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Chapter 11

An Analysis of the Beam-to-Beam Connections Effect and Steel-Concrete Interaction Degree Over the Composite Floors Dynamic Response

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1. Introduction

Nowadays steel and composite (steel-concrete) building structures are more and more becoming the modern landmarks of urban areas. Designers seem to continuously move the safety border, in order to increase slenderness and lightness of their structural systems. However, more and more steel and composite floors are carried out as light weight structures with low frequencies and low damping. These facts have generated very slender composite floors, sensitive to dynamic excitation, and consequently changed the serviceability and ultimate limit states associated to their design.

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. On the other hand, 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.

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Considering all aspects mentioned before, the main objective of this paper is to investigate the beam-to-beam connections effect (rigid, semi-rigid and flexible) and the influence of steel-concrete interaction degree (from total to various levels of partial interaction) over the non-linear dynamic behaviour of composite floors when 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 evaluation of the beam-to-beam connections effect and the influence of steel-concrete interaction degree over the investigated 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 standards [6,9]. 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 Rhythmic Activities

The description of the dynamic 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 dynamic actions [1-6].

Several investigations 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

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dynamic load [1-6]. 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 simulate human activities like aerobics, 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. Figure 2 and the Table 1 illustrate 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 2 presents the experimental parameters used for human rhythmic activities representation and Figure 3 presents examples of dynamic action related to human rhythmic activities investigated in this work.

$$F(t) = CD\left\{K_p P\left[0.5 - 0.5\cos\left(\frac{2\pi}{T_c}t\right)\right]\right\} \qquad (1)$$
$$F(t) = 0$$

When $t \le T_c$

When $T_c \le t \le T$

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

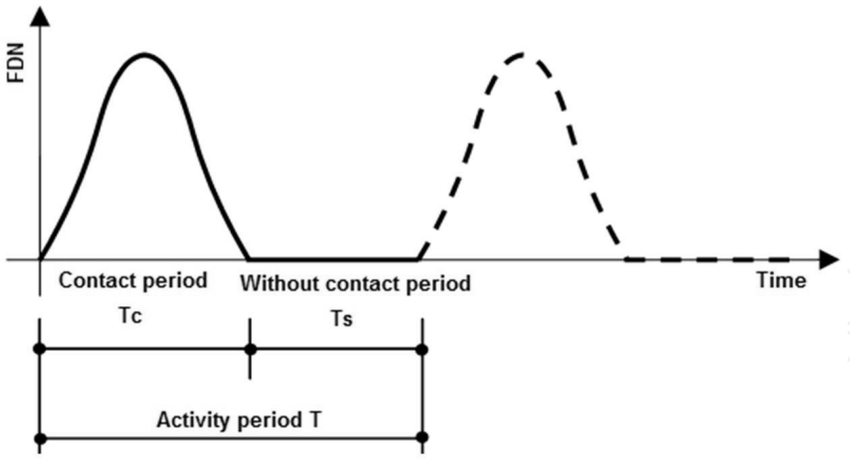


Figure 1. Representation of the dynamic loading induced by human rhythmic activities.

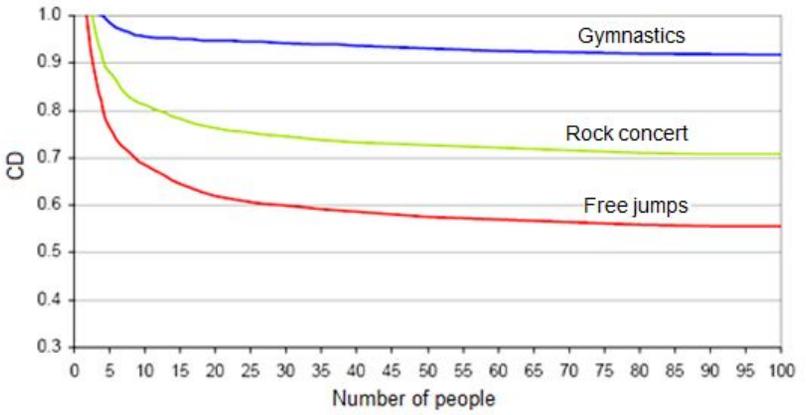


Figure 2. Variation of the phase coefficient CD for human rhythmic activities [7].

