Vibration analysis and human comfort assessment of composite floors subjected to dynamic loads induced by groups of people

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Abstract. This research works aims to assess the human comfort and study the structural behaviour of steel-concrete composite floors subjected to dynamic loadings induced by rhythmic human activities. In this paper, the analysed structural system corresponds to a steel-concrete composite floor with dimensions of 40m x 40m and total area of 1600m². The structure represents a typical interior floor of a commercial building commonly used for aerobics. The dynamic loadings were obtained through the use of traditional "only force" mathematical models, and also based on the consideration of biodynamic systems, in order to incorporate the human-structure interaction dynamic effect to assess the floor dynamic response. This way, the finite element model of the floor was developed based on the use of modelling techniques, adopting the mesh refinement present in the Finite Element Method (FEM) and implemented in the ANSYS software. The floor dynamic response, analysed based on the displacements and accelerations values, was determined through the investigation of several dynamic load models considering groups of people practicing rhythmic activities on the concrete slabs. Finally, it was concluded that the displacements and accelerations values have surpassed the design criteria recommended limits indicating that the floor human comfort was violated, inducing excessive vibrations and human discomfort.

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

1 Introduction

In recent years, there has been a significant increase in reported cases of excessive vibrations in building floors, particularly in structures that accommodate physical human activities such as those found in commercial or residential buildings [1, 2]. This phenomenon can be related to the multifunctionality of modern building projects, which often involve the adaptation of structures originally designed for different purposes, coupled with advancements in materials leading to the use of lighter and more resilient components.

The investigation of steel-concrete composite floors under the effect of rhythmic human activities, such as gyms, dance floors, or stadium grandstands, represents a complex challenge, particularly due to the relevance of cost-effective structural designs that often result in increasingly slender and flexible systems. In this context, excessive vibrations on building floors can occur due to the proximity between the excitation frequencies values, associated to rhythmic human activities, and the floors natural frequencies values, inducing resonance, amplifying the vibrations and also causing discomfort for building occupants.

Buildings floors with large spans are particularly susceptible to the resonance, as the users are more sensitive to vibrations within the frequency range between 4Hz to 8Hz. The combination of rhythmic human activities and the dynamic characteristics of steel-concrete composite floors further exacerbate the resonant behaviour, posing potential risks to the human comfort of the building occupants.

This way, this research work aims to assess the dynamic structural behaviour of a steel-concrete composite floor with dimensions of 40m x 40m and total area of 1600m². To do this, in this paper several mathematical formulations related to traditional dynamic loading models [3-5] (only force models) are considered to determine the floor dynamic response (displacements and accelerations) in time and frequency domain. On the other hand, biodynamic systems [2] are utilised to investigate the people-structure dynamic interaction, taking into account the dynamic characteristics of the individuals (mass, damping and stiffness), aiming to enable a more realistic human comfort assessment. Based on the calculated displacements and accelerations maximum values, and having in mind comparisons with recommended human comfort limits [5-7], it was concluded that the floor human comfort was violated, inducing excessive vibrations and human discomfort to the building occupants.

2 Mathematical modelling of the rhythmic human activities

In this research, the dynamic loadings were calculated based on the use of several traditional load models (only force models) proposed by Faisca [3], SCI [4], and AISC [5]. It is important to emphasize that these dynamic load models [3-5] do not consider the people-structure dynamic interaction effect, and the loads are applied directly on the concrete slabs. The dynamic loading model developed by Faisca [3] was formulated based on experimental tests considering the Hanning function. This way, eq. (1) represents the parameters considered in this mathematical model, such as the influence of the human activity impact on the structure.

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

The mathematical model proposed by SCI [4] 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 mathematical model are related to the number of participants performing human rhythmic activities on the floor, as shown in eq. (2).

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

The dynamic loading model proposed by AISC [5] recommendations utilises three harmonics associated with the excitation frequency due to human dynamic actions, considering a dynamic coefficient for each harmonic, according to eq. (3).

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

Considering the eq. (1) to eq. (3), it must be emphasized that 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), the CD is related to the lag coefficient; K_p is the impact coefficient; T_c is the activity contact period in (s), and T is the activity period in (s). 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 Equation (3), α_i represents the dynamic coefficient, and i is the harmonic number.

