Human comfort assessment of floors subjected to dynamic loading induced by people groups

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Abstract. This research work aims to investigate the dynamic structural behaviour and evaluate the human comfort of steel-concrete composite floors when subjected to loads induced by rhythmic human activities in places such as fitness centres, event halls and offices. The investigated structural model is characterised by a steel-concrete composite floor of a commercial building used for aerobics, which presents dimensions of 40m x 40m and a total area of 1,600m². The dynamic loads were obtained through the use of traditional mathematical models associated to "only force" and also based on the use of biodynamic systems, aiming to incorporate the human-structure interaction dynamic effect to assess the human comfort. The floor numerical model was developed based on usual modelling techniques, adopting the mesh refinement present in the Finite Element Method (FEM), and implemented in the computer program ANSYS. The dynamic structural response (displacements and accelerations) was determined through the investigation of several dynamic loading models related to people groups practising rhythmic activities on the floor concrete slab. Finally, based on the dynamic structural response (peak acceleration), the results were compared with the floor project serviceability limits, indicating that the maximum peak acceleration values surpass the design criteria, causing excessive vibration and human discomfort.

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

1 Introduction

Nowadays, there is an expansion of building projects with bold and modern architectures. In this context, the utilisation of structural systems related to steel-concrete composite floors stands out, with the aim of optimizing execution time and flexibility in terms of the final use. On the other hand, it should be noted that this construction method can directly influence the floor structural response due to the composite system's dynamic properties when subjected to human activities because of the tendency to lower natural frequencies and natural damping (with weight reduction).

In this sense, the problem associated with this excessive vibration occurs in fitness centres, events halls and offices, according to works dos Santos [1]. Therefore, this research work aims the assessment the dynamic structural behaviour of a steel-concrete composite floor, measuring 40m x 40m, with a total area of 1,600m² when subjected to human activities and to evaluation human comfort.

The study considers the dynamic loads representing human rhythmic activities based on the use of traditional "only force" models and also the mathematical formulation associated to the biodynamic systems. The traditional models can be found in the guides AISC [2] and SCI [3] and the research work developed by Faisca [4]. On the other hand, having in mind the most realistic representation of the human rhythmic activities, the biodynamic systems modelling is based on the dynamic properties of each individual [5].

This way, having in mind the mathematical modelling of the rhythmic human activities, the investigated composite floor's dynamic response (displacements and accelerations) was calculated in the time and frequency domain, and after that, the maximum values were compared with human comfort recommended limits established by traditional design criteria [2-3]. It must be emphasized that, based on the results obtained in this investigation, it can be concluded that the studied composite floor is susceptible to excessive vibrations and human discomfort.

2 Dynamic loading models: only-force

In this study, the analysis methodology consists of mathematically formulating these models, considering the investigated composite floor dynamic characteristics. This way, the parameters used to formulate the dynamic loading models (only force modes) are the step frequency (f = 2.20 Hz), the person's weight (P = 800 N), and the total number of participants (48 people). It must be emphasised that the only force models [3-5] don't consider the human-structure dynamic interaction effect, and the dynamic loads are applied directly on the concrete slab floor.

The Faisca [4] model was based on experimental tests carried out in the laboratory and performed by peoples's groups. Throughout the experiment, the impacts of a platform subjected to human rhythmic jumps as a function of time were monitored. The mathematical formulation was based on the use of the Hanning function, expressed in Eq. (1). Where F(t) represents the dynamic force in (N); CD is the lag coefficient; Kp is the impact coefficient; Tc is the contact period of the activity in (s); T is the activity period in (s), and t is the time in (s).

$$F(t) = CD\left\{K_P\ P\left[0.5\text{-}0.5\cos\left(\frac{2\pi}{T_c}t\right)\right]\right\},\ t \leq T_c \ \text{ or } \ F(t) = 0,\ T_c \leq t \leq T \tag{1}$$

The present "only force" model from SCI [3] was developed based on experimental tests considering groups of individuals performing rhythmic activities on the test structure. It is noteworthy that the parameters used in this model are related to the number of participants performing human rhythmic activities on the floor, as presented in Eq. (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; rn,v is the Fourier coefficient induced by v people; ϕn is the phase difference; fp is the load frequency, and t is the time in (s).

