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Non-Linear Dynamic Analysis of Steel-Concrete Composite Floors subjected to Human Rhythmic Activities

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Abstract

The main objective of this paper is to investigate the influence of steel-concrete interaction degree (from total to various levels of partial interaction) over the nonlinear dynamic behaviour of composite floors when subjected to human rhythmic activities. The investigated structural model was based on a steel-concrete composite floor spanning 40m by 40m, with a total area of 1600m^2. The structural system consisted of a typical composite floor of a commercial building. The peak accelerations found in the present analysis indicated that the investigated floor presented problems related with human comfort. Hence it was detected that this type of structure can reach high vibration levels that can compromise the user's comfort.

Keywords: non-linear dynamic analysis, steel structures, steel-concrete composite floors, human comfort, structural behaviour, computational modelling.

1 Introduction

The increasing incidence of building vibration problems due to human activities led to a specific design criterion to be addressed in structural design [1-7]. This was the main motivation for the development of a design methodology centred on the steel-concrete composite floors non-linear dynamic response submitted to loads due to human rhythmic activities.

On the other hand, the competitive trends of the world market have long been forcing structural engineers to develop minimum weight and labour cost solutions. A direct consequence of this new design trend is a considerable increase in problems related to unwanted composite floor vibrations. For this reason, the structural floors systems become vulnerable to excessive vibrations produced by impacts such as human rhythmic activities [1-7].

Considering all aspects mentioned before, the main objective of this paper is to investigate the influence of steel-concrete interaction degree (from total to various levels of partial inter-action) over the non-linear dynamic behaviour of composite floors subjected to human rhythmic activities [1, 2]. This way, the dynamic loads were obtained through experimental tests with individuals carrying out rhythmic and non-rhythmic activities such as stimulated and non-stimulated jumping and aerobic gymnastics [7]. Based on the experimental results, human load functions due to rhythmic and non-rhythmic activities are proposed [7].

The investigated structural model was based on a steel-concrete composite floor spanning 40m by 40m, with a total area of $1600m^2$. The structural system consisted of a typical composite floor of a commercial building. The composite floor studied in this work is supported by steel columns and is currently submitted to human rhythmic loads. The structural system is constituted of composite girders and a 100mm thick concrete slab [1, 2].

The proposed computational model adopted the usual mesh refinement techniques present in finite element method simulations, based on the ANSYS program [8]. This numerical model enabled a complete dynamic evaluation of the investigated steel-concrete composite floor especially in terms of human comfort and its associated vibration serviceability limit states.

Initially, all the composite floor natural frequencies and vibration modes were obtained. In sequence, based on an extensive parametric study, the floor dynamic response in terms of peak accelerations was obtained and compared to the limiting values proposed by several authors and design codes [6, 9].

An extensive parametric analysis was developed focusing in the determination of the influence of the steel-concrete interaction over the composite floor non-linear dynamic response, when submitted to human rhythmic activities. The structural system peak accelerations were compared to the limiting values proposed by several authors and design standard.

The current investigation indicated that human rhythmic activities could induce the steel-concrete composite floors to reach unacceptable vibration levels and, in these situations, lead to a violation of the current human comfort criteria for these specific structures.

2 Dynamic Loading Induced by Human Activities

The description of loads generated by human activities is not a simple task. The individual characteristics in which each individual perform the same activity and the existence of external excitation are key factors in defining the dynamic action characteristics. Numerous investigations were made aiming to establish parameters to describe such loads [1-6].

Several investigations [1-6] have described the loading generated by human activities as a Fourier series, which consider a static part due to the individual weight and another part due to the dynamic load. The dynamic analysis is performed equating one of the activity harmonics to the floor fundamental frequency, leading to resonance.

This study have considered the dynamic loads obtained by Faisca [7], based on the results achieved through a long series of experimental tests with individuals carrying out rhythmic and non-rhythmic activities. The dynamic loads generated by human rhythmic activities, such as jumps, aerobics and dancing were investigated by Faisca [7].

The loading modelling was able to emulate human activities like aerobic gymnastics, dancing and free jumps. In this paper, the Hanning function was used to represent the human dynamic actions. The Hanning function was used since it was verified that this mathematical representation is very similar to the signal force obtained through experimental tests developed by Faisca [7].

