Dynamic structural behaviour of steel-concrete composite floors subjected to rhythmic human activities

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Abstract. Over the last few years, a lot of structural problems associated with excessive vibration of building floor systems when induced by human rhythmic activities have occurred in places such as fitness centres, event halls and offices. On the other hand, it's well known that the resonance phenomenon can occur due to equality (or proximity) between one of the excitation frequencies and the structure natural frequencies. Having this thought in mind, this paper investigates the dynamic structural behaviour of a steel-concrete composite floor when subjected to loadings induced by human rhythmic activities. This way, the studied structural system consists of a health club that presents an area used for aerobics. The composite floor system presents dimensions of 22.5 m by 14 m and a total area of 315 m². In this study, the dynamic loadings were obtained through the use of several dynamic load models (only force models) and also based on the modelling of biodynamic systems, to incorporate the human-structure interaction dynamic effect to the analysis. The composite floor numerical model was generated based on usual modelling techniques adopting the mesh refinement present in the Finite Element Method (FEM) and implemented in the ANSYS program. The investigated floor dynamic structural response was calculated through the consideration of 20 people practising rhythmic activities on the original area specified in the project and on the other two possible areas of the structural system aiming to verify the occurrence of excessive vibration and also to assess the human comfort having in mind the recommended limits proposed in the traditional international design standards.

Keywords: composite floors, dynamic structural analysis, human comfort assessment.

1 Introduction

The new construction techniques of modern building design have increased the use of lightweight floors due to the construction time and the flexibility in the final use. This new trend impacts directly on the dynamical response of the composite steel-concrete floor when subjected to human activities, because of the tendency to lower natural frequencies and natural damping (with weight reduction). The problem associated with this excessive vibration occurs in fitness centres, events halls and offices, according to works Sousa [1], Branco et al. [2], and Sousa et al. [3].

This work aims to study the dynamic behaviour and evaluate the human comfort of a steel-concrete composite floor, when subjected to human rhythmic activities. The investigated structural model is related to a composite floor presenting dimensions of 22.5 m by 14 m, and total area of 315 m². The structure consists of a health club with area for aerobics. The dynamic loads representing the human rhythmic activities applied on the concrete slabs were obtained based on the use of the traditional "only-force" models AISC [4], SCI [5], and Faisca [6], and also considering the use of biodynamic systems investigated by Campista [7], aiming to include the people-structure dynamic interaction effect. The finite element modelling of the steel-concrete composite floor is based on the usual refinement techniques present in the ANSYS software [8]. This way, after the dynamic structural analysis, the human comfort was assessed based on the comparisons between the floor dynamic response and the recommended limits from the design standards.

2 Dynamic loading models: only-force

Determine the human activities effects in structures is not an easy assignment. The traditional way to represent this type of loading is through the "only-force" models, which apply a direct force on the structure. In this section, AISC [4], SCI [5], and Faisca [6] models were developed. The person's weight used in this work was 798 N, the step frequency was 2.20 Hz and the number of people practising activities on the floor was 20.

The mathematical model present in the AISC [4] guide takes into consideration three harmonic components as a function of time, indicates the values of step frequency and keeps the relationship with the dynamic coefficients for each harmonic, as expressed in eq. (1). Where F(t) represents the force in (N); Q is the person's weight in (N); α_i is the dynamic coefficient; i is the harmonic number; f_{step} is the step frequency in (Hz) and t is the time in (s).

$$F(t) = Q + \sum_{i=1}^{N} \alpha_i Q \sin(2\pi i f_{step} t - \phi_i) \tag{1}$$

The present "only-force" model from SCI [5] guide considers a crowd loading effect on the structure when submitted to rhythmic activities, as can be seen in eq. (2). This model is influenced by the first three terms of the Fourier series, determined based on the floor's characteristics and the number of people performing activities.

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

Where F(t) represents the dynamic force in (N); G is the person's weight in (N); n is the number of the Fourier term; v is the people's number; $r_{n,v}$ is the Fourier coefficient induced by v people; ϕ_n is the phase difference; f_p is the load frequency and t is the time in (s). The model developed by Faisca [6] is based on the mathematical Hanning function. The eq. (3) expresses this "only-force" model which was produced by experimental tests, where the loading was directly applied to the structure. Where the F(t) is the dynamic force in (N); CD is the lag coefficient; K_p is the impact coefficient; T_c is the contact period of the activity in (s); T is the activity period in (s) and t is the time in (s).

