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Vibration Analysis of Long Span Joist Floors Submitted to Human Rhythmic Activities

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1. Introduction

In the last years, 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 (steel-concrete) 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.

The increasing incidence of building vibration problems due to human rhythmic activities led to a specific design criterion for rhythmic excitations to be addressed in structural design (Allen et al. 1985); (Almeida, 2008); (Almeida et al., 2008); (Bachmann & Ammann, 1987); (Faisca, 2003); (Ji & Ellis, 1994); (Langer, 2009); (Murray et al., 2003); (Silva et al., 2008). This was the main motivation for the development of a design methodology centred on the structural system dynamical response submitted to dynamic loads due to human activities.

This paper investigated the dynamic behaviour of composite floors (steel-concrete) subjected to the human rhythmic activities. The dynamic loads were obtained through experimental tests conducted with individuals carrying out rhythmic and non-rhythmic activities such as stimulated and non-stimulated jumping and aerobics (Faisca, 2003).

The description of the 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 relevant factors when the dynamic action is defined. Numerous investigations were made aiming to establish parameters to describe such dynamic loads (Allen et al. 1985); (Bachmann & Ammann, 1987); (Faisca, 2003); (Murray et al., 2003).

The present investigation considered the dynamic loads, based on results achieved through a long series of experimental tests made with individuals carrying out rhythmic and non-rhythmic activities. This investigation described these dynamic loads, generated by human activities, such as jumps with and without stimulation, aerobics, soccer, rock concert audiences and dancing (Faisca, 2003).

The load modelling was able to simulate human activities like aerobic gymnastics, dancing and free jumps. In this paper, the Hanning function was used to represent the human dynamic actions since it was verified that this mathematical representation was very similar to the signal force obtained through experimental tests (Faisca, 2003). Based on the experimental results, human load functions due to rhythmic and non-rhythmic activities were proposed.

The computational model, developed for the composite floors dynamic analysis, adopted the usual mesh refinement techniques present in finite element method simulations implemented in the Ansys program (ANSYS, 2003). In the present computational model, the floor steel joists were represented by three-dimensional beam elements, considering flexural and torsion effects, while the composite slab was represented by shell finite elements.

The investigated structural model was associated to a floor composed by steel joists and a concrete slab. The structural system was a typical floor used as a restaurant with an adjacent dancing area (Almeida, 2008); (Almeida et al., 2008); (Murray et al., 2003); (Silva et al., 2008). The composite (steel-concrete) floor system consisted of long span (14m) joists supported by concrete block walls.

The floor effective weight was estimated to be equal to 3.6kPa, including 0.6kPa for people dancing and dining. The joists effective composite moment of inertia was selected based on its required strength, i.e., 1.1×10^6 mm⁴. This structural system geometry was based on a typical example described in literature (Almeida, 2008); (Almeida et al., 2008); (Murray et al., 2003); (Silva et al., 2008).

The parametric study considered correlations between analytical and numerical results found in literature. The peak acceleration values were compared to the limits proposed by design codes and recommendations (ISO 2631-2, 1989); (Murray et al., 2003), based on human comfort criteria. The results indicated that the limits suggested by the design recommendations were not satisfied. This fact indicated that these rhythmic activities could generate peak accelerations that surpass design criteria limits developed for ensuring human comfort.

2. Human-induced dynamic loads

Floor vibrations induced by human rhythmic activities like: walking, running, jumping or even aerobics consist on a very complex problem. This is due to the fact that the dynamical 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.

Human beings have always analysed the most apparent distinctions of the various activities they perform. However the fundamental mechanical analysis of these tasks was not possible before a significant development of the mechanical science. Initially the human motion received an incipient attention from researchers like Borelli in 1679 (Lehmkuhl & Smith, 1985) and the Weber brothers in 1836 (Lehmkuhl & Smith, 1985). The first pioneer on this field was Otto Fischer, a German mathematician that in 1895 made the first study containing a comprehensive evaluation of the forces involved in human motion.

In order to determine the dynamical behaviour of floor structural systems subjected to excitations from human activities, various studies have tried to evaluate the magnitude of these rhythmic loads. The following stage of this research line was the development of a

loading platform by Elftman (Lehmkuhl & Smith, 1985), that enable the determination of the ground reactions to the foot forces associated to the human walk motion. The typical force platform is made by an approximate 1m² steel plate supported by four small columns at the plate midsides. Load cells were installed at each of the columns to detect the magnitude of the load variation at these points. With these results in hand it was possible to determine the magnitude and direction of the forces transmitted to the supporting surface, denominated ground reaction forces.

Rainer also contributed in this investigation developing more sophisticated load platforms that recorded the ground reaction forces coming from the foot forces associated to the human motion (Rainer et al., 1987). Ebrahimpur developed a 14.2m length x 2m wide platform designed to record the actions from a single individual, or groups of two or four individual walk motion (Ebrahimpur, 1996).