People number	Aerobics gymnastics	Free Jumps
1	1	1
3	1	0.88
6	0.97	0.74
9	0.96	0.70
12	0.95	0.67
16	0.94	0.64
24	0.93	0.62
32	0.92	0.60

Table 1. Numeric values adopted for the phase coefficient CD [7].

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
Show	0.37±0.03	0.37±0.03	2.41±0.51

Table 2. Experimental parameters used for human rhythmic activities representation [7].

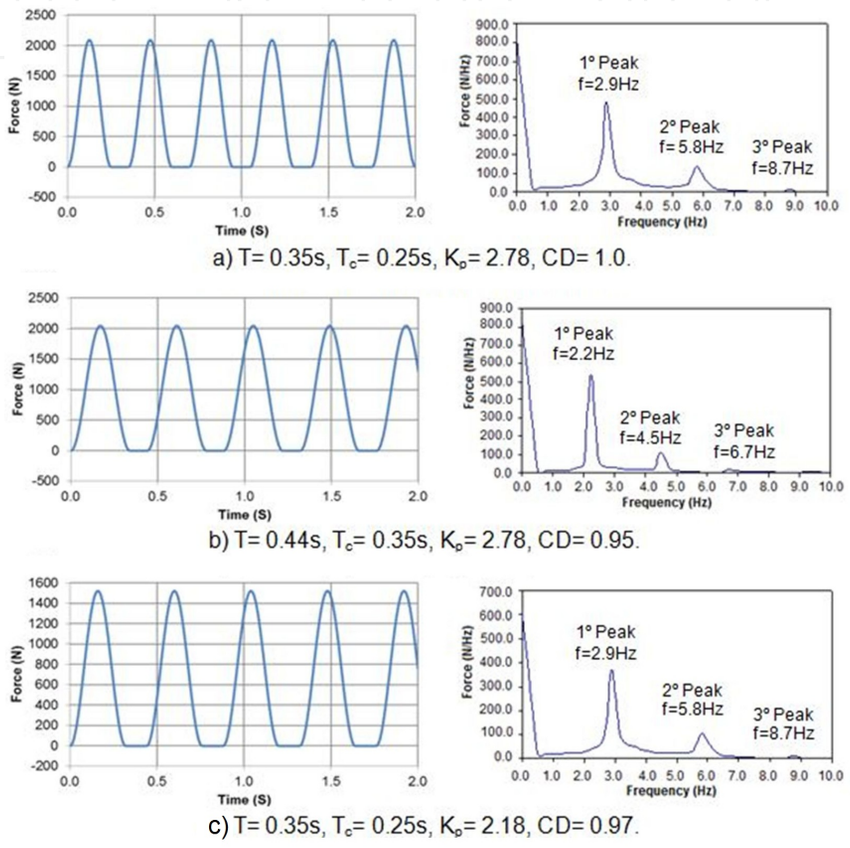


Figure 3. Dynamic loading induced by human rhythmic activities.

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 floor studied in this work is supported by steel columns and is currently submitted to human rhythmic loads. The model is constituted of composite girders and a 100mm thick concrete slab [1,2], see Figures 4 and 5.

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 3 depicted the geometric characteristics of the steel beams and columns.