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

3 Biodynamic modelling

The representation of the human-structure dynamic behaviour was studied by Campista [7] and based on many experimental tests the author developed a mathematical model which represents the "mass-spring-damper" system (see Fig. 1), as an alternative to the traditional "only-force" models. The modelling is represented by a single degree of freedom system and according to Barker [9] and Sim et al. [10] present goods result due to the variables associated with the dynamic equilibrium equations. The response parameters were determined based on the resolution of a classical optimization problem that used the genetic algorithmic methodology considering the results of a campaign of experimental tests with 100 people. The model is expressed by eq. (4) to (6).

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

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

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

Where $F_i(t)$ is the force produced by the individual in (N); k_i is the stiffness in (N/m); m_i is the mass in (kg); c_i is the damping in (N.s/m); $x_i(t)$ is the displacement in (m); $v_i(t)$ is the velocity in (m/s); $a_i(t)$ is the acceleration in (m/s²); f_i is the frequency in (Hz), t is the time in (s), and ξ is the damping coefficient, considered equal to 0.25 in this investigation. Each of these parameters is correlated to each person, as proposed by Campista [7].

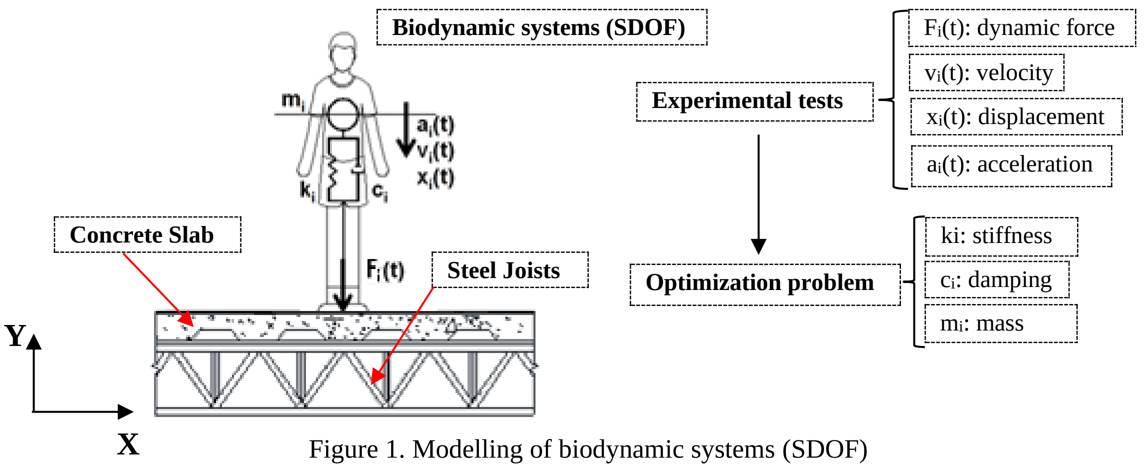


Figure 1. Modelling of biodynamic systems (SDOF)

4 Structural Model and Computational Modelling

The studied steel-concrete composite floor was constructed by steel joists and a concrete slab [4] and presents dimensions of 14m x 22.5m ($315m^2$), see Fig. 2(a, b, c). The steel joists present the following characteristics: bottom chords [2x(11/2''x1/8'']; top chords [2x (2"x1/8")]; vertical members [L(1/2''x1/8")]; diagonals [L(1/2"x1/8")]; the effective composite moment of inertia: 1.1×10^6 mm^4. Concerning the physical properties of the model was used in concrete, compression strength of 30 MPa and secant elasticity module of 26 GPa; and in the joists (steel), Young's modulus of 205 GPa and stress steel grade of 345 MPa.

The computational modelling of the structural model was developed based on the finite element method through ANSYS [8] software. The modelling of the concrete slab was made based on shell finite elements SHELL63 and the steel-joists were represented by three-dimension beam finite element BEAM88. Regarding mesh discretization, was used a mesh of 0.22 m x 0.25 m in the slab, as can be seen in Fig. 2(d).