3 Modelling of the biodynamic systems

Several authors have developed works highlighting the relevance of biodynamic systems, aiming to take into account the dynamic properties associated to each individual to achieve a more realistic representation of the people-structure dynamic interaction and the modelling of the human rhythmic activities [1-2, 8].

Campista [2] proposed a biodynamic model based on a single degree of freedom (SDOF) system (mass-spring-damper system: see Fig. 1). The dynamic properties of the individuals were obtained through several experimental tests, where the individuals performed jumps on a dynamic load platform. The analysis methodology provided the individual's acceleration and the dynamic force. The biodynamic systems parameters were calculated based on the dynamic equilibrium equation solution and the optimization problem [2] [see eq. (4) to eq. (8)]. The optimization objective function is the function on the decision variables to be minimized (F_{obj}) [see eq. (5)]. The individual experimental and optimized forces were mathematically correlated [see eq. (6)], and the experimental and the optimized forces are calculated trough eq. (7) and eq. (8).

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

$$F_{obj} = 1 - (corr\_1^2) \tag{5}$$

$$coor\_1 = corr(F_d, F_{d1}) \tag{6}$$

$$F_{d1} = F_{exp} - m\ acelfpa1 \tag{7}$$

$$F_d = x(1)\ velfpa1 + x(2)\ delsfpa1 \tag{8}$$

Concerning the parameters presented in eq. (4) to eq. (8); $F_{i(t)}$: force produced by the individual i (N); m_i (kg); c_i (Ns/m); k_i (N/m): mass, damping and stiffness of the individual i, respectively; $a_i(t)$ (m/s²); $v_i(t)$ (m/s); $x_i(t)$ (m): acceleration; velocity and displacement of the individual i, respectively; F_{obj}: function object; corr_1: correlation between forces (F_d, x F_{d1}); F_{d1}(N): experimental force of the individual i, excluding the parcel referring to the acceleration multiplied by mass; F_{exp} (N): experimental force of the individual i; m (kg): mass of each person; acelfpa1(m/s²); velfpa1(m/s); deslfpa1(m): experimental acceleration, experimental velocity and experimental displacement of the individual i, respectively; F_d (N): optimized force of the individual i; x(1) (Ns/m): optimized damping of the individual i; x(2) (N/m): optimized stiffness of the individual i.

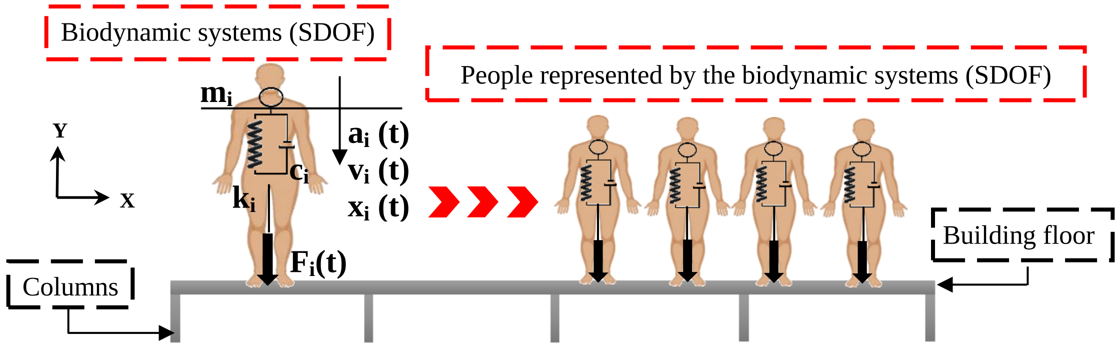
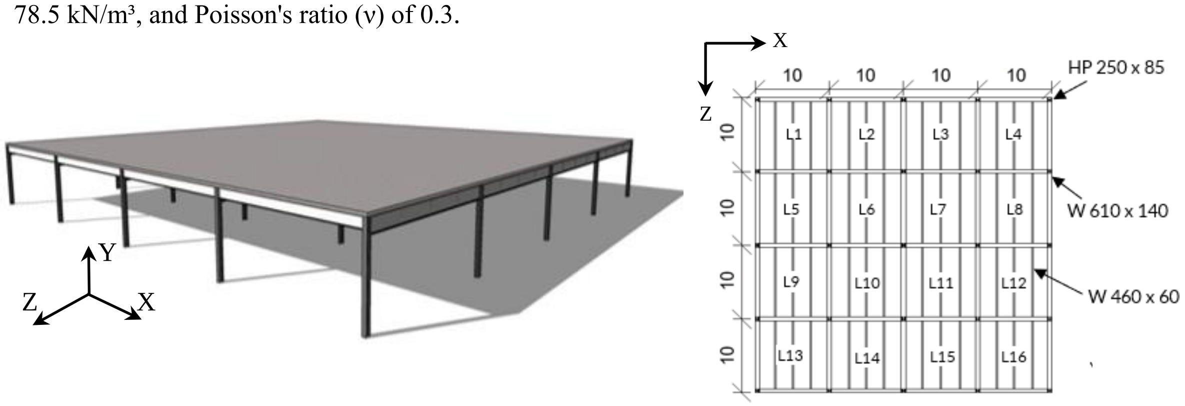


