Comfort; Steel-concrete

1 Introduction

According to ISO 10137 [4], the tendency of using more resistant materials leading to lighter, slender and less stiff solutions increases the susceptibility of modern structures to vibration problems, leading to greater responsibility for such structural assessments by the design engineer. Similarly, proper functioning of laboratory and industrial processes and instruments, work efficiency and human well-being increase the demand for “vibration free” environments.

In this context, a subject that has always been present is that of vibrations in steel-concrete composite and metallic floor structures, whose amplitudes are controlled, in accordance with NBR 8800:2008 [1], by limiting static deflections and natural frequencies. However, according to ISO 10137 [4], unsatisfactory vibration levels have been observed in buildings, which seems to indicate that the indirect criteria adopted by the Brazilian standard are no longer adequate.

Lighter compositions have emerged from the use of high strength materials such as steel, of computer aid for design and of LRFD (Load and Resistance Factor Design) for optimization of structure calculation based on force requirements. In addition, as set out in an analysis of vibrations and the design of a structure subject to the stimulation of human walking, by M. Setareh and M. Lovelace [5], innovative architect designs due to the demand for column free spaces, i.e., large beam spans, are a cause for reduced natural frequency and damping, which aggravates the discomfort of vibration.

Thus, according to Sedlacek [2], by determining the dynamic characteristics of a floor, such as natural frequency (f_n), modal mass (M_{mod}) and damping (D) it is possible to get the value OS-RMS90 (velocity value for a step comprising 90% of the steps of persons walking normally and corresponding to the harmonic vibration caused by the step on the floor) and to determine the vibration acceptance class according to **Table 1**, adapted from data presented by Sedlacek [2], with the aid of diagrams such as in **Fig. 1**. Such diagrams demonstrate that in the same set of M_{mod} and D, even frequencies often have an acceptance class lower than their previous odd frequency. Therefore, the relationship that the lower the frequency is, the worse the acceptance class will be is not valid, since, for certain modal mass and damping values, a 3 Hz frequency may characterize a better degree of acceptance than a 4Hz frequency, as show in **Fig. 1**. Such fact, associated with the rhythm of the human step, contrasts with the minimum limit of 4Hz imposed by the Brazilian Standard NBR 8800:2008 (item L.3.2) [1] for floors where people walk regularly, such as homes and offices.

Table 1. Floor response rating and recommendation for class application [6]

	OS-RMS$_{90}$		Function of Floor									
Class	Lower Limit	Upper Limit	Critical Workspace	Health	Education	Residential	Office	Meeting	Retail	Hotel	Industrial	Sport
A	0.0	0.1	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended
B	0.1	0.2	Critical	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended
C	0.2	0.8	Not recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended
D	0.8	3.2	Not recommended	Critical	Critical	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended	Recommended
E	3.2	12.8	Not recommended	Not recommended	Not recommended	Critical	Critical	Critical	Critical	Critical	Recommended	Recommended
F	12.8	51.2	Not recommended	Not recommended	Not recommended	Not recommended	Not recommended	Not recommended	Not recommended	Not recommended	Critical	Critical

Not recommended | Critical | Recommended

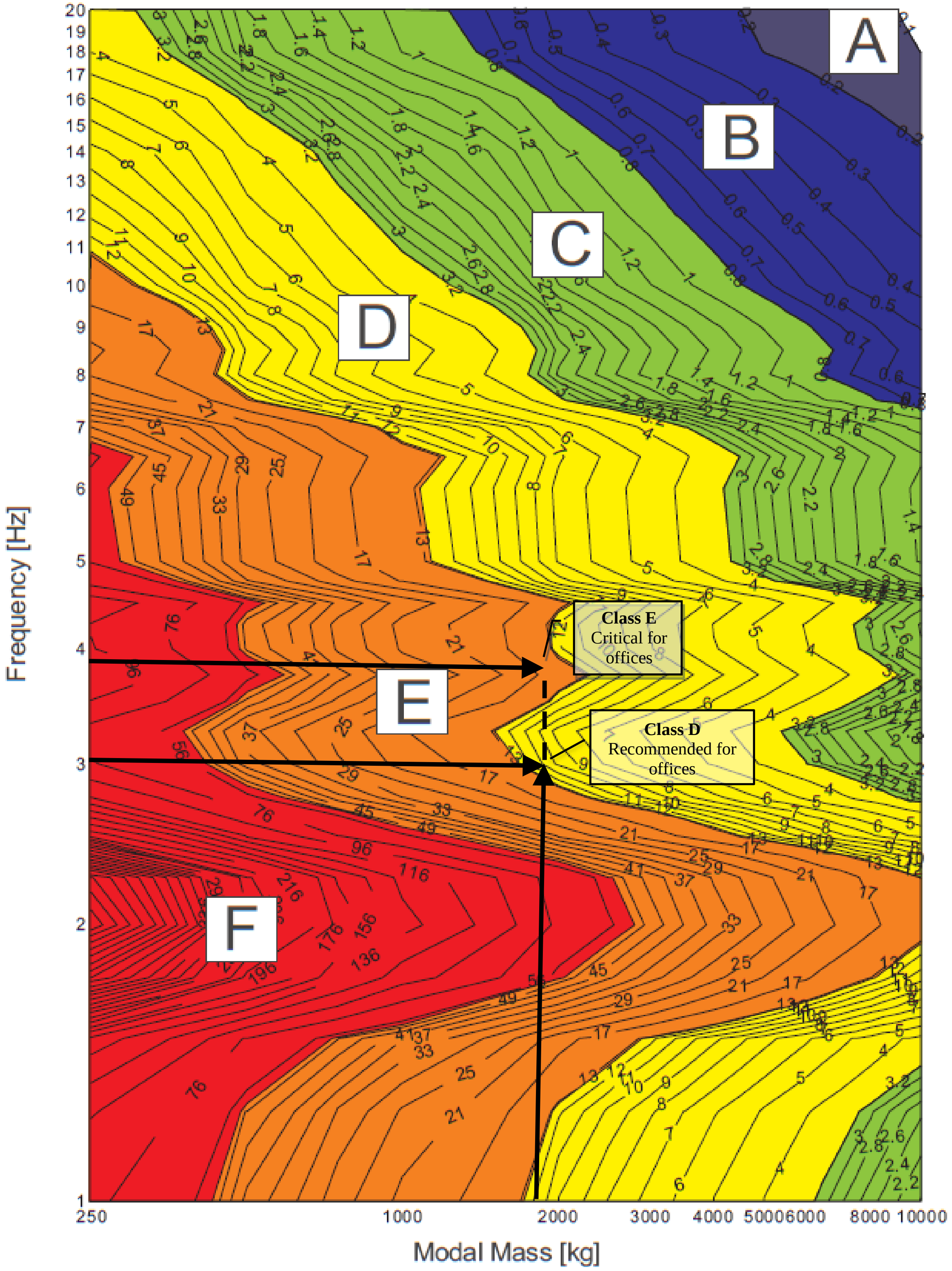


Figure 1. OS-RMS$_{90}$ and floor response rating, both for damping ratio of 4% [2]

Therefore, using as a study object a building in steel and steel-concrete composite structures, the Center of Excellence in Metallic and Steel-concrete Composite Structures (from Portuguese, NEXEM), exposed in **Fig. 2**, of Federal University of Espírito Santo (from Portuguese, UFES), it is intended to predict, by modeling and simulation in ANSYS 19.0, and to measure, by beam testing, the vibration levels from one of the building rooms. Finally, numerical results are compared and a comfort questionnaire, submitted to building users, provides a qualitative analysis of vibration levels.

