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Experimental and numerical dynamic analysis of buildings floors when subjected to human-induced loads

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Abstract. Numerous cases involving excessive vibrations on buildings floors due to human dynamic actions have been reported over the years. However, it is worth to mention that the human rhythmic activities, especially when performed by people groups tend to increase the degree of synchronization that may result in discomfort for the building users. Therefore, this research work aims to investigate the dynamic structural behaviour of a reinforced concrete floor when subjected to rhythmic human activities. The investigated floor corresponds to a gym with dimensions of 16 m x 35 m, and total area of 560 m². Initially, the floor dynamic properties (natural frequencies and structural damping) were determined based on the structure experimental monitoring. Afterwards, a floor numeric model was developed, based on the use of usual mesh refinement techniques present in Finite Element Method (FEM) simulations and implemented in software ANSYS. This way, several dynamic loadings mathematical formulations (only-force models and biodynamic systems) were implemented in order to assess the floor dynamic structural response. The obtained results (displacements and accelerations) and the human comfort assessment presented in this study indicate the relevance of the dynamic analysis to investigate the structural behaviour of the reinforced concrete floor and also the influence of the people-structure dynamic interaction.

Keywords: reinforced concrete floor, dynamic structural analysis, experimental test, human comfort.

1 Introduction

Over the years, cases of excessive vibrations on building floors have been reported due to human-structure interaction it has been investigated by several research works [1-4]. In this context, a number of factors may contribute to such occurrences, for example, the new trends of the building floor system present free spans areas and more slender elements directly impacting the modal parameters of the floors.

In addition, it is important to point out that the recent development of lightweight construction materials and design tools. Thus, the dynamic structural responses of the floor subject to human activities are analysed with the aim of achieving practical solutions that can be implemented even at the design stage.

In this paper, focuses on the analysis of the dynamic structural behaviour of reinforced concrete floor based on experimental dynamic monitoring and numerical modeling. The investigated floor corresponds to a gym with dimensions of 16 m x 35 m, and total area of 560 m² submitted to rhythmic human actions.

Initially, the floor dynamic properties were determined based on an on-site experimental test campaign (free vibration), through the use of different methodologies [2]. Afterwards, a floor numeric model was developed, based on the use of the Finite Element Method (FEM) via ANSYS [5] software.

This way, several dynamic loading mathematical models (only force models and biodynamic models) will be investigated aiming to study the reinforced concrete floor dynamic structural response (displacements and accelerations), having in mind qualitative and quantitative comparisons of the results, calculated based on the use of different modelling strategies to represent the rhythmic human dynamic loads. Finally, the floor human comfort assessment is considered in this investigation, based on the use of the recommended limits provided by technical standards and design guides.

2 Investigated structural model and finite element modelling

The investigated reinforced concrete floor corresponds to the real structural system to a fitness centre located on the eighth story of the State University of Rio de Janeiro (UERJ). The floor presents dimensions of 16 m x 35 m, and total area of 560 m², divided in 12 panels of concrete slabs with thickness equal to 12 cm (see figure 1). Regarding the materials physical properties, the concrete has a compressive strength equal to 13.7 MPa and modulus of elasticity equal to 17.6 GPa. The steel presents stress steel grade of 345 MPa and Young's modulus of 205 GPa. The numerical modelling of the reinforced concrete floor, was developed adopting the usual mesh refinement techniques present in the adopted finite element software ANSYS [5], as shown in Fig. 2. In the present computational model, finite shell elements SHELL63 were used to represent the reinforced concrete slab, while for the beams and columns the three-dimensional element BEAM44 was adopted. It should be emphasized that the reinforced concrete floor works in an elastic-linear regime. Thus, the cross sections remain plane after deformation (Bernoulli's theorem).

