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Vibration Control of Building Steel-Concrete Composite Floors Submitted to Aerobics Based on Optimization Techniques

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Abstract

The increasing incidence of building steel-concrete composite floors vibration problems due to human rhythmic activities led to a specific design criterion to be addressed in structural design. The current investigation indicated that human rhythmic activities could induce the floors to reach unacceptable vibration levels leading to a violation of human comfort criteria. Thus, the main objective of this paper is to develop a structural control strategy aiming to reduce the floor excessive vibrations based on the use of Tuned Mass Damper (TMD) systems. The proposed analysis methodology was focused on the TMD system's dynamic characteristics optimisation using the sub problem approximation method. The investigated structural model was based on a steel-concrete composite floor spanning 10m by 10m, with a total area of 100m². This system represents a typical interior floor bay of a commercial building for gym purposes, and designed according to the usual ULS and SLS Eurocode provisions. The results have shown that optimisation techniques are very useful, in order to improve the building steel-concrete composite floors vibration control.

Keywords: composite floors, dynamic analysis, finite element modelling, human comfort, excessive vibrations, vibration control, optimisation techniques.

1 Introduction

The use of more resistant and low weight materials have resulted in lighter structural systems. This way, such structural mass reduction associated to a low structural inherent damping have been leading several buildings designed to residencies, offices and gyms to excessive vibrations when subjected to human activities such as walking and aerobic activities (gymnastics, jumping) [1-8].

Although most of these excessive vibrations from humans do not compromise the structural health, they might cause human discomfort for the building users. The

main cause for this situation is due to a combination of factors. It is known that most disturbing vibrations related to human perception are in the range of 4 to 8 Hz [4-6] 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, 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 [2, 9-11]. This measure has been shown to be a good alternative whenever it is not possible to make significant changes in structural elements due to architectural and/or economic factors so that the fundamental natural frequency move away from the excitation frequency.

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 accelerations was obtained by numerical simulations and compared to the limiting values proposed by several authors and design codes [4-8]. Furthermore, a passive vibration control (TMD) was designed using optimisation techniques in order to mitigate annoying 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.

Several investigations [3, 4, 6,7] 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 has considered the dynamic loads obtained by Faisca [12], 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 [12].

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 [12].

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 illustrates the phase coefficient variation, CD , for human activities studied by Faisca [12], 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.

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

$$F(t) = 0 \quad \text{For } T_c \leq t \leq T$$

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.

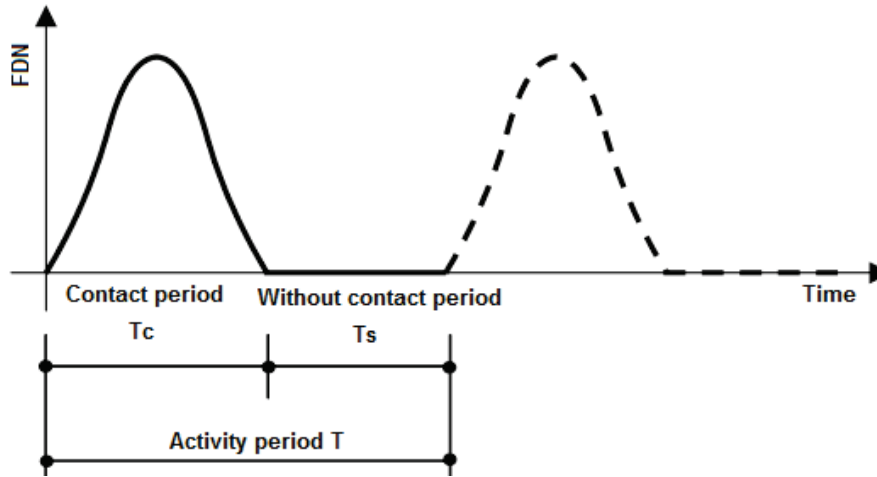


Figure 1: Generic representation of the dynamic loading induced by human rhythmic activities.

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 [12].

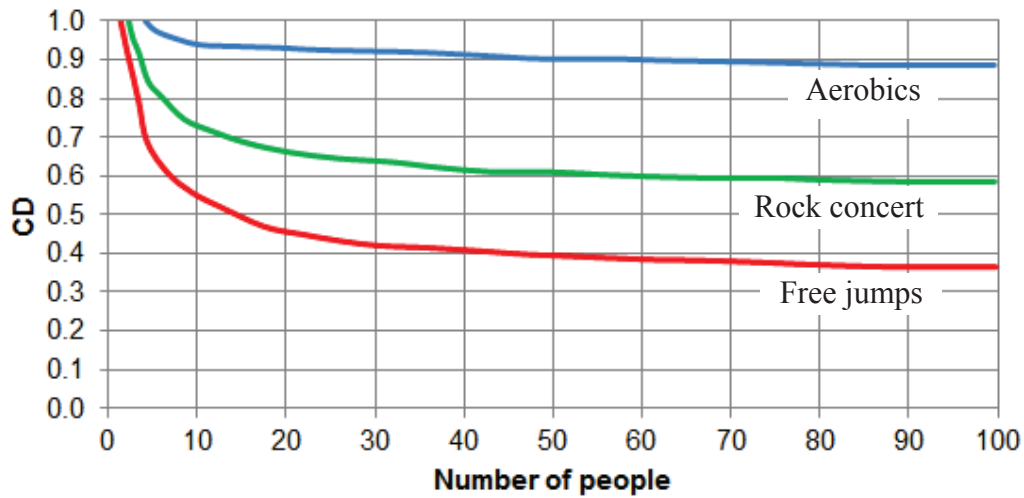


Figure 2: Phase coefficients for the studied activities [12].

