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Influence of the Human Rhythmic Activities Modelling on the Composite Floors Dynamic Response

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Abstract: The structural problems related with excessive vibrations of steel-concrete composite floors due to human rhythmic activities is the main motivation for the development of an analysis methodology supported by design guides and several researches aiming to obtain the dynamic response of a typical steel-concrete composite floor spanning 10 by 10 m when subjected to human rhythmic dynamic loadings. Therefore, this research develops an extensive study based on the use of four different mathematical formulations used for modelling of the human rhythmic actions. Furthermore, it was observed that high levels of annoying vibrations were reached on the investigated floor during the rhythmic activities. Besides, it was verified that the analysed composite floor may be leaded to a very conservative design depending on the choice of the used dynamic loading model. Finally, design considerations related to a more reasonable and economical dynamic loading models used to evaluate the human comfort of composite floors are discussed.

Key words: Steel-concrete composite floors, dynamic loading models, excessive vibrations, human comfort.

1. Introduction

Floor vibrations induced by human rhythmic activities like walking, running, jumping or aerobics consist on a very complex problem. The dynamic excitation characteristics generated during these activities are directly related to the individual body adversities and to the specific way in which each human being executes a certain rhythmic task. All these aspects do not contribute for an easy mathematical or physical characterization of this phenomenon. In this sense, several investigations [1-6] based on experimental tests have described the loading generated by human activities as a Fourier series. However, reference [6] has proposed that the use of the Hanning function is more suitable to represent human rhythmic actions.

On the other hand, most disturbing vibrations related to human perception are in the range of 4 to 8

Hz [1-9] and at the same time most of the natural frequencies of steel-concrete composite floor systems lie also in this range. In addition, the excitation force frequencies due to human rhythmic activities occur in this range as well. All these combinations make the structural systems more susceptible to the resonance phenomenon, causing undesirable vibrations in the frequency range that is the most noticeable to humans.

It is worth to note that increase of floor vibration problems related to human rhythmic activities is due to several combinations rather than a single one. Slender and more flexible structural systems has been associated to the technological advance in the materials field which has allowed the use of more resistant and low weight materials [7, 8]. In addition, in relation to non-structural elements, there is an architectural trend in buildings so that one replaces the interior walls by demountable partitions. Such

condition may significantly contribute to reducing the overall damping present in floors [7, 8].

Besides, it is important to highlight that many researchers have been dealing with excessive floor vibrations through the use of vibration control devices [10-13]. Therefore, in such cases, the human activity mathematical representation must be well characterised in order to achieve good numerical and experimental correlations.

Regarding all these aspects, this paper is intended to investigate the vibration levels of a typical steel-concrete composite floor submitted to human rhythmic activities (aerobics). Therefore, this research develops an extensive study based on the study of four different mathematical formulations used for modelling of the human rhythmic activities. Hence, the floor dynamic response in terms of peak accelerations was obtained by numerical simulations and compared to the limiting values proposed by several authors and design codes. Finally, in this investigation design considerations related to a more reasonable and economical dynamic loading models used to evaluate the human comfort of composite floors are discussed.

2. Human Rhythmic Activities Modelling

This section summarizes the main four human rhythmic dynamic loading mathematical models proposed by different authors and supported by standards and technical guides.

2.1 American Institute of Steel Construction-AISC

The Steel Design Guide Series 11 entitled “Floor Vibrations due to Human Activity” [2] supported by the American Institute of Steel Construction (AISC) proposes that the human activity can be represented as in Eq. (1) so that a harmonic force component matches the fundamental frequency of the floor.

$$F(t) = P \left[1 + \sum_{i=1}^n \alpha_i \cos(2\pi i f_{step} t) \right] \quad (1)$$

Where, F(t): dynamic load function (N); P: person’s weight (N); α_i : dynamic coefficient for the i^{th} harmonic

force component; i: harmonic multiple of the step frequency; f_{step} : step frequency (Hz); t: time (s).

The dynamic coefficient related to aerobics class is equal to 1.5; 0.6 and 0.1 for the first, second and third harmonic component, respectively. It must be emphasized that this dynamic loading model does not take into account the lack of coordination among the individuals during the activity.

2.2 Steel Construction Institute-SCI

The Steel Construction Institute (SCI) have published its technical guide entitled “Design of Floors for Vibration: A New Approach” [3] which presents the dynamic loading model based on Eqs. (2-5) developed by Ellis and Ji [4].