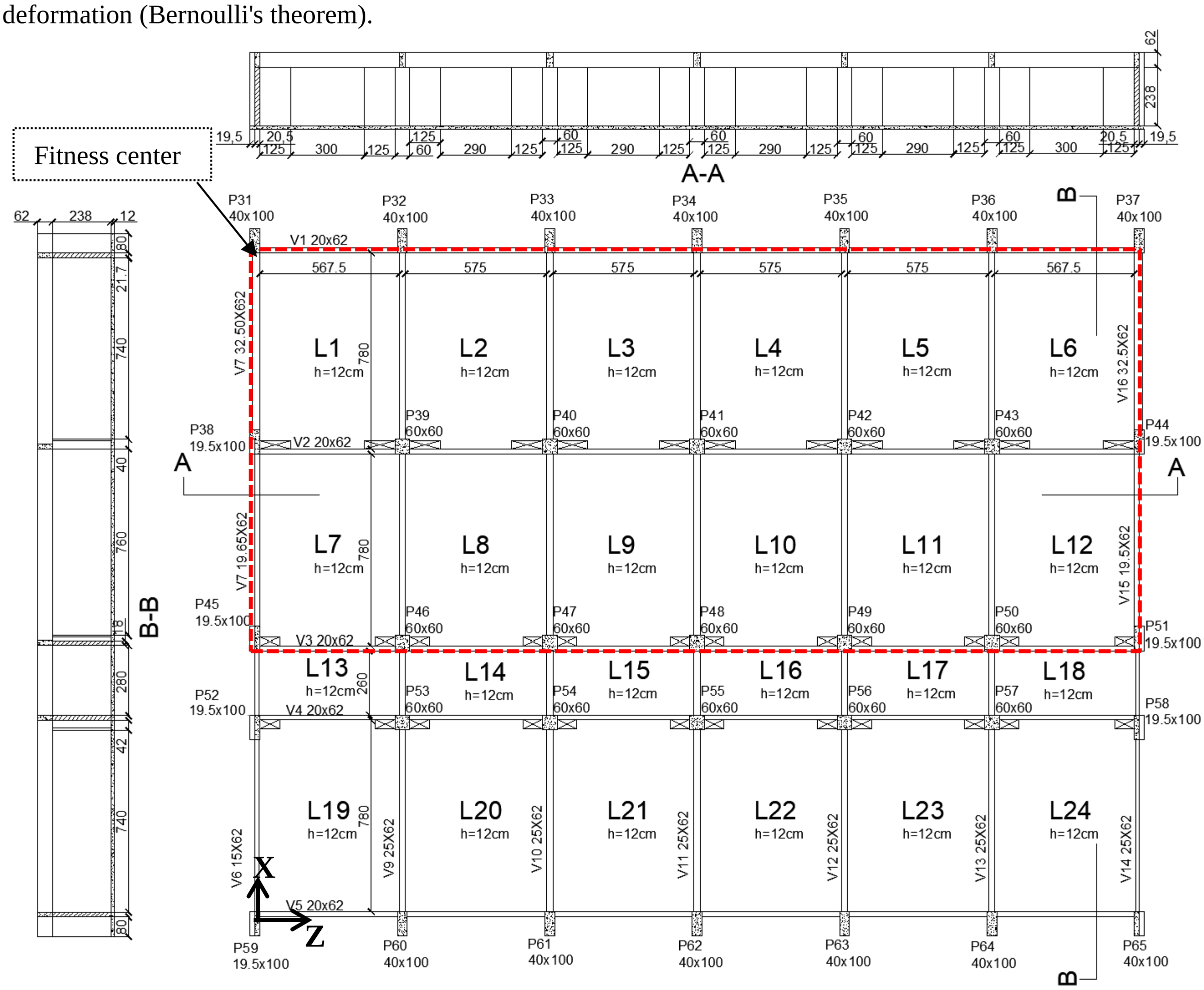


Figure 1. Structural model investigated (units in centimetres)

