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DYNAMIC ANALYSIS AND VIBRATION CONTROL OF STEEL-CONCRETE COMPOSITE FLOORS WHEN SUBJECTED TO HUMAN RHYTHMIC ACTIVITIES

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Abstract. *The main objective of this paper is to investigate the dynamic behaviour of composite floors when subjected to human rhythmic activities. The investigated structural model was based on building composite floors and consisted of a typical interior bay of a commercial building, which is used as a gym. An extensive parametric study was developed focusing in the determination of the composite floor peak accelerations due to human rhythmic activities. The peak accelerations were compared to the limiting values proposed by several authors and design standards. The results have demonstrated that the analysed composite floor have presented high values of accelerations and excessive vibrations. The analysis indicated that human rhythmic activities could induce the composite floors to reach unacceptable vibration levels and lead to a violation of the human comfort criteria. Considering all aspects mentioned before, it was developed a structural control strategy aiming to reduce the floor excessive vibrations. Finally, an investigation was performed based on structural control alternatives for attenuating excessive vibrations using Tuned Mass Damper (TMD) systems.*

1 INTRODUCTION

The technological advance in the materials field allows the use of more resistant and low weight materials that result in slender and more flexible structural systems [1]. In the particular case of a composite floor, this flexibility is due to the use of larger spans, thus leading the structural system to a lower inherent damping. Therefore such constructions designed to residencies, offices and gyms, for instance, are more susceptible to excessive vibrations originated mainly from human activities such as walking, aerobic activities (gymnastics, jumping) that may cause human discomfort [2-4].

It is well known that most disturbing vibrations related to human perception are in the range of 4 to 8 Hz [2-4] and at the same time most of the natural frequencies of composite floor systems lie also in this range. In addition, the excitation force frequencies due to human activities occur in this range as well. This combination makes the structural systems more susceptible to the resonance phenomenon, causing undesirable vibrations in the frequency range that is the most noticeable to humans.

In order to avoid unwanted vibrations, the structural engineer can resort to measures, still in the structural design stage, as increasing the structural stiffness and/or increasing or decreasing the mass system such that the fundamental natural frequency move away from the excitation frequency. However, it is not always possible to make significant changes in structural elements due to architectural and/or economic factors. Considering these limitations, several authors have proposed the use of vibration control devices associated with the main structural system, both in the design phase and for already built structures [1-3, 5].

Regarding all these aspects, this paper is intended to investigate the vibration levels of a typical steel-concrete composite floor submitted to human aerobic rhythm 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 [3, 4]. Furthermore, a passive vibration control was designed in order to mitigate excessive vibration amplitudes.

2 DYNAMIC LOADING INDUCED 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 key factors in defining the dynamic action characteristics. Numerous investigations were made aiming at establish parameters to describe such loads [2, 3].

Several investigations [2, 3] 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, the dynamic analysis is performed equating one of the activity harmonics to the floor fundamental frequency, leading to resonance.

This study has considered the dynamic loads obtained by Faisca [6], 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 [6].

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, because it was verified that this mathematical representation is very similar to the signal force obtained through experimental tests developed by Faisca [6].

The mathematical representation of the human dynamic loading using the Hanning function is given by Eq. (1) and illustrated in Figure 1. The required parameters for the use of Eq.

(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 illustrates the phase coefficient variation, CD, for human activities [6], considering a certain number of individuals and later extrapolated for larger number of individuals. 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.

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

$$F(t) = 0 \qquad \text{For } T_c \le t \le T$$

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.

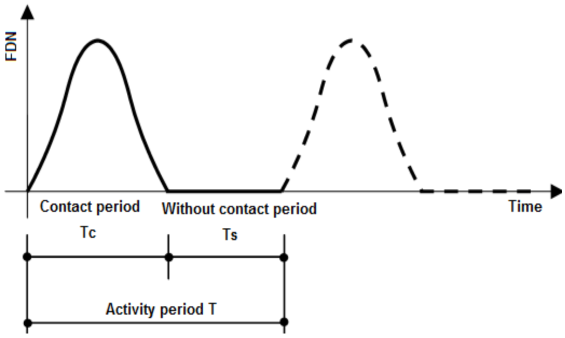


Figure 1: Dynamic loading induced by human rhythmic activities.