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

$$r_{1,v} = 1.61 v^{-0.082} \quad (3)$$

$$r_{2,v} = 0.94 v^{-0.24} \quad (4)$$

$$r_{3,v} = 0.44 v^{-0.31} \quad (5)$$

Where, F(t): dynamic load function (N); t: time (s); f_p : frequency of the jumping load (Hz); v: number of persons; $r_{n,v}$: Fourier coefficient (dynamic load factor) of the n^{th} term; G: person’s weight (N); ϕ_n : phase lag of the n^{th} term. Considering only one person practising the rhythmic activity, the Fourier coefficient ($r_{n,1}$) can be used according to Table 1. It is important to note that the lack of coordination is taken into account for various group sizes up to 64 persons through Eqs. (3-5). In addition, only the phase lag angles for “normal jumping” must be used for crowds jumping.

Table 1 Fourier coefficient and phase lag angles [4].

Activity Type	n						
	1	2	3	4	5	6	
Low aerobics	r_n	9/7	9/55	2/15	9/247	9/391	2/63
	ϕ_n	$-\pi/6$	$-5\pi/6$	$-\pi/2$	$-\pi/6$	$-5\pi/6$	$-\pi/2$
High aerobics	r_n	$\pi/2$	2/3	0	2/15	0	2/35
	ϕ_n	0	$-\pi/2$	0	$-\pi/2$	0	$-\pi/2$
Normal jumping	r_n	9/5	9/7	2/3	9/55	9/91	2/15
	ϕ_n	$\pi/6$	$-\pi/6$	$\pi/2$	$-5\pi/6$	$-\pi/6$	$-\pi/2$

2.3 Standard ISO 10137

The standard ISO 10137 [5] recommends the use of Eq. (6) to represent rhythmic exercises or coordinated jumping. It can be noted the similarity between Eqs. (2) and (6). However, this standard states that the phase angle can be assumed equal to zero for these activity types. In addition, the first three Fourier coefficients should be calculated by Eqs. (7-9), respectively.

$$F(t) = G \left\{ 1 + \sum_{n=1}^{\infty} \alpha_n \sin(2n\pi f_p t + \phi_n) \right\} \quad (6)$$

$$\alpha_1 = 2.1 - 0.15(f_p) \quad (7)$$

$$\alpha_2 = 1.9 - 0.17(2f_p) \quad (8)$$

$$\alpha_3 = 1.25 - 0.11(3f_p) \quad (9)$$

Where, F(t): dynamic loading function (N); t: time (s); f_p : frequency of the jumping load (Hz); α_n : Fourier coefficient of the n^{th} term; G: person's weight (N); ϕ_n : phase lag of the n^{th} term.

Alternatively, as a first approximation, the first three Fourier coefficients (α_1 , α_2 and α_3) can be taken as 1.7; 1.0 and 0.4, respectively [5]. Aiming to account the coordination effect, ISO 10137 [5] proposes a coordination factor, C(N), applied to the force function for evaluating the comfort of passive persons as in Eq. (10), based on the number of participants.

$$F(t)_N = C(N) \cdot F(t) \quad (10)$$

Table 2 shows the recommended values of C(N) for group size larger than 50 persons in function of coordination type i.e. high coordination (e.g. gymnasia activities), medium coordination (e.g. crowd viewing sports events), low coordination (e.g. crowd attending a pop concert). For groups smaller than or equal to 5 persons, the coordination factor should be equal to 1. For intermediate groups this factor can be obtained by linear interpolation. Additionally, the C(N) of the first harmonic may be used for all harmonics based on an evaluation in case of fear or panic [5].

2.4 Faisca

This loading model formulation is related to the dynamic actions induced by rhythmic activities such as aerobics and free jumps. This modelling is supported by experimental parameters according to Eq. (11) [6].

$$F(t) = CD \left\{ K_p P \left[0.5 - 0.5 \cos\left(\frac{2\pi}{T_c} t\right) \right] \right\} \quad t \leq T_c \quad (11)$$

$$F(t) = 0 \quad T_c \leq t \leq T$$

Where, F(t): dynamic loading function (N); t: time (s); T: activity period (s); T_c : activity contact period (s); P: person's weight (N); K_p : impact coefficient; CD: phase coefficient.

This way, Table 3 presents the experimental parameters used for human rhythmic activities representation. Fig. 1 shows the phase coefficient variation, CD, for people, based on probabilistic analyses [6].

It is important to emphasize that the impact coefficient, K_p , and the phase coefficient variation, CD, for human activities used in this investigation were obtained based on a long series of experimental

Table 2 Coordination factor [5].