Figure 2. NEXEM, UFES [personal collection]

2 Methodology

The research methodology to achieve the objectives of this article follows the model literature review, case study and analysis of results, in accordance with the flowchart presented in **Fig. 3**. It starts with a brief study on floor comfort assessment based on the dynamic characteristics of a floor, as presented in **item 1** of this paper.

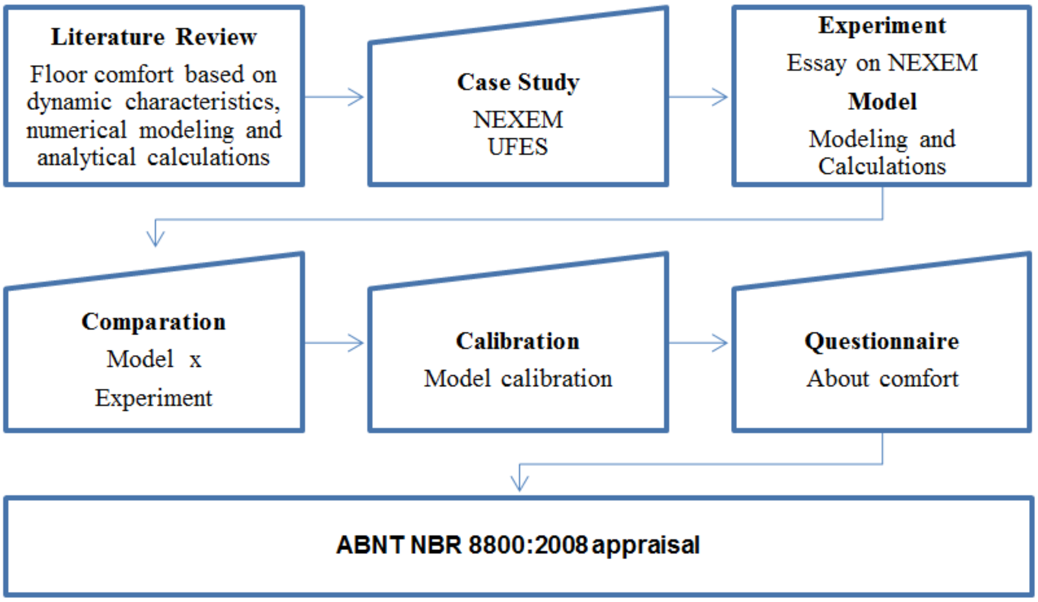


Figure 3. Methodology flowchart [personal collection]

Subsequently, taking the study object, NEXEM, the numerical modeling in ANSYS 19.0 is performed. After, one of the rooms of the building under study has its floor instrumented to obtain acceleration values as a function of time from induced stimuli at the time of the test, values which are treated in MATLAB.

Given the data obtained by the test, the vibration energy spectral analysis is performed for further comparison between the model and the experiment. Thus, it is possible to observe stiffness gains due to concrete aging for the model calibration.

Comfort questionnaires are distributed to the occupants of the unit evaluated and the answers obtained are discussed and compared to international publications. According to the results obtained, an appraisal is made to the chapter on ABNT NBR 8800:2008 [1] ongoing review, in order to integrate it new comfort limits and analysis methodologies.

2.1 Analytical Calculations and Design Process

Computational spreadsheet calculations, in turn, are used to obtain the natural frequency and the modal mass of the steel-concrete composite beam analyzed, as well as the system of the beams plus slab. For this purpose, the following input data presented in the **Table 2** are requested.

Table 2. Input variables

Variable	Description	Dimension
F_G	Value of permanent load applied to structure	[kg/m^2]
F_Q	Variable/accidental load value applied to structure	[kg/m^2]
$\%_{\mathrm{FQ,RMS90}}$	Variable load reduction factor applied to structure	[%]
L_V	Beam length	[m]
L_F	Beam Distance	[m]
$L_{V,P}$	Main beam length	[m]
$f_{1,V,P}$	Natural frequency of a second beam connected to the analyzed beam	[Hz]
ρ_a	Specific steel mass adopted	[kg/m^3]
ρ_c	Specific mass of concrete adopted	[kg/m^3]
f_{ck}	Characteristic compressive strength of concrete	[Mpa]
f_y	Steel yield strength	[Mpa]
f_u	Tensile strength of steel	[Mpa]
E_a	Steel modulus of elasticity	[Gpa]

The natural frequency of a second beam connected to the analyzed beam, $f_{1,\mathrm{V,P}}$[Hz], is previously calculated by the same worksheet or obtained in numerical modeling. There are still the input variables h_t, h_F, b_b, b_F and b_n, that represent the geometry of the concrete slab and are exposed in **Fig. 4** and the variables d, $b_{f,sup}$, $b_{f,inf}$, t_w, $t_{f,sup}$ and $t_{f,inf}$, which represent the cross-section geometry of the steel profile I beam and are exposed in **Fig. 5**.

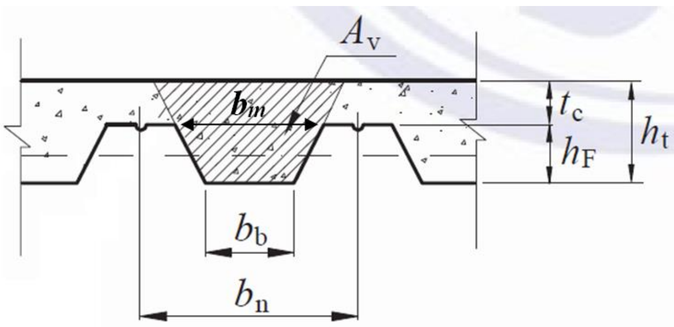


Figure 4. Concrete slab dimensions [1]

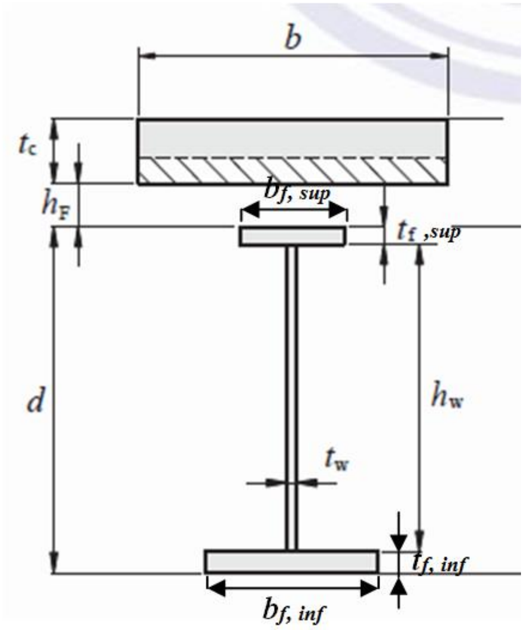


Figure 5. Steel beam dimensions [1]

After entering those data, the following results are generated according to the formulas and considerations made to be presented in **Table 3** and in **Table 4**.