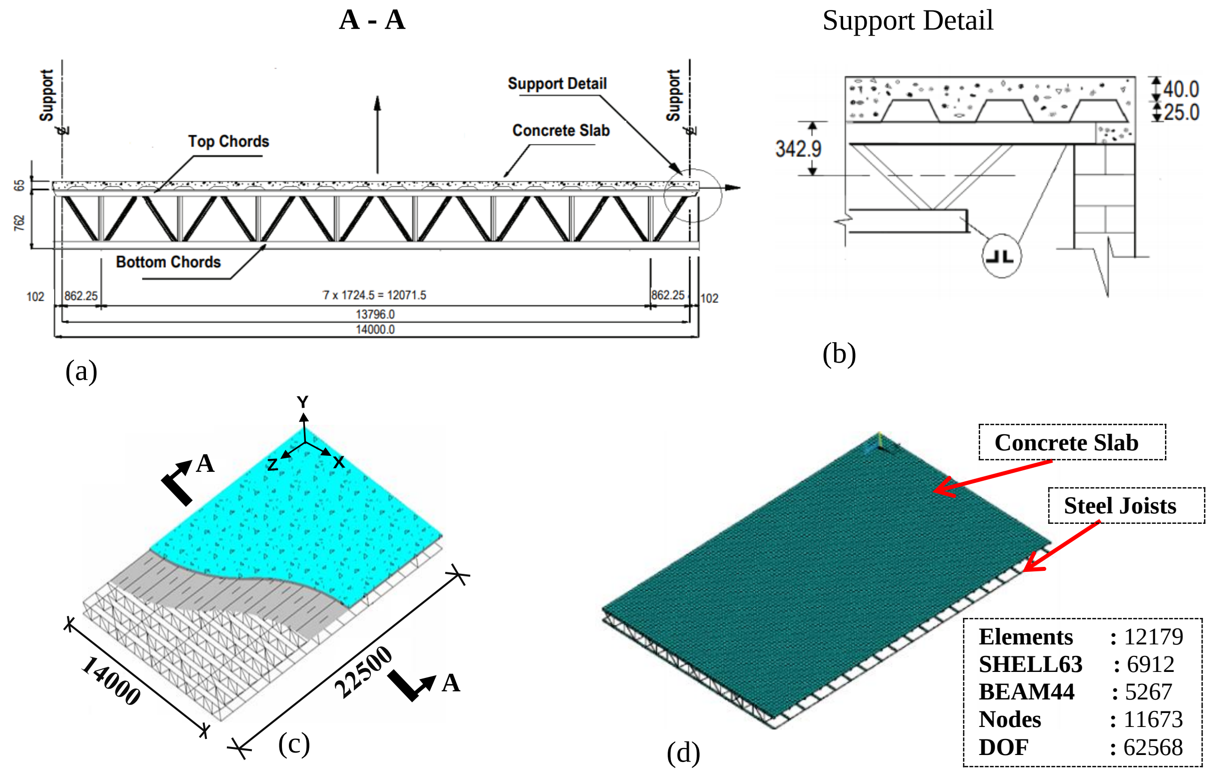


Figure 2. Structural model (a, b, c) (units in millimetres) and finite element modelling (d)

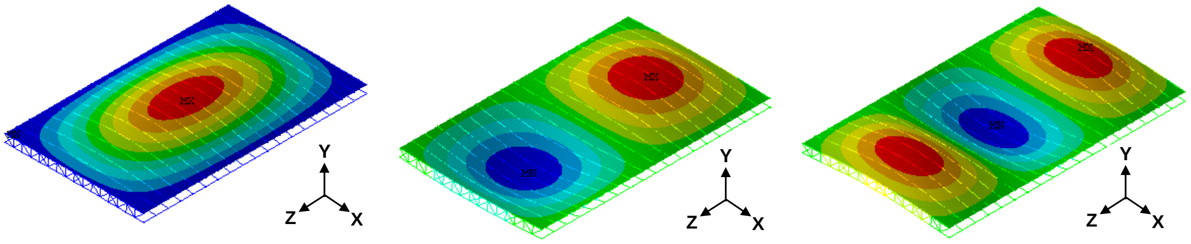
5 Modal analysis

Table 1 presents the dynamic characteristics of the steel-concrete composite floor based on the first six natural frequencies and the respective modal properties (mass, damping and stiffness) of the studied floor related to each vibration mode which is shown in Fig. 3. The developed finite element model is validated by the approximation of the numerical (f_{01N} = 5.60 Hz) and analytical (f_{01A} = 5.57 Hz) [4] fundamental frequencies.