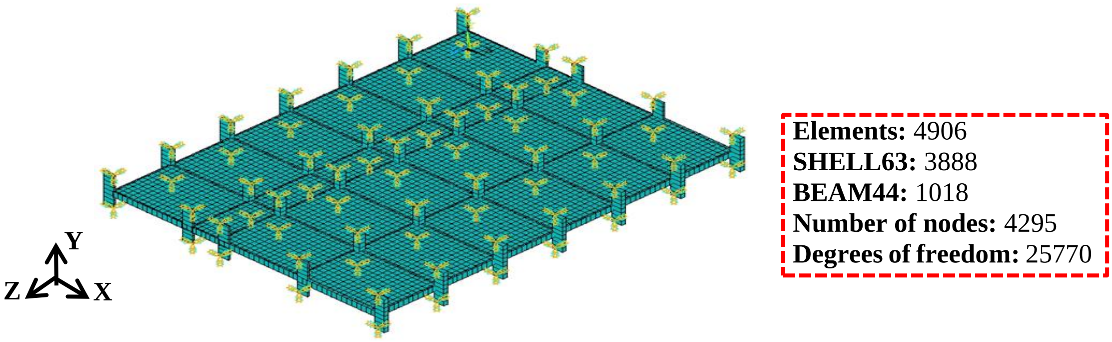


Figure 2. Finite element model

3 Dynamic loading models: only-force and biodynamic systems

The floor dynamic structural behaviour has been investigated by several research works [1-4]. In this work, the dynamic loadings were calculated through the use of several traditional only force models. The models (only-force) consist of mathematical functions utilised to represent the human dynamic loads on the investigated floor. In view of the above, this research work evaluates the dynamic structural responses obtained based on the use of the following dynamic loading models proposed by SCI [6], Faisca [7] and AISC [8]. The AISC guide [8] presents formulation that can be used to describe different situations of such as, for example, dancing aerobic activities and walking. The parameters depend on the following variables: human dynamic loading, three harmonic components as a function of time and dynamic coefficients variables, see Eq. (1). The SCI [6] model considers in the formulation the effects of crowd loading, as it is based on the parameters related to the number of participants performing human rhythmic activities on the floor, see Eq. (2). The Faisca model was developed based on a series of experimental tests, where the impact effects on human-structure interaction are considered, see Eq. (3).

$$F(t) = P\alpha_i \cos\left(2\pi i f_{step} t\right) \tag{1}$$

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

$$F(t) = CD\left\{K_p P\left[0.5 - 0.5\cos\left(\frac{2\pi}{T_c}t\right)\right]\right\} \therefore t \le T_c \therefore F(t) = 0 \therefore T_c \le t \le T \tag{3}$$

Considering the eqs. (1) to (3); F(t) represents the dynamic excitation in (N); Q, G and P represent the person's weight in (N); f_p is the step frequency in (Hz); t is the time in (s). In eq. (1), α_i represents the dynamic coefficient and i is the harmonic number. In eq. (2), n is associated with the number of terms of the Fourier series; v is the number of people; $r_{n,v}$ is the Fourier coefficient induced by v people; and ϕ_n is the phase difference. In eq. (3), Kp is the impact coefficient; CD is related to the lag coefficient; T is the activity period in (s) and Tc is the activity contact period in (s).

The rhythmic human dynamic actions can be numerically modelled based on the use of biodynamic systems, aiming to consider these dynamic loadings on the building floors, more realistically, due to the fact that these systems take into account the dynamic properties of each individual (mass, damping and stiffness) [9-10]. Thus, being an alternative to only-force models. Therefore, Campista [4] and Sousa [1] formulated a biodynamic model considering a single degree of freedom (SDOF). The biodynamic model characteristics were obtained experimentally considering the individuals jumping on a developed dynamic load platform. The testing system consists of accelerometers, load cells, a computer a signal acquisition and analysis system. The dynamic forces and accelerations associated with each individual were determined based on experimental monitoring. Based on the experimental results the parameters of the model were developed by solving the dynamic equilibrium equation, eq. (4) through the classical process of optimization, via genetic algorithms (GA).