Table 3. Calculated variables

Variable	Description	Dimension
A	Steel beam cross section area	[m^2]
$I_{y,t}$	Moment of inertia of slab profile around y (vertical axis) per meter	[m^4/m]
$EI_{y,C.D.}$	Y-stiffness (vertical axis) of steel-concrete composite beam section for short duration loads	[N.m^2]

Table 4. Variables calculated with their respective equations

Variable	Description e Dimension	Equation	Subtitle
E_{ci}	Concrete modulus of elasticity [GPa]	$5.6\sqrt{f_{ck}}+0.9$	(1)
μ_a	Steel beam linear specific mass [kg/m]	$A\times\rho_a$	(2)
μ_g	Steel-concrete composite beam linear specific mass [kg/m]	$\dfrac{L_F\left(\left(\dfrac{h_F(b_m+b_b)}{2}\right)+b_n(h_t-h_F)\right)}{b_n}\times\rho_c+\mu_a$	(3)
μ_F	Mass per unit area of the concrete slab plus additional permanent loads (which is permanent beyond the steel-concrete composite beam	$F_G+F_Q\times\%_{FQ,RMS90}+\dfrac{H_F(b_F+b_b)/2+b_n(h_T-h_F)}{b_n}\times\rho_c$	(4)

	and the slab) plus considered percentage of variable / accidental load [Kg/m²]		
μ_V	Linear mass of the steel-concrete composite beam plus permanent loads plus considered percentage of variable/accidental load applied at width corresponding to L_F (distance between beams) [Kg/m]	$L_F\,(F_G + F_Q \times \%_{FQ,RMS90}) + \mu_g$	(5)
$f_{1,F}$	Natural frequency of slab influence width [Hz]	$\frac{4}{\pi}\sqrt{\frac{3(E_{ci} \times I_{yt} \times 10^9)}{0.37\,\mu_F \times L_F^{\ 4}}}$	(6)
$f_{1,V}$	Natural frequency of the analyzed pinned-pinned beam represented in **Fig. 6** [Hz]	$f_{1,v} = \frac{2}{\pi}\sqrt{\frac{3(EI_{y,C.D.})}{0.49\,\mu_v \times L_V^{\ 4}}}$	(7)
f_1	Natural frequency of the system of analyzed beam plus second beam plus slab influence width [Hz]	$\frac{1}{f_1^{\ 2}} = \frac{1}{f_{1,F}^{\ 2}} + \frac{1}{f_{1,V}^{\ 2}} + \frac{1}{f_{1,V,P}^{\ 2}}$	(8)
$M_{\mathrm{mod},1}$	Modal mass of the analyzed pinned-pinned beam represented in **Fig. 6** [Kg]	$0.5\mu_V \times L_V$	(9)
M_{mod}	Modal mass of the system of analyzed beam plus second beam plus slab influence width [Kg]	$M_{\mathrm{mod1}} \times \frac{L_{vp}}{0.5} \times \frac{0.45}{L_F}$	(10)

The natural frequency and modal mass of a beam can be determined according to the support conditions. **Equations (7)** and **(9)** cater to isostatic beams, with symbolic representation in the **Fig. 6**, which will be the ones studied in the building in question.

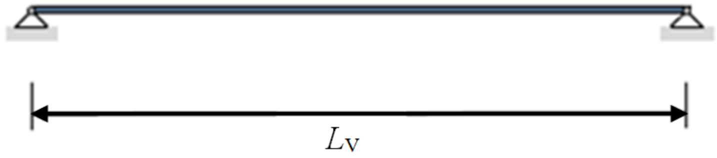


Figure 6. Pinned-pinned beam [personal collection]

There is also an approximation, called Dunkerley's approach, to the natural frequency of a system when performing manual analyzes. It is applied when the shape of the analyzed system mode is complex but it can be divided into single modes for which the natural frequency can be determined. Thus, the natural frequency of a system (f_1 in question) composed of three singular frequencies ($f_{1,F}$, $f_{1,V}$ and $f_{1,V,P}$, described earlier) is obtained by **Eq. (11)**.

$$\frac{1}{f_1^{\ 2}} = \frac{1}{f_{1,F}^{\ \ 2}} + \frac{1}{f_{1,V}^{\ \ 2}} + \frac{1}{f_{1,V,P}^{\ \ 2}} \tag{11}$$

After determining the natural frequency and modal mass of the system, a damping must be assumed. Such damping may be calculated, irrespective of the method chosen for the calculation of natural frequency and modal mass, by the sum of the damping due to the structure material, to the furniture and to the finishing, as shown in the **Table 5** and in the **Eq. (12)**.

Table 5. Determination of damping

Type	Damping (% of critical damping)
Structural Damping D_1	
Wood	6%
Concrete	2%
Steel	1%
Composite (steel-concrete)	1%
Damping due to furniture D_2	
Traditional office for 1 to 3 persons with separation walls	2%
Paperless office	0%
Open plan office	1%
Library	1%
Houses	1%
Schools	0%
Gymnastic	0%
Damping due to finishes D_3	
Ceiling under the floor	1%
Free floating floor	0%
Swimming screed	1%
Total Damping	$D = D_1 + D_2 + D_3$

$$D = D_1 + D_2 + D_3 \tag{12}$$

In the design process, the dynamic characteristics of the slab system (natural frequency, modal mass and damping) are determined by reading the OS-RMS$_{90}$ value and acceptance class in the diagram corresponding to the damping obtained, both at the intersection of the modal mass value on the x axis and the corresponding natural frequency on the y axis as shown in **Fig. 1**. Such process can be observed in the flowchart of the **Fig. 7** next.

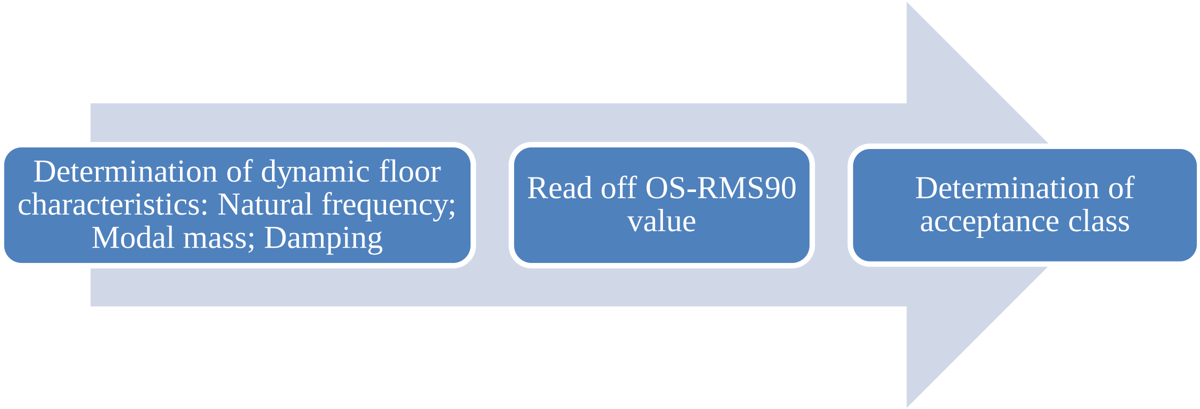


Figure 7. Design process flowchart [personal collection]

3 Case Study

At the case study, analyzes are performed by numerical modeling via ANSYS® 19.0 Multiphysics, by calculations via Excel and by an experiment of one of the rooms of the NEXEM from UFES. The following are presented the processes and results of those analyses.

The system analyzed is that of the room presented in **Fig. 8**. The dimensions of the beams V3 and V4, indicated in that same figure, and of the room floor slab are exposed in the **Table 6**. The beams parallel to V4 have the same cross-sectional dimensions. Already the specifications of the employed materials, steel and concrete, are displayed in **Table 7**. As for the loads, two analytical assessments are made, the first with the approximate real survey of the permanent and variable forces applied to V4 and the second with the assumption of the load imposed by the designer for these forces on the same beam. The input variable $f_{1,V,P}$, which represents the frequency of the primary beam (in this case the V3 beams are primary beams) is obtained from numerical modeling next to the experimental analysis, with a subsequent calibration made by analytical calculations. Then the results of f_1, M_{mod} and damping for the V3 + V4 + slab system in each of the two exposed load situations are presented. With values obtained, the acceptance class is determined.