Figure 1. Modelling of the biodynamic systems (SDOF).

4 Investigated structural model and finite element modelling

The investigated steel-concrete composite floor presents dimensions of 40m x 40m and total area of 1600 m². The floor is composed of concrete slab panels with a thickness of 10 cm and steel columns and beams, as shown in Fig. 2. The columns are med of profiles of HP250x85 type with 4m length, while the composite beams use profiles W610x140 and W460x60. Regarding the model physical properties, the concrete presents longitudinal elastic modulus of 31.7 GPa, density of 25 kN/m³, compressive strength of 30 MPa, and Poisson's ratio (ν) of 0.2. The steel has a Young's modulus of 205 GPa, stress steel grade of 345 MPa, specific weight of 78.5 kN/m³, and Poisson's ratio (ν) of 0.3.



(a) Three-dimensional view (b) Top view

Figure 2. Investigated structural model.

The floor finite element model was developed based on the use of the ANSYS [9] software. This way, the shell finite elements (SHELL63) were used to simulate the reinforced concrete slabs behaviour. Additionally, three-dimensional beam finite elements (BEAM44) were utilized to represent the composite beams and the steel columns. The floor structural connections between beams and columns were modelled using the spring finite elements (COMBIN39 and COMBIN7) for beam-to-column and beam-to-beam connections, respectively, aiming a proper representation of the connections. The floor finite element model is illustrated in Fig. 3.

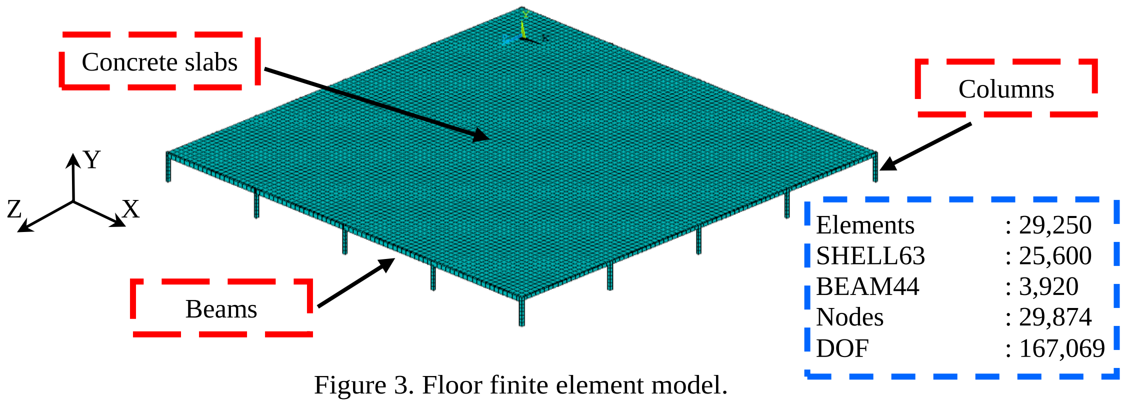
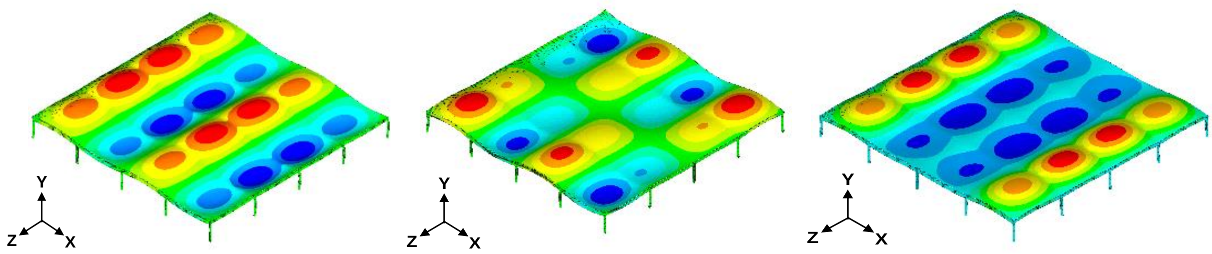


