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HUMAN COMFORT ANALYSIS AND VIBRATION CONTROL OF A STEEL-CONCRETE COMPOSITE FOOTBRIDGE

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Abstract. *This paper aims to investigate the dynamic behaviour of a steel-concrete composite footbridge submitted to human walking vibration and located at the mountain region of Rio de Janeiro. The structural system is constituted by steel sections and a concrete slab and is currently used for pedestrian crossing. The investigated structural system corresponds to a footbridge spanning 32m and composed by two steel trusses with welded connections that are intertwined by horizontal bracings in upper and lower chord of the trusses and floor concrete slabs forming a composite system with complete interaction. The structural system dynamic response, in terms of peak accelerations, was obtained and compared to the limiting values proposed by several authors and design standards. The peak acceleration values found in the present investigation indicated that the analysed footbridge have presented problems related with human comfort. This way it was understood that a structural control is necessary in order to reduce the footbridge excessive vibrations. Thus, an investigation was performed based on some structural control alternatives for attenuating excessive vibrations using Tuned Mass Damper (TMD) systems.*

1 INTRODUCTION

Steel and steel-concrete composite pedestrian footbridges are frequently subjected to dynamic actions with variable magnitudes due to the pedestrian crossing on the concrete deck. These dynamic actions can produce excessive vibrations and even generate the initiation of fractures or even their propagation in the structure [1-5]. Depending on their magnitude and intensity, these adverse effects can compromise the structural system's response and the reliability and may also lead to a reduction of the expected footbridge service life.

The structural engineers' experience and knowledge together with the use of newly developed materials and technologies have produced steel-concrete composite daring footbridges. This led to very slender steel and composite (steel-concrete) pedestrian footbridges and consequently changed their serviceability and ultimate limit states design. A direct consequence of this design trend is a considerable increase of structural vibrations [1-5].

Based on this scenario, this paper aims to investigate the dynamic behaviour of a steel-concrete composite footbridge submitted to human walking vibration and located at the mountain region of Rio de Janeiro [1]. The structural system is constituted by steel sections and a concrete slab and is currently used for pedestrian crossing.

The investigated structural system corresponds to a footbridge spanning 32m and composed by two steel trusses with welded connections that are intertwined by horizontal bracings in upper and lower chord of the trusses and floor concrete slabs forming a composite system with complete interaction [1].

The proposed computational model adopted the usual mesh refinement techniques present in finite element method simulations, based on the ANSYS program [6]. This numerical model enabled a complete dynamic evaluation of the investigated tubular footbridge especially in terms of human comfort and its associated vibration serviceability limit states.

The structural system dynamic response, in terms of peak accelerations, was obtained and compared to the limiting values proposed by several authors and design standards [3-4]. The peak acceleration values found in the present investigation indicated that the analysed footbridge have presented problems related with human comfort.

Considering that it was detected that this type of structure can reach high vibration levels that can compromise the footbridge user's comfort, it was understood that a structural control is necessary in order to reduce the footbridge excessive vibrations. Thus, an investigation was performed based on some structural control alternatives for attenuating excessive vibrations using Tuned Mass Damper (TMD) systems.

2 HUMAN WALKING MODELLING

Human loads comprise a large portion of the acting live loads in structures, especially in footbridges. In general, the human live loads are classified into two broad categories: in situ and moving. Periodic jumping due to music, sudden standing of a crowd, and random in-place movements are examples of in situ activities. Walking, marching, and running are examples of moving activities that may specifically act in footbridges. As the main purpose of these structures is the pedestrian's crossing, they must be safe and do not cause discomfort to users.

On the other hand, human activities produce dynamic forces and their associated vibration levels should not disturb or alarm their users. Therefore, this investigation describes one dynamic load model developed to incorporate the dynamic effects on the footbridges dynamic response induced by people walking. It must be emphasized that the geometry of the human body walking is an organized leg motion that cause an ascent and descending movement of the effective body mass at each step.

The human body mass accelerations are associated to floor reactions, and are approximately periodic to the step frequency. The two feet produce this type of load, as a function of the static parcel associated to the individual weight and three, four or even five harmonic load components. These harmonics appear due to the interaction between the increasing loads, represented by one foot, and the simultaneous unload of the other foot.