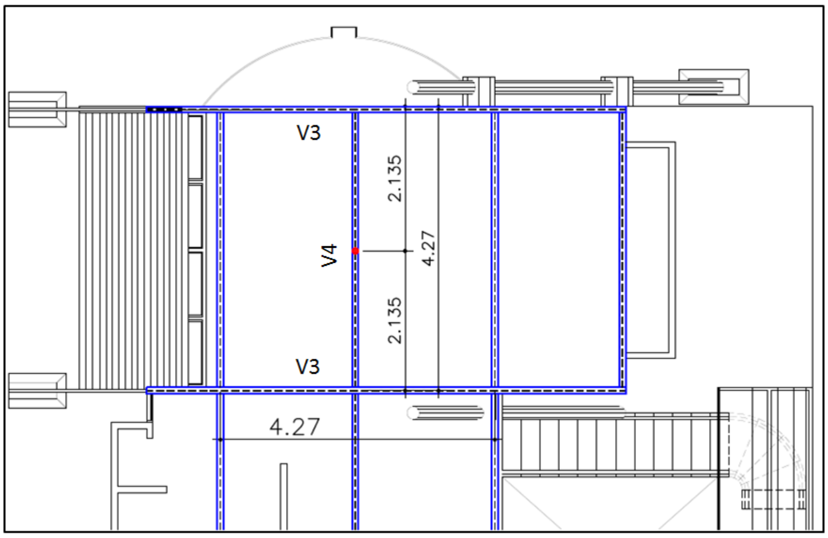


Figure 8. Floor plan of the analyzed room [personal collection]

Table 6. Dimensions of structural elements of the system V4+V3+Slab

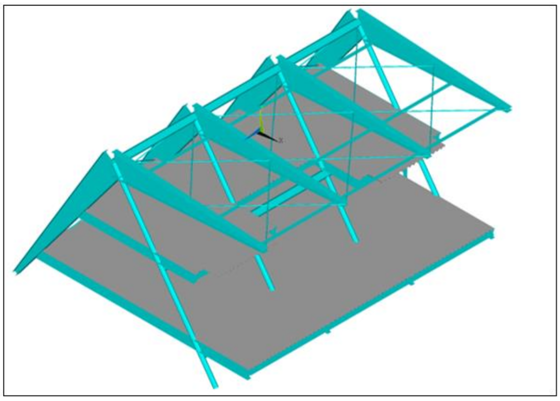
Beam				Slab	
V4		V3			
Dimension	Value	Dimension	Value	Dimension	Value
d (m)	0.2000	d (m)	0.3500	h_t (m)	0.1100
$b_{f,sup}$ (m)	0.1300	$b_{f,sup}$ (m)	0.2500	h_F (m)	0.0590
$b_{f,inf}$ (m)	0.1300	$b_{f,inf}$ (m)	0.2500	b_b (m)	0.0580
t_w (m)	0.0063	t_w (m)	0.0095	b_F (m)	0.1260
$t_{f,sup}$ (m)	0.0080	$t_{f,sup}$ (m)	0.0160	b_n (m)	0.2100
$t_{f,inf}$ (m)	0.0080	$t_{f,inf}$ (m)	0.0160		
L_V (m)	4.2737	$L_{V,P}$ (m)	4.2700	L_F (m)	2.1350

Table 7. Material specifications

Specifications	Value
ρ_a (kg/m3)	7850
ρ_c (kg/m3)	2500
f_{ck} (MPa)	25
f_y (MPa)	250
f_u (MPa)	400
E_a (GPa)	200

3.1 Model

The finite element model developed is generated in the *software* ANSYS® 19.0. Steel beams, columns, purlins and bracing structures are modeled with 2-node beam elements (BEAM188) with 6 degrees of freedom (DOF) on each node. The concrete slab is implemented in 8 node solid elements with 3 DOF per node (SOLID185). 4-node shell elements and 6 DOF per node (SHELL181) are used to represent the steel-deck incorporated into the concrete slab. **Figure 9** presents an isometric view of the developed model, on the left, and an enlargement of a section of the structure with the elements chosen to represent each structural component, on the right.



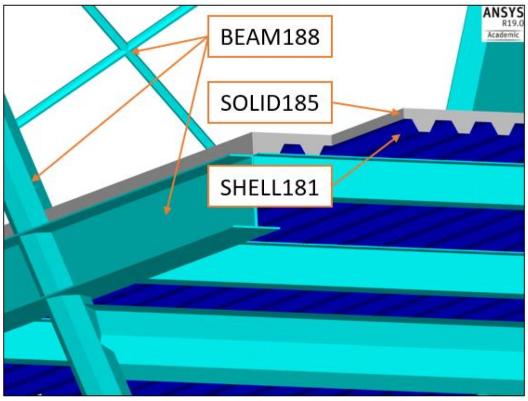


Figure 9. Finite element model developed

In the modeling is added to the concrete density a value corresponding to the applied overload, found by an approximation of the additional actual total load present during the test plus the permanent load of the ceramic floor covering. It is observed that the other permanent loads of the structure proper weight are already considered in the elements modeled by the program. The assessment of this approximate total additional load is detailed in **Table 8**. To add this value to the concrete density, a conversion is made according to the dimensions of the slab, such conversion is exposed by **Eq. (13)**, whose slab variables are indicated in **Fig. 4**. That slab dimensions are presented in **Table 6**. The result of this process is described at **Table 9**.

Table 8. Additional actual total load data collection

Object	Amount [un.]	Unit load [Kg]	Total load [Kg]
Metal cabinet (height ≈ 2 meters)	1	32.33	32.33
Metal bookcase (height ≈ 2 meters)	6	13.10	78.60
Books by shelf	250	1.30	2600.00
Drawer metal cabinet (height ≈ 1.5 meters)	2	23.00	46.00
Books in the drawer cabinets	100	1.30	260.00
Wooden cabinet (height ≈ 2 meters)	1	41.30	41.30
Wooden furniture (height ≈ 1 meters)	1	19.00	19.00
Wooden desk	2	42.40	84.80
Computer	2	12.00	24.00
Printer	1	12.90	12.90
Common chair	5	10.00	50.00
Swivel chair	2	12.50	25.00
People	4	80.00	320.00
Wood and metal round table	1	23.93	23.93
Sum of total loads (S_c) [Kg]:	3617.86		
Load application area (A_c) [m²]:	29.15	S_c/A_c [Kg/m²]:	124.11
		Load of ceramic floor covering [Kg/m²]:	85
		Additional total charge [Kg/m²]:	209.11

$$K = \frac{b_n}{\left(\left(b_m + b_b\right) \cdot h_f / 2 + \left(h_t - h_F\right) \cdot b_n\right)} \tag{13}$$

Table 9. Process results for obtaining the adopted density

Additional load [Kg/m²]	Correction factor (K) [adm.]	Additional density [Kg/m³]	Concrete density [Kg/m³]	Adopted density [Kg/m³]
209.11	13.01	2721.10	2500.00	5221.10

Proper choice of boundary conditions has a great impact on dynamic analysis. However, the representation of boundary conditions of a structure in service is not always as clear as in a computational model. Therefore, so that the results of the developed model are in favor of safety, links that in practice could be considered as semi-rigid, are implemented as flexible. So, to simulate the frame supports, the X, Y and Z axis translations are restricted at the lower end nodes of the pillars. Additionally, hinges are applied between the beam and column nodes whose connections are ideally designed as flexible. **Figure 10** illustrates the boundary conditions (red) and the hinges (green) applied to the developed model.