Coordination	1 st harmonic	2 nd harmonic	3 rd harmonic
High	0.80	0.67	0.50
Medium	0.67	0.50	0.40
Low	0.50	0.40	0.30

C(N) values apply only to the serviceability limit state [5].

Table 3 Human rhythmic activity representation [6].

Activity	T (s)	T_c (s)	K_p
Free Jumps	0.44 ± 0.15	0.32 ± 0.09	3.17 ± 0.58
Aerobics	0.44 ± 0.09	0.34 ± 0.09	2.78 ± 0.60

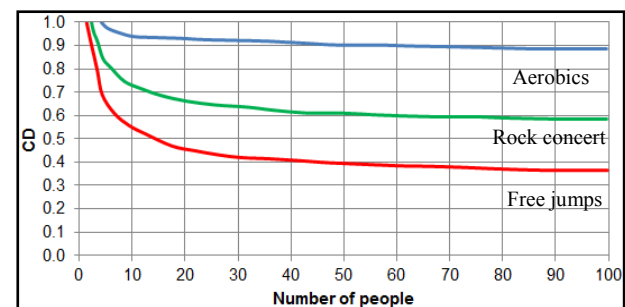


Fig. 1 Phase coefficients [6].

tests and probabilistic analyses. Relevant variations which lead to the reduction of the dynamic loading on the floor, such as phase lags between the individuals and change of rhythm during the activity are already embedded in these coefficients.

Besides, it was found that the half sine function, usually used by several authors, it is not so adequate to represent human rhythmic loads [6]. The Hanning function was the best one that fitted the signal obtained from the experimental results. Figs. 2-4 show a comparison among the investigated dynamic loading functions in time domain and frequency domain.

The comparison (Figs. 2-4) was obtained considering one person with weight equal to 800N practising aerobics (the SCI function [3] was considered as low aerobics) jumping at 2.12 Hz (step frequency). The Fourier coefficients for the ISO 10137 [5] function were calculated by Eqs. (7-9).

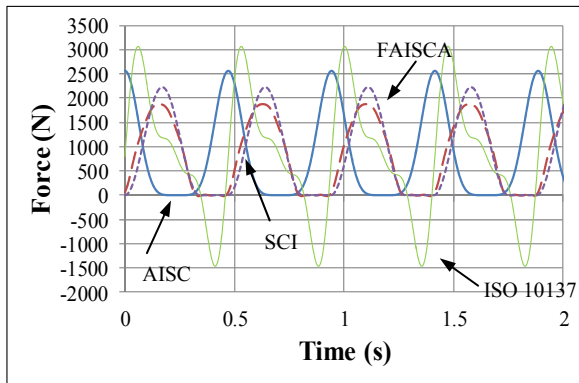


Fig. 2 Dynamic loading functions in time domain

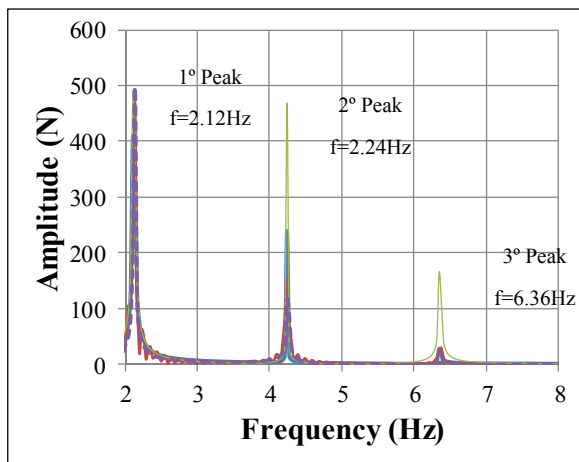


Fig. 3 Dynamic loading functions in frequency domain

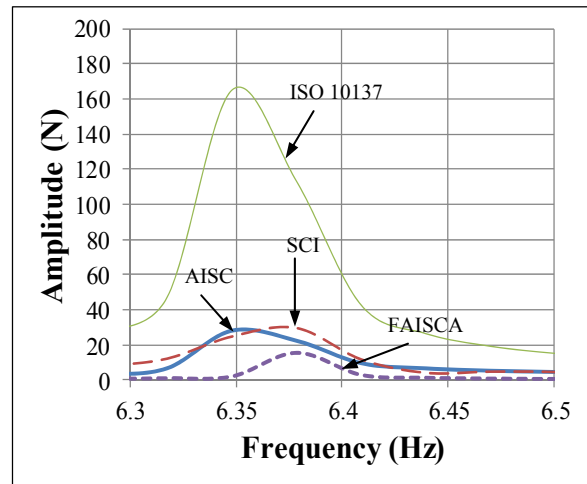


Fig. 4 Third harmonic of the investigated force functions

It can be noticed from Fig. 2 that the AISC [2], SCI [3] and Faisca [6] functions present a typical human rhythmic activity shape, i.e. a contact period with the ground and a loss of contact with the ground. On the other hand, the ISO 10137 [5] function does not show the same shape. It may indicate unexpected results considering this force function.