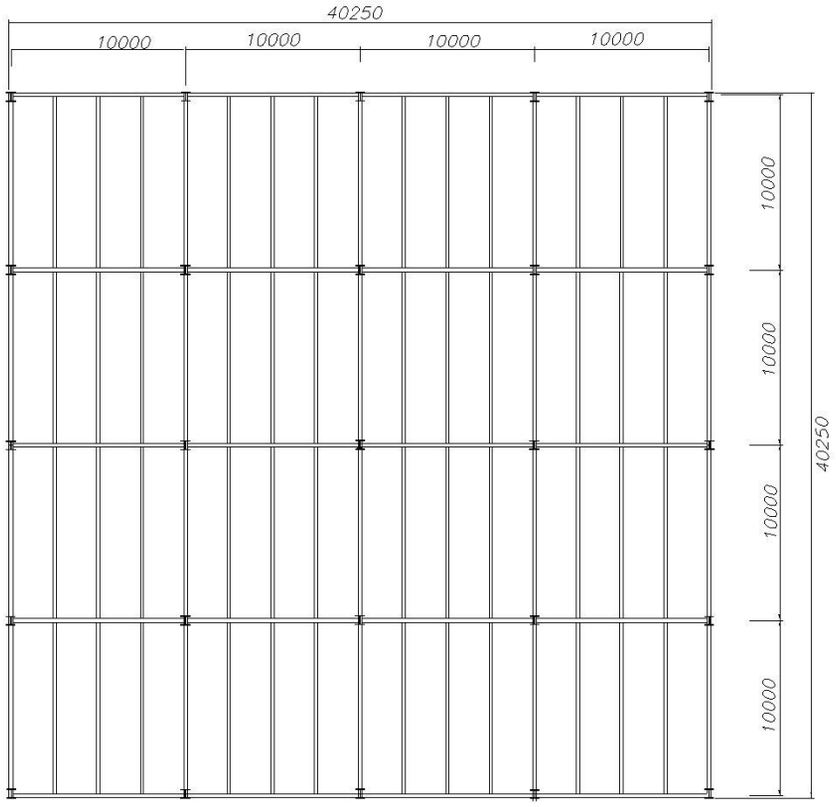


Figure 4. Structural model: composite floor (steel-concrete). Dimensions in (mm).

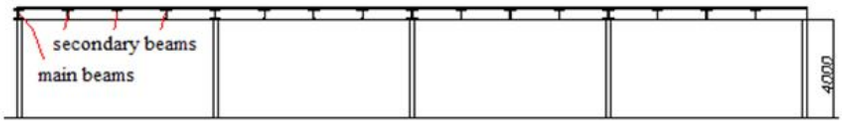


Figure 5. Cross section of the generic models. Dimensions in (mm).

Profile Type	Height (d)	Flange Width (b_f)	Top Flange Thickness (t_f)	Bottom Flange Thickness (t_f)	Web Thickness (t_w)
Main Beams (W610x140)	617	230	22.2	22.2	13.1
Secondary Beams (W460x60)	455	153	13.3	13.3	8.0
Columns (HP250x85)	254	260	14.4	14.4	14.4

Table 3. Geometric characteristics of the building composite floor (mm).

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The human-induced dynamic action was applied on the aerobics area, see Figure 6. 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, as illustrated in Figure 8. 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 8. 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].

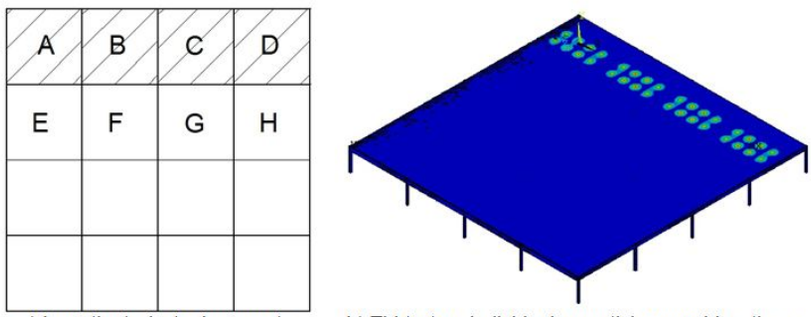


Figure 6. Dynamic loading: thirty two individuals practising aerobics on the investigated floor.

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]. The present investigation considered that both materials (steel and concrete) have an elastic behaviour. The finite element model is illustrated in Figure 7.

In this computational model, all "I" steel sections, related to beams and columns, were represented by three-dimensional beam elements (BEAM44 [8]) with tension, compression, torsion and bending capabilities. These elements have six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about x, y, and z axes, see Figure 8.

On the other hand, the reinforced concrete slab was represented by shell finite elements (SHELL63 [8]). This finite element has both bending and membrane capabilities. Both in-plane and normal loads are permitted. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z axes, see Figure 8.