The mathematical representation of the human dynamic loading using the Hanning function is given by Equation (1) and illustrated in Figure 1. The required parameters for the use of Equation (1) are related to the activity period, T, contact period with the structure, T_c, period without contact with the model, T_s, impact coefficient, K_p, and phase coefficient, CD.

In sequence of the paper, Figure 2 illustrates the phase coefficient variation, CD, for human activities studied by Faisca [7], considering a certain number of individuals and later extrapolated for large number of peoples, Table 1 presents the experimental parameters used for human rhythmic activities representation and Figure 3 presents an example of human dynamic action related to aerobics.

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

$$F(t) = 0 \quad \text{For } T_c \le t \le T \tag{1}$$

Where:

F(t) : dynamic loading (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.

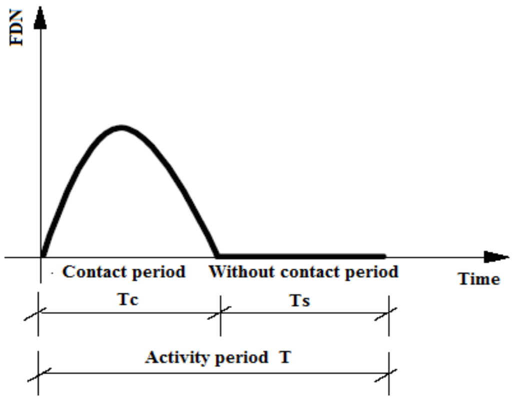


Figure 1: Generic representation of the dynamic loading induced by human rhythmic activities.

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

Table 1: Parameters used for human rhythmic activities representation [7].

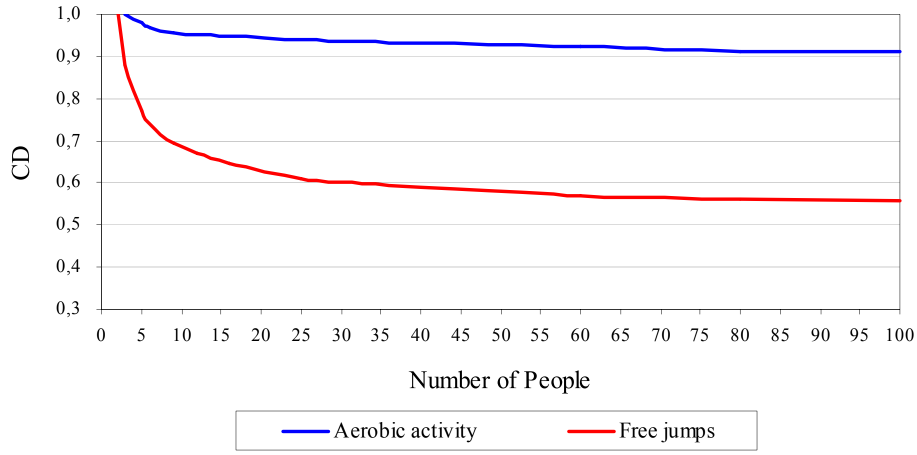


Figure 2: Phase coefficients for the studied activities [7].

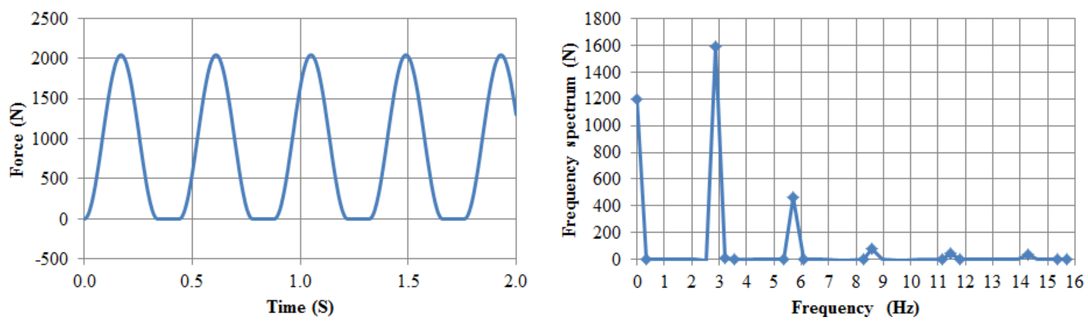


Figure 3: Dynamic loading induced by dancing (T=0.35s, T_c=0.25, T_s=0.10, K_p=2.78 and CD=1.0).

