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Dynamic experimental monitoring and numerical analysis of floors subjected to human activities

Felipe A. de Sousa[1], Jefferson V. Aguiar[1], Nathalia de A. C. Branco[1], José Guilherme Santos da Silva[1]

[1]*Civil Engineering Department Postgraduate Programme (PGECIV), State University of Rio de Janeiro (UERJ)*
São Francisco Xavier St., Nº 524, Maracanã, 20550-900, Rio de Janeiro/RJ, Brazil
felipesousa@id.uff.br, jefferson.docm@gmail.com, nathaliaacbranco@gmail.com, jgss@uerj.br

Abstract. The present work aims to evaluate the dynamic structural behaviour of a reinforced concrete floor located on the eighth story of the State University of Rio de Janeiro (UERJ). The investigated floor is currently used for rhythmic human activities (gym activities). In some situations, such rhythmic activities produce a high degree of synchronization, which on some occasions can stimulate high levels of vibrations that may cause discomfort to the users. This way, the investigated structural model consists of a reinforced concrete floor with dimensions of 16 m by 35 m and total area of 560 m². Initially, a dynamic experimental monitoring of the floor was performed aiming to determine the dynamical properties (natural frequencies and structural damping). After that, a numerical model was developed to represent the studied floor, based on the use of usual mesh refinement techniques present in the Finite Element Method (FEM) simulations and implemented in ANSYS program. In sequence, the experimental and numerical dynamic structural responses were compared and the finite element model of the reinforced concrete floor was properly calibrated. Finally, the floor was subjected to rhythmic human activities (gym activities) and the dynamic response was investigated based on the use of biodynamic models. The current outcome of this research paper enabled a complete structural dynamic assessment of the concrete floor in terms of human comfort and its associated vibration serviceability limit states. The results show the relevance of the dynamic analysis in the structural design of buildings, considering the human activities that take place and influence the structure.

Keywords: Reinforced concrete floors; Dynamic experimental monitoring; Human comfort.

1 Introduction

Currently, commercial buildings are adapted according to the new architectural, constructive and economic trends. This way, buildings are becoming more and more versatile in terms of their use because a single edition can have several functionalities. However, in addition to the rules of the ultimate limit states (ULS), it is worth emphasizing the importance of evaluating the serviceability limit states (SLS) to promote the users' comfort.

The research consists of a reinforced concrete floor investigation with different functionalities, in which the analyses are concentrated in the evaluation of the dynamic effects resulting from rhythmic human activities performed on the structures. Such activities reach a high degree of synchronization, which in some situations can promote high levels of vibrations, causing human discomfort and even panic to its users.

The investigated floor consists of an interdisciplinary room where rhythmic human activities are performed, located on the eighth story of the State University of Rio de Janeiro (UERJ), whose dimension is 35mx16m (560m²). Therefore, this work aims to carry out experimental and numerical monitoring where structural dynamic analysis will be carried out.

As follows, the dynamic loading models developed by Campista [1], Faisca [2], AISC [3] and SCI [4] were used aiming to simulate the dynamic actions of the people practicing aerobics on the floor. The finite element model representative of the investigated floor was developed based on the usual mesh refinement techniques present in Finite Element Method (FEM) simulations and implemented in the software ANSYS [5]. After that, the human comfort assessment will be evaluated based on the dynamic response of the reinforced concrete floor.