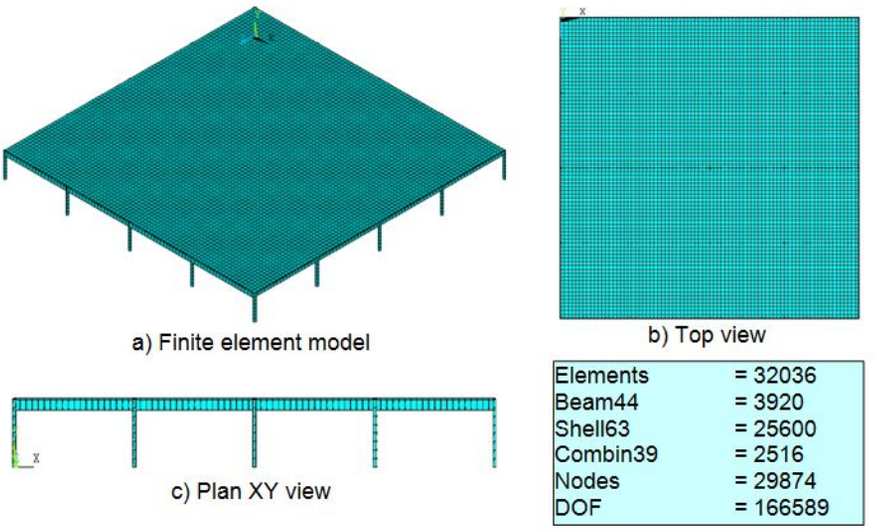


Figure 7. Steel-concrete composite floor finite element model mesh and layout.

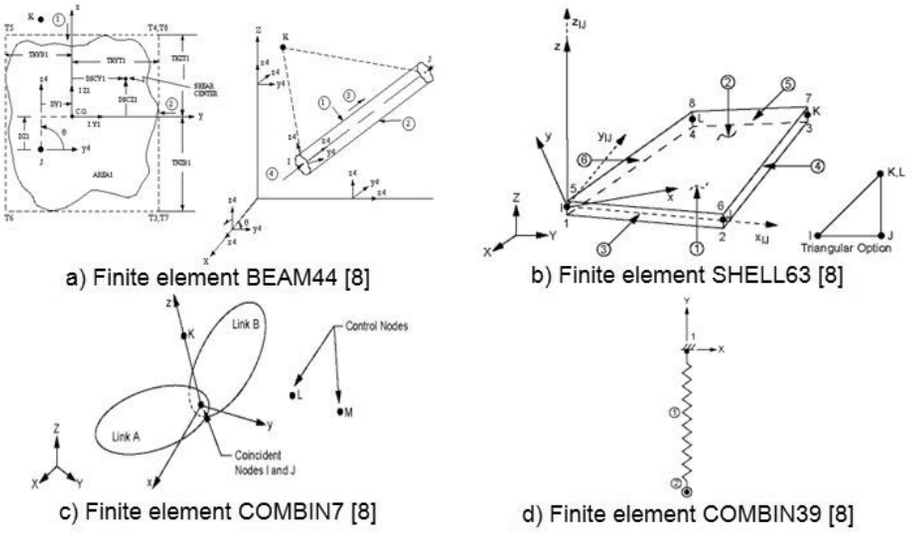


Figure 8. Finite elements used in the computational modelling.

The structural behaviour of the beam-to-beam connections (rigid, semi-rigid and flexible) present in the investigated composite floor was simulated by non-linear spring elements (COMBIN7 and COMBIN39 [8]), see Figure 8, which incorporates the geometric nonlinearity and the hysteretic behaviour effects. The moment versus rotation curve related to the adopted semi-rigid connections was based on experimental data [10], see Figure 9.

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

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slab and the "I" steel profiles, to represent the partial interaction (steel-concrete) cases, the modelling strategy used non-linear spring elements (COMBIN39 [8]), see Figure 8, simulating the shear connector actions. The adopted shear connector force versus displacement curves were also based on experimental tests [11,12], see Figure 10.