Figure 3. Floor finite element model.

5 Numerical modal analysis

The natural frequencies (eigenvalues) and vibration modes (eigenvectors) of the floor were determined based on a free vibration analysis (modal analysis) through the use of the ANSYS [9] software. The investigated first six floor vibration modes presented predominance of flexural behaviour (see Fig. 4). The numerical analysis carried out by Santos [1] has shown that the composite floor fundamental frequency f_{01} is equal to 6.21 Hz. It is important to emphasize that based on the Brazilian design code NBR 6118 [10] recommendations, this frequency value should be higher than the critical frequency value, in this situation, equal to 9.60 Hz ($f_C = 1.2 \times 8.0$ Hz) [$f_{01} = 6.21$ Hz $< f_C = 9.60$ Hz: rhythmic human activities].



(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)

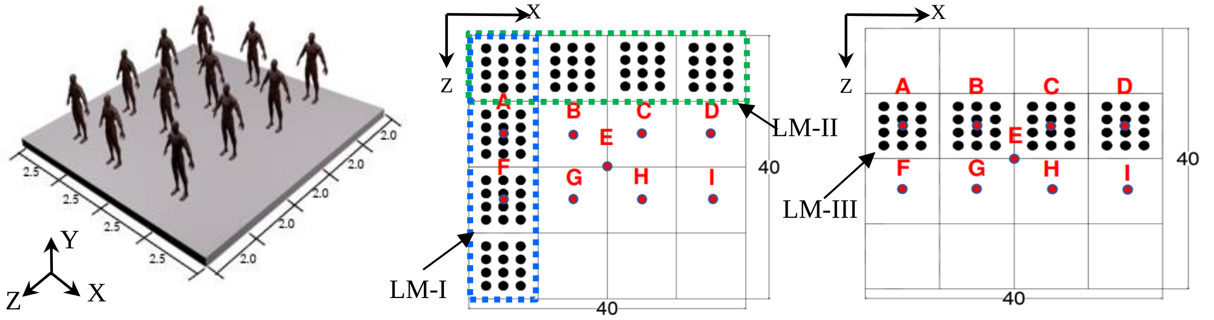
Figure 4. Steel-concrete composite floor vibration modes.

Furthermore, it is also noteworthy that the floor fundamental frequency ($f_{01} = 6.21$ Hz) is in the dynamic excitation frequency range (human rhythmic activities), of the second and the third harmonics, according to the ranges defined by Faisca [3] (5.66 to 8.57 Hz), and Ellis and Ji [7] (4.5 to 8.4 Hz), respectively. Thus, based on the modal analysis results, initially, it can be concluded that the investigated floor can be susceptible to excessive vibration and human discomfort.

6 Forced vibration analysis

The forced vibration analyses were conducted on the floor subjected to rhythmic human activities induced by 48 people, based on the use of three load cases (LM-I, LM-II, and LM-III), see Fig. 5. The dynamic analysis was performed utilising mathematical functions representing human rhythmic actions through traditional "only force" models (Faisca [3], SCI [4], and AISC [5]) and biodynamic systems [2]. The parameters used in the loading models ("only force" models) were: step frequency (f = 2.20 Hz) and person's weight (P = 800 N).

This way, the evaluation of human comfort criteria was achieved by assessing the dynamic response (a_p: peak accelerations; $a_{w,rms}$: RMS accelerations and VDV: vibration dose values) calculated on the floor's structural sections (SS: sections A to I) subjected to the "Loading Model I" (LM-I), "Loading Model II" (LM-II), and "Loading Model III" (LM-III). Thus, Fig. 5 provided the details related to the dynamic load distribution applied to each concrete slab panel, with 12 individuals per panel, resulting in a total of 48 people distributed across four panels (12 people x 4 concrete slab panels = 48 people).