Another load model used to represent the walk motion forces is expressed as a function of tests that recorded the heel impact over the floor. This load type, considered as the main excitation source during the human walk motion, produces a transient response, i.e., when the system is excited by an instantaneous force application. Its graphical representation was presented by Ohmart (Ohmart, 1968) in experiments denominated heel drop tests, where the individual drops its heel over the floor after elevating it to a height corresponding to its weight.

The heel drop test was also made by Murray and Hendrick in different building types (Murray & Hendrick, 1977). A 0.84kN impact force was measured by a seismograph in nine church ceremonial rooms, three slabs located at a shopping mall highest floor, two balcony slabs of a hotel and one slab located at a commercial building second floor. With these results in hand, the structural dynamic responses, in terms of the force amplitudes, frequencies and damping, associated to the investigated structural systems, could be determined.

Murray (Murray, 1975) classified the human vibration perception in four categories, i.e.: the vibration is not noticed by the occupants; the vibration is noticed but do not disturb the occupants; the vibration it is noticed and disturb the occupants; the vibration can compromise the security of the occupants. These categories were established based on 100 heel drop tests performed on composite floors made of steel beams and concrete slabs.

Allen et al. (Allen et al., 1985) proposed minimum values for the natural frequencies of structures evaluated according to the type of occupation and their main characteristics. These values were based on the dynamical load values produced by human rhythmic activities like dancing and aerobics and on the limit acceleration values associated to those activities.

A significant contribution to this field was made in Brazil by Alves (Alves, 1997) and Faisca (Faisca, 2003) based on experiments made with a group of volunteers acting on a concrete platform. These tests enabled the development of approximated descriptions of the loads induced by human activities such as: jumps, aerobics, soccer and rock show audience responses. These tests were executed over two concrete platforms, one rigid and the other flexible, both of them over movable supports. The experimental results analysis, allied to an analytical model, led to the development of load functions associated to synchronous and asynchronous activities that could be used in structural designs intended for stadiums and other related structures.

3. Loads generated by human activities

The description of the 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 relevant factors when the dynamic action is defined. Numerous investigations were made aiming to establish parameters to describe such loads (Allen et al. 1985); (Bachmann & Ammann, 1987); (Faisca, 2003); (Murray et al., 2003).

Several investigations described the loads 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 (Almeida, 2008); (Bachmann & Ammann, 1987); (Langer, 2009); (Murray et al., 2003); (Silva et al., 2008).

The present investigation considered the dynamic loads, based on results achieved through a long series of experimental tests made with individuals carrying out rhythmic and non-rhythmic activities (Faisca, 2003). These dynamic loads, generated by human activities, were described such as jumps with and without stimulation, aerobics, soccer, rock concert audiences and dancing.

The load modelling was able to simulate human activities like aerobic gymnastics, dancing and free jumps. In this paper, the Hanning function was used to represent the human dynamic actions since it was verified that this mathematical representation was very similar to the signal force obtained through experimental tests (Faisca, 2003).

The mathematical representation of the human dynamic loading is described by Equation (1). This expression requires some parameters like 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, see Fig. 1 and Table 1.

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

(1)

$$F(t) = 0, \text{ for } T_c < t \leq T$$

Where:
F(t)   : dynamic loading, in (N);
t   : time, in (s);
T   : activity period (s);
T_c : activity contact period (s);
P   : weight of the individual (N);
K_p : impact coefficient;
CD   : phase coefficient.

Figure 1 illustrates the phase coefficient variation, CD, for some human activities, initially, considering a few number of individuals and later extrapolating for a larger number of people (Faisca, 2003). Figure 2 presents an example of dynamic action related to human rhythmic activities using the following parameters: T = 0.53s, T_c = 0.43s, T_s = 0.10, K_p = 2.78 and CD = 1.0, see Table 1.
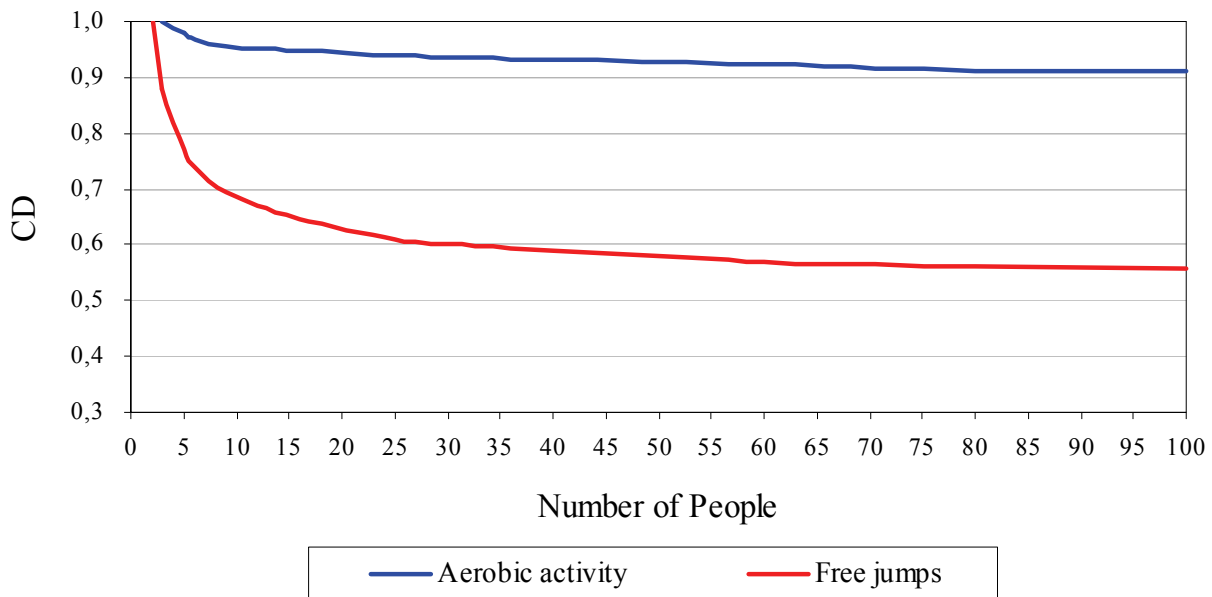
Fig. 1. Phase coefficients for the studied activities (Faisca, 2003)