Figs. 3 and 4 indicate that the third harmonic frequency corresponding (which represents the main interest range frequency for steel-concrete composite floors) the ISO 10137 [5] function may be overestimated. Thus, this fact will be investigated in this work.

3. Analysed Steel-Concrete Composite Floor

The investigated structural model was based on a steel-concrete composite floor spanning 10 m by 10 m, with a total area of 100 m². This system represents a typical interior floor bay of a commercial building for gym purposes. The floor studied in this work is supported by steel columns and is currently submitted to human rhythmic activities, see Figs. 5 and 6.

The steel sections used were welded wide flanges (WWF) made from a 345 MPa yield stress steel grade and a 205 × 10³ MPa Young’s modulus. The concrete slab has a 30 MPa specified compression strength and a 26 × 10³ MPa Young’s Modulus.

The dynamic loads were applied on the composite floor according to Fig. 7. The live load considered in this analysis corresponds to one person for each 4.0

m² (0.25 person/m²) [2]. It is also assumed that a single person’s weight is equal to 800N (0.8 kN) [1]. The Rayleigh damping was used in this work and the modal damping ratio adopted for the steel-concrete composite floor first and second vibration modes was equal to 0.01 ($\xi = \xi_1 = \xi_2 = 1\%$) [1, 2, 5]. This modal damping ratio ($\xi = 1\%$) was chosen according to ISO 10137 [5] and lies in the extreme range of 0.5% to 8.0% for fully composite steel beams with shear connectors to concrete slab.

In sequence, Fig. 8 presents the finite element model developed in the ANSYS program [14]. The present investigation considered that both materials (steel and concrete) have an elastic behaviour. The complete interaction between the concrete slab and steel beams was considered in the analysis, i.e. the numerical model coupled all the nodes between the beams and slab, to prevent the occurrence of any slip. Regarding the structural behaviour of the connections, the beam-to-beam connections were modelled as flexible joints whereas the beam-to-column connections were considered as rigid joints.

4. Composite Floor Dynamic Response

The composite floor natural frequencies and vibration modes were determined with the aid of the numerical simulations (modal analysis), based on the use of ANSYS program [14]. The eigenvalues are described in Table 4 and Fig. 9 presents the first two vibration modes of the investigated floor.

Regarding Table 4 results, it can be seen that the first natural frequency ($f_{01} = 6.36\text{Hz}$) of the floor is found in the force frequency range of aerobic activities. Namely the third harmonic of the forcing function may match this natural frequency and therefore lead the composite floor to a resonance state. Consequently, such situation might result in undesirable vibrations and thus human annoyance.

This way, in order to investigate the resonance possibility with the floor fundamental frequency ($f_{01} = 6.36\text{ Hz}$), two loading cases related to 1 person and 20

persons (crowd load) were applied on the steel-concrete composite floor according to the four force functions exposed in Section 2, see Fig. 7.

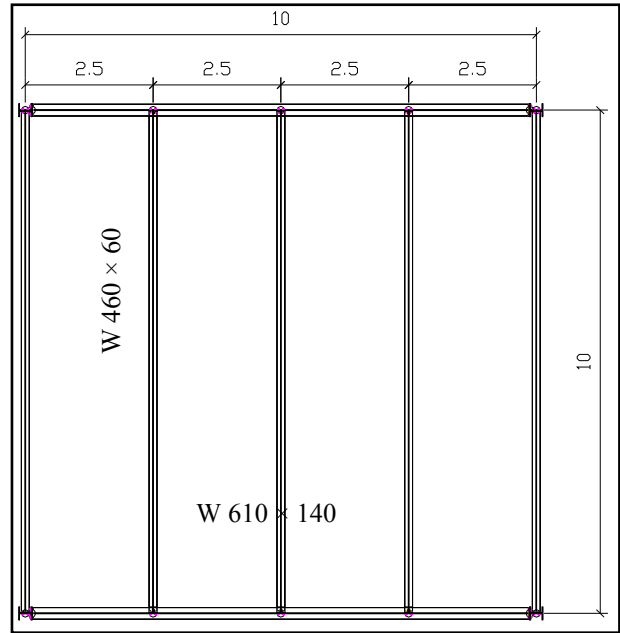


Fig. 5 Structural model top view (Dimensions in (m)).