3 Investigated Structural Model

The investigated structural model was based on a steel-concrete composite floor spanning 40m by 40m, with a total area of 1600m^2. The structural system consisted of a typical composite floor of a commercial building. The composite floor studied in this work is supported by steel columns and is currently submitted to human rhythmic loads. The structural system is constituted of composite girders and a 100mm thick concrete slab [1, 2], see Figure 4.

The steel sections used were welded wide flanges (WWF) made with a 345MPa yield stress steel grade. A 2.05x10^{5}MPa Young's modulus was adopted for the steel beams. The concrete slab has a 30MPa specified compression strength and a 2.6x10^4 MPa Young's Modulus. Table 2 depicted the geometrical characteristics of all the steel sections used in the structural model.

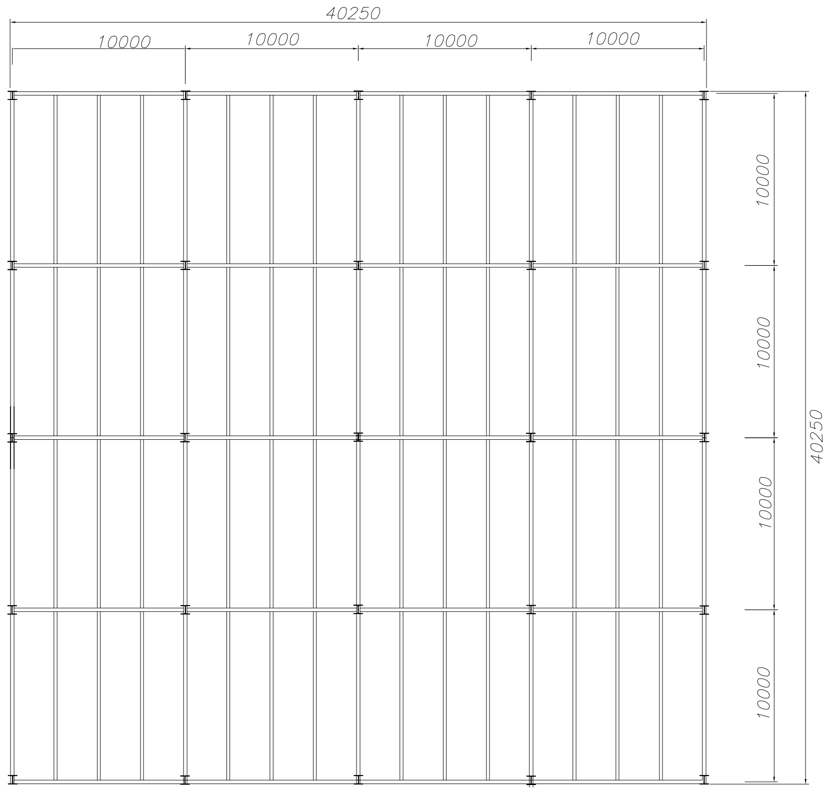


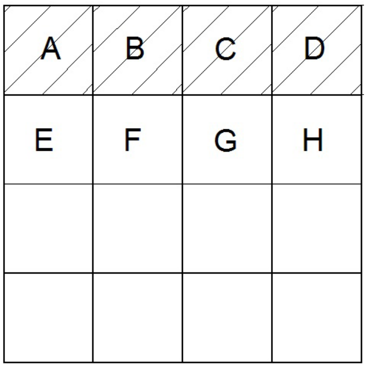
Figure 4: Structural model: composite floor (steel-concrete). Dimensions in (mm).

Profile Type	Height (d)	Flange Width (b_f)	Top Flange Thickness (t_f)	Bottom Flange Thickness (t_f)	Web Thickness (t_w)
Beams - W 610 x 140	617	230	22.2	22.2	13.1
Beams - W 460 x 60	455	153	13.3	13.3	8.0
Columns - HP 250 x 85	254	260	14.4	14.4	14.4

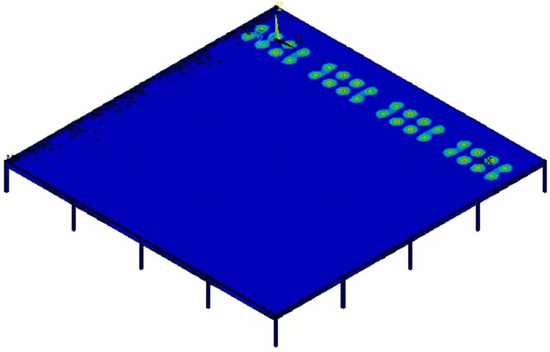
Table 2: Geometric characteristics of the building composite floor (mm).