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

Table 1. Parameters used for human rhythmic activities representation (Faisca, 2003)
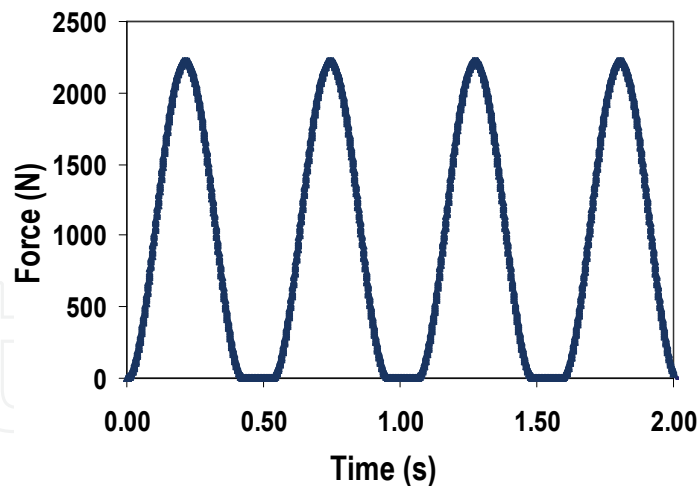

Fig. 2. Dynamic loads induced by dancing associated to the following parameters: T=0.53s, T_c=0.43s, T_s=0.10, K_p=2.78 and CD=1.0

4. Investigated structural model

The investigated structural model was associated to a floor composed by steel joists and a concrete slab, as presented in Figs. 3 to 6. The structural system was a typical floor used as a restaurant with an adjacent dancing area (Almeida, 2008); (Almeida et al., 2008); (Murray et al., 2003); (Silva et al., 2008).

The composite floor system consisted of long span (14m) joists supported by concrete block walls, see Figs. 3 to 6. The floor effective weight was estimated to be equal to 3.6kPa, including 0.6kPa for people dancing and dining. The joists effective composite moment of inertia was selected based on its required strength, i.e., 1.1×10^6 mm^4. This structural system geometry was based on a typical example described in literature (Almeida, 2008); (Almeida et al., 2008); (Murray et al., 2003); (Silva et al., 2008).

The adopted steel sections were made with a 300MPa yield stress steel grade. A 2.05×10^5 MPa Young's modulus was used for the steel joists. The concrete slab had a 30MPa specified compression strength and a 2.4×10^4 MPa Young's Modulus. The structural model geometrical characteristics are illustrated in Table 2.

Main Span	Bottom Chords	Top Chords	Vertical Members	Diagonals
14.0m	⌐L2x(1 ½″ x 1/8″)	⌐⌐2x(2″ x 1/8″)	L (½″ x 1/8″)	L (½″ x 1/8″)

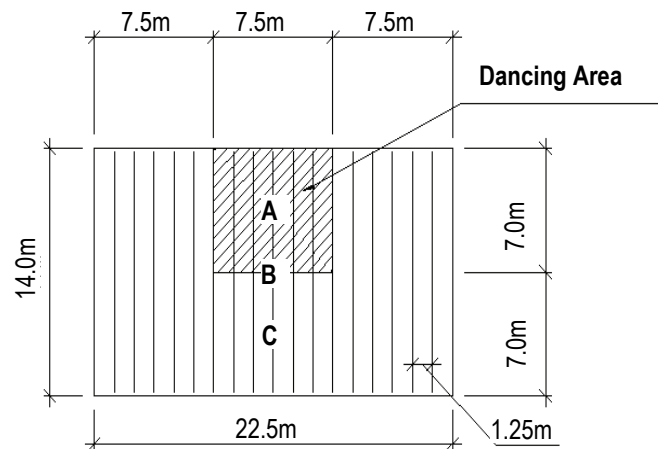Table 2. Structural model geometric properties