However, it is also necessary to incorporate several other parameters in the walking representation, like step distance and speed. These variables are related to the step frequency, excitation frequency values, dynamic coefficients and phase angles. Table 1 presents a detailed description of these parameters adopted in the mathematical representation of the dynamic loading model implemented in the present investigation.

Human Activity	Velocity: υ (m/s)	Step Distance: l_s (m)	Step Frequency: f_s (Hz)
Slow Walking	1.1	0.60	1.7
Normal Walking	1.5	0.75	2.0
Fast Walking	2.2	1.00	2.3
Slow Running (Jogging)	3.3	1.30	2.5
Fast Running (Sprinting)	> 5.5	> 1.75	> 3.2

Table 1: Characteristics of human walking [2].

The walking loading model implemented in this investigation can be represented based on the load static parcel, related to the individual weight, and a combination of five harmonic forces with frequencies that are multiples or harmonics of the basic frequency of the force repetition, e.g. step frequency, f_s, for human activities. This loading model has considered a space and temporal variation of the dynamic action on the structure and the time-dependent repeated force can be represented by the Fourier series, see Equation (1).

$$F(t) = P[1 + \sum \alpha_i \cos\left(2\pi i\, f_s\, t + \phi_i\right)] \quad (1)$$

Where:

F(t) : dynamic load;
P : person's weight (800 N [1-3]);
α_i : dynamic coefficient for the harmonic force;
i : harmonic multiple (i = 1,2,3…,n);
f_s : walking step frequency;
ϕ : harmonic phase angle;
t : time.

Five harmonics were considered to represent the dynamic load associated to human walking [2]. Table 2 shows the dynamic coefficients and phase angles used in this model. Figure 1 presents a dynamic loading function for a pedestrian walking with a step frequency of 2.4 Hz.

Harmonic i	Dynamic Coefficients α_i	Phase Angles ϕ_i
1	0.37	0
2	0.10	$\pi/2$
3	0.12	$\pi/2$
4	0.04	$\pi/2$
5	0.08	$\pi/2$

Table 2: Dynamic coefficients and phase angles [2].

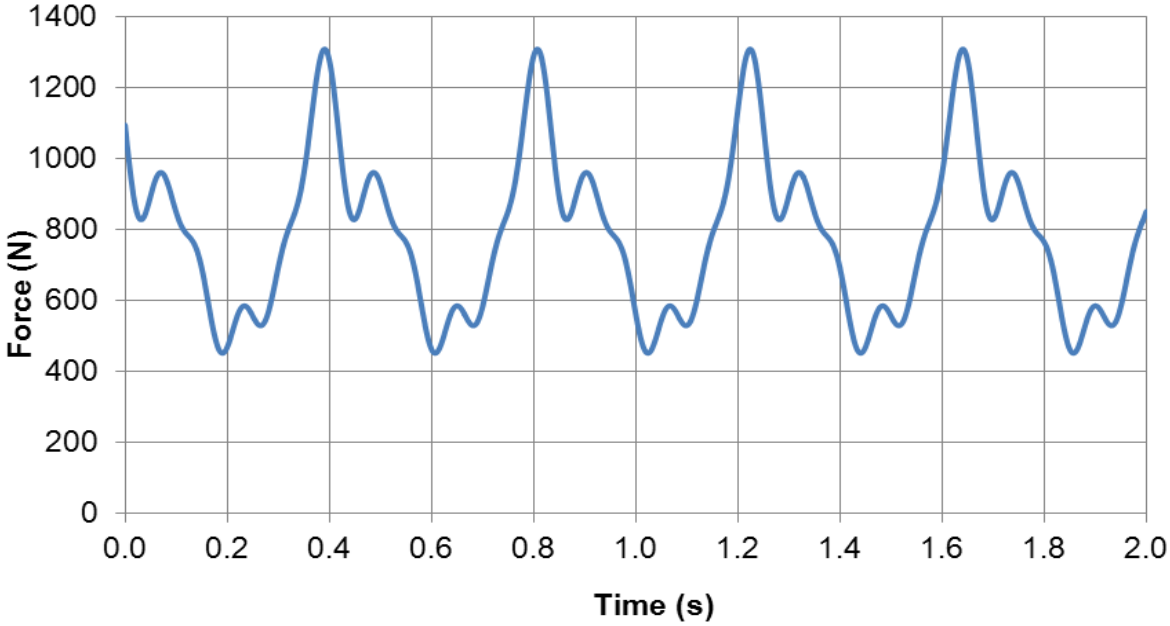


Figure 1: Dynamic load function for a single person walking (f_s = 2.4 Hz).