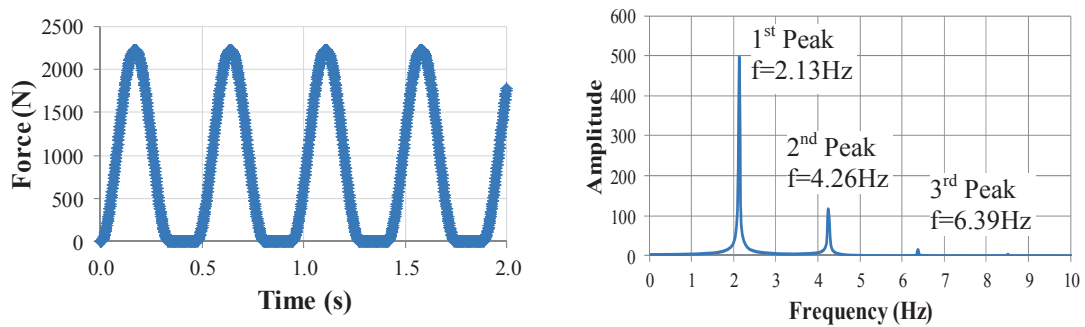
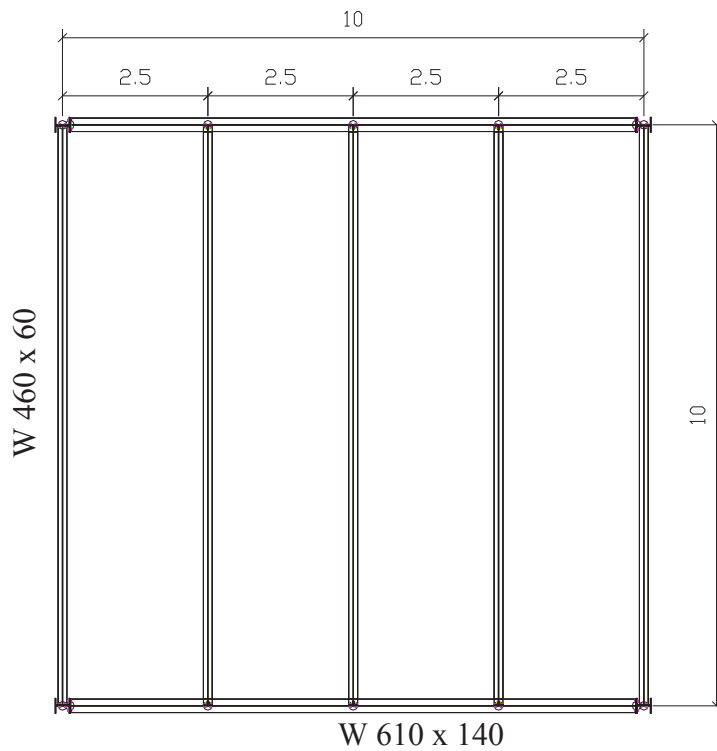


Figure 3: Dynamic loading induced by dancing ($T=0.47s$, $T_c=0.34$, $T_s=0.13$, $K_p=2.78$ and $CD=1.0$).

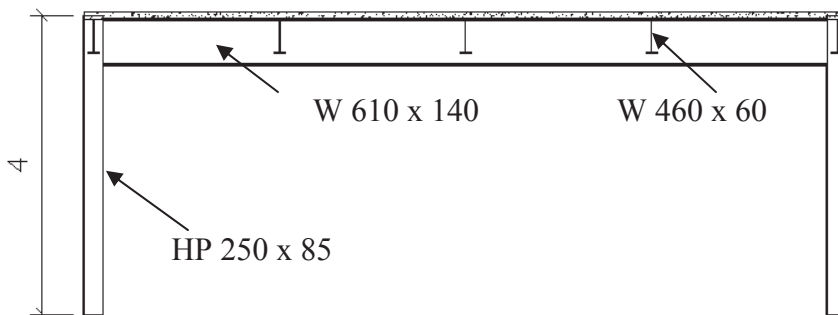
3 Investigated Steel-Concrete Composite Floor

The investigated structural model was based on a steel-concrete composite floor spanning 10m by 10m, with a total area of 100m². This system represents a typical interior floor bay of a commercial building for gym purposes. The composite floor studied in this work is supported by steel columns and is currently submitted to human aerobic rhythmic loads, as illustrated in Figure 4.

The structural system is made from composite beams and a 100mm thick concrete slab [1]. The columns height is equal to 4m, as presented in Figure 4. The steel sections used were welded wide flanges (WWF) made from a 345MPa yield stress steel grade. A 205×10^3 MPa Young's modulus was adopted for the steel beams. The concrete slab has a 30MPa specified compression strength and a 26×10^3 MPa Young's Modulus. Table 2 depicts the geometrical characteristics of all the steel sections used in the structural model.



a) Top view.