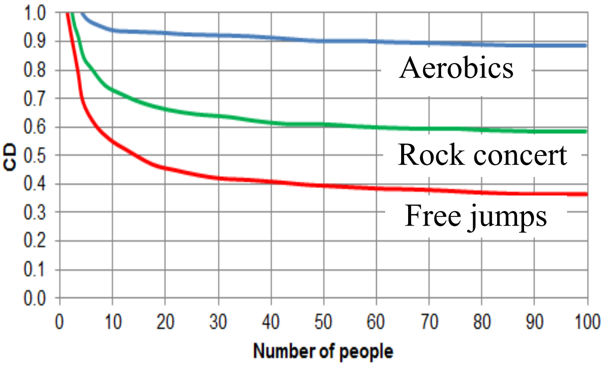


Figure 2: Phase coefficients for human rhythmic activities [15].

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 [6].

3 INVESTIGATED STEEL-CONCRETE COMPOSITE FLOOR

The structural model was based on a steel-concrete composite floor spanning 10m by 10m, with a total area of $100m^2$ like a typical interior floor bay of a commercial building used for gymnastics. The structural system is made from composite beams and a 100mm thick concrete slab [1], see Figure 4. The columns height is equal to 4m. The steel sections used were welded wide flanges (WWF) made from a 345MPa yield stress steel grade. A $205x10^3$MPa Young's modulus was adopted for the steel beams. The concrete slab has a 30MPa specified compression strength and a $26x10^3$ MPa Young's Modulus. Table 2 depicts the geometrical characteristics of all the steel sections used in the structural model.

The dynamic loadings were applied on the structural model corresponding to twenty individuals practising aerobics. The individuals' positions are shown in Figure 5. The live load considered in this analysis corresponds to one person for each 4.0m^2 (0.25 person/m^2) [2]. It is also assumed that a single person's weight is 800N (0.8kN) [2]. In this study a structural damping ratio of ξ=1% (ξ = 0.01) was considered [2].