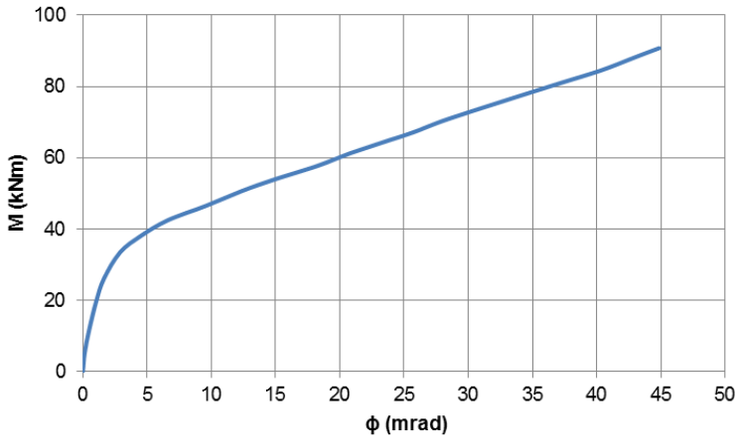


Figure 9. Moment versus rotation curve: beam-to-beam semi-rigid connections [10].

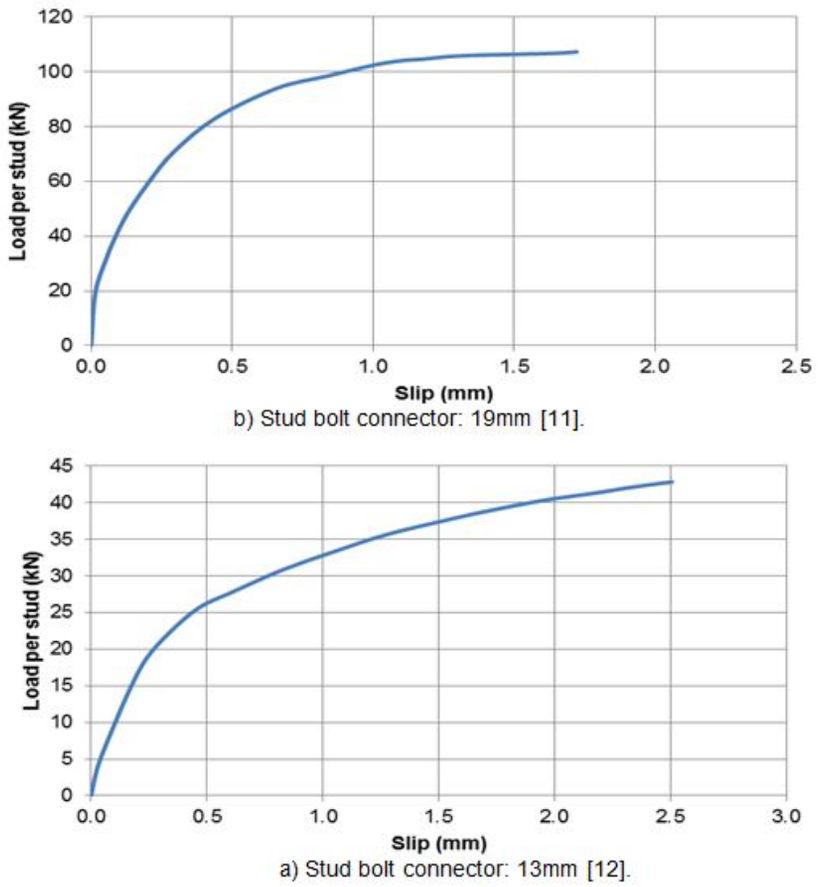


Figure 10. Force versus slip curve: shear connectors.

5. Dynamic Analysis

For practical purposes, a non-linear time-domain analysis was performed throughout this study. This section presents the evaluation of the composite floor vibration levels when submitted to human rhythmic activities. The 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 steel-concrete composite floor natural frequencies were determined with the aid of the numeric simulations, see Tables 4 and 5. The structural behaviour of the beam-to-beam connections (rigid, semi-rigid and flexible joints) and the stud connectors (from total to various levels of partial interaction cases) present in the investigated structural model were simulated objectifying to verify the influence of these connections and the steel-concrete interaction degree on the composite floor dynamic response.