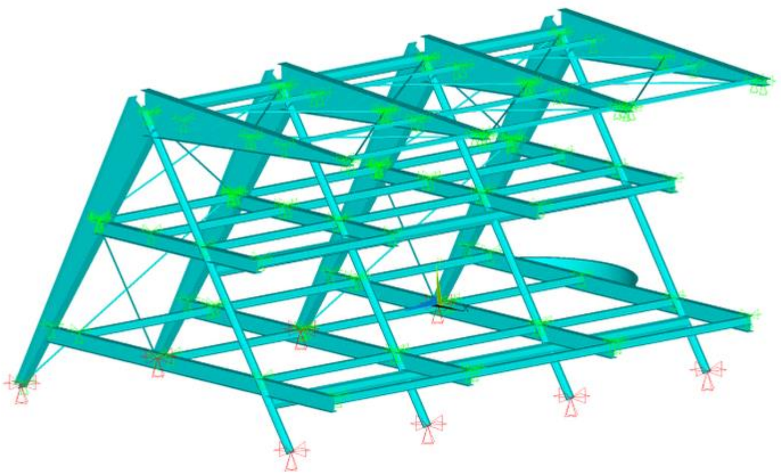


Figure 10. Representation of boundary conditions and hinges applied to the finite element model

To evaluate the sensitivity of the model to the finite element mesh size adopted, 39 free vibration analyzes are performed for different mesh densities. The number of model elements varies from 37194 elements to 765287 elements. The variable selected for the mesh study is the first natural frequency found in a modal analysis. The optimal mesh is determined considering a maximum percentage error of 1.5% in relation to the result with the most refined mesh. Thus, a mesh with 297999 elements (5873 BEAM188 elements, 89006 SHELL181 elements and 203120 SOLID185 elements), with an average element size of 100 mm, is considered optimal. **Figure 11** presents the results of the mesh strength study by means of a curve with the number of elements *versus* the first natural frequency obtained.

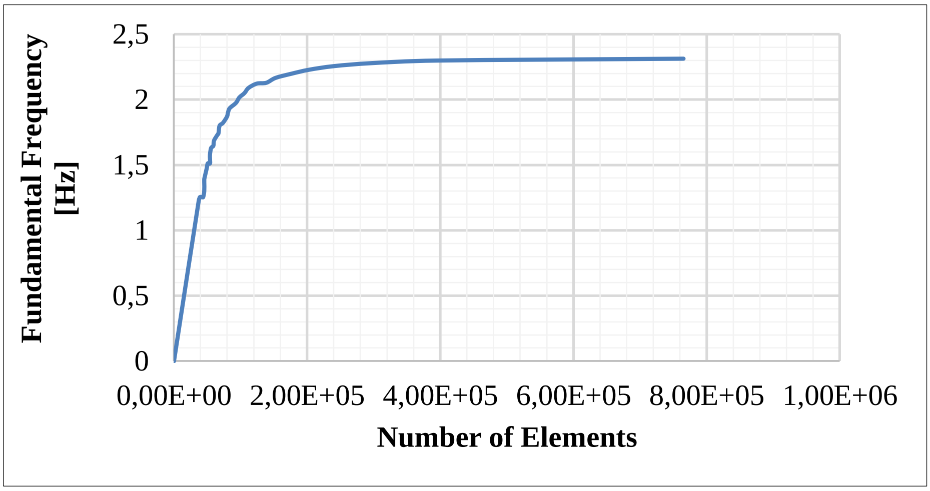


Figure 11. Sensitivity study of the finite element mesh in terms of number of elements *versus* the first natural frequency obtained [personal collection]

Remark 1: Analysis of modeling results to obtain natural frequencies $f_{1,V,P}$ of the primary beams V3. To obtain the natural frequencies $f_{1,V,P}$ of V3 it is performed an analysis of the vibration modes of the model structure made in ANSYS®. 280 vibration modes with frequencies ranging from 0 Hz to 30 Hz are analyzed. The following **Fig. 12** shows the frequencies of the modes in which the vibrations in the studied slab are most noticeable along with the illustration of their respective vibration modes. From the analytical calculations, the natural frequency of 12.46 Hz for the V4 beam is obtained according to the considerations presented in the ***Remark 2*** and of 13.90 Hz according to the considerations set out in ***Remark 3***. Thus, the value **a)** of **Fig. 12** is discarded to the natural frequency of V3. With the values presented in the experimental result in **3.2**, the values of **b)**, **c)** and **d)** of **Fig. 12** are possible natural frequency values for V3 primary beams.

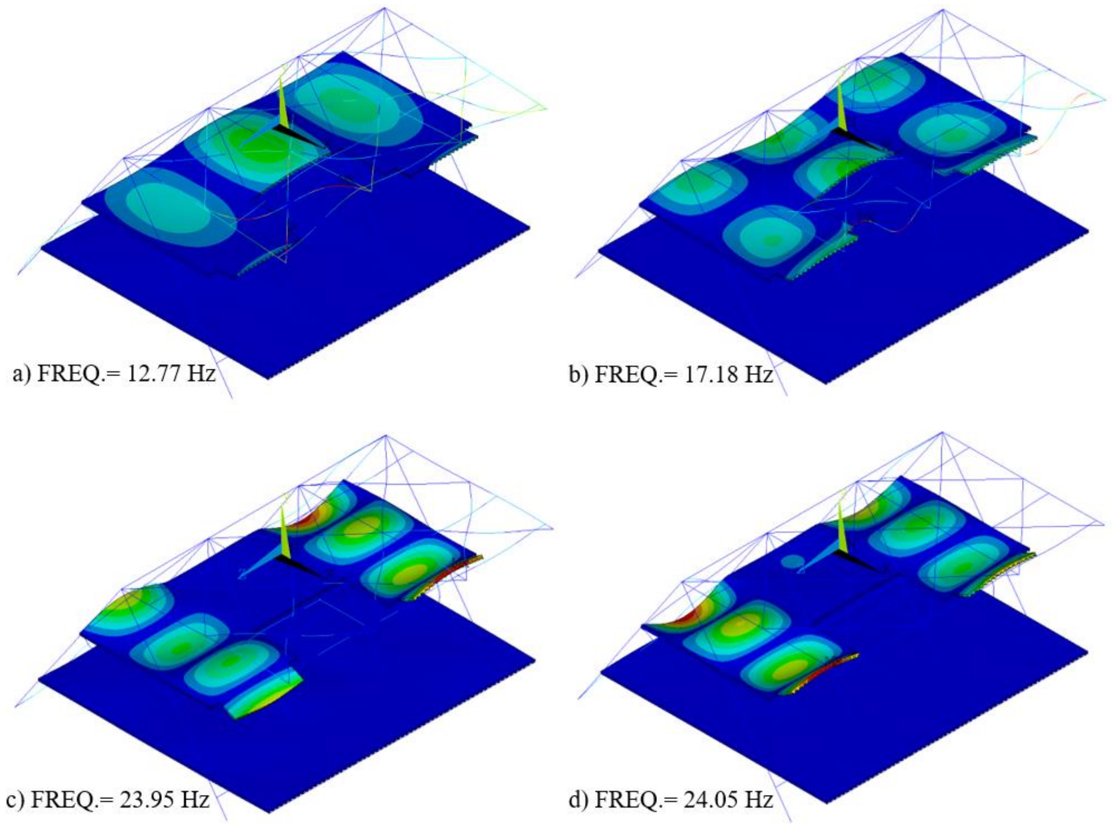


Figure 12. Vibration mode frequencies where the vibration of the studied slab is most noticeable [personal collection]

Remark 2: Analysis with approximated data collection of the real loads. The data collection of the real loads to obtain the permanent force, F_G, and the variable force, F_Q, applied to V4 is detailed in **Table 10**. Considering that the structure's self-weight (beam plus slab) is already considered in the calculation through other variables, the value of the permanent force, F_G, considers only the load of the ceramic floor covering. For the data collection of the real loads 100% of F_Q are applied, so $\%_{\mathrm{FQ,RMS90}}$ equals 100%. With this data, $f_{1,V} = 12.46$ Hz is obtained as the natural frequency value of beam V4.