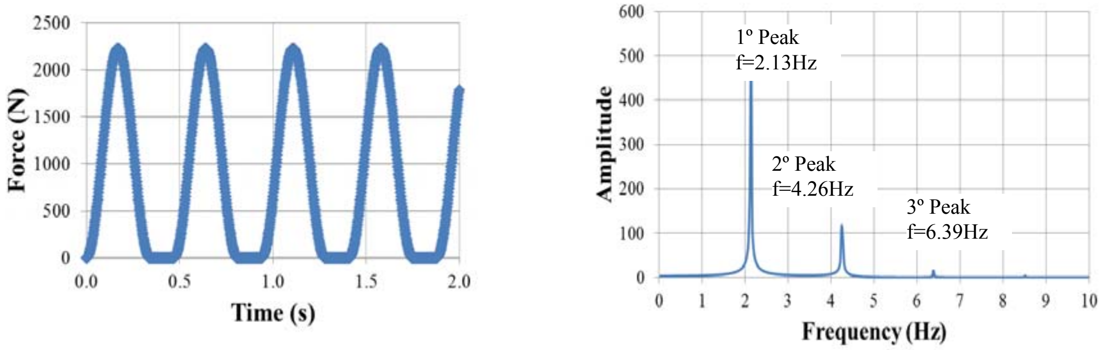
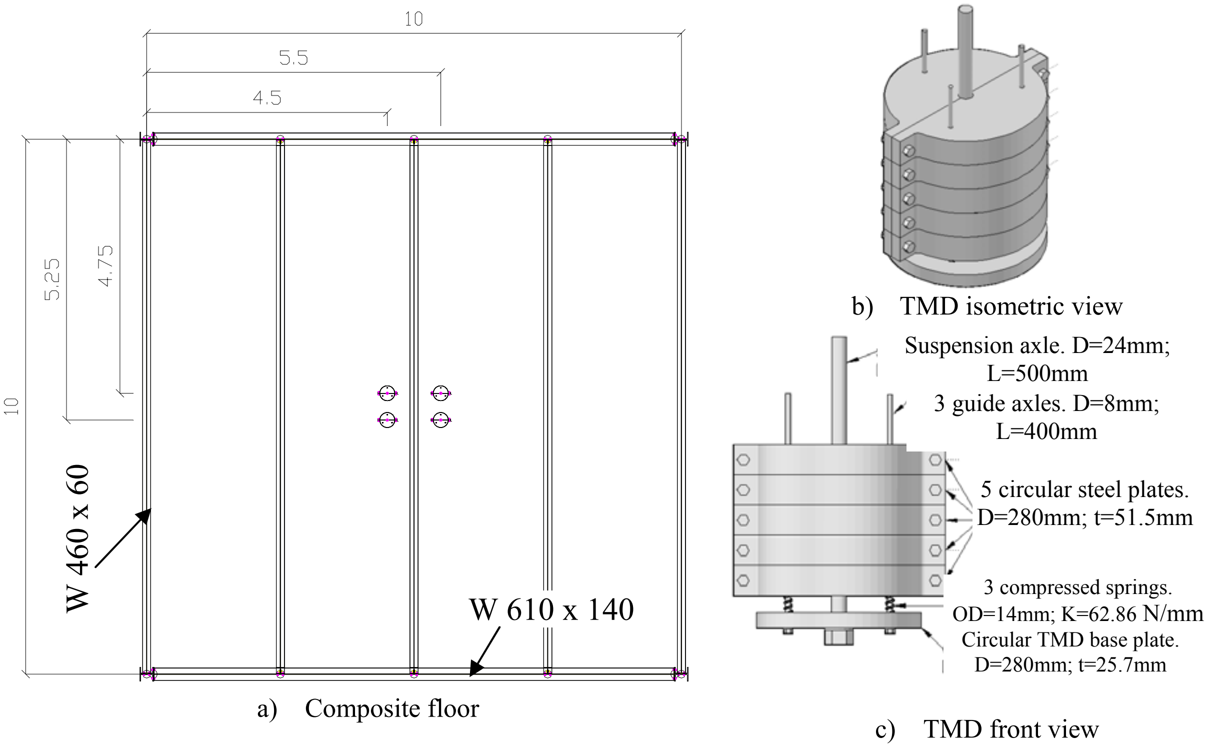


Figure 3: Dynamic loading induced by dancing (T=0.47s, Tc=0.34, Ts=0.13, Kp=2.78 and CD=1.0).



b) TMD isometric view

a) Composite floor

c) TMD front view

Figure 4: Investigated steel-concrete composite floor and TMDs layout. Dimensions in (m).

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).