The human-induced dynamic action was applied on the aerobics area, see Figure 5. The composite floor dynamic response, in terms of peak accelerations values, were obtained on the nodes A to H, in order to verify the influence of the dynamic loading on the adjacent slab floors, see Figure 5. In this investigation, the dynamic loadings were applied to the structural model corresponding to the effect of thirty two individuals practising aerobics.

The live load considered in this analysis corresponds to one person for each $4.0m^2$ (0.25 person/m^2), according to reference [5]. The load distribution was considered symmetrically centred on the slab panels, as depicted in Figure 5. It is also assumed that an individual person weight is equal to 800N (0.8kN) [5]. In this study, the damping ratio, ξ=1% (ξ = 0.01) was considered for all cases [5].



a) Investigated steel-concrete composite floor areas: top view

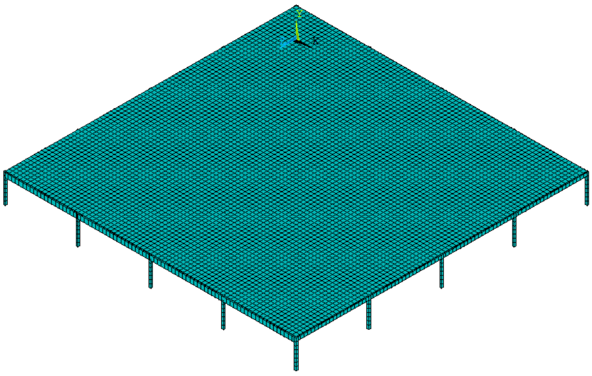


b) Thirty two individuals practising aerobics: three-dimensional view

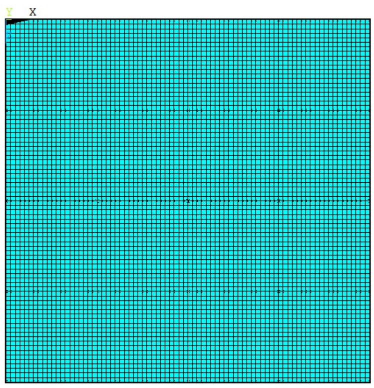
Figure 5: Dynamic loading: thirty two individuals practising aerobics on the investigated floor

4 Finite Element Modelling

The proposed computational model, developed for the composite floor dynamic analysis, adopted the usual mesh refinement techniques present in finite element method simulations implemented in the ANSYS program [8]. In this computational model, floor steel girders were represented by three-dimensional beam elements, where flexural and torsion effects are considered. The composite slab was represented by shell finite elements. The present investigation considered that both materials (steel and concrete) have an elastic behaviour. The computational model is illustrated in Figure 6.

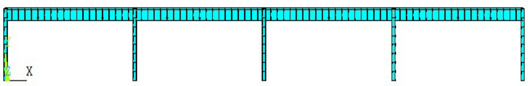


a) Finite element model



b) Top view

Elements	: 32036
BEAM44	: 3920
SHELL63	: 25600
COMBIN39	: 2516
Nodes	: 29874
DOF	: 166589



c) Plan XY view

Figure 6: Composite floor finite element model mesh and layout.

When the complete interaction between the concrete slab and steel beams was considered in the analysis, the numerical model coupled all the nodes between the beams and slab, to prevent the occurrence of any slip. On the other hand, to enable the slip between the concrete slab and the "I" steel profiles, to represent the partial interaction (steel-concrete) cases, the modelling strategy used nonlinear spring elements simulating the shear connector actions. The adopted shear connector force versus displacement curves were based on experimental tests [10].

The structural behaviour of the semi-rigid connections present in the investigated structural model was simulated by spring elements, which incorporates the geometric nonlinearity and the hysteretic behaviour effects. The moment versus rotation curve related to the adopted semi-rigid connections was also based on experimental data [11].