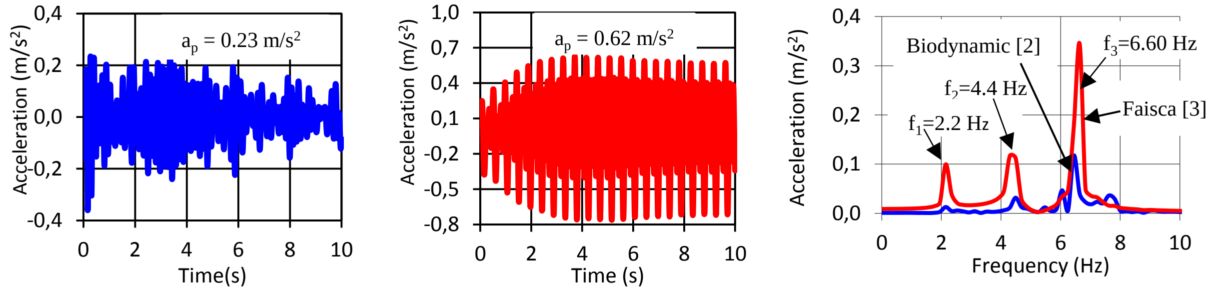


(a) Load details (slab) (b) LM-I and LM-II (C) LM-III

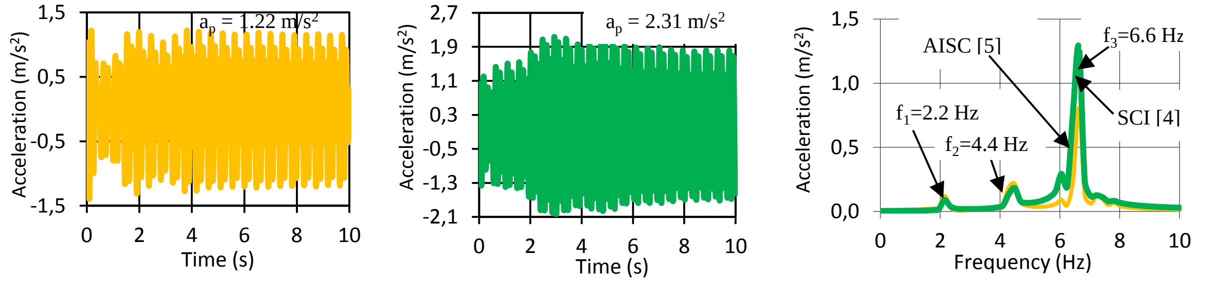
Figure 5. Dynamic loading induced by people on the concrete floor slabs (units in metres).

Based on the dynamic structural response of the floor (LM-I, LM-II, and LM-III), it was observed that the “only force” models have produced higher dynamic responses when compared to those associated to the biodynamic systems (see Tab. 1). The peak acceleration values calculated based on the use of the SCI [4] and AISC [5] models exceeded the recommended limit ($a_{p,lim}$ < 0.5 m/s² [5]) in all analysed scenarios. However, the Faisca [3] model surpassed the limit only considering the LM I scenario with a peak acceleration of 0.62 m/s² (SS-A) (see Tab. 1). On the other hand, when the biodynamic systems [2] were utilised, the floor dynamic response (peak acceleration values) attended the human comfort criterion. This discrepancy can be attributed to the differences in the formulation of the mathematical models, due to the fact that the biodynamic systems take into account the dynamic characteristics of different individuals (mass, damping and stiffness), providing a more accurate representation of the floor’s behaviour under rhythmic human activities (see Tab. 1).

Moreover, based on the RMS accelerations criterion, only the results provided by SCI [4] model surpassed the human comfort limit, reaching a maximum value of 0.83 m/s² (LM-I: $a_{w,rms}$ = 0.83 m/s²; SS-A), exceeding the admissible limit ($a_{w,rms}$ = 0.35 m/s² [4]) (see Tab. 1). Furthermore, the evaluation of the VDV criterion indicated that “only force” models [3-5] generated dynamic response levels that exceeded the VDV limit (VDV < 0.50 $m/s^{1.75}$ [6] and 0.66 $m/s^{1.75}$ [7]) (see Tab. 1). In sequence of the investigation, Fig. 6 shows the floor dynamic structural response in the time domain considering the investigated models [2-5], respectively. Additionally, Fig. 6(c) and Fig. 6(f) depict the dynamic response in the frequency domain for the LM I scenario associated to the structural section A (SS-A).