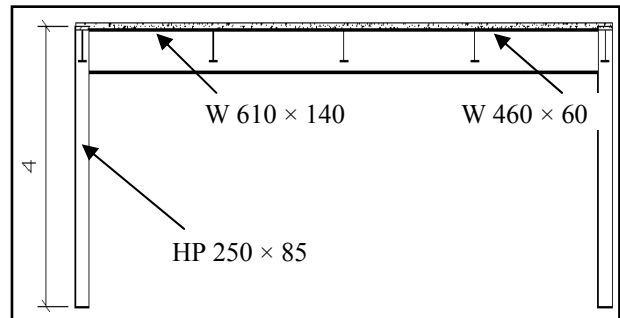


Fig. 6 Structural model cross section (Dimensions in (m)).

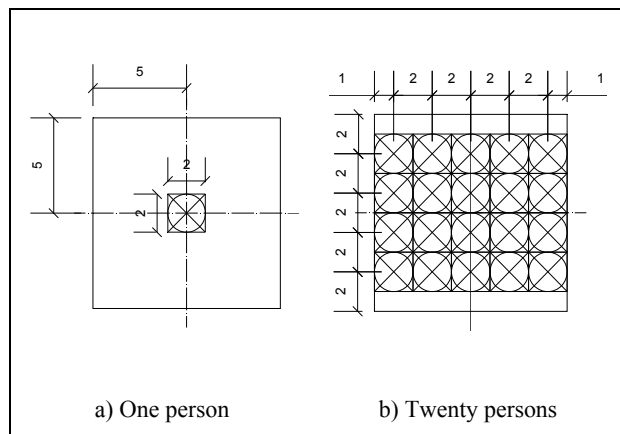


Fig. 7 Dynamic loading of individuals practicing rhythmic activities on the steel-concrete composite floor (Dimensions in (m)).

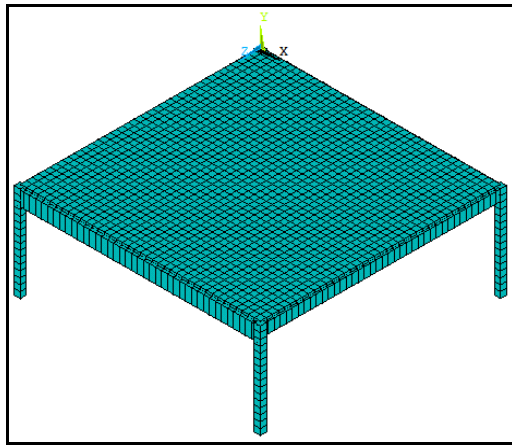
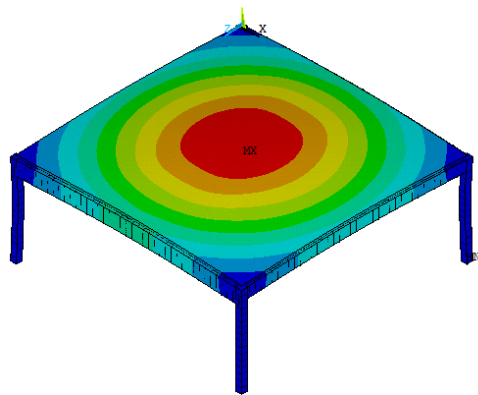
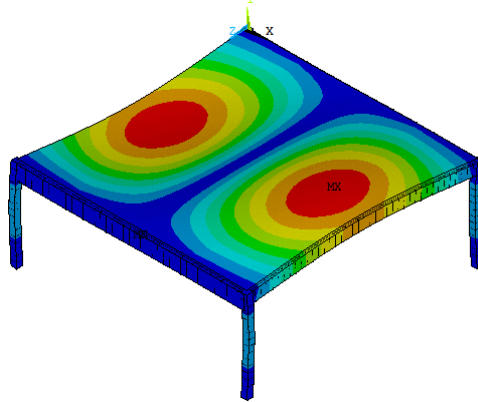


Fig. 8 Steel-concrete composite floor finite element model.



a) 1st Vibration mode ($f_{01}=6.36\text{Hz}$)



b) 2nd Vibration mode ($f_{02}=9.78\text{Hz}$)

Fig. 9 Investigated structural model vibration modes.

Table 4 Composite floor natural frequencies.