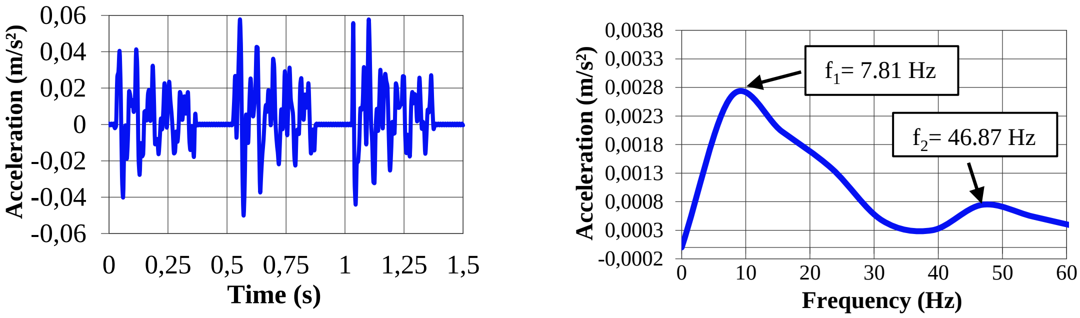
2 Dynamic experimental monitoring

The experimental tests were carried out on a 16m x 35m (A = 560m²) reinforced concrete floor which corresponds to an interdisciplinary room located on the eighth story of the State University of Rio de Janeiro (UERJ). The equipment selected for the tests were: Resistive accelerometer, an ADS 2002 data acquisition system and a computer. A free vibration test was carried out to determine the damping of the structure as well as its natural frequency and the vibration modes through an impact load resulting from a human jump on the floor as shown in Fig. 1. This procedure was repeated three times and the results were obtained through the accelerometer that was located in the region adjacent to the jump, these signals were transmitted to the data acquisition system. It is noteworthy that the speed and displacement values were obtained via the integration of the experimental acceleration signal, using the MATLAB [6] software.

a) The preparation b) Jump c) Landing

Figure 1. Free vibration experiment

In these terms, Fig. 2 presents the results of the experimental test, from which the structural damping was determined through the logarithmic decrease, presenting the following results: average 5.39%, standard deviation 0.38%, and coefficient of variation less than 10%, which according to Gomes [7], the results are highly accurate.



a) Time-domain b) Frequency domain

Figure 2. Acceleration: time domain and frequency domain

3 Dynamic loading models

Over the years, dynamic loading models have been developed to assess man-structure interaction through mathematical functions, such as the traditional unique force models developed by the authors Faisca [2], AISC [3], and SCI [4]. It is important to note that the parameters used in such models correspond to the variables associated with the rhythmic activities, considering mass of 74.0 kg and a 2.20 Hz step frequency for each individual. The loading model proposed by Faisca [2] consists of a Hanning mathematical function developed through experimental tests, in which the loading was directly applied to the structure represented by Eq. (1).

$$F(t) = CD\left\{K_p P\left[0.5 - 0.5\cos\left(\frac{2\pi}{T_c}t\right)\right]\right\} \therefore t \le T_c \therefore F(t) = 0 \therefore T_c \le t \le T \quad (1)$$

Where F (t) is the mathematical representation of time loading in newton, CD is the lag coefficient, K_p is the impact coefficient, P is the person's weight in newton, T is the activity period in seconds, T_c is the contact period of the activity in seconds and t is the time in seconds. A value of 0.32 was considered for the activity contact period T_c, while 3.24 for the impact coefficient K_p and 0.55 for the lag coefficient CD.

The model presented in the AISC [3] project guide, considers a single harmonic component as a function of time, as expressed in Eq. (2). However, it is important to consider that the guide indicates the values of the step frequency and the dynamic coefficients are presented in this standard.

$$F(t) = P\alpha_i \cos\left(2\pi i f_{step} t\right) \tag{2}$$

Where P is the weight of a person in newton; α_i is the dynamic coefficient; i is the harmonic number; f_{step} is the step frequency in hertz. The model developed by SCI [4] considers the effect of a crowd loading imposed on the structure when submitted to rhythmic activities, as expressed in Eq. (3). The first three terms of the Fourier series present in the formulation were determined according to the characteristics of the floor and the number of participants performing activities on it.

$$F(t) = G\left\{1 + \sum_{n=1}^{\infty} r_{n,v} \sin\left(2n\pi f_p t + \phi_n\right)\right\} \tag{3}$$

Where G is the weight of a person in newton; $r_{n,v}$ is the Fourier coefficient induced by v people; n is the number of Fourier terms; v is the number of people; ϕ_n is the phase difference; f_p is the loading frequency. The Fourier coefficients were determined with the number of people totalling 18.