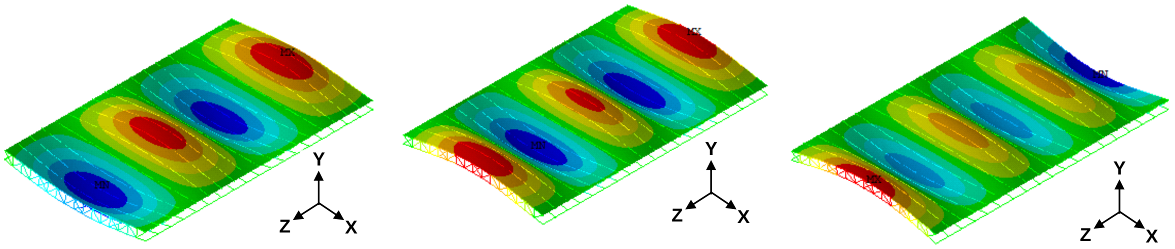
Table 1. Studied composite floor dynamic characteristics

Frequency (Hz)		Modal mass (kg)	Modal stiffness (N/m)	Modal damping ratio ξ (%)
f_{01}	5.60	8385.68	5.20×10^5	4.63%
f_{02}	5.65	356.64	5.32×10^5	5.05%
f_{03}	5.77	8645.60	5.68×10^5	5.16%
f_{04}	6.01	8552.17	6.09×10^5	5.93%
f_{05}	6.40	7670.83	6.21×10^5	6.07%
f_{06}	6.97	5332.95	5.11×10^5	6.33%

The numerical fundamental frequency of this composite floor is within the bounds of the third harmonic frequency range proposed by Faisca [6] (5.66 to 8.57 Hz) and the proposed by Ellis and Ji [11] (4.5 to 8.4 Hz). Furthermore, this fundamental frequency is below the minimum value (f_{min} = 9.6 Hz) of the Brazilian Association of Technical Standards [12]. These facts show that the studied structure presents the susceptibility to resonance phenomenon.



a) 1° Mode shape (f_{01} = 5.60 Hz) b) 2° Mode shape (f_{02} = 5.65 Hz) c) 3° Mode shape (f_{03} = 5.77 Hz)



d) 4° Mode shape (f_{04} = 6.01 Hz) d) 5° Mode shape (f_{05} = 6.40 Hz) d) 6° Mode shape (f_{06} = 6.97 Hz)

Figure 3. Composite floor vibration modes

6 Forced Vibration Analysis

The dynamic response of the composite floor subjected to human activities was based on the dynamic loadings related to 20 people practising aerobics in an area of 52.5 m². This load was applied in the structure based on traditional "only-force" models, AISC [4], SCI [5], and Faisca [6] and based on biodynamic systems proposed by Biodynamic [7]. The considered person's weight was 798 N and the step frequency was 2.20 Hz.

This work analysis was divided into three different areas on the steel-concrete composite floor named as

Loading Model (LM) aiming to evaluate if there is a difference in the structure response if the aerobic area changes its location. The three different loading models can be seen in Fig. 4(a), and load detail in Fig. 4(b). The dynamic responses were investigated based on structural sections A to G, see Fig. 4(a).

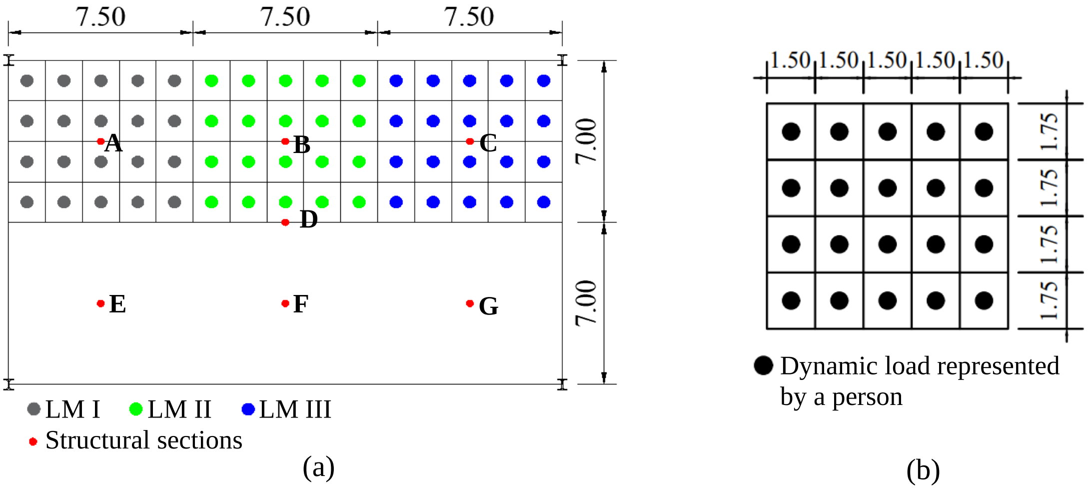


Figure 4. Composite floor (a) and load detail (b) (units in metres)

After the analysis, it was possible to observe the high values of dynamical response in all three loading model cases, see Table 2. Therefore, the greater values in LM I occur in section A for the AISC [4], Faisca [6], and Campista [7] models. For the SCI [5] model, the greater values occur in sections E, F, and G. In those sections the dynamical response for other models has also high values that approximate the critical ones. In the second loading model (LM II), the higher values occur in section D and the third loading model case (LM III) the critical response occur in section C for all loading models [4-7], due to mode shapes.