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

The mathematical model proposed by AISC [2] Design Guide recommendations utilizes three harmonics associated with the excitation frequency due to dynamic human actions, considering a dynamic coefficient for each harmonic, according to Eq. (3). 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_p is the step frequency in (Hz), and t is the time in (s).

$$F(t) = Q + \left\{\sum_{i=1}^{N} \alpha_i\ Q\sin\left(2\pi f_p t+\phi_i\right)\right\} \tag{3}$$

3 Modelling of the biodynamic systems

Hand having in mind a more realistic representation of the rhythmic human activities, biodynamic systems modelling is considered in this research work due to the fact that it is based on the dynamic properties of each individual. This way, Campista [5] formulated a biodynamic model considering a single degree of freedom [6] (SDOF), consisting of a mass-spring-damper system (see Fig. 1). The people's dynamic properties were determined based on several experimental tests, considering the individuals jumping on a developed dynamic load platform. After that, using a data acquisition system, the dynamic response of each individual (acceleration and dynamic force) was determined based on the use of accelerometers placed on the individuals' body and load cells located under the load platform. This way, the biodynamic system variables used to model each person (SDOF) were determined considering the solution of the dynamic equilibrium equation and the classical optimization problem through the use of genetic algorithms (GA), as presented in Eq. (4) to (6).

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

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

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

In Equations (4) to (6) $F_i(t)$ is the dynamic force in (N); k_i is the stiffness in (N/m); m_i is the mass in (kg); c_i is the damping in (Ns/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/s^2); f_i is the frequency in (Hz); ξ is the damping coefficient, considered equal to 0.25 [5] in this work.

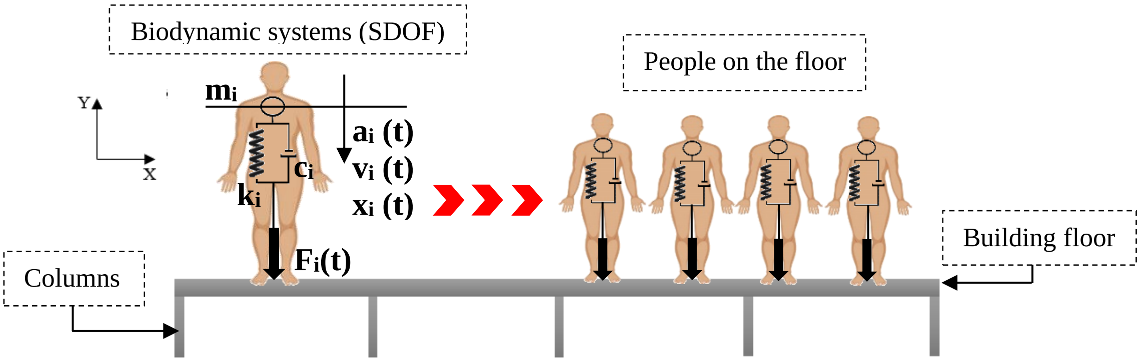
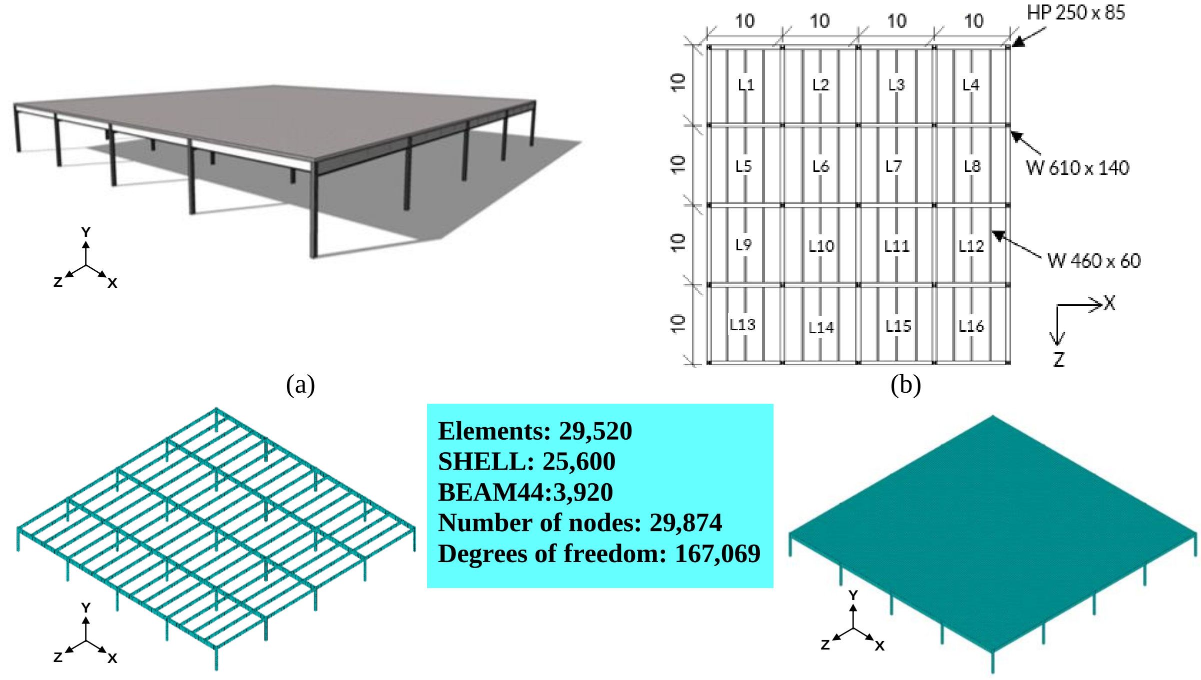