$$F_i(t) = \underbrace{4\pi^2 f_i^2 m_i}_{Ki} x_i(t) + \underbrace{4\pi m_i \xi f_i}_{Ci} v_i(t) + m_i a_i(t) \tag{4}$$

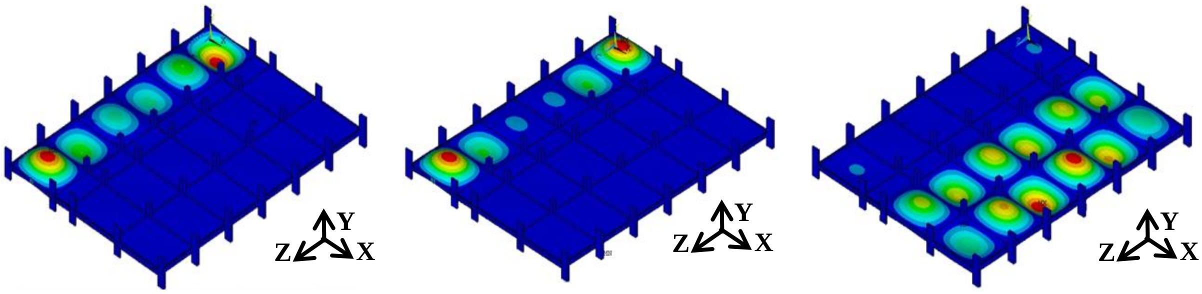
Concerning the parameters in Eqs. (4); Fi(t) is the dynamic force in (N); ki is the stiffness in (N/m); mi is the mass in (kg); ci is the damping in (Ns/m); xi(t) is the displacement in (m); vi(t) is the velocity in (m/s); ai(t) is the acceleration in (m/s^2); fi is the frequency in (Hz); ξ is the damping coefficient, considered equal to 0.25 [4] in this work. This way, the dynamic loading related to 36 (thirty-six) people practising aerobics was applied on the floor and to investigate the dynamic structural response

4 Modal analysis: eigenvalues and eigenvectors

Based on a modal analysis performed using the ANSYS [5] software, Table 1 presents the reinforced concrete floor natural frequencies (eigenvalues) and the structural system dynamic properties (modal mass, modal damping and modal stiffness), and Figure 3 illustrates the first three vibration modes (eigenvectors). Thus, Tab. 1 presents the modal parameters obtained, it was verified that the floor natural frequency (f_{01} = 7.89 Hz), is in the same range of the excitation frequency corresponding to the third harmonic of rhythmic human activities (aerobic gymnastics), varying from 5.66 to 8.57Hz and from 4.5 to 8.4Hz, according to Faisca [7] and Elis and Ji [11], respectively. Thus, the structure is more susceptible to the resonance phenomenon, can occur due to equality (or proximity) between one of the excitation frequencies and the structure natural frequencies.

Table 1. Dynamic characteristics of the studied reinforced concrete floor

Frequency (Hz)		Modal mass (kg)	Modal stiffness (N/m)	Modal damping ratios ξ (Ns/m)
f_{01}	7.91	10059.42	2.48 x10^7	3.01 x10^4
f_{02}	7.94	8653.81	2.15 x10^7	2.60 x10^4
f_{03}	8.00	663.26	1.69 x10^6	2.02 x10^3
f_{04}	8.17	16017.17	4.21 x10^7	4.94 x10^4
f_{05}	8.30	13139.01	3.57 x10^7	4.13 x10^4
f_{06}	8.35	9646.43	2.65 x10^7	2.99 x10^4



a) 1° Mode shape (f_{01} = 7.91 Hz) b) 2° Mode shape (f_{02} = 7.94 Hz) c) 3° Mode shape (f_{03} = 8.00 Hz)