5 Dynamic Analysis

For practical purposes, a nonlinear time-domain analysis was performed throughout this study. This section presents the evaluation of the steel-concrete composite floor vibration levels when submitted to human rhythmic activities. The steel-concrete composite floor dynamic response was determined through an analysis of its natural frequencies and peak accelerations. The results of the dynamic analysis were obtained from an extensive parametric analysis, based on the finite element method using the ANSYS program [8].

In order to evaluate quantitative and qualitatively the obtained results according to the proposed methodology, the composite floor peak accelerations were calculated and compared to design recommendations limiting values [6, 9]. This comparison was made to access a possible occurrence of unwanted excessive vibration levels and human discomfort.

5.1 Natural Frequencies and Vibration Modes

The composite floor natural frequencies (associated to complete and partial interaction cases) were determined with the aid of the numerical simulations, see Tables 3 and 4, while the corresponding vibration modes are shown in Figure 7.

Frequencies (Hz)	Total Interaction			Partial Interaction (50%)		
	Rigid	Semi-rigid	Flexible	Rigid	Semi-rigid	Flexible
f_{01}	6.49	6.08	5.93	6.32	5.91	5.76
f_{02}	6.61	6.33	6.22	6.45	6.19	6.05
f_{03}	6.95	6.44	6.50	6.76	6.27	6.31
f_{04}	6.95	6.63	6.50	6.77	6.46	6.31
f_{05}	7.02	6.87	6.76	6.87	6.72	6.58
f_{06}	7.16	6.99	6.88	7.01	6.83	6.68

Table 3: Composite floor natural frequencies (Stud 13mm and Sj = 65kN/mm).

Frequencies (Hz)	Total Interaction			Partial Interaction (50%)		
	Rigid	Semi-rigid	Flexible	Rigid	Semi-rigid	Flexible
f_{01}	6.55	6.11	5.98	6.39	5.98	5.84
f_{02}	6.67	6.38	6.27	6.52	6.26	6.13
f_{03}	7.01	6.50	6.35	6.84	6.35	6.19
f_{04}	7.02	6.69	6.56	6.85	6.54	6.40
f_{05}	7.22	6.92	6.81	6.94	6.79	6.67
f_{06}	7.27	7.10	6.99	7.11	6.97	6.83

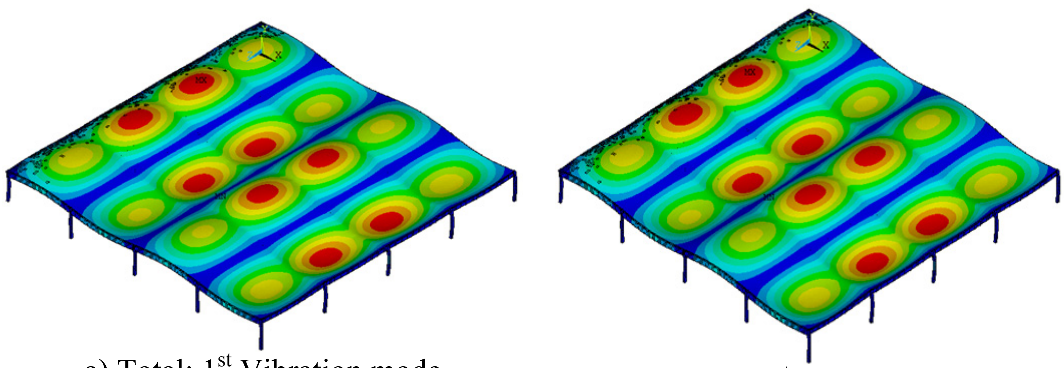
Table 4: Composite floor natural frequencies (Stud 19mm and Sj = 200kN/mm).

The structural behaviour of the connections present in the investigated structural model was also simulated, considering rigid, semi-rigid and flexible joints, objectifying to verify the influence of these connections on the composite floor dynamic response. The moment versus rotation curve related to the semi-rigid connections was based on experimental data [11].

Considering the investigated composite floor natural frequencies, a small difference between the numerical results obtained with the use of total interaction or partial interaction (50%) can be observed. The largest difference between the natural frequencies was approximately equal to 5%, as presented in Tables 3 and 4.

Another interesting fact concerned that when the joints flexibility (rigid to flexible) and steel-concrete interaction degree (total to partial) decreases the composite floor natural frequencies become smaller. This conclusion is very important due to the fact that the structural system becomes more susceptible to excessive vibrations induced by human rhythmic activities.