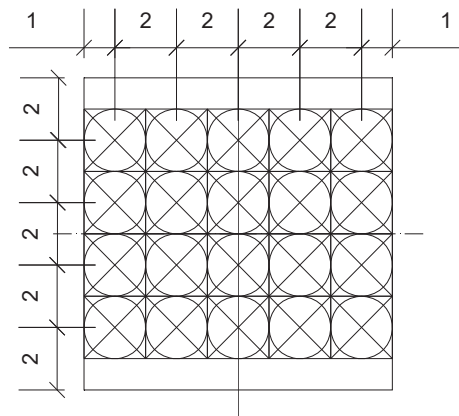
b) Cross section.

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

The human rhythmic dynamic loadings were applied on the investigated 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) [3]. It is also assumed that a single person's weight is 800N (0.8kN) [3]. In this study a structural damping ratio of $\xi=1\%$ ($\xi = 0.01$) was considered. This damping value was chosen according to ISO 10137 [5] and lies in the extreme range of 0.5 to 8.0% for fully composite steel beams with shear connectors to concrete slab.



a) Twenty persons

Figure 5: Twenty people practising aerobics on the investigated composite 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 [13], see Figure 6. In this computational 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, as presented in Figure 6.

The present investigation considered that both materials (steel and concrete) have an elastic behaviour. The complete interaction between the concrete slab and steel beams was considered in the analysis, i.e. the numerical model coupled all the nodes between the beams and slab, to prevent the occurrence of any slip.

Regarding the structural behaviour of the connections present in the investigated structural model, the beam-to-beam connections were modelled as flexible joints whereas the beam-to-column connections were considered as rigid joints. In other words, the degrees of freedom relative to rotation were only released in beam to beam connections.

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.

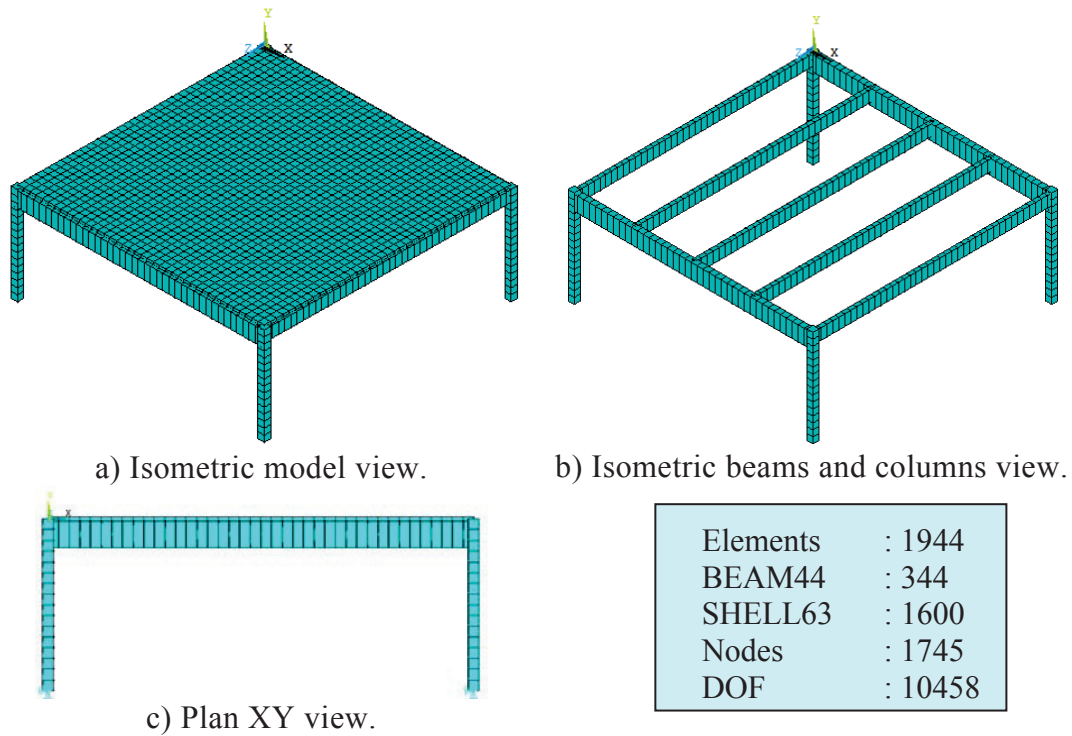


Figure 6: Composite floor finite element model mesh and layout.

5 Optimisation Techniques

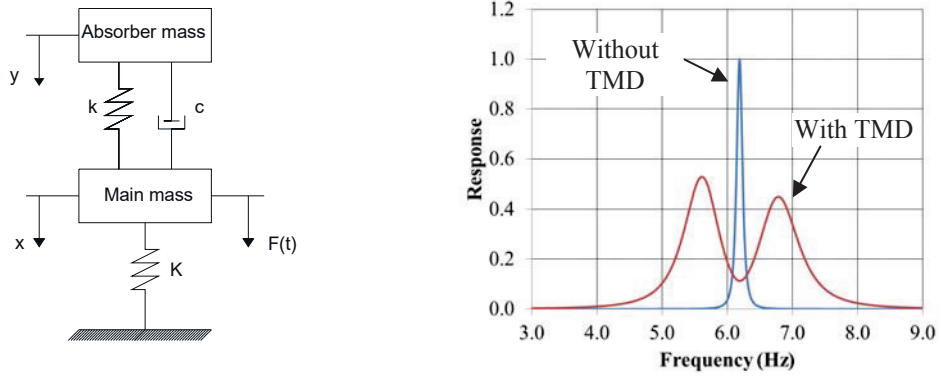
5.1 Introduction

This section presents the optimisation techniques employed in this study aiming to optimise tuned mass damper (TMD) parameters based on the finite element method using the ANSYS program [13].