Table 10. Approximated data collection of the real loads to obtain F_G and F_Q

Variable loads acting on V4	Load [Kg]
Wooden cabinet (height ≈ 2 meters)	41.30
Drawer metal cabinet (height ≈ 1.5 meters)	23.00
Wood and metal round table	11.97
Common chair	25.00
Metal bookcase (height ≈ 2 meters)	26.20
Books by shelf	975.00
Books in the drawer cabinets	130.00
People (4 people)	320.00
Total	1552.47
Permanent loads acting on V4	**Load [Kg]**
Ceramic floor covering	775.57
Dimensions of application area of loads acting on V4	**Value [m]**
L_V	4.27

L_F	2.14
Resulting forces	Value [kg/m²]
F_G	85
F_Q	170.15

Remark 3: Analysis with the assumption of the loads imposed by the designer. Assuming the loads imposed by the designer on the V4 beam, F_G equals 85 kg/m², equivalent to the ceramic floor covering load, F_Q equal to 300 kg/m², equivalent to the minimum vertical load value for establishments that received public by NBR 6120:2000 [7] , and $\%_{FQ,RMS90}$ equal to 40%, being considered as the effective combination factor for variable actions caused by the use and occupation, in almost permanent service combinations, for places where there is a predominance of weights and equipment that remain fixed, as exposed by NBR 8800:2008 [1]. With this data, $f_{1,V} = 13.90$ Hz is obtained as the natural frequency value of beam V4.

3.2 Experiment

For the performance of the vibration test, the equipment represented in **Fig. 13** are used. They consist of three to four main items, which are an excitation mechanism to make the analyzed structure vibrate, in the case of the figure represented by an impact hammer; transducer equipment for measuring the parameters of interest; an analog to digital (A/D) converter exposed in **Fig. 14**, for transforming continuous time signals (analog signals) from transducers into discrete signals (digital signals); and a computer system, whose storage unit can be used to store and postprocess the data from the transducers, extract the modal parameters, animate the vibration modes, among other functions.

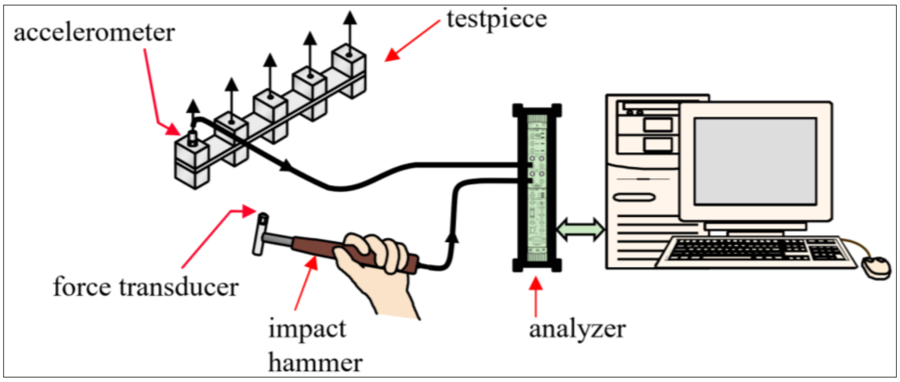


Figure 13. Experimental Setup Where Impact Hammer is Used for Excitation [8]

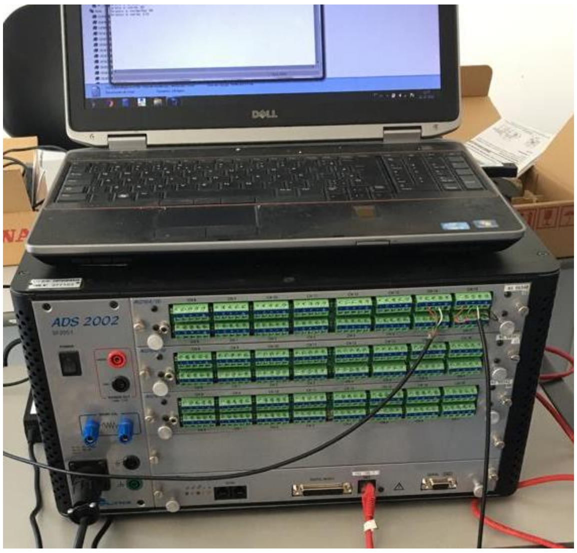


Figure 14. Analog to digital converter (A/D) [personal collection]

In the preparation of the test, the equipment and the type of excitation are chosen. The structure, the points of the structure at which measurements are made and the mechanisms for measuring excitation and response are described. The equipment chosen for the perception of the data is two accelerometers and the vibration is induced by the dynamic actions of 4 people of approximately 80 kg each. The excitation input in turn is not measured in this experiment, but it can be assumed. The structure of the room tested is shown in **Fig. 8** and the points where measurements are taken are shown in **Fig. 15**, on the left. Channels 14 and 15, shown in this figure, represent each of the two accelerometers, which are positioned on the bottom flange of beam V4, at opposite sides to the profile web. Both are fixed with clamps, as shown in **Fig. 15**, on the right.

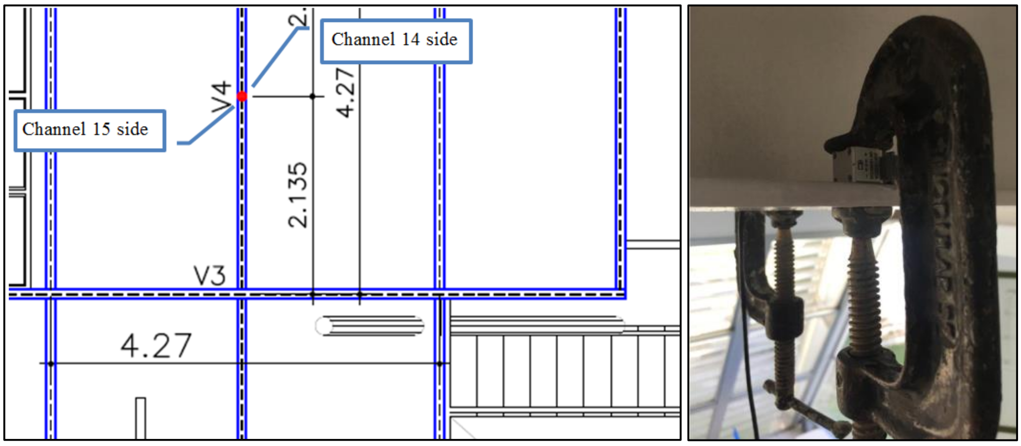


Figure 15. Position of accelerometers in the structure (left) and its fixation under the slab (right) in test [personal collection]

For the experimental analysis, the steel-concrete composite slab under study is instrumented to obtain velocity and acceleration kinematic values. On the bottom flange of beam V4 are placed two accelerometers, one representing channel 14 and the other channel 15, whose positions are shown in **Fig. 15**. The acceleration values as a function of time obtained are treated and the resulting graphs are presented in **Fig. 17**. The peak frequencies of these graphs represent possible natural frequency values of the structural elements, beams V3 or V4, or even another element of the analyzed system. For channels 14 and 15, the angular frequencies of 115 rad/s and 156 rad/s are highlighted for the peaks highlighted by the circumferences in **Fig. 16**. Calculating these frequencies in Hz, they correspond to, respectively, 18.30 Hz and 24.82 Hz.