3 STRUTURAL MODEL

The investigated structural model is constituted by steel sections and a concrete slab and is currently used for pedestrian crossing. The model corresponds to a pedestrian footbridge spanning 32m and composed by two steel trusses with welded connections that are inter-twined by horizontal bracings in upper and lower chord of the trusses and floor concrete slabs forming a composite system with complete interaction [1], as presented in Figure 2.

The pedestrian footbridge steel sections are related to welded wide flanges (WWF) made with ASTM - A572 steel with a 300 MPa yield stress steel grade. A 2.05 x 10^{11} N/m^2 Young's modulus was adopted for the footbridge steel beams. The structural system concrete slab has a 30 MPa specified compression strength and a 3.0 x 10^{10} N/m^2 Young's Modulus [1].

4 FINITE ELEMENT MODEL

The developed computational model adopted the usual mesh refinement techniques present in finite element method simulations, based on the ANSYS program [6]. This model enabled a complete dynamic evaluation of the investigated pedestrian footbridge especially in terms of human comfort and its associated vibration serviceability limit states, as shown in Figure 3.

In this computational model, all steel sections were represented by three-dimensional beam elements (BEAM44 [6]) with tension, compression, torsion and bending capabilities, see Figure 3. 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.

On the other hand, the reinforced concrete slab was represented by shell finite elements (SHELL63 [6]). This finite element has both bending and membrane capabilities with in-plane and normal loads permitted, see Figure 3. 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.

The finite element model presented 14556 degrees of freedom, 2448 nodes and 2836 finite elements (BEAM44 [6]: 1812 and SHELL63 [6]: 1024), as illustrated in Figure 3. It was considered that both structural elements (steel sections and concrete slab) have total interaction with an elastic behaviour, as presented in Figure 3.