Frequencies (Hz)	Total Interaction			Partial Interaction (50%)		
	Rigid	Semi-rigid	Flexible	Rigid	Semi-rigid	Flexible
f_{01}	6.57	6.14	6.00	6.32	5.91	5.76
f_{02}	6.69	6.41	6.30	6.45	6.19	6.05
f_{03}	7.03	6.52	6.37	6.76	6.27	6.31
f_{04}	7.04	6.71	6.58	6.77	6.46	6.31
f_{05}	7.11	6.97	6.85	6.87	6.72	6.58
f_{06}	7.28	7.10	6.98	7.01	6.83	6.68

Table 4. Composite floor natural frequencies (Beam-to-beam semi-rigid connections: S_j = 12kNmm/rad. Stud 13mm: S_j = 65kN/mm).

Considering the investigated composite floor natural frequencies, a small difference between the numeric 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% to 7%, as presented in Tables 4 and 5 and illustrated in Figure 11.

Another interesting fact concerned that when the joints flexibility (rigid to flexible) and steel-concrete interaction degree (from total to partial) decreases the composite floor natural frequencies become smaller, see Tables 4 and 5. This conclusion is very important due to the

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fact that the structural system becomes more susceptible to excessive vibrations induced by human rhythmic activities.

Frequencies (Hz)	Total Interaction			Partial Interaction (50%)		
	Rigid	Semi-rigid	Flexible	Rigid	Semi-rigid	Flexible
f_{01}	6.63	6.18	6.06	6.39	5.98	5.84
f_{02}	6.75	6.46	6.36	6.52	6.26	6.13
f_{03}	7.10	6.58	6.43	6.84	6.35	6.19
f_{04}	7.11	6.77	6.65	6.85	6.54	6.40
f_{05}	7.17	7.02	6.91	6.94	6.79	6.67
f_{06}	7.35	7.16	7.05	7.08	6.91	6.78

Table 5. Composite floor natural frequencies (Beam-to-beam semi-rigid connections: S_j = 12kNmm/rad. Stud 19mm: S_j = 200kN/mm).