(a) Time domain biodynamic [2] (b) Time domain Faisca [3] (c) Frequency domain [2,3]



(d) Time domain AISC [5] (e) Time domain SCI [4] (f) Frequency domain [4, 5]

Figure 6. Dynamic response of the critical section A (SS-A): LM I in the time and frequency domain.

Table 1. Dynamic structural response of the investigated floor: $a_{peak,}$ $a_{w,rms}$ and VDV values

	SS	Biodynamic [2]			Faisca [3]			AISC [5]			SCI [4]		
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	0.23	0.09	0.21	0.62	0.29	0.67	1.22	0.31	0.72	2.31	0.83	1.77
	B	0.32	0.12	0.28	0.35	0.16	0.37	0.87	0.22	0.51	1.19	0.47	0.99
	C	0.21	0.08	0.18	0.35	0.16	0.37	0.87	0.22	0.51	1.19	0.47	0.99
	D	0.30	0.12	0.27	0.42	0.19	0.45	1.01	0.25	0.59	1.67	0.65	1.38
	E	0.02	0.01	0.01	0.02	0.01	0.02	0.03	0.01	0.02	0.06	0.02	0.05
	F	0.30	0.12	0.27	0.63	0.29	0.67	1.22	0.31	0.72	2.13	0.83	1.77
	G	0.09	0.04	0.08	0.16	0.07	0.16	0.66	0.17	0.39	0.89	0.35	0.74
	H	0.03	0.01	0.02	0.05	0.02	0.05	0.13	0.03	0.08	0.21	0.08	0.17
	I	0.27	0.11	0.24	0.42	0.19	0.45	1.01	0.25	0.59	1.68	0.65	1.39
LM II (loading model II)	SS	Biodynamic [2]			Faisca [3]			AISC [5]			SCI [4]		
		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	0.18	0.07	0.16	0.20	0.10	0.18	0.72	0.18	0.42	0.67	0.26	0.56
	B	0.01	0.01	0.01	0.09	0.05	0.08	0.59	0.15	0.35	0.45	0.18	0.37
	C	0.12	0.04	0.10	0.10	0.05	0.09	0.39	0.10	0.23	0.38	0.15	0.32
	D	0.19	0.07	0.17	0.20	0.10	0.18	0.72	0.18	0.42	0.67	0.26	0.56
	E	0.02	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.02
	F	0.12	0.04	0.10	0.19	0.09	0.17	0.43	0.11	0.26	0.70	0.27	0.58
	G	0.11	0.04	0.09	0.09	0.05	0.08	0.59	0.15	0.35	0.45	0.18	0.37
	H	0.01	0.01	0.01	0.07	0.04	0.07	0.29	0.07	0.17	0.22	0.08	0.18
	I	0.01	0.01	0.01	0.19	0.09	0.17	0.43	0.11	0.25	0.70	0.27	0.58
LM III (loading model III)	SS	Biodynamic [2]			Faisca [3]			AISC [5]			SCI [4]		
		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	0.11	0.05	0.06	0.28	0.13	0.29	1.05	0.27	0.61	0.98	0.39	0.82
	B	0.03	0.07	0.09	0.24	0.12	0.26	1.31	0.39	0.83	1.08	0.32	0.81
	C	0.02	0.01	0.01	0.08	0.04	0.09	0.40	0.15	0.36	0.40	0.18	0.37
	D	0.01	0.01	0.01	0.30	0.14	0.31	1.12	0.28	0.64	1.07	0.39	0.83
	E	0.02	0.02	0.02	0.01	0.01	0.01	0.05	0.02	0.04	0.03	0.02	0.04
	F	0.03	0.01	0.03	0.18	0.09	0.19	0.46	0.25	0.51	0.67	0.44	0.88
	G	0.10	0.04	0.09	0.24	0.11	0.25	1.24	0.32	0.79	1.00	0.40	0.84
	H	0.01	0.01	0.01	0.03	0.01	0.03	0.14	0.04	0.12	0.12	0.05	0.09
	I	0.01	0.01	0.01	0.20	0.09	0.21	0.49	0.27	0.56	0.70	0.48	0.97
Tolerance peak acceleration: 0.5 m/s^2 AISC [5]													
Limits: $a_{w,rms}$<0.35 m/s^2 SCI [4]; VDV<0.50 $m/s^{1,75}$ Setareh [6] and VDV<0.66 $m/s^{1,75}$ Ellis & Littler [7].													