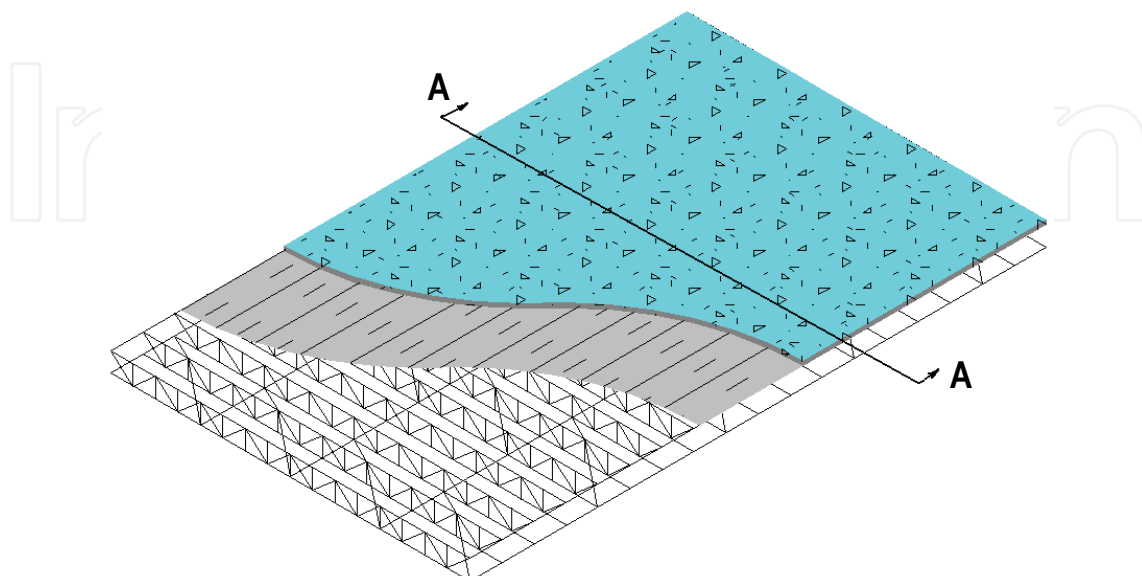Fig. 3. Dancing floor layout (dimensions in m)

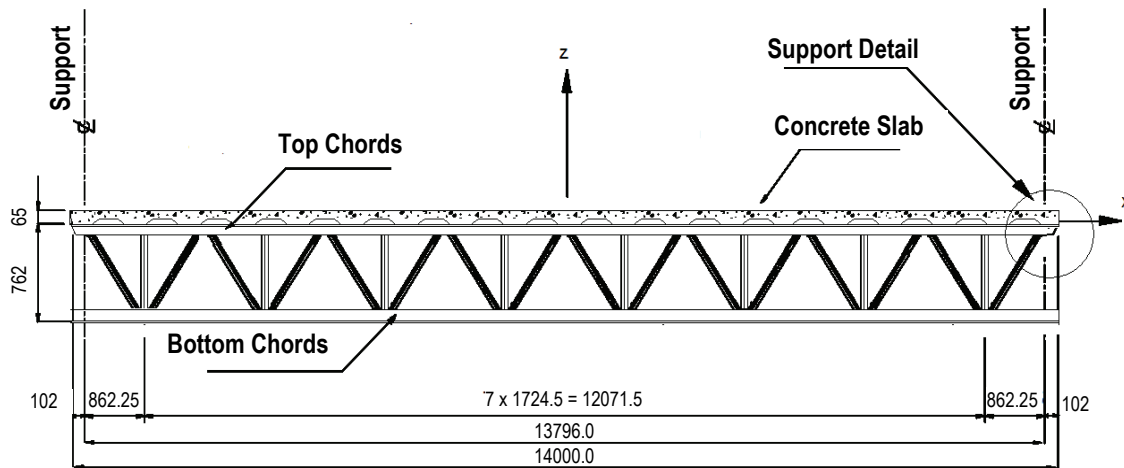Fig. 4. Structural model three-dimensional view

Fig. 5. Composite floor cross section - Section AA (dimensions in mm)
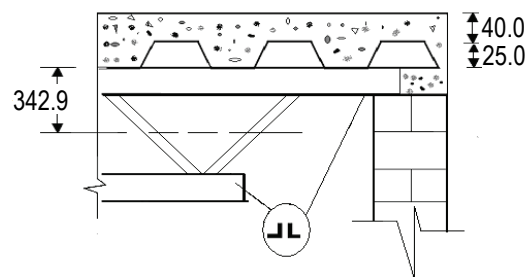

Fig 6. Support details (dimensions in mm)