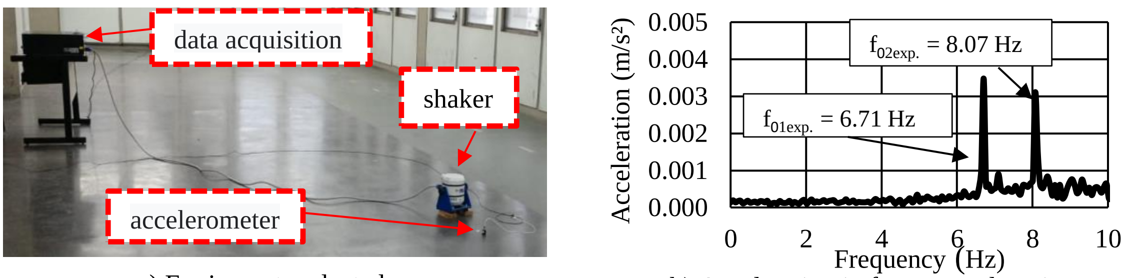
Figure 3. Investigated floor vibration modes

5 Experimental testing on free vibration

The experimental tests were performed on the fitness centre of the Institute of Physical Education and Sports (IEFD) of State Universyty of Rio de Janeiro (UERJ). The experimental dynamic monitoring data were obtained at the structural section where the maximum modal amplitude occurs (slab L3) referring to the third mode of vibration based on the response provided by the numerical model [1], see Fig. 3. Given the above, in order to obtain the experimental modal parameters of the floor, the following methodologies were employed: experimental test I (modal shakers), experimental test II (impact hammer on the floor) and experimental test III (experimental structural damping).

5.1 Experimental test I: modal shakers

The experimental modal shakers consists of modelling the dynamic behaviour of a structure through monitoring the acceleration (slab L3) while the floor is excited by the shaker, as illustrated in Fig. 4. The equipments selected for the tests were: an accelerometer, a data acquisition system, a computer and a shaker.



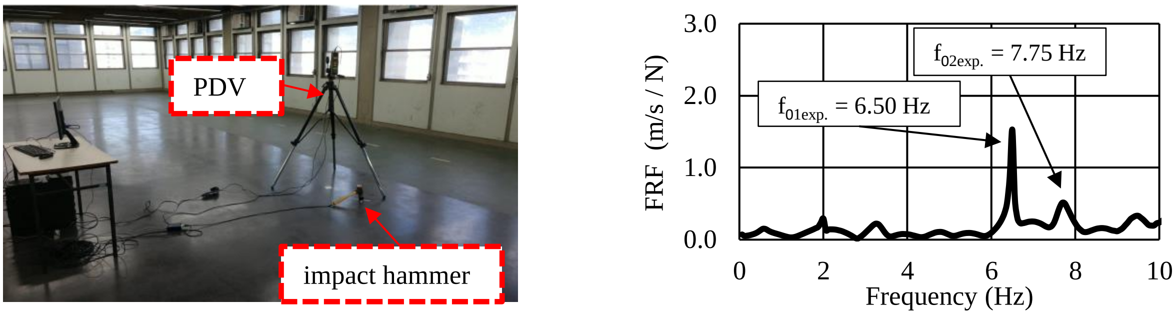
a) Equipments selected b) Acceleration in frequency domain

Figure 4. Experimental testing on free vibration (Test I)

In order to identify the floor natural frequencies, dynamic excitations were applied on the concrete slabs (1 Hz to 10 Hz). Based on the presented results, it is observed the the energy transfer peak associated to 8.07 Hz corresponds to the floor third natural frequency, and the other energy transfer peak related to 6.71 Hz is associated to the excitation frequency (impact shaker applied on the floor).