4 Modelling of the biodynamic systems

To represent the interaction of the person and the structure, Campista [1] developed the model of biodynamic systems that consists of a "mass-spring-damper" system, being an alternative to hard-force models. According to the authors, Sim et al. [8], Littler [9], Barker and Mackenzie [10] and Campista [1] this model presents satisfactory results, as it involves variables associated with the dynamic equilibrium equation. Thus, Campista [1] carried out a campaign of experimental data in the laboratory with 100 people in various profiles. The parameters of the dynamic response presented in Eqs. (4) to (6) were determined from the resolution of the optimization problem where the generic algorithm methodology was used.

$$F_i(t) = k_i x_i\left(t\right) + c_i v_i\left(t\right) + m_i a_i\left(t\right) \tag{4}$$

$$k_i = 4\pi^2 f_i^2 m_i \tag{5}$$

$$c_i = 4\pi m_i \xi f_i \tag{6}$$

Since $F_i(t)$ is the force produced by an individual i in N, k_i is the stiffness of the individual in N/m, m_i is the mass of individual in kg, c_i is the damping of individual in ns/m, $x_i(t)$ is the displacement of the individual over time in m, $v_i(t)$ is the velocity of the individual over time in m/s, $a_i(t)$ is the acceleration of individual over time in m/s^2, f_i is the individual frequency in Hz and ξ is the damping coefficient equal to 0.25.

5 Investigated reinforced concrete floor

In this work, the studied reinforced concrete floor is located on the 8th story of the State University of Rio de Janeiro (UERJ), Rio de Janeiro/RJ, and presents a total area of 560 m^2, and dimension is 16 x35m, consisting of 12 concrete slabs panels with 12cm in thickness, as shown in Fig. 3. The concrete presents a compression characteristic resistance (f_{ck}) of 13.7 MPa and secant elastic modulus (E_{cs}) of 17.6 GPa. The floor is used as a gym and the rhythmic human activities are performed on the slabs L1 to L6, while on the slabs L7 to L12 other activities are carried out, such as dancing, weight training, and functional training, see Fig. 3. The dynamic loading related to 18 people practising aerobics was applied in three cases: LM I (loading model I) at slabs L1 and L2 represented in red; LM II (loading model II) at slabs L3 and L4 represented in green; LM III (loading model III) at slabs L5 and L6 represented in black and each person has occupied an area of 4m^2 (2m x 2m), as shown in Fig. 4. This way, to verify the dynamic structural response generated by each dynamic load model, 6 structural sections were established and represented by letters from A to F, corresponding to the centre of each slab, illustrated in Fig. 4.