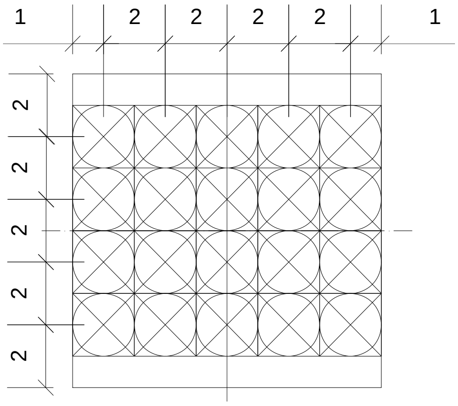
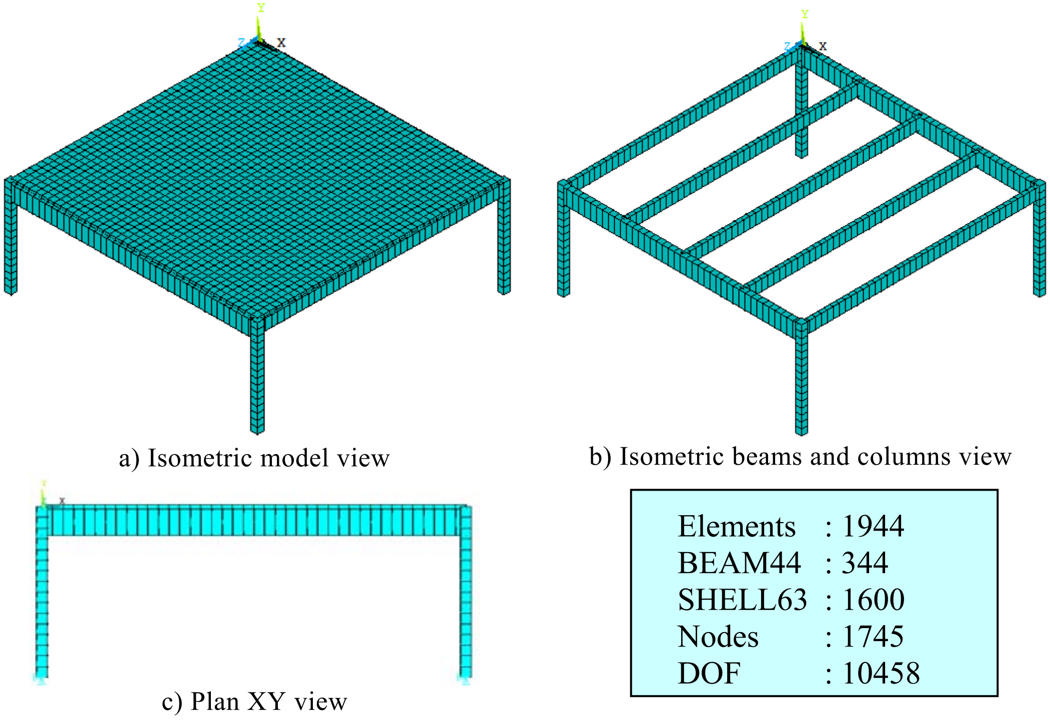


Figure 5: Dynamic loading of twenty individuals practising aerobics on the investigated floor. Dimensions in (m).

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 [7]. In this model, floor steel beams 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 the complete interaction between the concrete slab and steel beams and both materials (steel and concrete) have an elastic behaviour, see Figure 6.



a) Isometric model view

b) Isometric beams and columns view

c) Plan XY view

Elements : 1944
BEAM44 : 344
SHELL63 : 1600
Nodes : 1745
DOF : 10458

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

In respect to the development of the passive tuned mass damper system (TMD), as mentioned before, a spring-damper element was employed as well as a mass one in order to simulate together a mass-spring-damper system. Thus, these two elements were attached to the main structure such that they represent a TMD system.