Figure 1. Modelling of biodynamic systems (SDOF).

4 Structural model and finite element modelling

The investigated steel-concrete composite floor represents a typical interior floor of a commercial building used for aerobics. The composite floor presents dimensions of 40 m x 40 m and a total area of 1,600 m², divided in 16 panels of concrete slabs with a thickness equal to 10 cm. The columns height is equal to 4m. In this context, it is worth mentioning that the steel-concrete composite floor is formed by three types of laminated profiles: steel columns: HP250x85; composite beams: W610x140 and W460x60, as illustrated in Fig. 2(a) and Fig. 2(b). Regarding the materials physical properties, the concrete has a compressive strength equal to 26 MPa, modulus of elasticity equal to 31.7 GPa, Poisson's ratio equal to 0.2 and a specific weight of 25 kN/m³. The steel presents a stress steel grade of 345 MPa, Young's modulus of 205 GPa, Poisson's ratio 0.3 and specific weight of 78.5 kN/m³.

The computational modelling of the structural model was developed based on the finite element method through ANSYS [7] software. In this numerical model, finite shell elements SHELL63 were used to represent the reinforced concrete slab, while for the composite beams and steel columns, the three-dimensional element BEAM44 was adopted. The beam-column and beam-beam connections were modelled using the finite elements COMBIN39 and COMBIN7, respectively. The floor finite element model is illustrated in Fig. 2(c) and Fig. 2(d).



Elements: 29,520
SHELL: 25,600
BEAM44:3,920
Number of nodes: 29,874
Degrees of freedom: 167,069

(a) (b)

(c) (d)