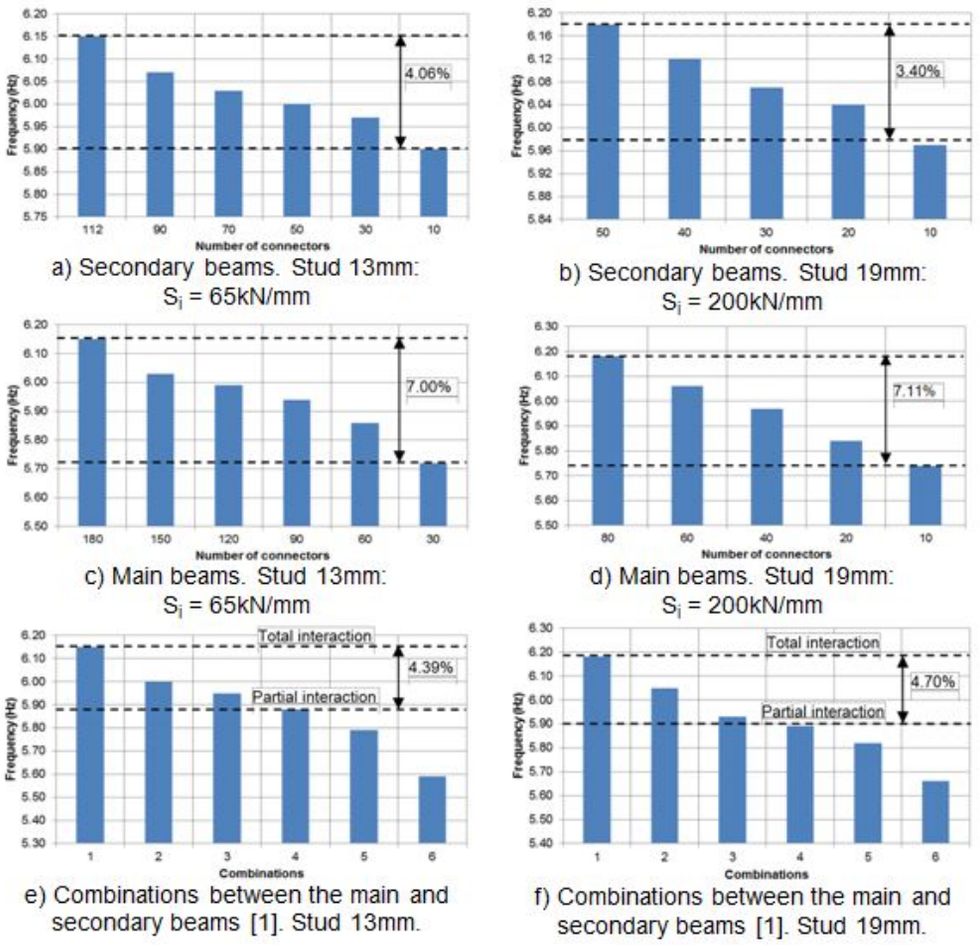


Figure 11. Steel-concrete composite floor fundamental frequency (f_{01}) variation.

In sequence, Figure 12 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 12.

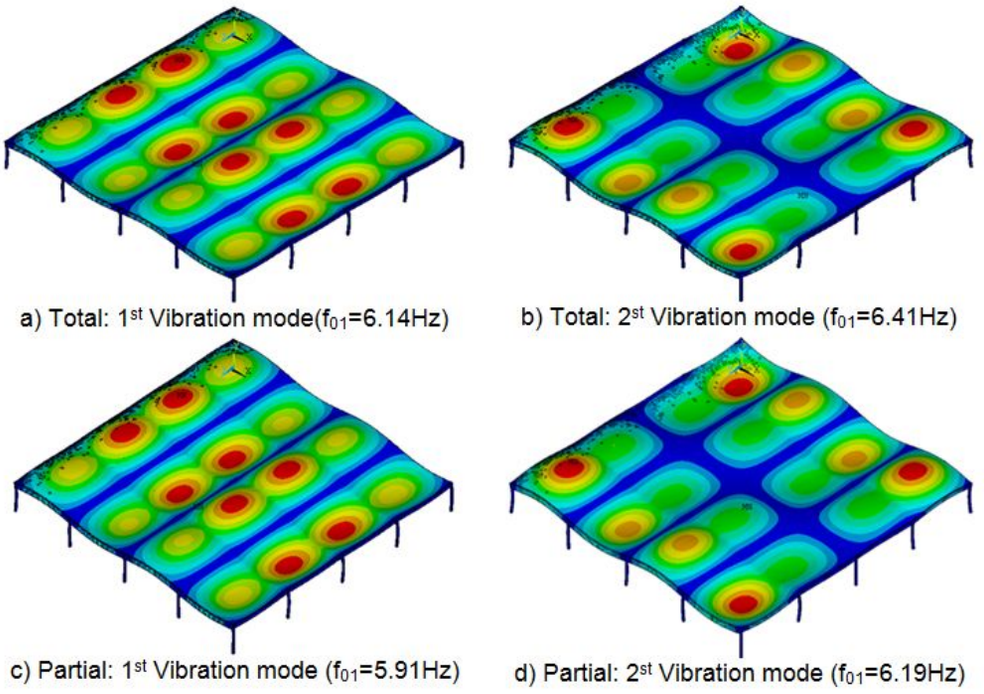


Figure 12. Investigated structural model vibration modes (total and partial interaction).

5.2. Maximum accelerations (peak accelerations) analysis

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 work 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 floor dynamic behaviour was evaluated keeping the impact coefficient value, K_p, equal to 2.78 (K_p = 2.78). Figures 13 and 14 illustrate the dynamic response (displacements and accelerations) related to nodes A and B (see Figure 6) when thirty two people are practising aerobics on the composite floor.

Based on the results presented in Figures 13and 14, it is possible to verify that the dynamic actions coming from aerobics, represented by the dynamic loading model (see Equation (1)

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and Figure 6), 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.