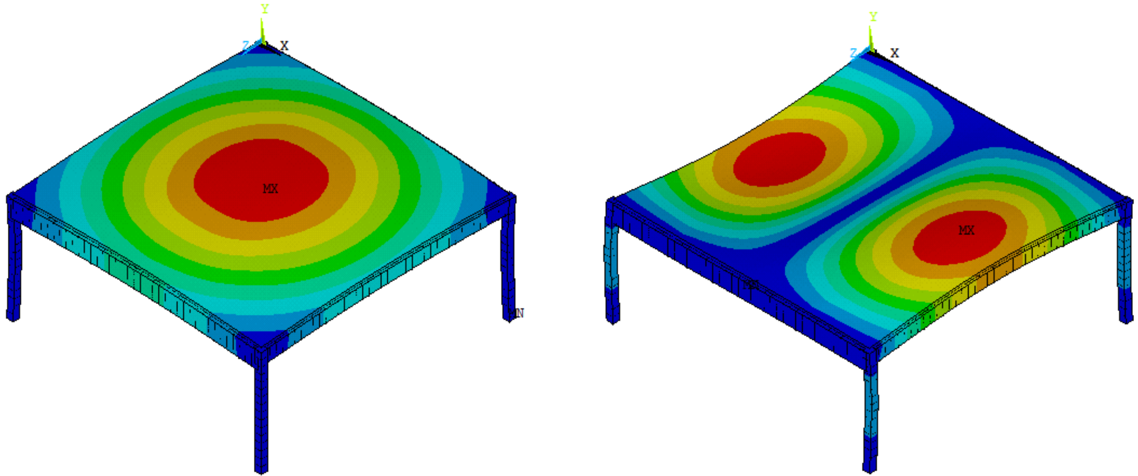
5 DYNAMIC ANALYSIS

The composite floor natural frequencies and vibration modes were determined with the aid of the numerical extraction methods (modal analysis). The eigenvalues are described in Table 3 while the corresponding two first vibration modes are shown in Figure 7.

Frequencies (Hz)	Composite Floor 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

Table 3: Steel-concrete composite floor natural frequencies.

Regarding Table 3, it can be seen that the first natural frequency (f_{01}=6.36Hz) 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. [2, 3].



a) 1st Vibration mode (f_{01}=6.36Hz) b) 2nd Vibration mode (f_{02}=9.78Hz)

Figure 7: Investigated structural model vibration modes.

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. As mentioned before, resonance effect state may occur with the first natural floor frequency of 6.36Hz is equal to the third harmonic excitation frequency (3 x 2.13Hz).

Hence, this study is intended to evaluate the floor response in case of resonance, quasi-resonance and out of resonance with the third harmonic of the force function. Therefore the present investigation has considered the contact period, simulating aerobics on the composite floor, T_c, the period without contact with the structure, T_s, resulting in the activity period, T. Table 4 shows these values and the first three harmonics of the force function totalizing five cases. It must be noted that all these period values lie in the aerobic force period range according to the Section 2.

Load Cases	T_c (s)	T_s (s)	T (s)	f_{01}(Hz)	f_{02}(Hz)	f_{03}(Hz)
1 (out of resonance)	0.34	0.01	0.35	2.86	5.71	8.57
2 (quasi-resonance)	0.34	0.12	0.46	2.17	4.35	6.52
3 (resonance)	0.34	0.13	0.47	2.13	4.26	6.38
4 (quasi-resonance)	0.34	0.14	0.48	2.08	4.17	6.25
5 (out of resonance)	0.34	0.19	0.53	1.89	3.77	5.66

Table 4: Parameters used for human aerobic activities representation.

Based on the experimental results [6], the composite floors dynamic behaviour was evaluated keeping the impact coefficient value, K_p, equal to 2.78 ($K_p = 2.78$). Table 5 shows the steady-state amplitude in terms of displacements and accelerations related to the central node of the structural model considering the five load cases.

Load Cases	Steady-State Amplitude Response	
	Displacement (mm)	Acceleration (m/s²)
1 (out of resonance)	1.77	0.43
2 (quasi-resonance)	2.27	**1.22**
3 (resonance)	2.67	**2.01**
4 (quasi-resonance)	1.69	**0.93**
5 (out of resonance)	1.84	**0.54**
Limiting Acceleration: $a_{lim} = 0.5m/s^2$ [3, 4].		

Table 5: Composite floor dynamic response (central node).