The human-induced dynamic action was applied to the dancing area, see Figs. 3 and 7. The composite floor dynamical response, in terms of peak accelerations values, were obtained on the nodes A, B and C, to verify the influence of the dynamical loads on the adjacent slab floor, see Figs. 3 and 7. In the current investigation, the human rhythmic dynamic loads were applied to the structural model corresponding to the effect of 1, 3, 6, 9 and 12 individuals practicing aerobics or couples dancing.
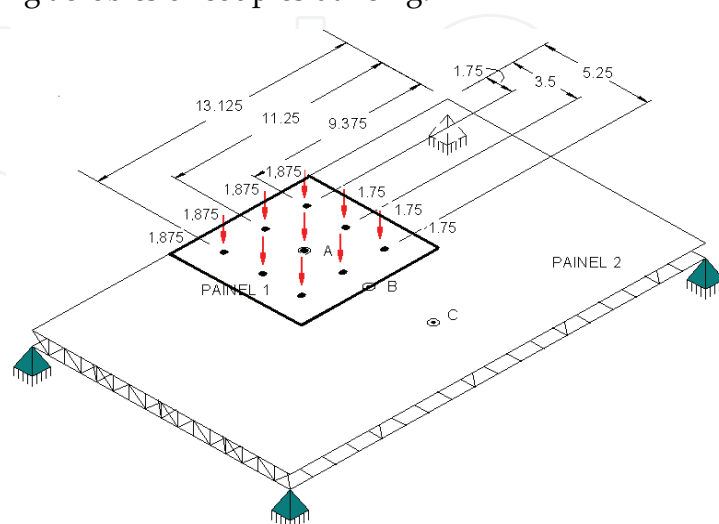

Fig. 7. Load distribution associated to nine individuals acting on the floor (dimensions in m)

The live load considered in this analysis corresponds to one individual for each 4.0m² (0.25 person/m²), (Bachmann & Ammann, 1987). The load distribution was considered symmetrically centred on the slab panel, as depicted in Fig. 7. The present investigation also assumed that an individual person weight was equal to 800N (0.8kN) (Bachmann & Ammann, 1987) and that the adopted damping ratio was equal to, ξ=3% (ξ = 0.03) in all studied cases (Almeida, 2008); (Almeida et al., 2008); (Murray et al., 2003); (Silva et al., 2008).

5. Finite element modelling

The proposed computational model, developed for the composite floors dynamic analysis, adopted the usual mesh refinement techniques present in finite element method simulations implemented in the ANSYS program (ANSYS, 2003). In the present computational model, the floor steel joists were represented by three-dimensional beam elements (BEAM44), with tension, compression, bending and torsion capabilities (ANSYS, 2003). The composite slab was represented by shell finite elements (SHELL63) (ANSYS, 2003), as illustrated in Fig. 8. In this investigation, it was considered that both materials (steel and concrete) presented total interaction and have an elastic behaviour. The finite element model has 11673 nodes, 5267 three-dimensional beam elements (BEAM44), 6912 shell elements (SHELL63) and 62568 degrees of freedom. The developed computational model is illustrated in Fig. 8.
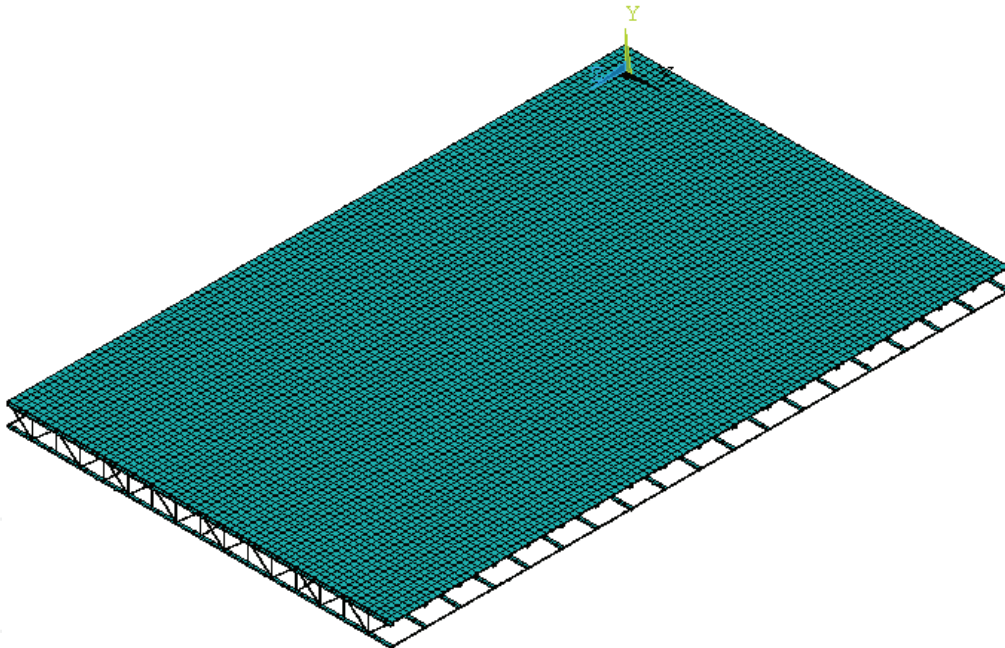

Fig. 8. Composite floor (joists and concrete slab) finite element model

6. Natural frequencies and vibration modes

The composite (steel-concrete) floor natural frequencies were determined with the aid of the numerical simulations, as illustrated in Table 3. The structural system vibration modes were illustrated in Fig. 9.