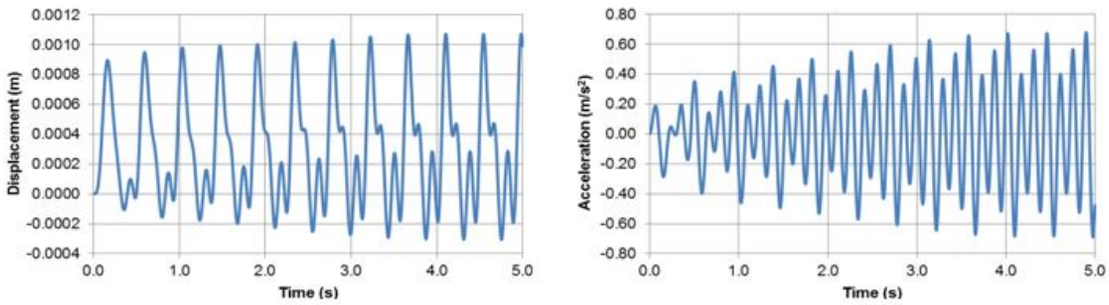


Figure 13. Composite floor dynamic response. Semi-rigid connections and partial interaction): Node A.

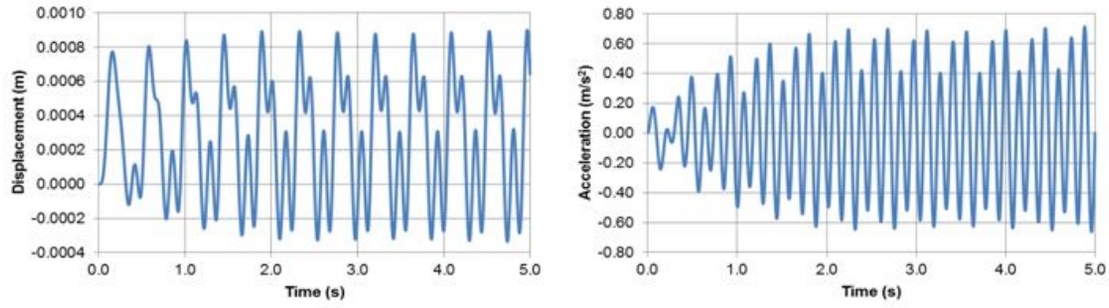


Figure 14. Composite floor dynamic response (Semi-rigid connections and partial interaction): Node B.

In sequence of the study, Tables 6 and 7 show the peak accelerations, a_p (m/s^2), corresponding to nodes A to H (Figure 6), when thirty two dynamic loadings, simulating individual practising aerobics were applied on the composite floor.

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} = 0.50m/s^2 (5%g - g: gravity) [6,9]					

Table 6. Composite floor peak accelerations: Nodes A, B, C and D (see Figure 6).

Interaction	Model	a_p (m/s²) Node E	a_p (m/s²) Node F	a_p (m/s²) Node G	a_p (m/s²) 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} = 0.50m/s² (5%g - g: gravity) [6,9]					

Table 7. Composite floor peak accelerations: Nodes E, F, G and H (see Figure 6).

The results presented in Tables 6 and 7 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.

It must be emphasized that individuals practising aerobics on the structural model led to peak acceleration values higher than 5%g [6,9], when the composite floor was submitted to thirty two people practising aerobics, violating the human comfort criteria (a_{max} = 0.50m/s²> a_{lim} = 0.50m/s²), see Tables 6 and 7. However, these peak acceleration values tend to decrease when the floor dynamic response obtained on the nodes E to H (see Figure 6) was compared to the response of nodes A to D (see Figure 6), see Tables 6 and 7.

6. Final Remarks

The main objective of this paper was to investigate the beam-to-beam structural connections effect (rigid, semi-rigid and flexible) and the influence of steel-concrete interaction degree (from total to various levels of partial interaction) over the non-linear dynamic behaviour of composite floors when subjected to human rhythmic activities. This way, an extensive parametric analysis was developed focusing in the determination quantitative aspects of the composite floors dynamic response.

The investigated structural model was based on a steel-concrete composite floor spanning 40m by 40m, with a total area of 1600m². 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.

The proposed computational model adopted the usual mesh refinement techniques present in finite element method simulations, based on the ANSYS program. The 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 19mm) on the composite floor natural frequencies was very small, when the steel-concrete interaction degree (from total to partial) was considered in the analysis. The largest difference was approximately equal to 5% to 7%.

On the other hand, when the joints flexibility (rigid to flexible) and steel-concrete interaction degree (from 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 found in this work 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) [6,9]. The structural system peak accelerations were compared to the limiting values proposed by several authors and design standard [6,9]. 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.

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