5.2 Experimental test II: impact hammer on the floor

The developed experimental test consists of evaluating the floor dynamic structural response (velocity), based on the results determined via laser signal applied on the investigated concrete slab (L3 slab), as illustraed in Fig. 5. The equipments selected for the tests were: a data acquisition system, a computer (ADS 2500), a portable digital vibrometer (PDV-100) and an impact hammer. It should be noted that the floor was excited by the application of force (impact hammer), where the impacts were monitored along with the responses of the floor [2]. Based on the experimental results the fractional flow reserve (FFR) was applied, with this it was possible to identify again the experimental frequency ($f_{02exp.}$ = 7.75 Hz) proximity with the first frequency obtained in the computational model ($f_{03num.}$ = 8.00 Hz).



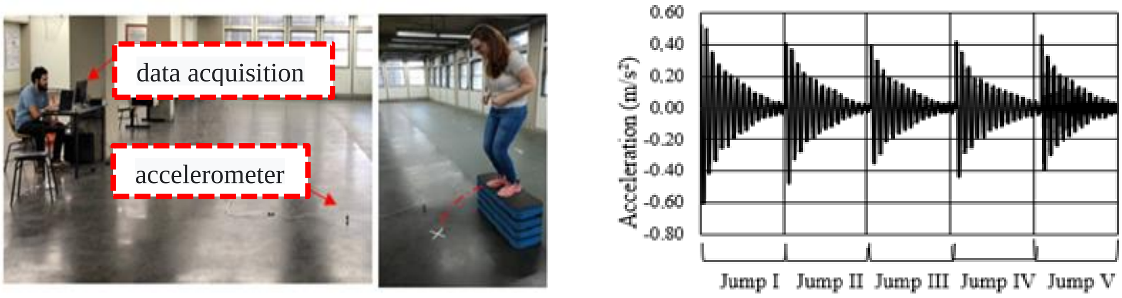
a) Equipments selected

b) FRF frequency domain

Figure 5. Experimental testing on free vibration (Test II)

5.3 Experimental test III: jumping on the floor

The experimental test developed consists of evaluating the dynamic structural response of the floor (acceleration) resulting from the accelerometer fixed on the floor, in the structural section of interest (slab L3). The equipments selected for the tests were: an accelerometer, a data acquisition system and a computer. It should be noted that 5 (five) human jumps were performed in order to obtain a sample of significant results, where the individual jumped from the platform and, after damping the floor, repeated the same procedure (see figure 6) [2]. Based on the experimental results, the structure damping was determined through the logarithmic decrement method, whose value is equivalent to 2.62 % and a coefficient of variation of less than 10%, which according to Gomes [12], indicates that the results present high precision.



a) Equipments selected

b) Dynamic structural response (acceleration)

Figure 6. Experimental testing on free vibration (Test III)

6 Forced vibration analysis

Based on the numerical model developed reinforced concrete floor, the following dynamic loading models were applied: Faisca [7], SCI [6], AISC [8] and biodynamic [1]. Therefore, Fig. 7 presents the dynamic loading related to 36 (thirty-six) people practising aerobics was applied on the floor, where the dynamic structural responses were investigated at the centre of each slab, represented by the letters A to F. It should be noted that the excitation frequency ($f_{exc.}$ = 2 Hz) is in resonance with the third vibration mode ($f_{03num.}$ = 8.00 Hz). Table 2 presents the results of the dynamic responses (a_p: peak acceleration; $a_{w,rms}$: RMS acceleration; VDV: vibration dose values) the investigated structural sections (A-F), when perform rhythmic human activities. The AISC and SCI models showed higher values for peak acceleration, being: [a_p: 0.853 m/s² - section C] and [a_p: 0.942 m/s² - section C].

On the other hand, the highest peak acceleration values of the Biodynamic [1] and Faisca [7] models occur in sections B and A, respectively (see table 2). With regard to the VDV human comfort parameters, the Biodynamic [1], SCI [6] and AISC [8] models exceeded the standard limits (VDV<0.50 $m/s^{1,75}$ Setareh [13]), see table 2. However, the RMS acceleration values are within acceptable limits in all models assessed ($a_{w,rms}$<0.35 m/s² SCI [6]).