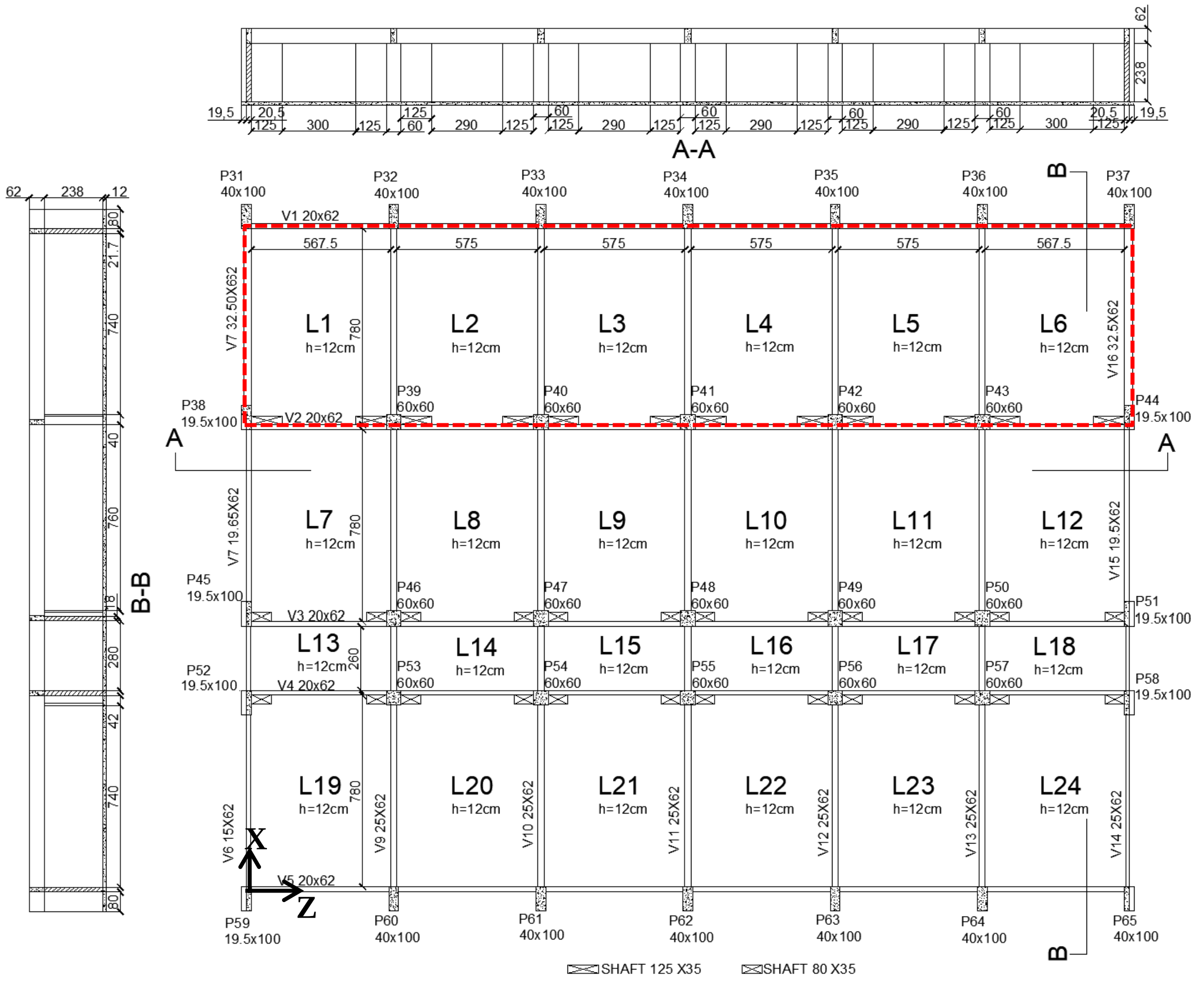


Figure 3. Reinforced concrete floor upper view (units in centimetres)

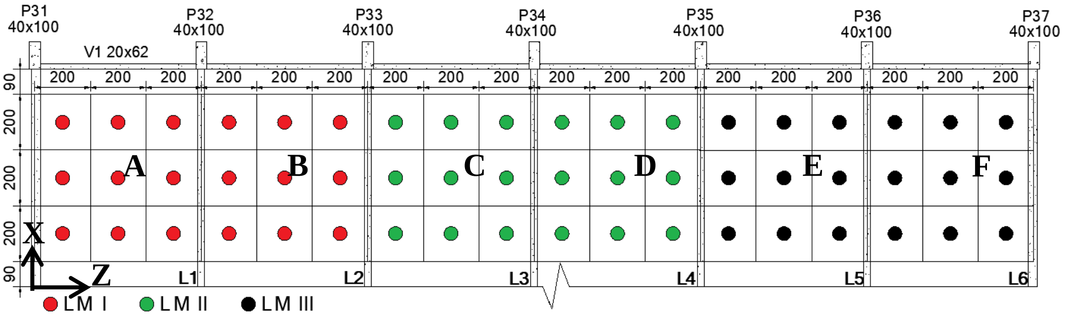
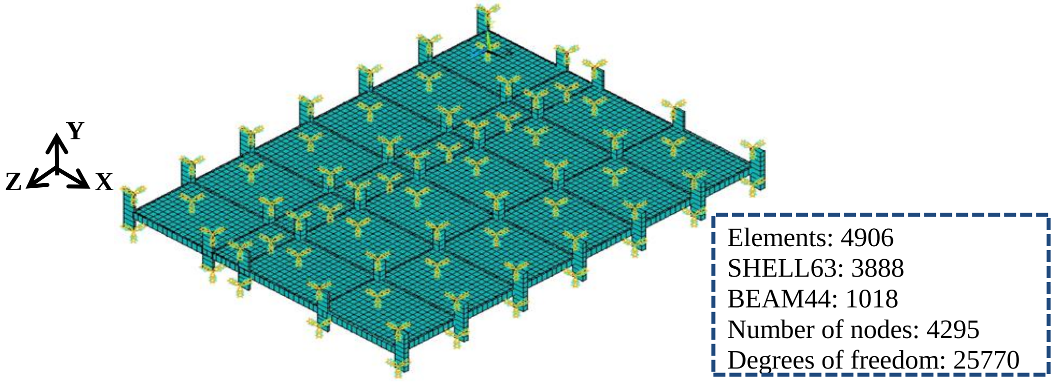