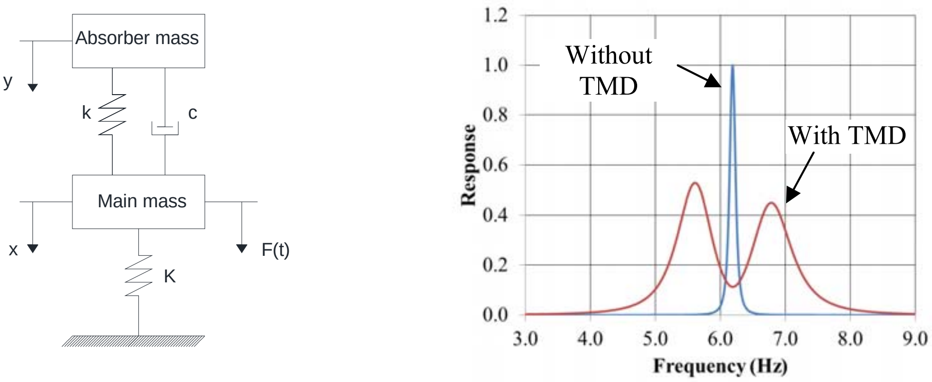
Regarding the results from Table 5, it can be noticed that despite the fact that displacements of the floor were small; the peak acceleration values from the load case number 2 until 5 corresponding to twenty persons practising aerobics were higher than the limit of 0.5 m/s² (5%g) [3, 4], see Table 5. Considering the fact that such vibration levels lead to human discomfort, this situation motivated a development of a low-cost passive tuned mass damper (TMD) aiming at reducing them to acceptable levels.

6 VIBRATION CONTROL

With the objective of control the floor vibration response, an absorber which dissipates part of the main system energy is needed. In other words, such dispositive attached to the floor structure counteracts the forces applied to it and then less work is done on the floor system [2]. This absorber (also known as Tuned Mass Damper: TMD) is made up in general of a mass-spring-damper assemble. It is important to note that this device is a passive system, i.e. the absorber does not apply any external force to the main structure.

Another important point is that the TMD is more effective if tuned close to the main structure natural frequency. In addition, the absorber splits the natural frequency of the main system in two others frequencies, as shown in Figure 8. The energy associated to these natural frequencies will depend on the absorber damping value [2].

Based on an absorber system proposed and experimentally tested by Varela [5], a similar system was developed in this work. The TMD was tuned to the first modal frequency (f_{01}=6.36Hz) of the composite floor in order to control the resonant motion. The effective modal mass of the structural model for the first mode relative to the central node is 10.5t, which corresponds to 32% of the structure total mass (32.7t). The structural damping ratio equal to ξ=1% was considered. The mass ratio (μ) is 0.049 which gives an absorber mass of 520kg. Table 6 presents the absorber parameters [1].



a) Schematic of a two DOF system b) TMD response in frequency domain

Figure 8: Theoretical TMD characteristics.

Absorber Parameters	Optimum TMD	Actual TMD
f_{opt}	0.9529	0.9532
f_a (Hz)	6.0595	6.0617
ζ_a (%)	12.7	1.5
k_a (N/m)	753761	754320
m_a (kg)	520	520
c_a (N.s/m)	5016	594

Table 6: Absorber parameters [1].

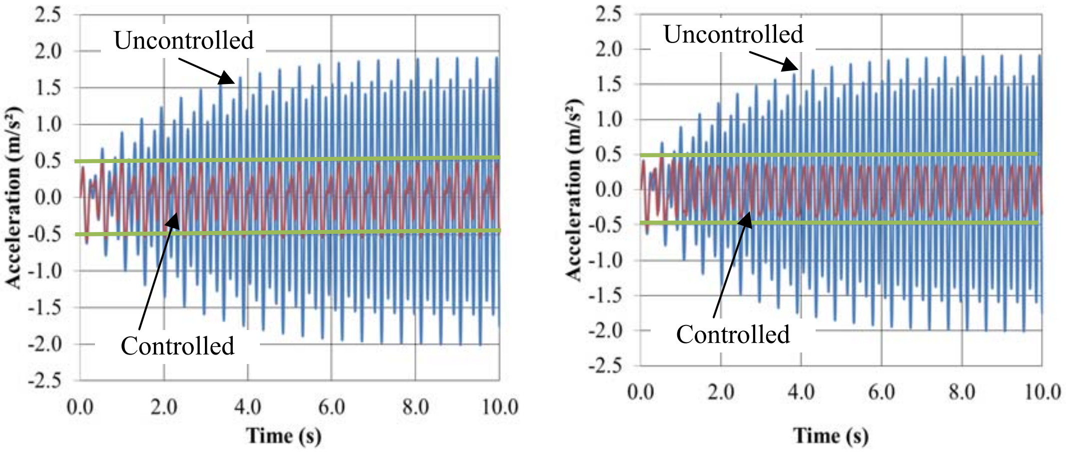
It can be seen from Table 6 that all actual TMD parameters are very close to those from the optimum TMD except for the damping values. The actual TMD has no physical dashpot but rather an inherent damping due to its mechanism and some friction between its moving masses (see Figure 4). The damping ratio values were obtained experimentally and fell in the range 1-1.5% [5]. Such condition was investigated in the present study.