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

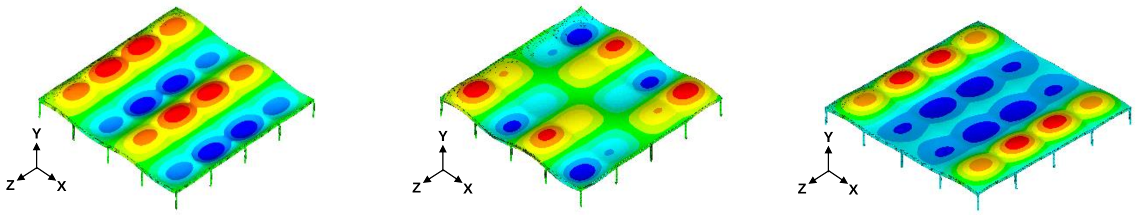
5 Modal analysis

The natural frequencies (eigenvalues) and vibration modes (eigenvectors) of the empty composite floor were determined using the ANSYS [7] computer program based on free vibration analysis. The first six natural frequencies and their respective modal mass, modal stiffness, and modal damping values associated with each vibration mode are presented in Table 1. Fig. 3 presents the first six modes of vibration of the structural model associated with their respective natural frequencies.

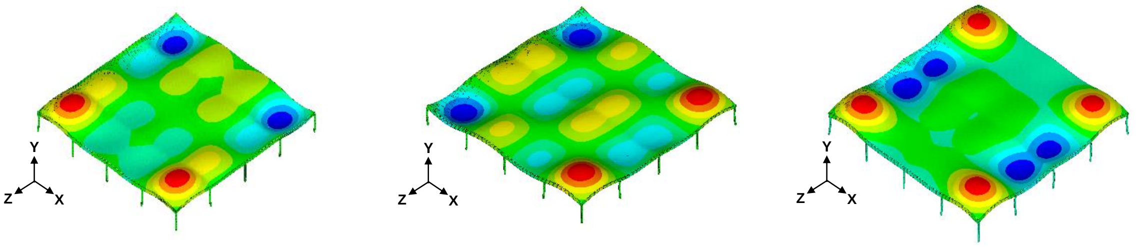
Table 1. Studied composite floor dynamic characteristics.

Frequency (Hz)		Modal mass (kg)	Modal stiffness (N/m)	Modal damping (Ns/m)
f_{01}	6.21	118896.06	1.81×10^8	9.28×10^4
f_{02}	6.51	90656.22	1.52×10^8	7.42×10^4
f_{03}	6.60	73780.97	1.27×10^8	6.12×10^4
f_{04}	6.81	52552.65	9.62×10^7	4.51×10^4
f_{05}	7.07	62172.95	1.23×10^8	5.55×10^4
f_{06}	7.19	59858.58	1.22×10^8	5.45×10^4

The fundamental numerical frequency of this composite floor is within the bounds of the third harmonic frequency range proposed by Faisca [4] (5.66 to 8.57 Hz) and the proposed by Ellis and Ji [8] (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 [10]. These facts show that the studied structure presents the susceptibility to a resonance phenomenon.



a) 1° Mode shape (f_{01} = 6.21 Hz). b) 2° Mode shape (f_{02} = 6.51 Hz). c) 3° Mode shape (f_{03} = 6.60 Hz).

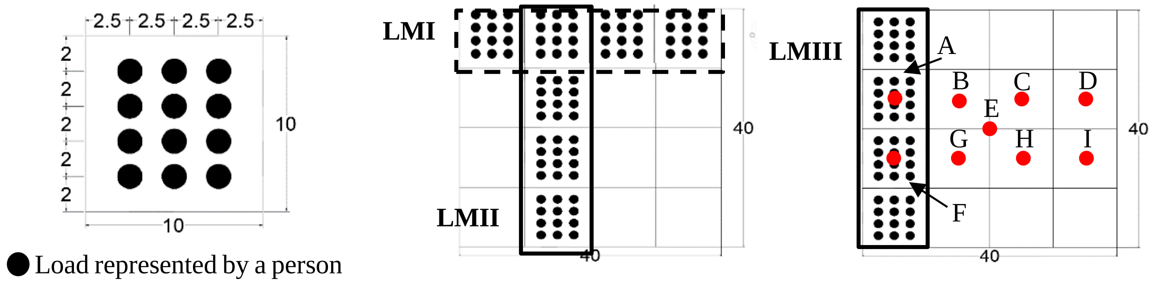


d) 4° Mode shape (f_{04} = 6.81 Hz). d) 5° Mode shape (f_{05} = 7.07 Hz). d) 6° Mode shape (f_{06} = 7.19 Hz).