On the other hand, when examining the acceleration results in the frequency domain [see Fig. 6(c) and Fig. 6(f)], it is evident that multiple energy transfer peaks are present in the dynamic response, corresponding to the excitation frequency (f = 2.20 Hz). The most significant amplitudes (displacements and accelerations) occurs when the third harmonic of the excitation frequency (f = 3 x 2.20 Hz) matches the third floor natural frequency (f_{03} = 6.60 Hz), resulting in resonance. Furthermore, it is worth mentioning that the dynamic load model proposed by the SCI [4] exhibits the highest energy transfer peak associated to the floor's dynamic response.

7 Conclusions

This research work focused on the assessment of the dynamic structural behaviour of a steel-concrete composite floor system with dimensions of 40m x 40m and total area of 1600m², subjected to rhythmic human activities. In this work several mathematical formulations were used to determine the dynamic loads and evaluate the floor dynamic structural response. Therefore, the following conclusions can be drawn from the results presented in paper:

1. According to the design criteria standards for rhythmic activities practiced on floors, it is observed that the composite floor fundamental frequency is equal to 6.21 Hz (f_{01} = 6.21 Hz), and this frequency value is below the minimum value recommended by NBR 6118 [10] (9.6 Hz). Moreover, this frequency is in the range of the human excitation frequency, indicating a tendency of excessive vibration and human discomfort.

2. The floor dynamic structural response assessment indicated that the traditional "only force" models (Faisca [3], SCI [4] and AISC [5]) induced higher levels of displacements and accelerations than those provoked by the biodynamic systems [2]. This can be explained, due to the fact the biodynamic models take into account the people-structure dynamic interaction and also incorporate the people's damping effect in the dynamic analysis. This way, based on the use of biodynamic systems, the dynamic structural analysis and the human comfort assessment of the floor tends to be more realistic.

3. Having in mind the worst design situation associated to the LM-I and considering the dynamic excitation provided by the "only force" models [3-5] it is evident that the peak acceleration limit was surpassed, causing human discomfort: SCI [4] (a_p = 2.31 m/s² > a_{lim} = 0.50 m/s²; LM-I: SS-A); AISC [5] (a_p = 1.31 m/s² > a_{lim} = 0.50 m/s²; LM-III: SS-B); Faisca [3] (a_p = 0.62 m/s² > a_{lim} = 0.50 m/s²; LM-I: SS-A). Moreover, considering the design limits for RMS accelerations and VDV values, the calculated results indicated that these limits were exceeded as well, with the most critical values obtained in the following cases: SCI [4] ($a_{w,rms}$ = 0.83 m/s² > 0.35 m/s² and VDV = 1.77 $m/s^{1.75}$ > 0.50 $m/s^{1.75}$; LM-I: SS-A); AISC [5] (VDV = 0.72 $m/s^{1.75}$ > 0.50 $m/s^{1.75}$; LM-I: SS-A); and Faisca [3] (VDV = 0.67 $m/s^{1.75}$ > 0.50 $m/s^{1.75}$; LM-I: SS-A).

4. On the other hand, investigating the floor's dynamic response in the same design situation associated with LM-I, but considering the results taking into account the people-structure dynamic interaction effect through the use of biodynamic systems, there are no problems related to excessive vibrations or human discomfort. The peak acceleration (a_p = 0.32 m/s² < a_{lim} = 0.50 m/s²; section B), RMS acceleration ($a_{w,rms}$ = 0.12 m/s² < 0.35 m/s²; section B), and VDV (VDV = 0.28 $m/s^{1.75}$ < 0.50 $m/s^{1.75}$; section B) values attends with the human comfort criteria. Finally, it is important to emphasize that the dynamic loads generated based on the use of the biodynamic systems [2] provides a more realistic structural response and a better floor human comfort assessment, due to the fact that this modelling strategy incorporates the dynamic characteristics of different individuals (mass, damping and stiffness: people-structure dynamic interaction effect).

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