It can be clearly noticed from Table 3 results, that there is a very good agreement between the structural model fundamental frequency value calculated using finite element simulations and the AISC recommendation (Murray et al., 2003).

Such fact validates the numeric model here presented, as well as the results and conclusions obtained throughout this work. It must be emphasized that the structural model presented vibration modes with a predominance of flexural effects, as illustrated in Fig. 9.

Natural Frequencies (Hz)						AISC*	Error
f_{01}	f_{02}	f_{03}	f_{04}	f_{05}	f_{06}	f_{01}	%
5.70	5.91	6.13	6.42	6.56	7.89	5.80	2.0

*(Murray et al., 2003)

Table 3. Composite floor (steel-concrete) natural frequencies

a) Vibration mode associated to the first natural frequency: f_{01}=5.80 Hz.

b) Vibration mode associated to the second natural frequency: f_{02}=5.91 Hz.

c) Vibration mode associated to the third natural frequency: f_{03}=6.13 Hz.

d) Vibration mode associated to the fourth natural frequency: f_{04}=6.42 Hz.

e) Vibration mode associated to the fifth natural frequency: f_{05}=6.56 Hz.

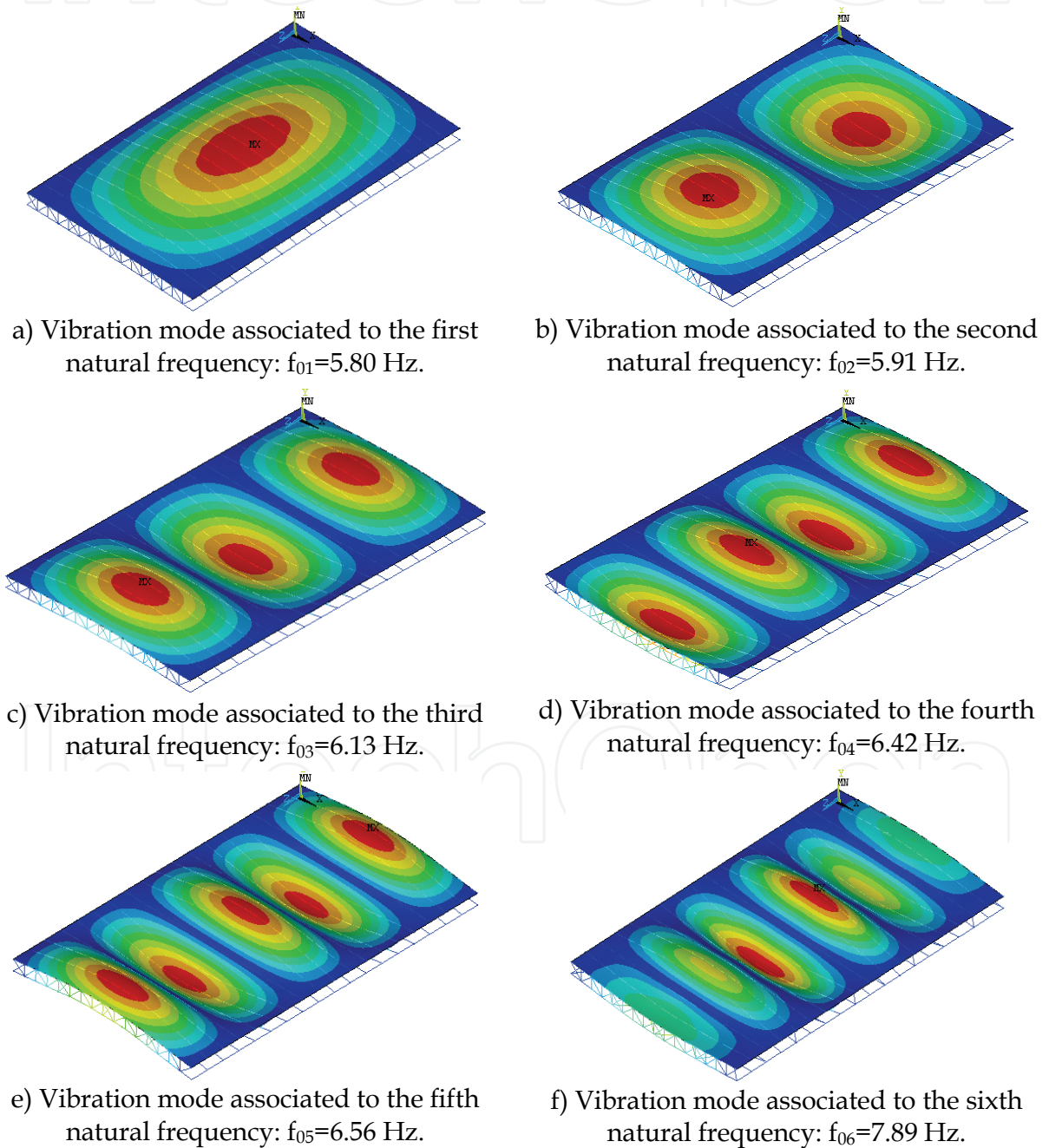f) Vibration mode associated to the sixth natural frequency: f_{06}=7.89 Hz.