Figure 3. Composite floor vibration modes.

6 Forced Vibration Analysis

In this research work, the composite floor dynamic response was calculated considering the dynamic loads related to 48 people practising aerobics on the concrete slabs. This load was applied in the structure based on traditional "only force" models, AISC [2], SCI [3] and Faisca [4] and based on biodynamic systems proposed by Campista [5]. The considered person's weight was 800 N, and the step frequency was 2.20 Hz. This way, three dynamic loading situations were assessed (LMI, LMII and LM III), where the number of people (48 individuals) in each model remained constant, but the people were arranged on different concrete slabs panels, see Fig 4 (b) and Fig. 4 (c). Moreover, Fig. 4 (a) shows the details of the dynamic loadings applied on each concrete slab panel [12 people x 4 panels = 48 people].

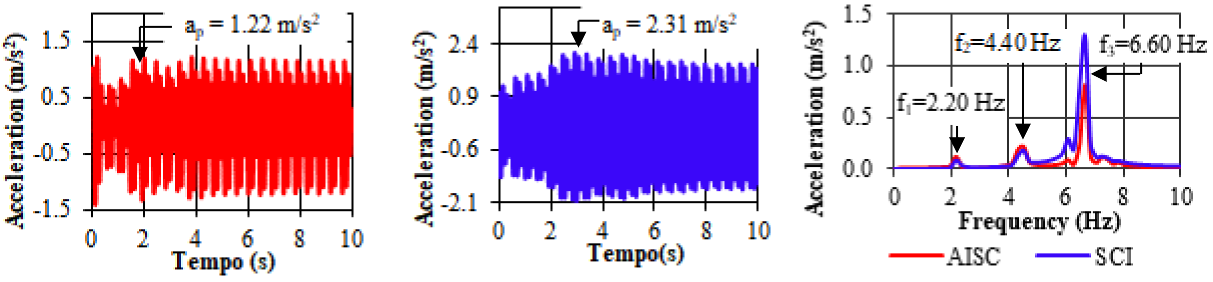


(a) (b) (c)

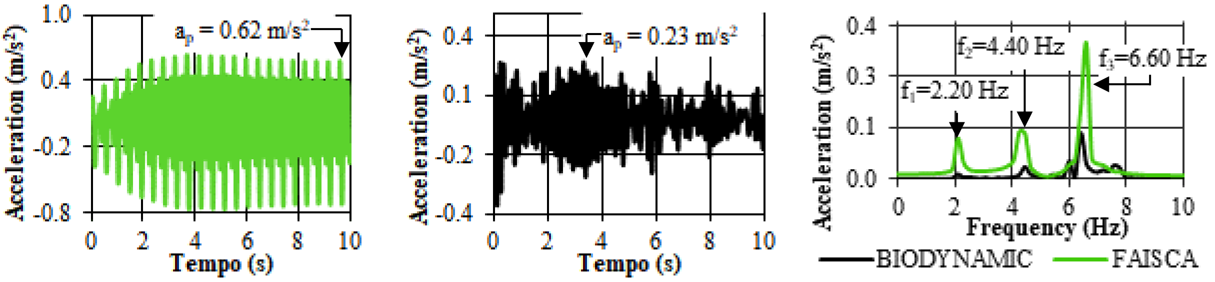
Figure 4. Load detail (a); Dynamic loading situations (units in metres).

Initially, the dynamic structural response values were calculated on the floor structural sections located in the regions of maximum and minimum modal amplitudes (A to I), as illustrated in Fig. 4(c). Considering the human comfort criterion ($a_{p,lim}$ < 0.5 m/s² [3]) it was verified that the peak accelerations values calculated based on the use of the load models proposed by AISC [2] and SCI [3] had surpassed the acceleration limit in all analysed situations. However, the mathematical model developed by Faisca [4] induced peak accelerations that violated the proposed limit only when the LM III was considered in the analysis, see Table 2. On the other hand, when the biodynamic systems [5] were used to model the dynamic loads, the dynamic floor response (peak accelerations values) are in accordance with the human comfort criterion ($a_{p,lim}$ < 0.5 m/s² [3]), due to the fact that the biodynamic modelling considers the people-structure dynamic interaction effect in a more realistic way and also incorporates the people damping, causing a reduction of the dynamic structural response.