The Figure 7 presents the composite floor vibration modes when total and partial interaction situations were considered in the numerical analysis. It must be emphasized that the composite floor vibration modes didn't present significant modifications when the connections flexibility and steel-concrete interaction was changed. It must be emphasized that the structural model presented vibration modes with predominance of flexural effects, as illustrated in Figure 7



a) Total: 1st Vibration mode (f_{01}=6.11Hz)

b) Partial: 1st Vibration mode (f_{01}=5.98Hz)

Figure 7: Structural model vibration modes (total and partial interaction).

5.2 Peak Accelerations

The present study proceeded with the evaluation of the structural model performance in terms of human comfort and vibration serviceability limit states. The peak acceleration analysis was focused in aerobics and considered a contact period carefully chosen to simulate this human rhythmic activity on the analysed composite floor.

The present investigation have considered a contact period, simulating aerobics on the composite floor, T_c, equal to 0.34s (T_c = 0.34s) and the period without contact with the structure, T_s, of 0.10s (T_s = 0.10s). Based on the experimental results [7], the composite floors dynamic behaviour was evaluated keeping the impact coefficient value, K_p, equal to 2.78 (K_p = 2.78). Figures 8 and 9 illustrate the dynamic response (displacements and accelerations) related to nodes A and B (see Figure 5) when thirty two people are practising aerobics on the composite floor.

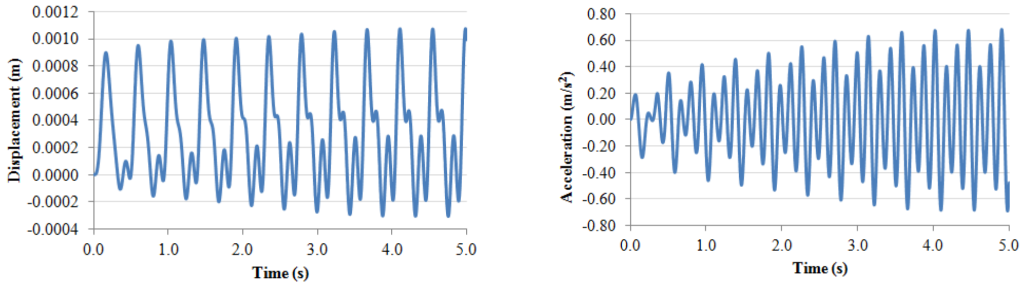


Figure 8: Composite floor dynamic response (Semi-rigid connections and Partial Interaction): Node A

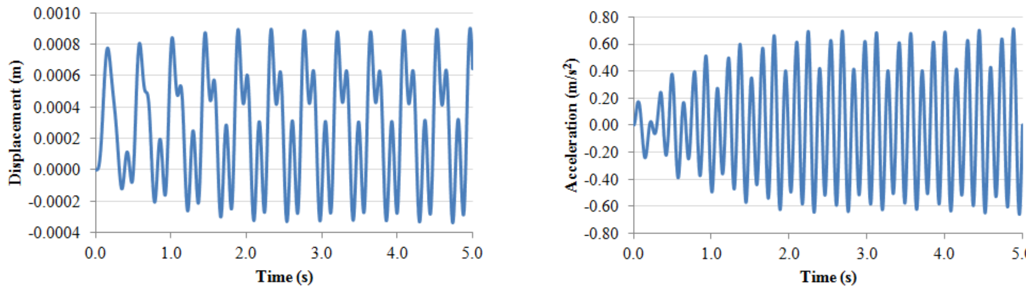


Figure 9: Composite floor dynamic response (Semi-rigid connections and Partial Interaction): Node B

Based on the results presented in Figures 8 and 9, it is possible to verify that the dynamic actions coming from aerobics, represented by the dynamic loading model (see Figure 5), have generated peak accelerations higher than 0.5%g [6, 9]. This trend was confirmed in several other situations [1, 2], where the human comfort criterion was violated.

In sequence, Tables 5 and 6 show the peak accelerations, a_p, corresponding to nodes A to H (see Figure 5), when thirty two dynamic loadings, simulating individual practising aerobics were applied on the investigated composite (steel-concrete) floor.

The results presented in Tables 5 and 6 have indicated that when the joints flexibility (rigid to flexible) and steel-concrete interaction degree (total to partial) decreases the composite floor peak accelerations become larger. These variations (joints flexibility and steel-concrete interaction) were very relevant to the composite floor non-linear dynamic response when the human comfort analysis was considered.