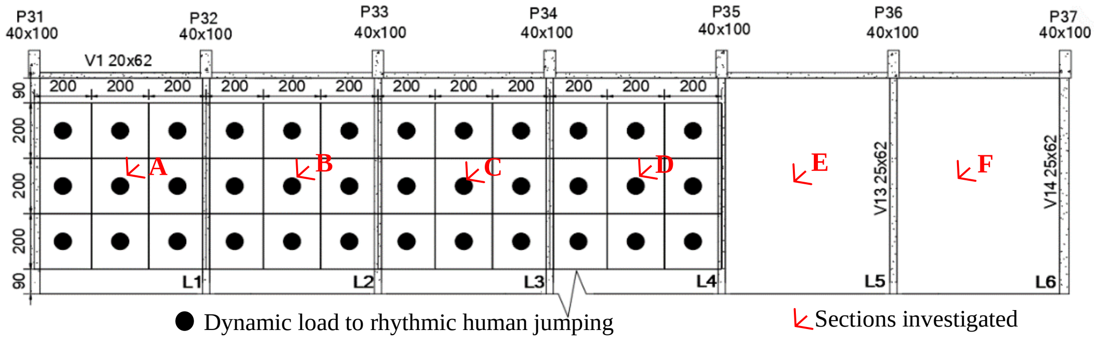


Figure 7. Dynamic loads on the reinforced concrete floor (units in centimetres)

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

LM I (loading model)	SS	Biodynamic [1]			Faisca [7]			AISC [8]			SCI [6]		
		a_p	$aw_{,rms}$	VDV	a_p	$aw_{,rms}$	VDV	a_p	$aw_{,rms}$	VDV	a_p	$aw_{,rms}$	VDV
		m/s²	m/s²	$m/s^{1.75}$	m/s²	m/s²	$m/s^{1.75}$	m/s²	m/s²	$m/s^{1.75}$	m/s²	m/s²	$m/s^{1.75}$
	A	0.157	0.045	0.104	0.195	0.084	0.165	0.723	0.150	0.465	0.811	0.140	0.452
	B	0.161	0.053	0.121	0.175	0.074	0.147	0.833	0.152	0.511	0.925	0.144	0.505
	C	0.154	0.042	0.097	0.184	0.078	0.153	0.853	0.152	0.515	0.942	0.143	0.508
	D	0.150	0.042	0.098	0.185	0.082	0.161	0.514	0.133	0.387	0.584	0.124	0.366
	E	0.074	0.012	0.027	0.037	0.011	0.025	0.365	0.050	0.208	0.325	0.047	0.193
	F	0.030	0.005	0.012	0.014	0.002	0.007	0.203	0.035	0.129	0.193	0.033	0.122
Tolerance peak acceleration: 0.5 m/s²													
Limits: $a_{w,rms}$<0.35 m/s² SCI [6]; VDV<0.50 $m/s^{1,75}$ Setareh [14] and VDV<0.66 $m/s^{1,75}$ Ellis & Littler [11];													

7 Conclusions

The present research work focuses on investigating the dynamic structural response of a reinforced concrete floor through experimental tests and numerical modelling. According to the results, it can be concluded that:

1. The experimental fundamental frequency [Test I: $f_{02exp.}$ = 8.06 Hz and Test II: $f_{02exp.}$ = 7.75 Hz] approached the numerical fundamental frequency ($f_{3num.}$ = 8.00 Hz), validating the developed finite element model. According to the data obtained in the experimental tests. In addition, the data experimental related to the structural damping (ξ = 2.62 %) with a coefficient of variation less than 10%.

2. According to the design criteria standards for rhythmic activities practiced on floors, it is observed that the fundamental frequency of the floor [Test I: $f_{02exp.}$ = 8.06 Hz; Test II: $f_{02exp.}$ = 7.75 Hz; Numerical model: $f_{03num.}$ =

8.00 Hz] is below the minimum value recommended by NBR 6118 [13] (9.6 Hz). This situation leads to a high probability of problems related to excessive vibrations and human discomfort.