The responses obtained to analyze the behaviour of the composite floor was peak acceleration (a_{peak}), RMS weighted acceleration ($a_{w,rms}$) and vibration dose values (VDV). The peak acceleration related to the critical sections of each loading model case are shown in Table 2 and all of the responses exceed the recommended tolerance ($a_{peak} \leq 0.50$ m/s²) from AISC standard [4]. After analysing the three loading model cases (LM I, II and III), the acceleration in frequency and time domain were obtained for each critical section for the LM II, see Fig. 5(a) and Fig. 5(b), respectively.

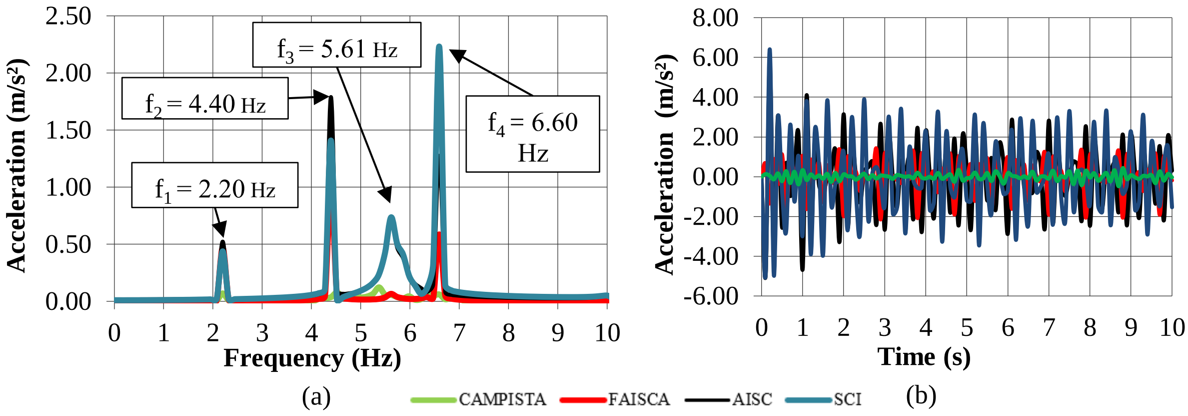


Figure 5. Dynamic response of critical section D for LM II in frequency (a) and time domain (b)

For all loading models cases (LM I, II and III) the traditional “only-force” models present large energy peak transfer due to the nature of the force application, which was directly applied to the slab. At the same time, the biodynamic systems incorporate the human-structure interaction and the person's dynamic characteristics. This consideration includes the damping contribution of each person practising aerobics, which was experimentally determined in Campista [7] works and for this reason, the energy peak transfer in the slab became lower producing lower dynamic responses. It is noteworthy that the maximum dynamic responses were obtained in the structural sections where the load was applied, also it is possible to observe high values in adjacent sections. This behaviour occurs due to floor modal parameters, which has a direct impact on the structural response.