Frequencies (Hz)	Natural frequencies
f_{01}	6.36
f_{02}	9.78
f_{03}	12.56
f_{04}	13.62
f_{05}	18.32
f_{06}	21.72

5. Human Comfort Evaluation

The steel-concrete composite floor accelerations were calculated based on the four dynamic loading models described in Section 2. The total time in which the aerobic activity was performed on the floor was equal to 10s and the dynamic response of the structure was obtained from its central node. Table 5 shows the human comfort acceptance criteria [3, 15, 16] and Tables 6 and 7 present the results related to the two investigated loading cases (Fig. 7).

Regarding the results from Tables 6 it can be noticed that the two worst cases are related to the SCI

Table 5 Human comfort acceptance criteria.

Smith et al. [3]	Ellis and Littler [15]	Setareh [16]	Person's reaction
$a_{w,rms}$ (m/s^2)	VDV ($\text{m/s}^{1.75}$)	VDV ($\text{m/s}^{1.75}$)	
< 0.35	< 0.66	< 0.50	Reasonable limit: passive persons
0.35 - 1.27	0.66 - 2.38	0.50 - 3.50	Disturbing
1.27 - 2.47	2.38 - 4.64	3.50 - 6.90	Unacceptable
> 2.47	> 4.64	> 6.90	Probably causing panic

Table 6 Floor dynamic response for 1 person.

Dynamic loading models	Activity type	Floor dynamic response		
		Acceleration (m/s^2)		VDV ($\text{m/s}^{1.75}$)
		a_p	$a_{w,rms}$	
AISC	Aerobics	0.408	0.247	0.503
	Low aerobics	0.535	0.315	0.655
SCI	High aerobics	0.128	0.063	0.134
	Normal jumping	2.675	1.584	3.278
ISO 10137	Gymnasia	2.105	1.310	2.757
Faisca	Aerobics	0.177	0.095	0.200
	Free jumping	0.106	0.045	0.101

Limiting acceleration: $a_{lim} = 0.5 \text{ m/s}^2$ [2].

Table 7 Floor dynamic response for 20 persons.

Dynamic loading models	Activity type	Floor dynamic response		
		Acceleration (m/s^2)		VDV ($\text{m/s}^{1.75}$)
		a_p	$a_{w,rms}$	
AISC	Aerobics	5.039	3.094	6.277
SCI	Normal Jumping	8.377	5.273	10.850
ISO 10137	Gymnasia	24.528	15.410	32.400
Faisca	Aerobics	2.013	1.118	2.337
	Free jumping	1.538	0.854	1.786

Limiting acceleration: $a_{lim} = 0.5 \text{ m/s}^2$ [2].

(normal jumping) [3] and ISO 10137 [5] dynamic loading models. The maximum acceleration values of 2.675 m/s²; 1.584 m/s² and 3.278 m/s^{1.75} for the SCI loading model [3] (peak acceleration, RMS and VDV, respectively) and 2.105 m/s²; 1.310 m/s² and 2.757 m/s^{1.75} for the ISO 10137 [5] dynamic loading model (peak acceleration, RMS and VDV, respectively) were found along the analysis. These values clearly indicate disturbing and unacceptable vibration levels to the only one person who practice the aerobic activity according to the human comfort acceptance criteria, as presented in Table 5.

On the other hand, considering the floor dynamic response for 20 persons (crowd load) all investigated dynamic loading models (except for the Faisca [6]) reached extremely uncomfortable vibration levels (probably causing panic, Table 5). The Faisca [6] dynamic loading model vibration levels were classified as disturbing.

It can be noted that for 20 persons the ISO 10137 [5] dynamic loading model results does not seem reasonable due the shape of its force function, see Fig. 2. It must be emphasized that a coordination factor of 0.93 was applied to this function through linear interpolation. Fig. 10 shows a comparison among the loading function results considering the floor dynamic response for 20 persons.

It is important to emphasize that the ISO10137 [5] function was not included in Fig. 10 only due to the order of magnitude. The AISC [2] formulation does not incorporate any variations which lead to the reduction of the dynamic loading on the floor (phase lags between the individuals and change of rhythm during the activity). In this situation the dynamic loads are in phase on the floor and the peak acceleration values are overestimated and not realistic.

It can be noticed that the SCI [3] function have presented higher acceleration values than Faisca [6] model and this means that their third Fourier coefficient is more energetic than the Faisca [6] function. On the other hand, through a comparison

among the four investigated force functions, the Faisca [6] dynamic load model seems to offer larger design parameters variations. Therefore, an extensive parametric study of the contact period (T_c) was evaluated based on aerobics (Table 3 and Fig. 11).