3. Based on the human comfort criteria limits. It was verified that the floor presents peak acceleration exceeding the limits (0.5 m/s²). The maximum dynamic responses generated by SCI [6] [a_p = 0.942 m/s^2], AISC [8] [a_p = 0.853 m/s^2]. This way, high levels of vibration and human discomfort. However, the Faisca model meets the standard criteria.

4. It can be observed that the biodynamic model presented lower responses than the models (AISC [8] and SCI [6]) because the mathematical formulation considers in the modeling the characteristics of the individuals that may have influenced on the dynamic responses.

Finally, it is important to carry out a series of experimental tests of forced vibration on the reinforced concrete floor, with the aim of identifying the dynamic loading model best suited to reality. Furthermore, new compositions of dynamic loading models may be investigated in future work.

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References

[1] F. A. de Sousa. *Analysis of the dynamic structural response of building floors subjected to rhythmic human activities based on the use of biodynamic systems (In Portuguese. In development).* PhD Thesis Civil Engineering Post-graduate Programme, PGECIV. State University of Rio de Janeiro, UERJ. Rio de Janeiro, RJ, Brazil, 2022.
[2] B. E. Ferreira, H. Carvalho, J. G. S.. Da Silva, R. B. Caldas and J. V. Aguiar (2021) Experimental evaluation of induced human walking vibrations on steel-concrete composite floors. *Rev. IBRACON Estrut. Mater.*
[3] F. Liu, J. N. Battini and C. Pacoste. Experimental and numerical analyses of single pedestrian walking on a hollow core concrete floor, *International Journal of Civil Engineering*, pp.1-9, 2018.
[4] F. F. Campista. *Modelling of biodynamic systems for evaluation of the dynamic structural behaviour of steel concrete composite building floors subjected to human rhythmic activities (in Portuguese)*. PhD Thesis Civil Engineering Post-graduate Programme, PGECIV. State University of Rio de Janeiro, UERJ. Rio de Janeiro, RJ, Brazil, 2019.
[5] ANSYS Swanson Analysis Systems Inc. (2009), Theory Reference (R. 12.1).
[6] A. L. Smith, S.J. Hicks and P.J. Devine. "Design of floors for vibrations: A new approach", SCI Publ. P354, Ascot, 2009.
[7] R. G. Faisca. *Characterization of Dynamic Loads due to Human Activities (in Portuguese)*, 230f. Thesis Civil Engineering Post-Graduate Programme, - COPPE/UFRJ, Rio de Janeiro, RJ, Brazil, 2003.
[8] AISC/CISC Steel Design Guide Series No. 11 *Vibrations of Steel-Framed Structural Systems Due to Human Activity*, Chicago, Second Edition, 2016.
[9] Y. Fu and N. LI. *Dynamic response of biodynamic model seated on a crashworthy seat with composite absorber*. IOP Conference Series: Materials Science and Engineering, Guangzhou, China, 2019.
[10] E. Shahabpoor, A. Pavic and V Racic. Interaction between walking humans and structures in vertical direction: a literature review. Shock and Vibration *Shock and Vibration*, pp. 12–17, 2016.
[11] B. R Ellis, J. D. Littler. "Response of cantilever grandstands to crowd loads. Part I: Serviceability evaluation", in Proceedings of the Institution of Civil Engineers – Structures and Buildings 157(SB4): 235-241, 2004.
[12] P. F. Gomes. Curso de Estatística Experimental. 15. Ed. Fealq, Piracicaba. 2009.
[13] NBR 6118. A.B.N.T. Concrete Structure Design - Procedure. In: *Brazilian Association of Technical Standards*, Rio de Janeiro, RJ, Brazil, 2014.
[14] M. Setareh. Evaluation and assessment of vibrations owing to human activity. Proceedings of the Institution of Civil Engineers - Structures and Buildings, v. 165, iss, SB5, p. 219-231, 2012.