Fig. 9. Composite floor (steel-concrete) vibration modes

7. Time domain analysis

For practical purposes, a linear time-domain analysis was also performed throughout this study. This section presents the evaluation of the structural systems vibrations levels when submitted to dynamic excitations coming from human rhythmic activities (aerobics and dancing).

The composite floor (steel-concrete) dynamic responses were determined through an analysis of its displacements and accelerations. The results of the dynamic analysis were obtained from an extensive numerical analysis, based on the finite element method using the ANSYS program (ANSYS, 2003).

Figures 10 and 11present the vertical displacement and acceleration, respectively, versus time graphs for the analysed composite floor (steel-concrete) at point A (see Figs. 3 and 7), when only one individual is acting on the structural model (aerobics).
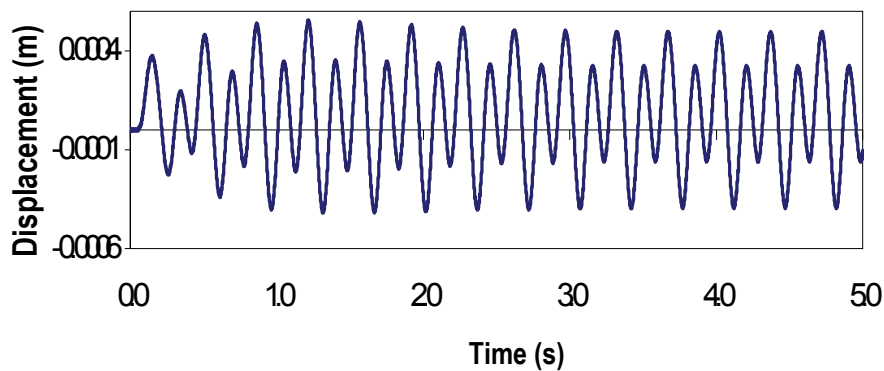

Fig. 10. Composite floor displacement response due to one individual practicing aerobics at Point A (see Figs. 3 and 7): T_c=0.25s, T_s=0.10s, K_p=2.78 and CD=1.
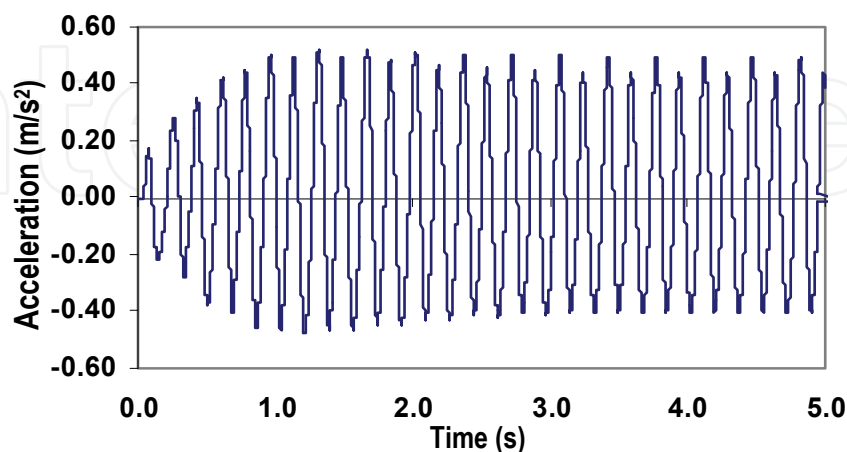

Fig. 11. Composite floor acceleration response due to one individual practicing aerobics at Point A (see Figs. 3 and 7): T_c=0.25s, T_s=0.10s, K_p=2.78 and CD=1.

Figures 10 and 11 show that, the vertical displacement and acceleration, at point A (see Figs. 3 and 7) of the structural model, gradually increase with time until the beginning of the composite floor steady state response, which occurred at the time of approximately 2.0 seconds. From this point (t = 2.0s) onwards, the maximum displacement and acceleration values were, respectively, equal to 0.051 cm and 0.55 m/s².

It must be emphasized that considering only one individual acting on the floor (aerobics) the calculated peak acceleration value ($a_p = 0.55 m/s^2$), was higher than limits proposed by design recommendations ($a_{lim} = 5\% g = 0.50 m/s^2$), violating the human comfort criteria (ISO 2631-2, 1989); (Murray et al., 2003).

8. Peak accelerations

The peak acceleration analysis was focused in dancing activities and considered a contact period carefully chosen to simulate dancing activities on the composite floor. The adopted parameters were: T_c, equal to 0.43s ($T_c = 0.43s$) and the period without contact to the structure, T_s, of 0.10s ($T_s = 0.10s$). Based on the experimental results (Faisca, 2003), the composite floors dynamic behaviour was evaluated keeping the impact coefficient value, K_p, equal to 2.78 ($K_p = 2.78$). Tables 4 and 5 depict the peak accelerations, a_p, corresponding to nodes A, B and C, see Figs. 3 and 7, when 1, 3, 6, 9 and 12 dynamical loads, simulating individual dancing, see Table 4, and couples dancing, see Table 5, were applied to the composite floor.