Several authors have developed similar devices concerning optimum parameters in order to minimise the structural system dynamic response [14-18] through an analytical processes. For instance, the most known formulation developed by Den Hartog [15] has considered optimum parameters based on two degrees of freedom system [see Figure 7 and Equations (2) to (6)].

These optimum expressions were obtained considering that a harmonic excitation force acts on the undamped main system. Nevertheless, they can be used with a good approximation for a damped main system and periodical load [3].

On the other hand, the use of analytical optimal expressions may require some trial and error by the structural engineers in finite element method simulations. In this sense, it seems to be useful to use optimisation tools directly applied on the finite element model.



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

Figure 7: Theoretical TMD characteristics.

$$\mu = \frac{m_a}{M} \quad (2)$$

$$f_{opt} = \frac{1}{1 + \mu} \quad (3)$$

$$f_a = f_{opt} \times f_n \quad (4)$$

$$\zeta_{opt} = \sqrt{\frac{3\mu}{8(1 + \mu)^3}} \quad (5)$$

$$c_a = 2 \zeta_{opt} m_a \omega_a \quad (6)$$

Where:

m_a : absorber mass;

M : main mass;

μ : mass ratio;

f_{opt} : optimum frequency ratio;

f_n : natural frequency of the main system (Hz);

f_a : natural frequency of the absorber (Hz);

ω_a : natural frequency of the absorber (rad/s);

ζ_{opt} : optimum damping ratio of the absorber;

c_a : damping of the absorber (Ns/m);

5.2 Constrained Optimisation Process

Many engineering problems must satisfy certain design conditions, such as limits on stress, geometry, displacement. For instance, a classical constrained optimisation problem is to minimise the structural weight which is function of the structural geometry subject to stress and displacement constraints.

In this study, the mass and spring of the TMD are called the independent variables (design variables), the optimum frequency ratio (fopt) and the floor acceleration criterion are the dependent variables (state variables or design constraints) and the objective function to be minimised is the floor kinetic energy. Both design and states variables are subject to upper and lower limits.

The design sets that satisfy all constraints are referred to as feasible designs. On the other hand, design sets with one or more violations are termed infeasible. In defining feasible design space, a tolerance is added to each state variable limit. The best design set is defined according to one of the following conditions:

- If one or more feasible sets exist the best design set is the feasible one with the lowest objective function value.
- If all design sets are infeasible, the best design set is the one closest to being feasible, irrespective of its objective function value.

5.2.1 Subproblem Approximation Method

This method of optimization can be described as an advanced, zero-order method that requires only the values of the dependent variables (objective function and state variables) and not their derivatives [13].

The dependent variables are first replaced with approximations by means of least squares fitting, and the constrained minimization problem is converted to an unconstrained problem using penalty functions. This method is also known as a sequential unconstrained minimization technique (SUMT) [19, 20].

Minimization is then performed every iteration on the approximated penalized function until convergence is achieved or the termination criteria are met. For this method each iteration is equivalent to one complete analysis loop. Equation (7) states the unconstrained problem.

$$F(x, p_k) = \hat{f} + f_0 p_k \left(\sum_{i=1}^n X(x_i) + \sum_{i=1}^{m_1} G(\hat{g}_i) + \sum_{i=1}^{m_2} H(\hat{h}_i) + \sum_{i=1}^{m_3} W(\hat{w}_i) \right) \quad (7)$$

Where:

- x : design variables;
- \hat{f} : approximate objective function;
- $\hat{g}_i, \hat{h}_i, \hat{w}_i$: approximate state variables containing the design;
- X : penalty function used to enforce design variable constraints;
- G, H, W : penalty functions for state variable constraints;
- f_0 : the reference objective function value;
- p_k : penalty parameter (k=1,2...);

All penalty functions used are of the extended-interior type [19, 20]. The SUMT algorithm is employed to reach the minimum unconstrained objective function

($\tilde{F}^{(j)}$), at design iteration j , see Equation (8). The final step performed each design iteration is the determination of the design variable vector to be used in the next iteration ($j+1$). The vector $x^{(j+1)}$ is determined according to Equation (9) [13].

$$x^{(j)} \rightarrow \tilde{x}^{(j)} \quad as \quad F^{(j)} \rightarrow \tilde{F}^{(j)} \quad (8)$$

$$x^{(j+1)} = x^{(b)} + C (\tilde{x}^{(j)} - x^{(b)}) \quad (9)$$

Where:

$\tilde{x}^{(j)}$: design variable vector corresponding to $\tilde{F}^{(j)}$;

$x^{(b)}$: best design set constants;

C : vary between 0 and 1, considering the number of infeasible solutions.

This way, the subproblem approximation iterations continue until either convergence is achieved or termination occurs.

6 Dynamic Analysis

6.1 Natural Frequencies and Vibration Modes

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 8.

Frequencies (Hz)	Steel-Concrete 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 ($f_{01}=6.36\text{Hz}$) of the floor is found in the force frequency range of aerobic activities. Namely the third harmonic of the forcing function may match this natural frequency and therefore lead the composite floor to a resonance state. Consequently, such situation might result in undesirable vibrations and thus human annoyance. [3].

With the objective of avoiding unwanted vibrations the fundamental floor frequency should be at least equal to 9.2 Hz for aerobics considering the structural system as a light floor. [4].