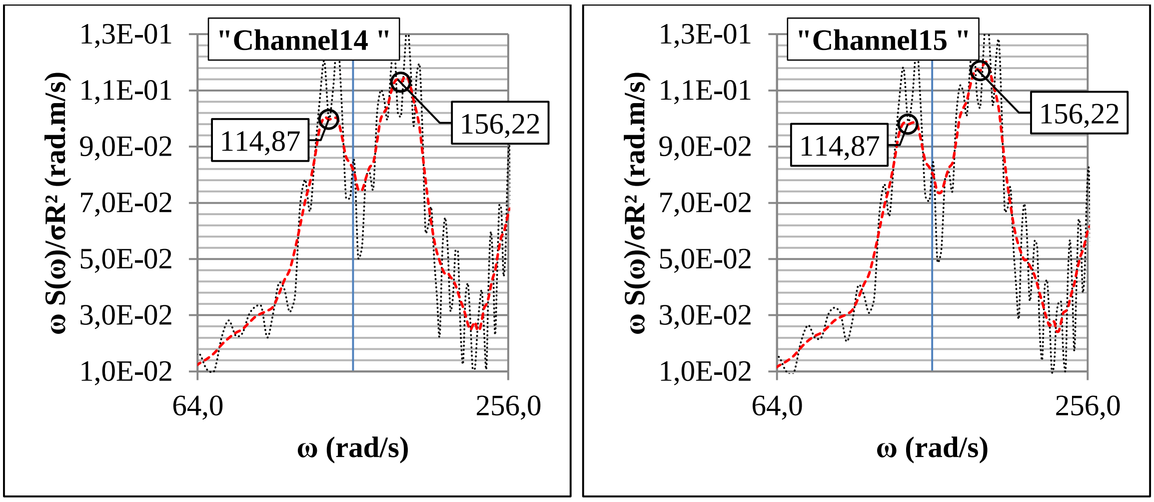


Figure 16. Spectral density in function of frequency, from data from channel 14 (to the left) and 15 (to the right) [personal collection]

4 Discussion

4.1 Comparison (Model x Experiment)

Both natural frequency values measured with the accelerometers are slightly larger than the calculated values shown in **Fig. 12 b)**, **c)** and **d)**, concerning the natural modes of vibration of the floor beams V3. This increase was 6.5% for the first case (18.30 Hz compared to 17.18 Hz) and 3.5% for the second case (24.82 Hz compared to 23.95 Hz).

Such an increase may be partially explained by one of the phenomena studied by Kim et al. [3] in natural frequency analysis of horizontal vibration of tall buildings, in this case the aging of concrete. Kim et al. [3] and Ferrareto [9] found significant increases in the natural frequencies of structures after considering this effect. The values found by the authors were, respectively, 0-4% and 3-5%.

4.2 Model Calibration

According to NBR 6118:2014 [10], The modulus of elasticity for concrete aging can be described by **Eq. (14)** below:

$$E_{Ci,\infty} = \lim_{t \to \infty} E_{Ci,28}\{\exp\{s[1-(28/t)^{0.5}]\}\}^{0.5} = E_{Ci,28}\exp(s/2)\,. \tag{14}$$

Where:

$\boldsymbol{E_{Ci,28}}$: Young's Modulus of concrete after 28 days, as NBR 6118-2014;

$\boldsymbol{t}$: Represents the age of the concrete, in days, here considered to be physically infinite;

$\boldsymbol{s}$: Coefficient dependent on the cement category (in the structure analyzed in chapter **3**, it assumes the value of 0.25);

$\boldsymbol{E_{\mathrm{Ci},\infty}}$: means Young's Modulus of matured concrete: probable E.

Considering the above hypotheses, for calculation purposes in *Service Limit State* only, the modulus of elasticity of the concrete according to **Eq. (15)** assumes a value 13% higher. Thus, by introducing this new value of $E_{Ci,\infty}$ in the beam calculations, it has:

$$E_{Ci,\infty} = 1.13E_{Ci,28}\,. \tag{15}$$

Thus, the natural frequency presented in the **Fig. 12 b)** assumes the value 18.07 Hz and those shown in the **Fig. 12 c)** e **d)** assume the value 25.15 Hz. The primary beam V3 of the bottom part of

Fig. 8 assumes the natural frequency value of 18.07 Hz and that of the top part of the same figure assumes the natural frequency of 25.15Hz. Values and assignments provided by analytical calculations, which approximate the results of the modeling. From this, four vibration comfort ratings are made, as shown in **Fig. 17**. Diagram I of this figure considers the data $f_{1,V}$ =12.46 Hz (relative to V4 for real loads) and $f_{1,V,P}$ =18.07 (relative to V3 from the bottom of **Fig. 8**). Diagram II considers the data $f_{1,V}$ = 12.46 Hz (relative to V4 for actual loads) and $f_{1,V,P}$ = 21.15 Hz (relative to V3 from the top of **Fig. 8**). Diagram III considers the data $f_{1,V}$ =13.90 (relative to V4 for design loads) and $f_{1,V,P}$ = 18.07 (relative to V3 from the bottom of **Fig. 8**). Diagram IV considers the data $f_{1,V}$ = 13.90 Hz (relative to V4 for design loads) and $f_{1,V,P}$ = 25.15 Hz (relative to V3 from the top of **Fig. 8**). These and other data considered in the classifications are shown in **Table 11**. The diagrams presented consider a 4% damping. That damping is obtained considering the room in study made of a steel-concrete composite structure, being a traditional office for 1 to 3 people with separation walls and with ceiling under the floor, following **Table 5**. The recommendation presented on **Table 11** is for an application on spaces for education use.