The investigation proceeds with the simulation of the four (optimum and actual) TMDs as they were installed to the composite floor model, see Figure 4. Table 7 shows the steady-state acceleration amplitude responses relative to the central node of the floor for the five load cases and their respective effectiveness. Concerning the TMDs effectiveness, the minus sign indicates the acceleration reduction relative to the uncontrolled system.

Based on Table 7 results, a good percentage reduction varying from 48 to 73% (optimum TMDs) and 51 to 81% (actual TMDs) was obtained for the cases 2, 3 and 4.Thus, it can be seen that the TMD system is more effective in case of resonance state or nearly so, see Figures 9 and 10. With respect to the out of resonance cases (1 and 5), for the case 1 both the optimum and actual TMDs seem to be not effective whereas for the case 5 the actual TMDs presented a slight effectiveness enough to respect the limiting acceleration of $0.5 m/s^2$ [3, 4]. Still considering this case, it is remarkable that though the third harmonic (5.66Hz) of the force function is not in resonance with the floor frequency (6.36Hz), the uncontrolled acceleration response ($a_p = 0.54 m/s^2$) was greater than the limit of $0.5 m/s^2$. Nevertheless, a value of $0.54 m/s^2$ is still tolerable for people practising aerobics only [3].

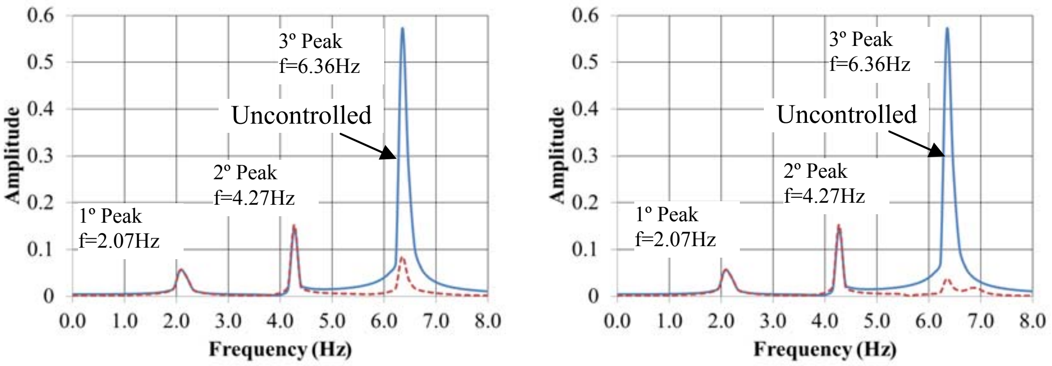
Load Cases	Vibration Control	Acceleration (m/s²)	
		Optimum TMDs	Actual TMDs
1 (out of resonance; T=0.35s)	*Uncontrolled*	0.428	0.428
	Controlled	0.420	0.436
	Effectiveness (%)	-2	2
2 (quasi-resonance; T=0.46s)	*Uncontrolled*	1.222	1.222
	Controlled	**0.630**	0.450
	Effectiveness (%)	-48	-63
3 (resonance; T=0.47s)	*Uncontrolled*	2.013	2.013
	Controlled	**0.541**	0.378
	Effectiveness (%)	-73	-81
4 (quasi-resonance; T=0.48s)	*Uncontrolled*	0.932	0.932
	Controlled	0.472	0.460
	Effectiveness (%)	-49	-51
5 (out of resonance; T=0.53s)	*Uncontrolled*	0.538	0.538
	Controlled	**0.543**	0.444
	Effectiveness (%)	1	-18
Limiting Acceleration: $a_{lim} = 0.5 m/s^2$ [3, 4].			