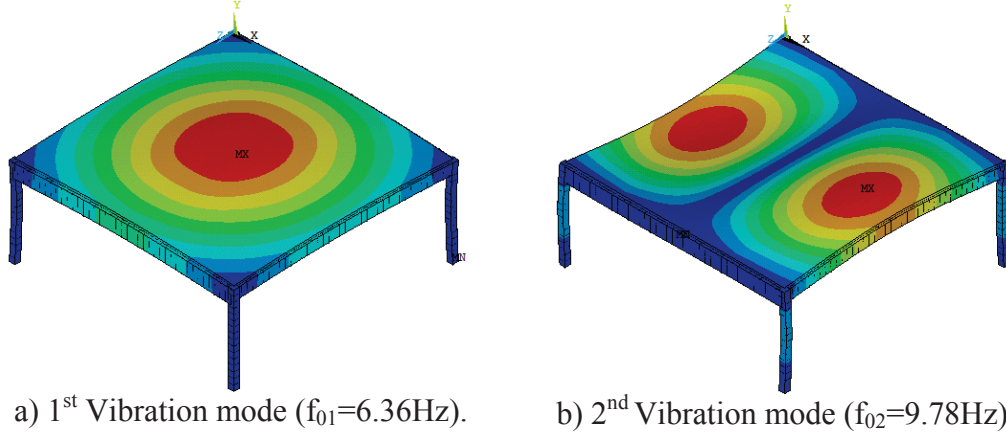


Figure 8: Investigated structural model vibration modes.

6.2 Human Comfort Evaluation

Concerning the human comfort analysis, to the authors' knowledge, it is worth to note that there is no generally agreed acceptance criterion for human rhythmic activities [6]. In others words, several authors [3, 4, 6-8] have been established comfort limits in function of acceleration assessment methods.

Therefore, the steel-concrete composite floor accelerations herein were evaluated based on peak unweighted accelerations (steady-state response), a_p , RMS weighted accelerations, $a_{w,rms}$, and vibration dose values, VDV. Table 4 shows the RMS weighted accelerations and the VDV acceptance criteria respectively. The limiting value concerning aerobics and related to the peak unweighted acceleration is equal to 5%g ($a_{lim} = 0.49 \text{ m/s}^2$) [3].

SCI [6]	Ellis and Littler [7]	Setareh [8]	Person's Reaction
$a_{w,rms} \text{ (m/s}^2\text{)}$	VDV ($\text{m/s}^{1.75}$)	VDV ($\text{m/s}^{1.75}$)	
< 0.35	< 0.66	< 0.50	Reasonable limit: passive persons
0.35 - 1.27	0.66 - 2.38	0.50 - 3.50	Disturbing
0.35 - 24.7	2.38 - 4.64	3.50 - 6.90	Unacceptable
> 24.7	> 4.64	> 6.90	Probably causing panic

Table 4: Human comfort criteria for human rhythmic activities.

As mentioned before in Section 6.1, resonance state may occur with the first natural floor frequency of 6.36 Hz. Hence, this study is intended to evaluate the floor response in case 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 , equal to 0.34s ($T_c = 0.34s$), the period without contact with the structure, T_s , of 0.13s ($T_s = 0.13s$), resulting in the activity period, T , of 0.47s ($f = 2.13\text{Hz}$) and its third harmonic so very close to resonance ($3 \times 2.13 = 6.39\text{Hz}$). According to the experimental results [12], the composite floors dynamic behaviour was evaluated keeping the impact coefficient value, K_p , equal to 2.78 ($K_p = 2.78$). The total time in which the aerobic activity was carried out is equal to 10s.

7 Tuned Mass Damper Design

7.1 Introduction

Based on an absorber system proposed and experimentally tested by Varela [9], a similar system was development herein. This TMD system has no physical dashpot but rather an inherent damping due to its mechanism and some friction between its moving masses (see Figure 10). The damping ratio values were obtained experimentally and fell in the range 1-1.5% [9]. The main advantage of this absorber is referred to its simplicity, i.e. the TMD may be easily installed under the floor slab.

The TMD was tuned to the first modal frequency ($f_{01}=6.36\text{Hz}$) of the composite floor in order to control the resonant motion and installed on the first mode maximum amplitude location. 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 $\xi=1\%$ was considered [5].

7.2 TMD Optimisation Technique

Considering the subproblem approximation method described in section 5.2, Table 5 presents the design variables (DV) and state variables (SV) of the optimisation problem. The objective function to be minimised is the maximum kinetic energy during the aerobic activity.

Variable Type	Variables	Bound Limits	
		Lower	Upper
DV	k_a (N/m)	76663.18	1596886.20
DV	m_a (kg)	50	1000
SV	f_{opt}	-	0.99
SV	VDV ($\text{m/s}^{1.75}$)	-	0.50

Table 5: Design and state variables for the optimisation problem.

Note that the damping ratio of the absorber was kept constant (equal to 1.5%) due its physical limitation. However, the damping of the absorber (c_a) varies in function of its mass and natural frequency (see Equation 6). Regarding the state variables (f_{opt} and VDV), it can be seen that no lower limit was adopted. This way, the optimum

frequency ratio may vary in function of the mass and stiffness of the TMD system. The upper limit is equal to 0.99 because the TMD works better close to the floor frequency [15]. Besides, the upper limit of the state variable (VDV) was chosen according to the most conservative human comfort criterion [8] (see Table 4).