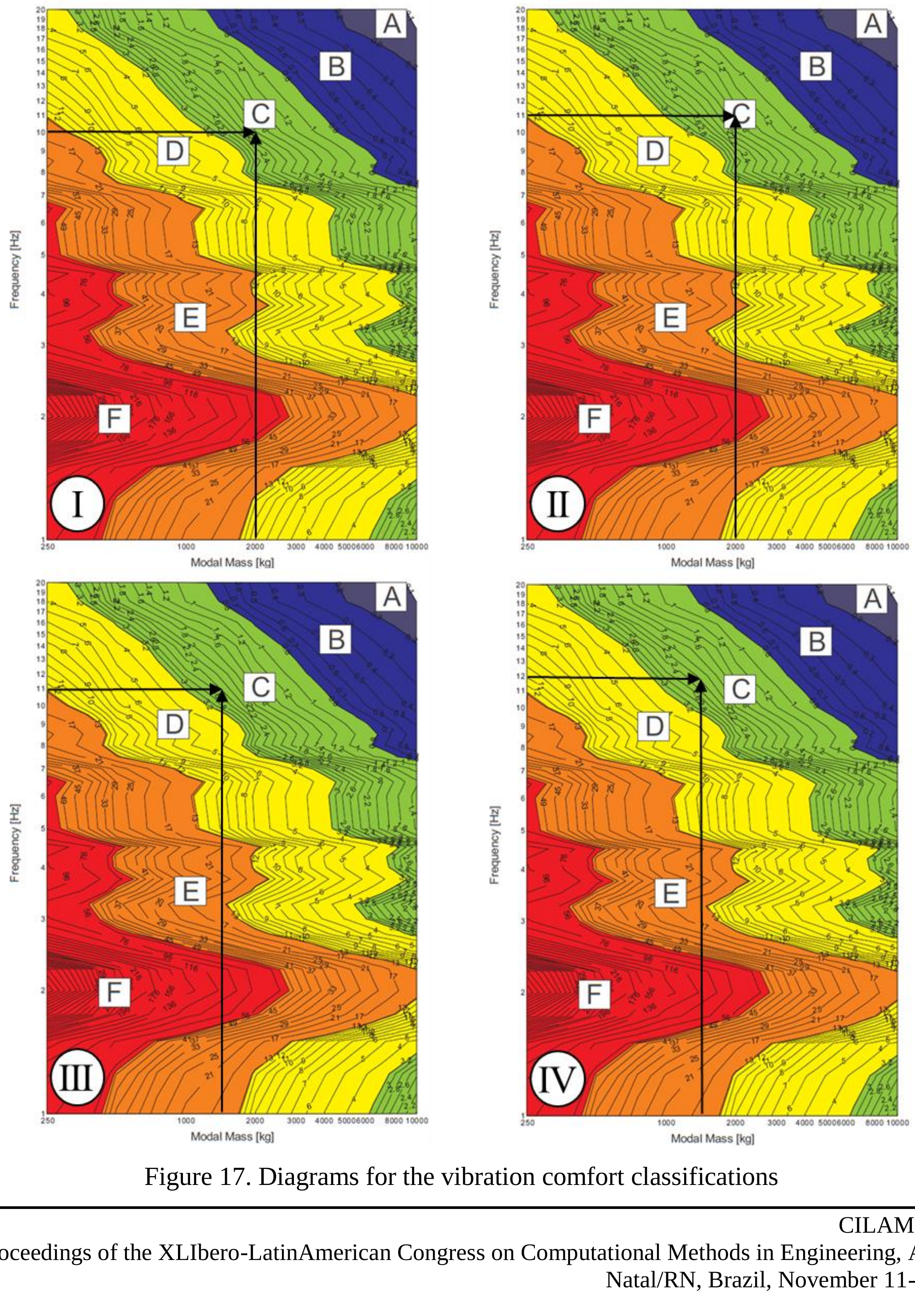


Figure 17. Diagrams for the vibration comfort classifications

Table 11. Data considered in the classification

Diagram	$f_{1,F}$ (Hz)	$f_{1,v}$ (Hz)	$f_{1,v,p}$ (Hz)	f_1 (Hz)	$M_{mod,1}$ (kg)	Class	Recommendation
I	81,6	12,46	18,07	10,18	2095	C	Recommended
II	81,6	12,46	25,15	11,06	2095	C	Recommended
III	91,3	13,9	18,07	10,94	1684	C	Recommended
IV	91,3	13,9	25,15	12,06	1684	C	Recommended

4.3 Standard Appraisal

Following item 11 and annex L of NBR 8800: 2008 [1], vibration-susceptible flooring systems, such as areas without damping mechanisms, must be dimensioned so as to avoid the appearance of unacceptable vibrations due to walk from people or other sources. This fact includes the room under study.

According to Annex L, the natural frequency of the floor structure cannot be less than 3 Hz. In modeling, the first mode of vibration of the slab structure under study, illustrated in **Fig. 18**, is 9.72 Hz. For simplified analysis exposed in NBR 8800:2008 [1], on floors where people walk regularly, which includes the room under test, the lowest natural frequency cannot be less than 4 Hz or, in some cases, 3Hz, which is vaguely described. However, the standard also suggests a static analysis of deflection. The standard says that this condition is satisfied if the total vertical displacement of the floor caused by permanent actions, excluding the time-dependent portion, and by variable actions, calculated by considering the beams as pinned-pinned and using the frequent service combinations given in section 4 of this same standard, do not exceed 20 mm. This value is calculated and 5.2 mm vertical displacement is obtained for V4 with the design loads, which is enough for design acceptance.

However, one may notice that the frequency values of 4 Hz and 9.72 Hz and the displacement values of 5.2 mm and 9.72 mm used for normative classification are relatively distant. These circumstances expose that the structure analyzed passes the vibration evaluation with a much larger clearance in the analysis by NBR than by the comfort analysis proposed on this paper and illustrated in **Fig. 17**.

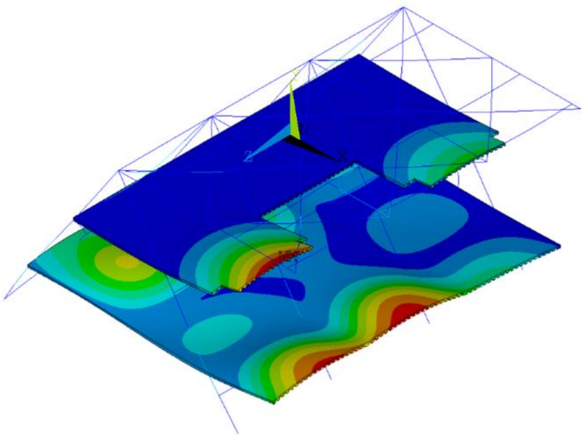


Figure 18. First vibration mode of the slab in study

4.4 Occupant Comfort Questionnaire

A questionnaire to assess the vibration comfort of the structure studied is delivered to the occupants of NEXEM. The questionnaire is answered by 15 occupants, of whom 5 are under 30 years old, 6 are between 30 and 40 years old, 3 are between 40 and 60 years old and 1 is over 60 years old. This analysis is exposed as age influences the perception of discomfort that may be caused by vibrations. Amongst the 15 people, 4 declared the vibration of the building irritating or annoying, most often once every two weeks. 3 people even find the vibration disturbing or frightening, as shown in **Fig. 19**, most often once every 6 months, especially on the ramp and stairs of the building. 5 people find the vibration most noticeable when they are less busy. Variations in personal thermal sensations do not appear to influence the perception of vibrations. None of the occupants answering the questionnaire has ever made a complaint about vibration, but 3 of the respondents imagine them making that in the future.

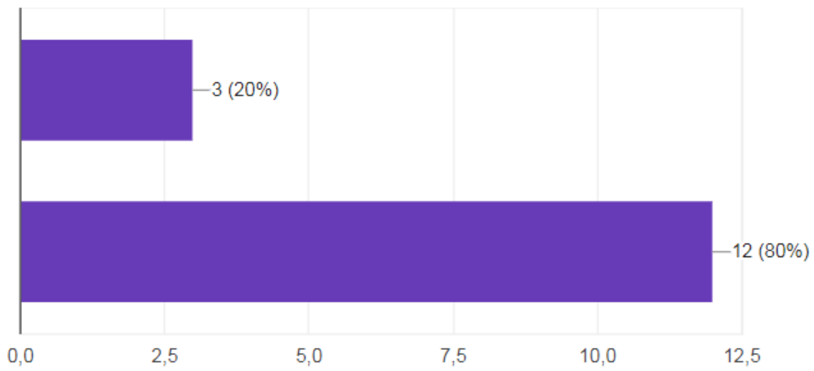


Figure 19. Twenty percent of the people questioned find the vibration disturbing or frightening

5 Conclusions

Considering the results presented by the questionnaire, it is possible to say that the vibration in the building of the NEXEM is noticeable and can be annoying or even frightening. Through the vibration comfort classification obtained and exposed in the diagrams of **Fig. 17**, it is clear that the chart assessments are very close to class D, which is considered critical for floors with educational function. However, the analysis made by building code NBR 8800:2008 shows a situation that is quite far from critical, as explained in **4.3**. From these facts, it is essential to evaluate a metallic or a steel-concrete composite structure considering the complete dynamic characteristics of the structure, as performed in **4.2**.

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