Table 7: TMDs effectiveness comparison.



a) Optimum TMDs b) Actual TMDs

Figure 9: Investigated steel-concrete composite floor time domain response.



a) Optimum TMDs b) Actual TMDs

Figure 10: Steel-concrete composite floor frequency response.

7 CONCLUSIONS

This investigation analysed the dynamic behaviour of a steel-concrete composite floor spanning 10m by 10m used for gymnastics. 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 6.36Hz. This frequency value lies in the frequency range of aerobic activities which may lead the composite floor to a resonant motion state. The dynamic analysis carried out shown that the peak accelerations obtained from the studied gymnastics situations were higher than the limit of 0.5m/s². This situation led to human discomfort for the individuals practising aerobics on the composite floor.

Aiming to reduce such excessive vibrations, the use of four passive TMDs were simulated as they were attached to the floor. The maximum reduction obtained for twenty individuals practising aerobics in resonant motion (the worst case to design) was of 81%, which resulted in a peak acceleration of 0.38m/s² and thus lower than the limit of 0.5m/s². It can be concluded that the use of TMD systems has shown to be a low-cost alternative to respect the intended human comfort criteria for composite floors when submitted to human rhythm activities.

8 ACKNOWLEDGEMENTS

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REFERENCES

[1] C.M.R. Gaspar, "Dynamic Analysis and Vibration Control of Steel-Concrete Composite Floors when Submitted to Human Rhythmic Activities", MSc Dissertation (In Portuguese), Civil Engineering Post-graduate Programme, PGECIV, State University of Rio de Janeiro, UERJ, Rio de Janeiro/RJ, Brazil, 2013.

[2] H. Bachmann, W.J Ammann, F. Deischl, J. Eisenmann, J. Floegl, G.H. Hirsch, et al., "Vibration problems in structures - practical guidelines", Basel (Switzerland):Institut für Baustatik und Konstruktion, Birkhäuser; 1995.

[3] T.M. Murray, D.E. Allen, E.E Ungar, "Floor Vibrations due to Human Activity", Steel Design Guide Series, American Institute of Steel Construction, AISC, Chicago, USA, 2003.

[4] International Standard Organization. Evaluation of Human Exposure to Whole-Body Vibration, Part 2: Human Exposure to Continuous and Shock-Induced Vibrations in Buildings (1 to 80Hz), ISO 2631-2, 1989.

[5] W.D Varela, R.C. Battista, "Control of vibrations induced by people walking on large span composite floor decks", Engineering Structures, Vol. 33, Issue 9, 2485-2494, 2011.

[6] R.G. Faisca, "Characterization of Dynamic Loads due to Human Activities", PhD Thesis (In Portuguese), Civil Engineering Department, COPPE/UFRJ, Rio de Janeiro/RJ, Brazil, 2003.

[7] ANSYS Swanson Analysis Systems, Inc., P. O. Box 65, Johnson Road, Houston, PA, 15342-0065. Release 11.0, SP1 UP20070830, ANSYS, Inc. is a UL registered ISO 9001:2000 Company. Products ANSYS Academic Research, Using FLEXlm v10.8.0.7 build 26147, Customer 00489194, 2007.