Regarding the floor rms accelerations ($a_{w,rms}$) and vibration dose values (VDV), Table 2 present the dynamic response calculated only for the most relevant critical sections when the LM III was investigated. This way, it is possible to verify that only force models [2-4] have produced dynamic response levels that violate the VDV limit [10]. Nevertheless, only the rms accelerations determined based on the use of the SCI [3] model surpass the allowed value for $a_{w,rms}$ [3]. In this sense, the Fig. 5(a), Fig. 5(b), Fig. 5 (d) and Fig. 5 (e) present the floor dynamic structural response in the time domain [LM-III: section A] for models AISC [2], SCI [3], Faisca [4] and biodynamic [5], respectively. As well as Fig. 5 (c) and Fig. 5 (f) present the dynamic response in the frequency domain [LM III: section A].



(a) Time domain AISC [2]. (b) Time domain SCI [3]. (c) Frequency domain AISC [2] and SCI [3].



(d) Time domain Faisca [4]. (e) Time domain Biodynamic [5]. (f) Frequency domain Biodynamic [5] and Faisca [4].

Figure 5. Dynamic response of critical section A for LM III in the time(a,b,d,e) and frequency (c,f) domain.

In addition, it is possible to check that Fig. 5 (c) and 5 (f) present multiple energy transfer peaks in frequency domain, associated to the excitation frequency (f = 2.20 Hz). It is important to emphasize that the largest amplitude (energy transfer peaks) related to the displacements and accelerations occur when the third harmonic of the excitation frequency (f = 3 x 2.20 Hz) is equal to the third floor natural frequency (f_{03} = 6.60 Hz), representing the resonance. It is also possible to verify that the dynamic loading function proposed by the SCI [3] presents the highest energy transfer peak on the floor dynamic response.