Figure 4. Dynamic loads of 18 people on the slabs (units in centimetres)

6 Finite element modelling

The reinforced concrete floor numerical model was developed based on the usual modelling techniques, through the Finite Element Method (FEM), and using the software ANSYS [5], see Fig. 5. The element BEAM44 was used to model the reinforced concrete beams and columns, while the shell element SHELL63 was used to represent the concrete slabs. The numerical model considered that the material presents an elastic behaviour and the plane sections remain plane after the floors deform. The structural beam-beam and beam-column connections were considered to be rigid.



Elements: 4906
SHELL63: 3888
BEAM44: 1018
Number of nodes: 4295
Degrees of freedom: 25770

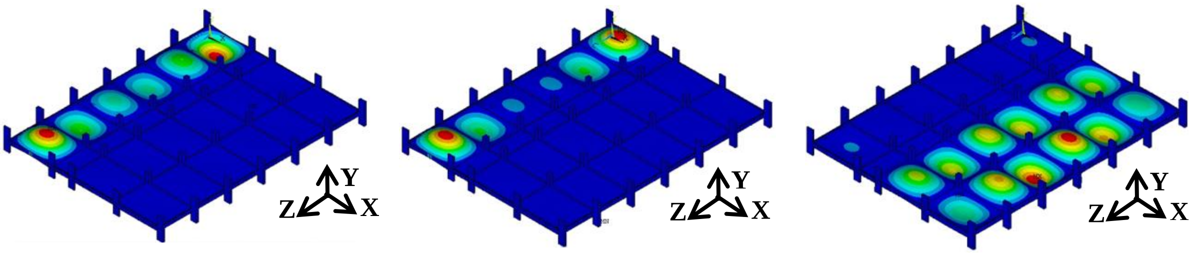
Figure 5. Finite element model

7 Modal analysis

The first six natural frequencies and their respective values of modal mass, modal stiffness and modal damping, corresponding to each mode of vibration, see Table 1. Fig. 6 shows the first three vibration modes of the structural model associated with their respective natural frequencies. Based on the modal analysis, it was found that the fundamental frequency of the floor (f_{01} = 8.12 Hz) is in the same range as the excitation frequency corresponding to the third harmonic of rhythmic human activities (aerobic gymnastics), ranging from 5.66 Hz to 8.57 Hz and from 4.5 Hz to 8.4 Hz, according to Faisca [2] and SCI [4], respectively. The fundamental frequency of the floor (f_{01} = 8.12 Hz) is below the minimum value recommended by NBR 6118 [11] (9.6 Hz).

Table 1. Dynamic characteristics of the studied reinforced concrete floor

Frequency (Hz)		Modal mass (kg)	Modal stiffness (N/m)	Modal damping ratios ξ (%)
f_{01}	8.12	9,676	1.26×10^7	1.22%
f_{02}	8.16	8,266	1.09×10^7	1.38%
f_{03}	8.23	21,520	2.87×10^7	1.91%
f_{04}	8.37	15,510	2.15×10^7	2.42%
f_{05}	8.52	12,630	1.81×10^7	2.43%
f_{06}	8.57	9,235	1.34×10^7	2.79%



a) 1° Mode shape (f_{01} = 8.12 Hz) b) 2º Mode shape (f_{02} = 8.16 Hz) c) 3° Mode shape (f_{03} = 8.23 Hz)