The strategy used in this study aiming to control the floor vibration was based on three design stages: pre-design, optimum design and final design. The first one is related to the first design set, i.e. the initial set points. It must be emphasise that these initial points were not chosen randomly but rather based on practical values.

This means that this first design set might be the first one chosen by the structural engineer. Therefore, the total mass of the TMD was considered as 1% [3, 11] of the modal mass associated to the first mode and the frequency ratio (f_a/f_n) equal to 0.98. The second stage (optimum design) corresponds to the best design set when the subproblem approximation method was carried out. The third stage (final design) is related to the actual TMDs based on commercial values for the design variables (DV). Thus, this phase represents the last one before execution. Table 6 indicates the design sets for the three mentioned design sets. Figure 9 shows how the VDV and kinetic energy vary in function of the TMD mass during the optimisation process.

Variable Type	Variables	Design Sets		
		Pre-Design	Optimum Design	Actual Design
DV	k_a (N/m)	160990	617780	617780
DV	m_a (kg)	105.00	399.82	400
SV	f_{opt}	0.98000	0.98379	0.98365

Table 6: TMD design sets.

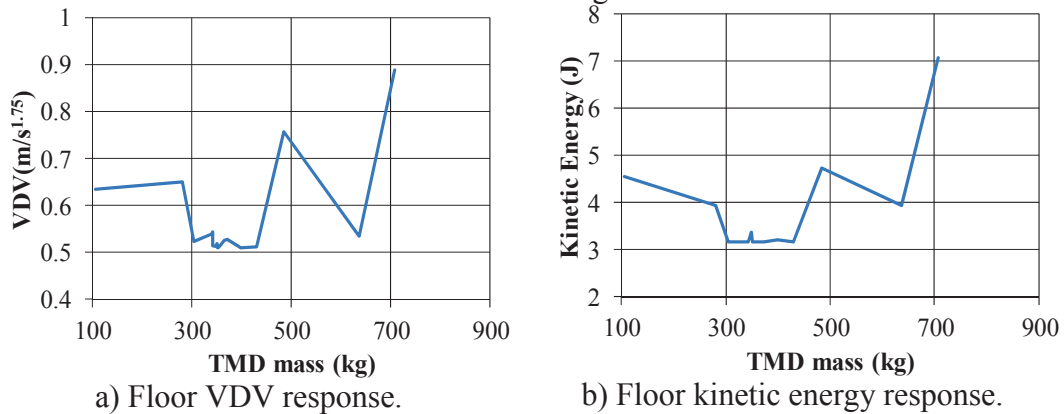
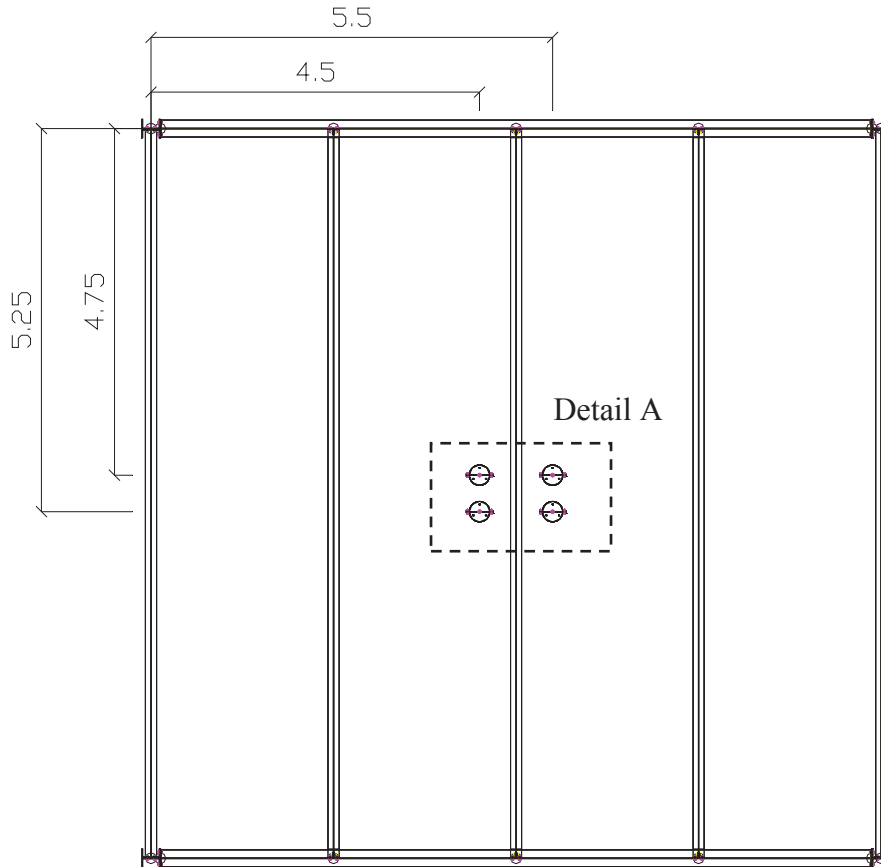


Figure 9: TMD optimisation process.