Based on the Fig. 11 results, the contact period (T_c) variation presented a polynomial behaviour. Comparing Figs. 10 and 11 it is possible to conclude that depending on the chosen T_c value, the floor dynamic response obtained from the Faisca [6] function can be reach the vibration levels according to SCI [3] functions.

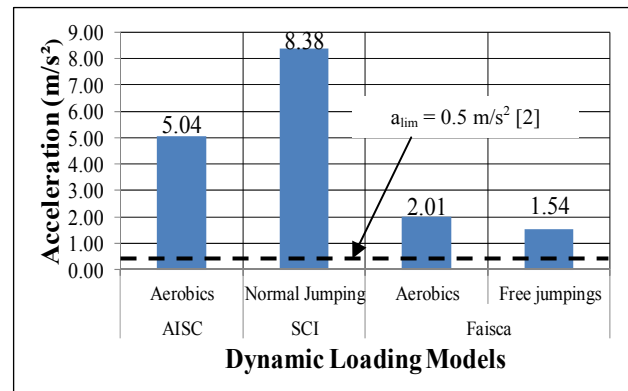


Fig. 10 Floor dynamic response comparison.

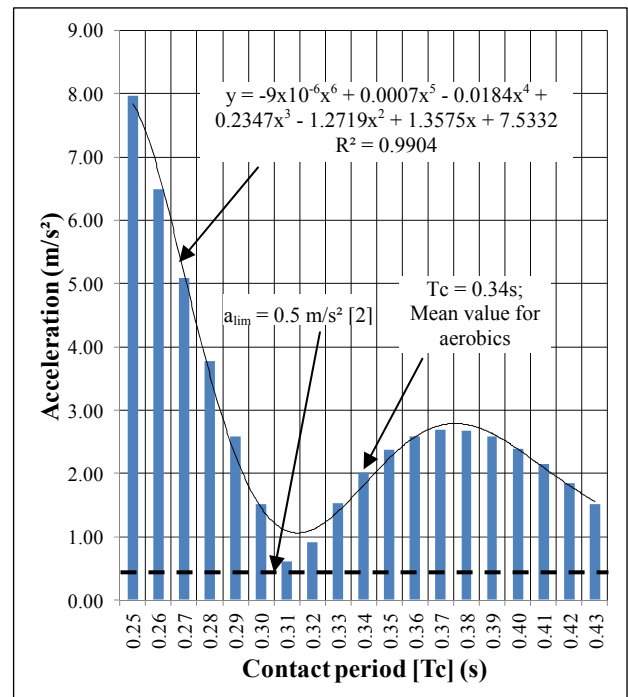


Fig. 11 Activity contact period variation.

In addition, keeping the T_c value equal to 0.34s and varying the upper and lower limits of the impact coefficient, K_p (Table 5), an steady-state acceleration value of 2.45 m/s^2 ($K_p = 3.38$) and 1.58 m/s^2 ($K_p = 2.18$) were obtained, respectively. This way, Figs. 12 and 13 show the composite floor dynamic response in time domain whereas Fig. 14 shows in the frequency domain considering 20 persons (aerobics) for the AISC [2], SCI [3], ISO 10137 [5] and Faisca [6] dynamic loading models (Table 7).

Considering all obtained results along the investigation, the Faisca [6] function might be considered for an economical design by using the mean value of the contact period equal to 0.34s ($T_c = 0.34s$). It is important to emphasize that the impact coefficient, K_p , and the phase coefficient variation, CD, for human rhythmic activities used in Faisca [6] dynamic load model were obtained based on a long series of experimental tests and probabilistic analyses.

Important variations which lead to the reduction of the human dynamic actions on the structure, such as phase lags between the individuals and change of rhythm during the activity are already embedded in these coefficients (Eq. (11), Table 3 and Fig. 1). Besides, this dynamic loading model might offer better adjustment of the human rhythmic activities parameters based on a developed extensive experimental programme.