Figure 6. Investigated floor vibration modes

8 Forced vibration analysis

The dynamic loading models of Campista [1], Faisca [2], AISC [3] and SCI [4] were implemented in the ANSYS [5]. The modelling was based on the excitation frequency of 2.2 Hz, where according to AISC [3] the referred frequency investigated is ranging from 2 to 2.75 Hz, which corresponds to the first harmonic of aerobic activities. However, it should be stressed that the compatibility of the floor's natural frequency of 8.12 Hz with the frequency located in the third harmonic ranging from 6 to 8.25 Hz, could result in higher accelerations since the structure would be more susceptible to the resonance phenomenon. Table 2 presents the dynamic response (a_p: peak acceleration; $a_{w,rms}$: RMS acceleration; VDV: vibration dose values) for the structural sections (SS) for different load models. Fig. 7 illustrates the acceleration in time and frequency domain for the LM II (SS C).

Table 2. Dynamic structural response: $a_{w,rms}$, a_{peak} and VDV values

	SS	Campista [1]			Faisca [2]			AISC [3]			SCI [4]		
		a_p	$aw,_{rms}$	VDV	a_p	$aw,_{rms}$	VDV	a_p	$aw,_{rms}$	VDV	a_p	$aw,_{rms}$	VDV
		m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$
LM I (loading model)	A	**0.102**	**0.031**	**0.072**	**0.195**	**0.083**	**0.163**	**1.081**	**0.550**	**1.115**	**0.609**	**0.168**	**0.399**
	B	**0.103**	**0.033**	**0.076**	**0.191**	**0.083**	**0.163**	**0.973**	**0.390**	**0.831**	**0.543**	**0.166**	**0.378**
	C	0.024	0.009	0.021	0.040	0.012	0.027	0.347	0.200	0.400	0.231	0.040	0.133
	D	0.008	0.003	0.008	0.012	0.002	0.007	0.130	0.088	0.174	0.082	0.013	0.051
	E	0.010	0.002	0.005	0.004	0.001	0.002	0.070	0.047	0.094	0.034	0.005	0.021
	F	0.004	0.001	0.003	0.002	0.000	0.001	0.035	0.024	0.048	0.017	0.003	0.011
LM II (loading model II)	SS	Campista [1]			Faisca [2]			AISC [3]			SCI [4]		
		a_p	$aw,_{rms}$	VDV	a_p	$aw,_{rms}$	VDV	a_p	$aw,_{rms}$	VDV	a_p	$aw,_{rms}$	VDV
		m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$
	A	0.010	0.004	0.011	0.015	0.002	0.008	0.180	0.134	0.266	0.107	0.018	0.069
	B	0.024	0.009	0.021	0.040	0.012	0.027	0.341	0.239	0.477	0.225	0.040	0.129
	C	**0.111**	**0.035**	**0.080**	**0.197**	**0.086**	**0.168**	**1.007**	**0.467**	**0.978**	**0.574**	**0.170**	**0.389**
	D	**0.098**	**0.029**	**0.068**	**0.185**	**0.081**	**0.158**	**0.946**	**0.436**	**0.916**	**0.559**	**0.160**	**0.366**
	E	0.029	0.008	0.018	0.038	0.011	0.025	0.340	0.239	0.477	0.227	0.038	0.130
	F	0.010	0.003	0.009	0.015	0.002	0.008	0.180	0.134	0.266	0.107	0.018	0.069
LM III (loading model III)	SS	Campista [1]			Faisca [2]			AISC [3]			SCI [4]		
		a_p	$aw,_{rms}$	VDV	a_p	$aw,_{rms}$	VDV	a_p	$aw,_{rms}$	VDV	a_p	$aw,_{rms}$	VDV
		m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$	m/s^2	m/s^2	$m/s^{1.75}$
	A	0.003	0.001	0.002	0.002	0.000	0.001	0.035	0.024	0.048	0.017	0.003	0.011
	B	0.004	0.001	0.003	0.004	0.001	0.002	0.071	0.047	0.093	0.033	0.005	0.021
	C	0.009	0.003	0.007	0.013	0.002	0.007	0.138	0.094	0.186	0.088	0.014	0.055
	D	0.027	0.008	0.018	0.038	0.011	0.025	0.319	0.187	0.373	0.210	0.037	0.124
	E	**0.099**	**0.030**	**0.070**	**0.186**	**0.081**	**0.159**	**0.965**	**0.377**	**0.805**	**0.523**	**0.161**	**0.368**
	F	**0.110**	**0.034**	**0.079**	**0.195**	**0.083**	**0.163**	**1.081**	**0.550**	**1.115**	**0.609**	**0.168**	**0.399**
Tolerance peak acceleration: 0.5 m/s^2													
Limits: $a_{w,rms}$<0.35 m/s^2 SCI [4]; VDV<0.66 $m/s^{1,75}$ Ellis & Littler [12]; VDV<0.50 $m/s^{1,75}$ Setareh [13]													