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

	SS	AISC [4]			SCI [5]			Faisca [6]			Biodynamic [7]		
LM I (loading model)		a_{peak}	$a_{w,rms}$	VDV	a_{peak}	$a_{w,rms}$	VDV	a_{peak}	$a_{w,rms}$	VDV	a_{peak}	$a_{w,rms}$	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	6.20	1.31	3.02	6.21	1.30	3.18	1.10	0.66	1.56	0.66	0.22	0.49
	B	0.95	0.30	0.78	1.02	0.35	0.91	0.09	0.02	0.06	0.82	0.17	0.40
	C	0.58	0.24	0.58	0.71	0.29	0.72	0.05	0.02	0.04	0.36	0.12	0.29
	D	1.08	0.42	1.06	1.30	0.50	1.27	0.11	0.03	0.08	0.96	0.23	0.55
	E	5.15	1.14	2.82	6.33	1.34	3.25	1.02	0.54	1.19	0.56	0.21	0.47
	F	5.15	1.14	2.82	6.33	1.34	3.25	1.02	0.54	1.19	0.56	0.21	0.47
	G	5.15	1.14	2.82	6.33	1.34	3.25	1.02	0.54	1.19	0.51	0.21	0.47
LM II (loading model II)	SS	AISC [4]			SCI [5]			Faisca [6]			Biodynamic [7]		
		a_{peak}	$a_{w,rms}$	VDV	a_{peak}	$a_{w,rms}$	VDV	a_{peak}	$a_{w,rms}$	VDV	a_{peak}	$a_{w,rms}$	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	0.94	0.30	0.78	1.03	0.35	0.90	0.09	0.03	0.07	0.34	0.12	0.29
	B	5.85	1.33	3.01	5.89	1.44	3.28	1.17	0.68	1.63	0.53	0.14	0.32
	C	0.94	0.30	0.78	1.03	0.35	0.90	0.09	0.03	0.07	0.35	0.14	0.32
	D	6.14	1.80	4.03	6.74	2.17	4.73	1.48	0.90	2.06	0.73	0.20	0.45
	E	0.91	0.30	0.78	1.13	0.35	0.90	0.11	0.03	0.07	0.32	0.12	0.29
	F	0.91	0.30	0.78	1.13	0.35	0.90	0.11	0.03	0.07	0.32	0.12	0.29
	G	0.91	0.30	0.78	1.13	0.35	0.90	0.11	0.03	0.07	0.32	0.12	0.29
LM III (loading model III)	SS	AISC [4]			SCI [5]			Faisca [6]			Biodynamic [7]		
		a_{peak}	$a_{w,rms}$	VDV	a_{peak}	$a_{w,rms}$	VDV	a_{peak}	$a_{w,rms}$	VDV	a_{peak}	$a_{w,rms}$	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	0.58	0.24	0.58	0.71	0.29	0.72	0.05	0.02	0.04	0.32	0.10	0.24
	B	0.95	0.30	0.78	1.02	0.35	0.91	0.09	0.02	0.06	0.60	0.14	0.35
	C	6.20	1.31	3.02	6.21	1.30	3.18	1.10	0.66	1.56	0.81	0.25	0.57
	D	1.08	0.42	1.06	1.30	0.50	1.27	0.11	0.03	0.08	0.84	0.20	0.48
	E	0.67	0.24	0.58	0.80	0.29	0.72	0.05	0.02	0.04	0.32	0.10	0.24
	F	0.67	0.24	0.58	0.80	0.29	0.72	0.05	0.02	0.04	0.32	0.10	0.24
	G	0.67	0.24	0.58	0.80	0.29	0.72	0.05	0.02	0.04	0.32	0.12	0.29
Tolerance peak acceleration: 0.5 m/s^2 AISC [4]													
Limits: $a_{w,rms}$<0.35 m/s^2 SCI [5]; VDV<0.50 $m/s^{1,75}$ Setareh [13] and VDV<0.66 $m/s^{1,75}$ Ellis & Littler [14].													

7 Conclusions

This investigation consists of the evaluation dynamic structural behaviour of a steel-concrete composite floor subjected to dynamic loads produced by 20 people practising aerobics and verify the occurrence of excessive vibration and also assess human comfort. For future works, the authors suggest relocating the area used for aerobics for other places on the floor to analyse if this change reaches the human comfort criteria from the standards and also focus on the development of several forced vibration experimental tests on real structures to calibrate and validate the numerical modelling. Based on the obtained results, the authors conclude that:

1. The numerical fundamental frequency (f_{01N} = 5.60 Hz) is below the minimum value (f_{min} = 9.6 Hz) of the Brazilian Association of Technical Standards [12], indicating a tendency to human discomfort;
2. The maximum dynamic responses were obtained in the structural sections where the load was applied and high response values were observed in adjacent sections. Thus, even maintaining the same people number and just changing its location (LM I, LM II and LM III), it can be observed the influence of floor modal parameters, which has a direct impact on the structural response;
3. Based on human comfort criteria determined by SCI [5], Setareh [13] and Ellis and Littler [14], the biodynamic model is the only which presents dynamic responses that reached these standards limits ($a_{w,rms}$ and VDV) in all investigated loading model cases. On the other hand, the four applied load models present peak acceleration higher than the standard proposed by AISC ($a_{peak} \leq 0.50$ m/s²) [4], resulting in discomfort for its users.

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