Interaction	Model	a_p (m/s^2) Node A	a_p (m/s^2) Node B	a_p (m/s^2) Node C	a_p (m/s^2) Node D
Complete	Rigid	0.26	0.17	0.17	0.26
	Semi-rigid	0.28	0.20	0.20	0.28
	Flexible	0.30	0.44	0.43	0.30
Partial (50%)	Rigid	**0.53**	0.36	0.36	**0.53**
	Semi rigid	**0.62**	**0.63**	**0.63**	**0.62**
	flexible	**0.60**	**0.80**	**0.80**	**0.60**
Limiting Acceleration: $a_{lim} = 0.5 m/s^2$ [6, 9]					

Table 5: Composite floor peak accelerations: Nodes A, B, C and D (see Figure 5).

Interaction	Model	a_p (m/s^2) Node E	a_p (m/s^2) Node F	a_p (m/s^2) Node G	a_p (m/s^2) Node H
Complete	Rigid	0.035	0.035	0.035	0.035
	Semi rigid	0.087	0.036	0.036	0.087
	flexible	0.088	0.09	0.09	0.088
Partial (50%)	Rigid	0.30	0.13	0.13	0.30
	Semi-rigid	0.40	0.14	0.14	0.40
	Flexible	0.32	0.24	0.24	0.32
Limiting Acceleration: $a_{lim} = 0.5 m/s^2$ [6, 9]					

Table 6: Composite floor peak accelerations: Nodes E, F, G and H (see Figure 5).

The results presented in Tables 5 and 6 have indicated that individuals practising aerobics on the structural model led to peak acceleration values higher than 0.50 m/s^2 (5%g) [6, 9], when the composite floors was submitted to thirty two individuals practising aerobics (see Figure 5), violating the human comfort criteria, see Tables 5 and 6. However, these peak acceleration values tend to decrease when the floor dynamic response obtained on the nodes E to H (see Figure 5) was compared to the response of nodes A to D (see Figure 5), see Tables 5 and 6.

6 Conclusions

The main objective of this paper was to investigate the influence of steel-concrete interaction degree (from total to various levels of partial interaction) over the composite floors non-linear dynamic behaviour. An extensive parametric analysis was developed focusing in the determination of the influence of the steel-concrete interaction over the composite floors non-linear dynamic response, when subjected to human rhythmic activities.

The investigated structural model was based on a steel-concrete composite floor spanning 40m by 40m, with a total area of 1600m^2. The structural system consisted of a typical composite floor of a commercial building. The composite floor studied in this work is supported by steel columns and is currently subjected to human rhythmic loads. The structural system is constituted of composite girders and a 100mm thick concrete slab.

The proposed computational model adopted the usual mesh refinement techniques present in finite element method simulations, based on the ANSYS program. This numerical model enabled a complete dynamic evaluation of the investigated steel-concrete composite floor especially in terms of human comfort and its associated vibration serviceability limit states.

The influence of the investigated connectors (Stud Bolts: 13mm and 19mmm) on the composite floor natural frequencies was very small, when the steel-concrete interaction degree (total to partial) was considered. The largest difference was approximately equal to 5%. On the other hand, when the joints flexibility (rigid to flexible) and steel-concrete interaction degree (total to partial) decreases the composite floor natural frequencies become smaller. This fact is very relevant because the system becomes more susceptible to excessive vibrations.

The composite floor vibration modes didn't present significant modifications when the connections flexibility and steel-concrete interaction was changed. The investigated structure presented vibration modes with predominance of flexural effects. The results have indicated that when the joints flexibility (rigid to flexible) and steel-concrete interaction degree (total to partial) decreases the composite floor peak accelerations become larger.

The maximum acceleration value was equal to 0.80m/s^2 (a_p = 0.80 m/s^2: flexible model) and 0.63m/s^2 (a_p = 0.63 m/s^2: semi-rigid model), while the maximum accepted peak acceleration value is equal to 0.50m/s^2 (a_{lim} = 0.50m/s^2). The structural system peak accelerations were compared to the limiting values proposed by several authors and design standard. The current investigation indicated that human rhythmic activities could induce the steel-concrete composite floors to reach unacceptable vibration levels and, in these situations, lead to a violation of the current human comfort criteria for these specific structures.

Acknowledgements

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