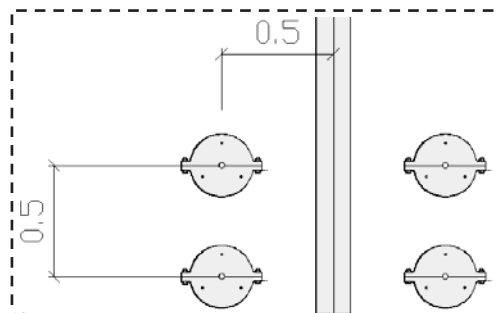
It can be seen from Figure 9 that a minimum region was found during the optimisation process as the TMD mass values in the range of 300 to 430 kg. This way, the best design set found in this region was enough to respect the VDV constraint of 0.5 ($m/s^{1.75}$). Note that a too high TMD mass does not mean that the VDV will reduce directly proportional. Psychically, less work would be done by the absorber in order to dissipate the floor kinetic energy.

7.3 Actual TMDs Modelling

Based on the optimum design (see Table 6), the actual TMD was proportionally divided in four TMDs with the same tuning to make it lighter and consequently easier to install. The TMDs were symmetrically arranged at the floor centre and were attached to the floor bottom. The TMDs location and details are presented in Figures 10 and 11, respectively.



a) Top view.



b) Detail A.

Figure 10: Location of the TMDs on the steel-concrete composite floor.

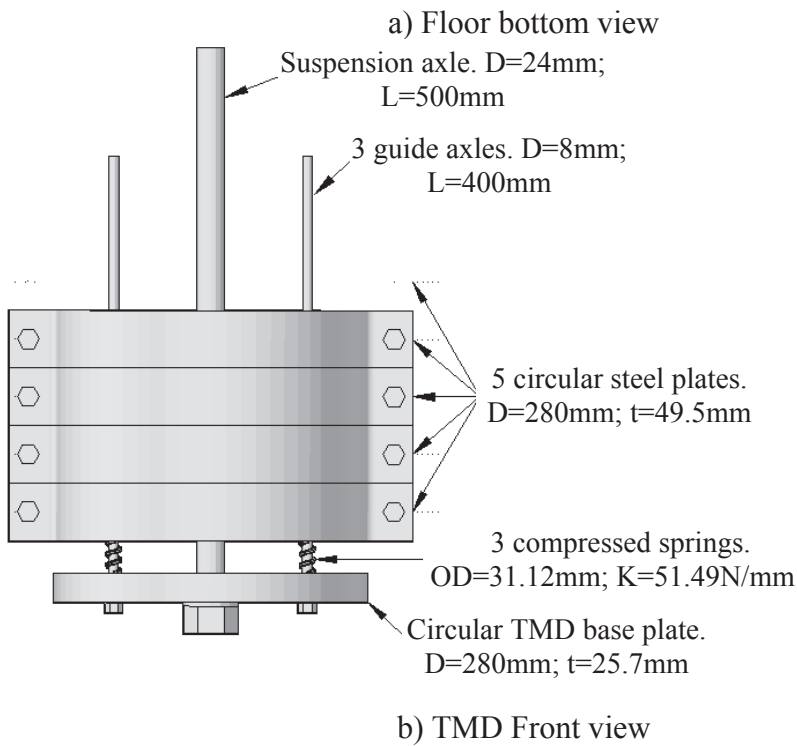
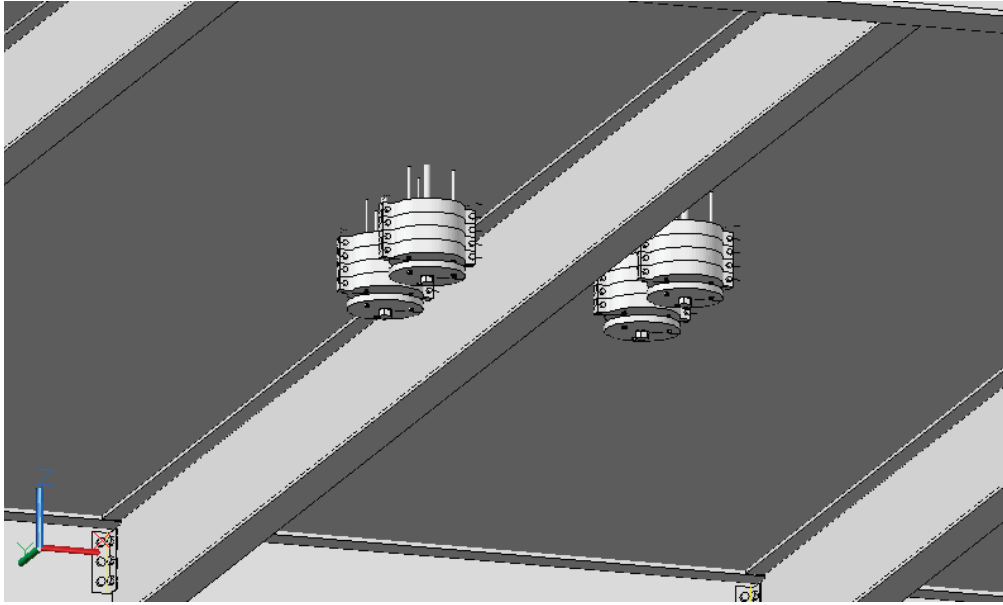


Figure 11: Details and physical characteristics of the TMDs.

From Figures 10 and 11, the effective total mobile mass of each TMD is equal to 100 kg, which corresponds to four circular steel plates of 25 kg. The stiffness of each compressed spring (spring rate) is equal to 51.49 N/mm which gives a total stiffness per TMD of 154.47N/mm (154,470N/m). The inherent damping value for each TMD is equal to 117.91N.s/m. The total sum of the four TMDs parameters is shown in Table 5 (actual design).