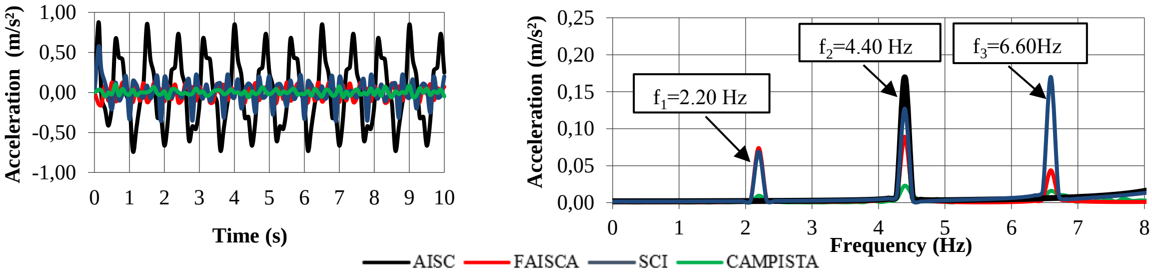


Figure 7. Floor acceleration: time and frequency domain (LM II: Structural Section C)

The maximum values related to the dynamic structural response of the floor was observed on the concrete slabs were the dynamic loads representative of the people were applied. The peak acceleration value [LM 2: Section C] corresponds to 0.11 m/s^2 when Campista model [1] was used, 0.19 m/s^2 when Faisca model [2] was considered, 1.00 m/s^2 for AISC formulation [3] and 0.57 m/s^2 for SCI mathematical model [4]. Based on the human comfort criteria limits, when the dynamic load models generated by AISC [3], and SCI [4] were considered in the investigation, it was verified that the floor presents excessive vibration and human discomfort. On the other hand, when the dynamic response of the structure was evaluated based on the dynamic load models proposed by Campista [1] and Faisca [2] the structural system attends the human comfort criteria and there are no excessive vibrations. However, it must be emphasized that the Campista dynamic loading mathematical model [1] was formulated based on the use of biodynamic systems, and also presents the lowest acceleration values in the dynamic analysis, due to the fact that the dynamic characteristics of the people were considered and also the human damping was included in the formulation.

9 Conclusions

This investigation consists of the dynamic structural analysis of a reinforced concrete floor, through experimental tests and numerical modelling. Based on the results, it can be concluded that:

1. The numerical fundamental frequency (f_{01N} = 8.12 Hz) approached the experimental fundamental frequency (f_{01E} = 7.81 Hz), validating the developed finite element model. Besides, the experimental results related to the structural damping (ξ = 5.39%) with a coefficient of variation less than 10%.

2. Based on the human comfort criteria limits, when the dynamic loadings generated by AISC mathematical model [3] [a_p = 1.00 m/s²], and SCI formulation [4] [a_p = 0.57 m/s²] were considered in the investigation, it was verified that the floor presents excessive vibration and human discomfort.

3. On the other hand, when the dynamic response of the structure was evaluated based on the dynamic loading models proposed by Campista [1] [a_p = 0.11 m/s²] and Faisca [2] [a_p = 0.19 m/s²], the structural system attends the human comfort criteria and there are no excessive vibrations.

It must be emphasized that further investigations will focus on the development of a series of forced vibration experimental tests aiming to validate the numerical results related to the peak acceleration values.

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