Nodes (see Fig. 3)	Number of individuals - a_p (m/s²)					ISO 2631-2 and AISC* (m/s²)
	1	3	6	9	12	
A	0.12	0.24	0.41	0.52	0.69	
B	0.11	0.28	0.53	0.72	0.88	0.50
C	0.07	0.17	0.31	0.42	0.54	
*(ISO 2631-2, 1989); (Murray et al., 2003)						

Table 4. Structural model peak accelerations corresponding to individuals dancing: T_c=0.43s; T_s=0.10s; K_p=2.78.

Nodes (See Fig. 3)	Number of couples - a_p (m/s²)					ISO 2631-2 and AISC* (m/s²)
	1	3	6	9	12	
A	0.23	0.47	0.83	1.05	1.36	
B	0.23	0.57	1.04	1.45	1.76	0.50
C	0.13	0.34	0.62	0.83	1.09	
*(ISO 2631-2, 1989); (Murray et al., 2003)						

Table 5. Structural model peak accelerations corresponding to couples dancing: T_c=0.43s; T_s=0.10s; K_p=2.78

It can be verified that the obtained peak acceleration values are proportional to an increase of the number of considered individuals, Tables 4 and 5. These values tend to decrease when the dynamical response obtained on the node C (see Figs. 3 and 7) was compared to the response of nodes A and B (see Figs. 3 and 7), as presented in Tables 4 and 5.

Based on the results presented in Table 4, it was possible to verify that dancing activities on the structural model, represented by Equation (1), led to peak accelerations higher than 0.50 m/s² (5%g) (ISO 2631-2, 1989); (Murray et al., 2003), when the composite floors was submitted to six individuals dancing, violating the human comfort criteria. The situation becomes even more significant when nine and twelve individuals were considered in the analysis, see Table 4.

On the other hand, when couples dancing were considered, the human comfort criterion was violated starting from cases associated with only three couples. It must be emphasized that in this situation the peak accelerations presented higher values when compared to individual dancing.

Observing the results illustrated in Tables 4 and 5, it was also possible to verify that the analyzed composite floor presented peak accelerations higher than 5.0% g (ISO 2631-2, 1989); (Murray et al., 2003) and the human comfort criteria was not satisfied even when an adjacent area, where no dancing actions are present (Node C, see Figs. 3 and 7), was investigated, Tables 4 and 5.

9. Final remarks

This paper investigated the dynamic behaviour of composite floors (steel-concrete) when subjected to the human rhythmic activities corresponding to aerobics and dancing effects. The dynamic loads were obtained through experimental tests conducted with individuals carrying out rhythmic and non-rhythmic activities such as stimulated and non-stimulated jumping and aerobics.

The proposed analysis methodology adopted the usual mesh refinement techniques present in the finite element method (FEM). Based on the experimental results (Faisca, 2003), human load functions due to rhythmic and non-rhythmic activities were proposed. The investigated structural system was a typical floor used as a restaurant with an adjacent dancing area. The composite floor system consisted of long span (14m) joists supported by concrete block walls.

The parametric analysis considered correlations between analytical and numerical results found in literature. The results, in terms of maximum accelerations, were compared to the limits proposed by design recommendations, focusing on human comfort considerations.

The results obtained throughout this study indicated that the limits recommended by design standards (ISO 2631-2, 1989); (Murray et al., 2003) were not satisfied for the investigated structural model when subjected dancing load actions. Such fact shows that these rhythmic activities may generate peak accelerations that violated design criteria related to human comfort.

The present investigation also indicated that these dynamic loads can even generated considerable perturbations on adjacent areas, where there is no human rhythmic activity of such kind present. Despite this fact there was still a surpassing of the associated human comfort criteria.

10. Acknowledgements

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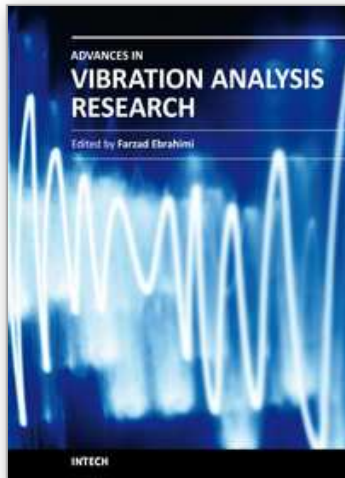
Advances in Vibration Analysis Research

Edited by Dr. Farzad Ebrahimi

Vibrations are extremely important in all areas of human activities, for all sciences, technologies and industrial applications. Sometimes these Vibrations are useful but other times they are undesirable. In any case, understanding and analysis of vibrations are crucial. This book reports on the state of the art research and development findings on this very broad matter through 22 original and innovative research studies exhibiting various investigation directions. The present book is a result of contributions of experts from international scientific community working in different aspects of vibration analysis. The text is addressed not only to researchers, but also to professional engineers, students and other experts in a variety of disciplines, both academic and industrial seeking to gain a better understanding of what has been done in the field recently, and what kind of open problems are in this area.

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