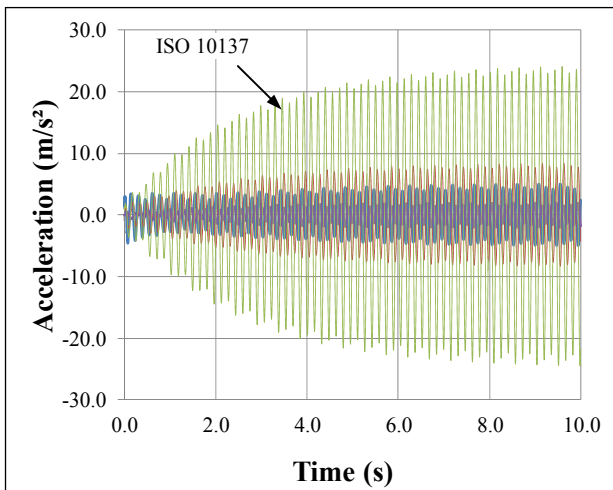


Fig. 12 Floor dynamic response. ISO 10137 force function.

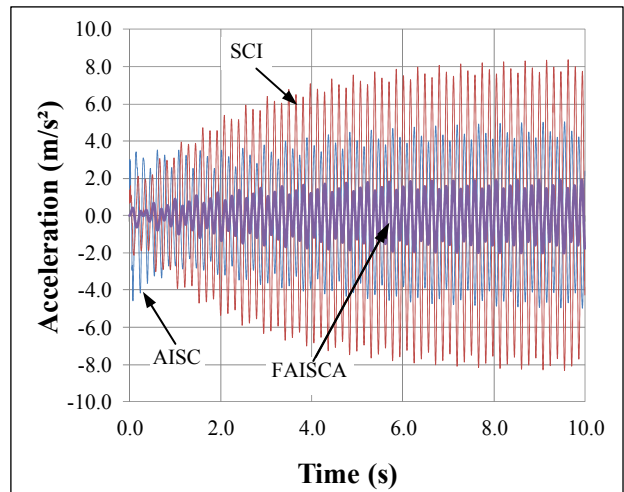


Fig. 13 Floor dynamic response. AISC, SCI and Faisca force functions.

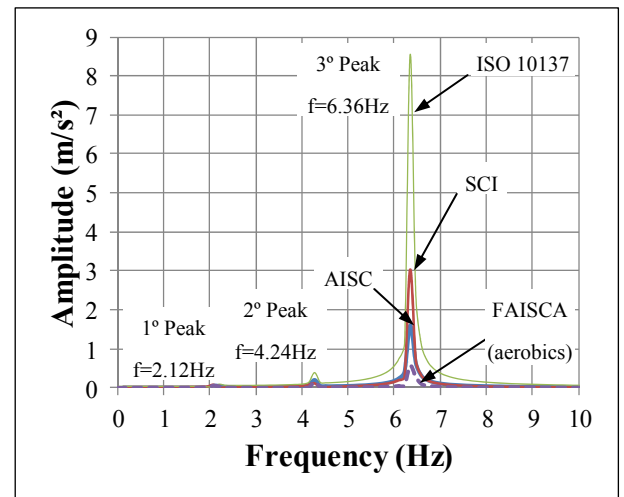


Fig. 14 Floor dynamic response in frequency domain.

6. Conclusions

This investigation analysed the dynamic behaviour of a steel-concrete composite floor spanning 10 m by 10m used for human rhythmic activities. The proposed numerical model adopted the usual mesh refinement techniques present in finite element method simulations, based on the ANSYS program. This model enabled a complete dynamic evaluation of the investigated floor in terms of human comfort and its associated vibration serviceability limit states.

The modal analysis indicated that the first floor frequency was equal to 6.36 Hz. This frequency value lies in the frequency range which may resonate with the third harmonic of the human rhythmic activity

practiced on the structure so that excessive vibrations might cause human discomfort.

Aiming the evaluation of the vibrations levels of the investigated floor two loading cases of individuals practicing aerobics on the structural system were considered (one and twenty persons). In addition, four representative mathematical models of human rhythmic activities were studied, evaluated and compared.

The maximum acceleration values of 8.377 m/s^2 ; 5.273 m/s^2 and $10.850 \text{ m/s}^{1.75}$ for the SCI [3] loading model (peak acceleration, RMS and VDV, respectively) and 24.528 m/s^2 ; 15.410 m/s^2 and $32.400 \text{ m/s}^{1.75}$ for the ISO 10137 [5] dynamic loading model (peak acceleration, RMS and VDV, respectively) were found along the analysis.

It must be emphasized that these acceleration values have indicated extremely uncomfortable vibration levels to the persons who practice the aerobic activity according to design standards and technical recommendations [2, 3, 15, 16]. Furthermore, based on the found results and in the author's opinion, it was also verified that the Faisca [6] dynamic loading model have presented an economical design recommendation in comparison with the others investigated dynamic loading models. In addition, this force function might offer better adjustment of the human rhythmic activities design parameters.

Acknowledgments

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