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

	SS	AISC [2]			SCI [3]			Faisca [4]			Biodynamic [5]		
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	0.72	0.18	0.42	0.67	0.26	0.56	0.20	0.10	0.18	0.18	0.07	0.16
	B	0.59	0.15	0.35	0.45	0.18	0.37	0.09	0.05	0.08	0.01	0.01	0.01
	C	0.39	0.10	0.23	0.38	0.15	0.32	0.10	0.05	0.09	0.12	0.04	0.10
	D	0.72	0.18	0.42	0.67	0.26	0.56	0.20	0.10	0.18	0.19	0.07	0.17
	E	0.02	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.02
	F	0.43	0.11	0.26	0.70	0.27	0.58	0.19	0.09	0.17	0.12	0.04	0.10
	G	0.59	0.15	0.35	0.45	0.18	0.37	0.09	0.05	0.08	0.11	0.04	0.09
	H	0.29	0.07	0.17	0.22	0.08	0.18	0.07	0.04	0.07	0.01	0.01	0.01
	I	0.43	0.11	0.25	0.70	0.27	0.58	0.19	0.09	0.17	0.01	0.01	0.01
LM II (loading model II)	SS	AISC [2]			SCI [3]			Faisca [4]			Biodynamic [5]		
		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	0.90	0.23	0.53	1.13	0.44	0.94	0.33	0.16	0.35	0.18	0.06	0.16
	B	1.06	0.26	0.62	1.03	0.40	0.86	0.25	0.12	0.26	0.10	0.04	0.09
	C	1.05	0.26	0.62	1.04	0.41	0.86	0.24	0.11	0.25	0.09	0.03	0.08
	D	0.69	0.17	0.41	0.82	0.32	0.68	0.15	0.07	0.16	0.08	0.03	0.07
	E	0.04	0.01	0.02	0.04	0.02	0.03	0.01	0.01	0.01	0.01	0.01	0.01
	F	0.86	0.22	0.51	1.10	0.43	0.91	0.32	0.15	0.34	0.10	0.04	0.09
	G	0.76	0.19	0.45	0.81	0.32	0.67	0.15	0.07	0.16	0.01	0.01	0.01
	H	0.13	0.03	0.08	0.15	0.06	0.12	0.04	0.02	0.05	0.01	0.01	0.01
	I	0.66	0.16	0.39	0.82	0.32	0.68	0.15	0.07	0.16	0.07	0.03	0.06
LM III (loading model III)	SS	AISC [2]			SCI [3]			Faisca [4]			Biodynamic [5]		
		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	1.22	0.31	0.72	2.31	0.83	1.77	0.62	0.29	0.67	0.23	0.09	0.21
	B	0.87	0.22	0.51	1.19	0.47	0.99	0.35	0.16	0.37	0.32	0.12	0.28
	C	0.87	0.22	0.51	1.19	0.47	0.99	0.35	0.16	0.37	0.21	0.08	0.18
	D	1.01	0.25	0.59	1.67	0.65	1.38	0.42	0.19	0.45	0.30	0.12	0.27
	E	0.03	0.01	0.02	0.06	0.02	0.05	0.02	0.01	0.02	0.02	0.01	0.01
	F	1.22	0.31	0.72	2.13	0.83	1.77	0.63	0.29	0.67	0.30	0.12	0.27
	G	0.66	0.17	0.39	0.89	0.35	0.74	0.16	0.07	0.16	0.09	0.04	0.08
	H	0.13	0.03	0.08	0.21	0.08	0.17	0.05	0.02	0.05	0.03	0.01	0.02
	I	1.01	0.25	0.59	1.68	0.65	1.39	0.42	0.19	0.45	0.27	0.11	0.24
Tolerance peak acceleration: 0.5 m/s^2 AISC [2]													
Limits: $a_{w,rms}$<0.35 m/s^2 SCI [3]; VDV<0.50 $m/s^{1,75}$ Setareh [10] and VDV<0.66 $m/s^{1,75}$ Ellis & Littler [11].													

7 Conclusions

The main conclusions obtained in this research work aim to alert the structural engineers to the possible variations associated with the steel-concrete composite floor dynamic structural response and human comfort assessment, when subjected to rhythmic human activities, through different mathematical formulations are used to calculate the dynamic loads.

1. The modal analysis shows that the composite floor fundamental frequency (f_{01} = 6.21 Hz) is lower than the minimum value (f_C = 9.60 Hz) recommended by the Brazilian design standard NBR 6118 [9]. Moreover, this value is in the range of the human excitation frequency, indicating a tendency of excessive vibration and human discomfort. The floor dynamic structural response assessment indicated that the only force loading models (AISC [2], SCI [3] and Faisca [4]) have induced higher levels of displacements and accelerations than the biodynamic systems [5]. This fact is associated to the difference between the mathematical models formulation, especially the biodynamic systems that incorporate the people's dynamic characteristics (mass, stiffness and damping).

2. The dynamic loading model proposed by SCI [3] produced the highest impacts on the floor dynamic response. The forced vibration analysis indicated the maximum values [LM III: section A]: peak accelerations (a_p = 2.31 m/s²), rms accelerations ($a_{w,rms}$ = 0.83 m/s²) and VDV values (VDV = 1.77 $m/s^{1.75}$). On the other hand, when the biodynamic modelling was considered on the floor dynamic analysis the following results were obtained [LM III: section A]: peak accelerations (a_p = 0.23 m/s²), rms accelerations ($a_{w,rms}$ = 0.09 m/s²) and VDV values (VDV = 0.21 $m/s^{1.75}$).

3. Based on the criteria proposed by the AISC [2], it can be stated that in all evaluated situations (LM I to LM III) the peak accelerations limit was surpassed, causing human discomfort. On the other hand, based on the design criteria for rms accelerations [3] and VDV [10], the limit values were exceeded in the situations LM II and LMIII, for the AISC [2] and SCI [3] models, as well as LMIII load model, except when the biodynamic systems were considered in investigation [5].

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