8 Controlled Composite Floor Dynamic Response

Based on Table 6 results, it can be noticed that although a good percentage reduction was obtained for the pre-design set of 75%, 73% and 72% (peak unweighted acceleration, RMS acceleration and VDV values, respectively), a 20% reduction in the maximum kinetic energy was not enough to respect all human comfort criteria simultaneously. However, the pre-design set might be considered as a good start point. In comparison with the pre-design set, the optimum and actual designs presented a better percentage reduction of 80%, 78% and 79% (peak unweighted acceleration, RMS acceleration and VDV values, respectively).

Therefore, a 44% reduction in the maximum kinetic energy was enough to respect all human comfort criteria at the same time. Thus, considering that there is no generally agreed acceptance criterion for human rhythmic activities [6], it is prudent to compare each one instead of to choose one. Concerning the actual design, the commercial values of the TMDs springs and masses were carefully chosen aiming to match as much as possible the optimum design set.

Design Set	Vibration Control	Acceleration (m/s ²)		VDV (m/s ^{1.75})	Maximum Kinetic Energy (J)
		a _p	a _{w,rms}		
Pre-Design	<i>uncontrolled</i>	2.017	1.118	2.337	5.684
	<i>controlled</i>	0.512	0.307	0.658	4.553
	<i>reduction (%)</i>	-75	-73	-72	-20
Optimum Design	<i>uncontrolled</i>	2.017	1.118	2.337	5.684
	<i>controlled</i>	0.398	0.242	0.481	3.208
	<i>reduction (%)</i>	-80	-78	-79	-44
Actual Design	<i>uncontrolled</i>	2.017	1.118	2.337	5.684
	<i>controlled</i>	0.398	0.241	0.481	3.201
	<i>reduction (%)</i>	-80	-78	-79	-44

Table 7: Vibration control effectiveness.

The steel-concrete composite floor dynamic response in time and frequency domain for the actual design is shown in Figure 12. Regarding the Figure 12b, it must be emphasized that the 3rd peak associated to the fundamental frequency of the floor ($f=6.36$ Hz) was reduced when the TMDs were attached to the floor bottom.

The total time in which the aerobic activity was carried out on the composite floor was equal to 10s. It must be emphasized that the red dashed line in Figure 12b is related to the steel-concrete composite floor controlled response.

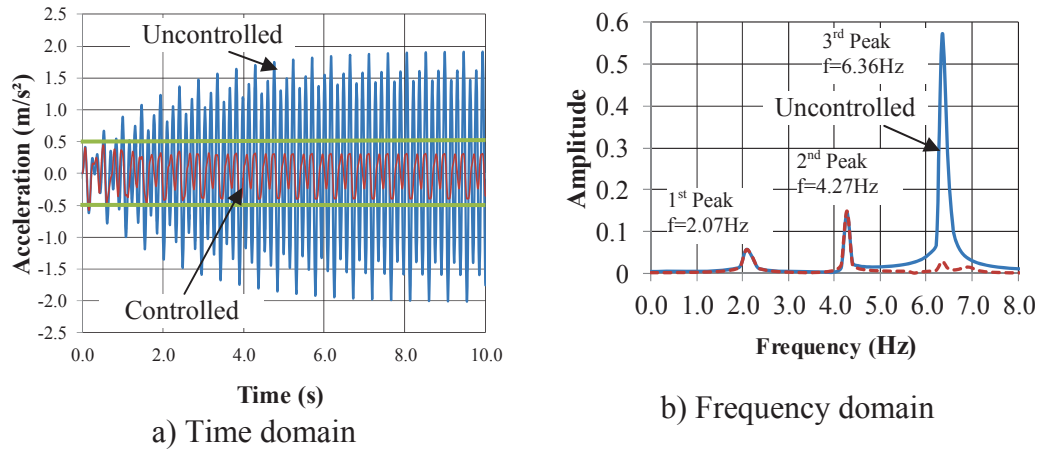


Figure 12: Investigated steel-concrete composite dynamic floor response

9 Conclusions

The excessive vibration problems due to human rhythm activities concerning building steel-concrete composite floors have been related by several authors in the last years. Having this problem in consideration, this paper analysed numerically a typical steel-concrete composite floor spanning 10m by 10m used for aerobics activities using ANSYS program.

The modal analysis performed indicated that the fundamental frequency of the composite floor was equal to 6.36Hz. This frequency value lies in the frequency range of aerobic activities which may lead the structure to a resonant motion state. In order to evaluate quantitative and qualitatively this possibility, the force frequency was set equal to 2.13Hz such that its third harmonic of 6.38Hz matched the first mode of the structure.

The present investigation indicated that the current human rhythmic activity led the building steel-concrete composite floor to an unacceptable vibration level and consequently to a violation of human comfort criteria. Thus, it was developed a structural control strategy aiming to reduce the floor excessive vibrations through the use of Tuned Mass Damper (TMD) systems, based on an optimisation process considering the subproblem approximation method and a sequential unconstrained minimization technique using the ANSYS optimisation tool.

The maximum reduction obtained for twenty individuals practising aerobics was about 80%, which resulted in an unweighted peak acceleration, RMS acceleration and VDV of 0.40m/s², 0.24m/s² and 0.48m/s^{1.75}, respectively. The results have shown that optimisation techniques directly applied on the finite element model were very useful, in order to improve the building steel-concrete composite floors vibration control.

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