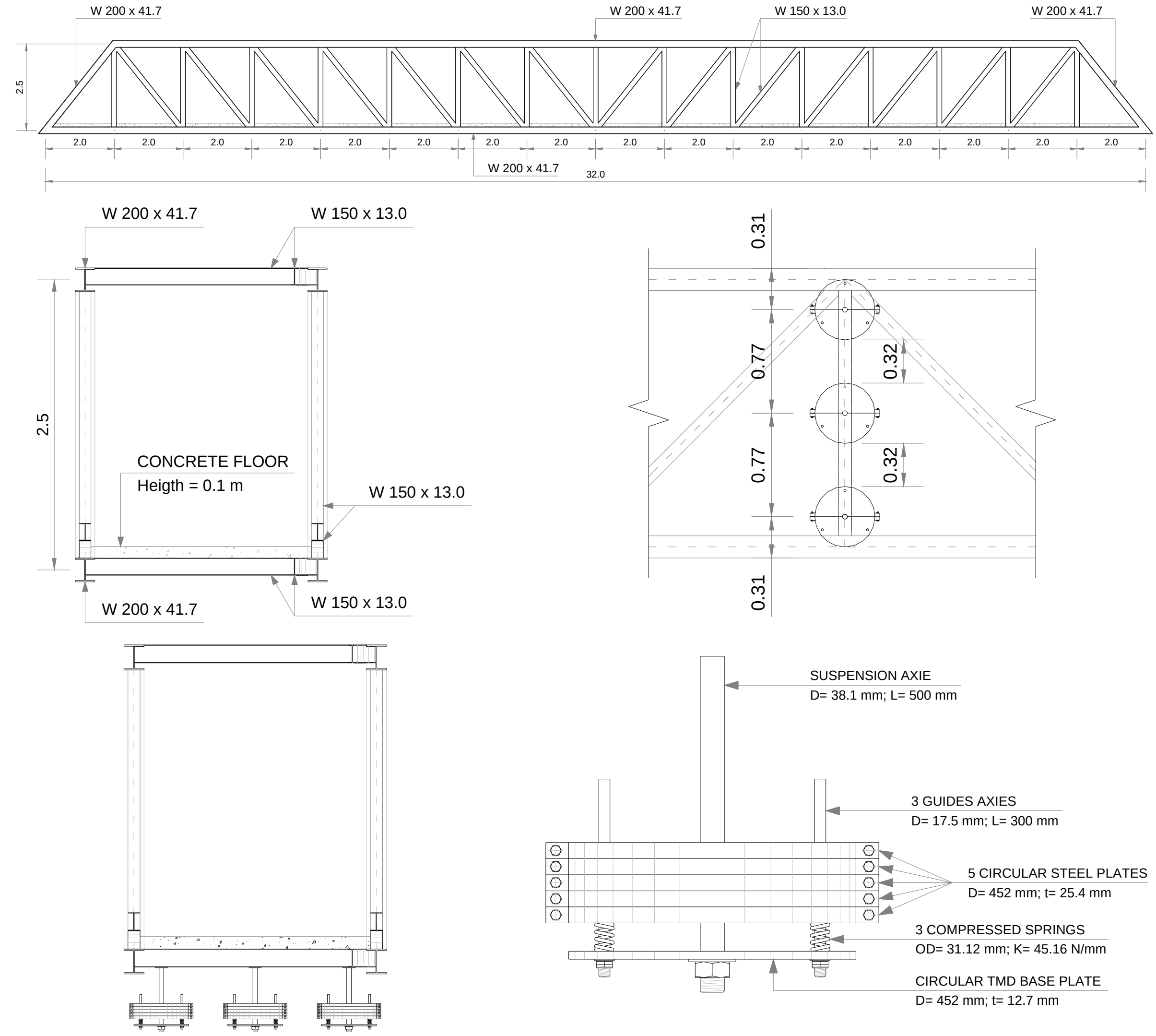


Figure 2: Investigated structural model and developed TMD system. Dimensions in (m).

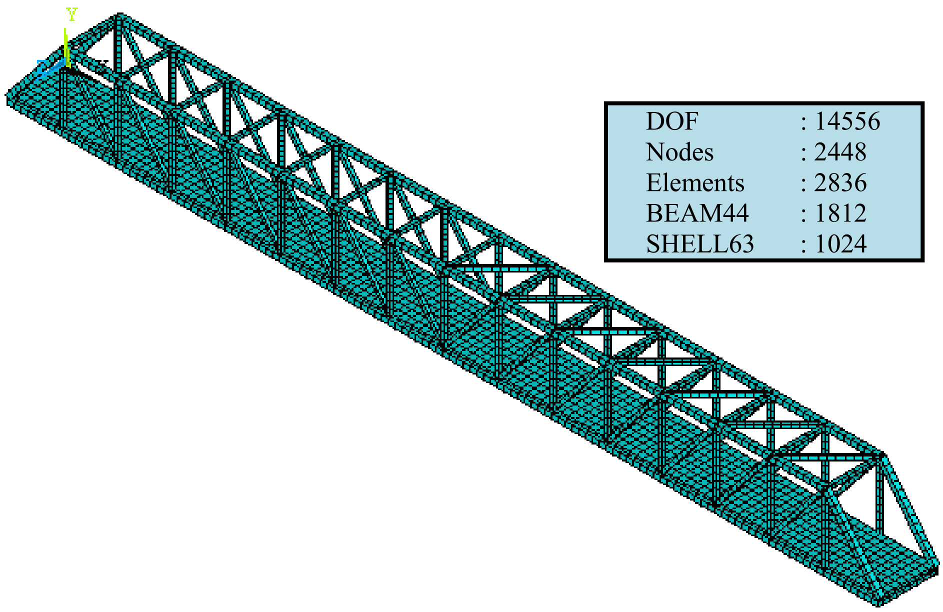


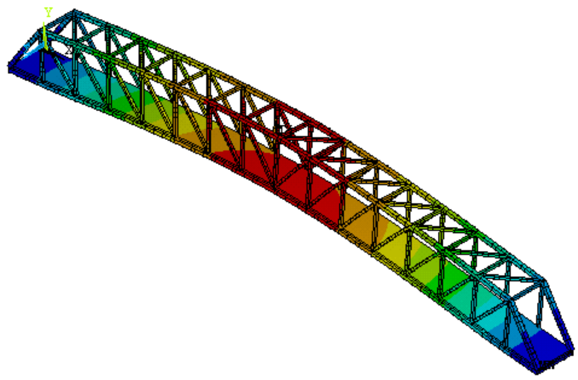
Figure 3: Steel-concrete composite footbridge finite element model mesh and layout.

5 DYNAMIC ANALYSIS

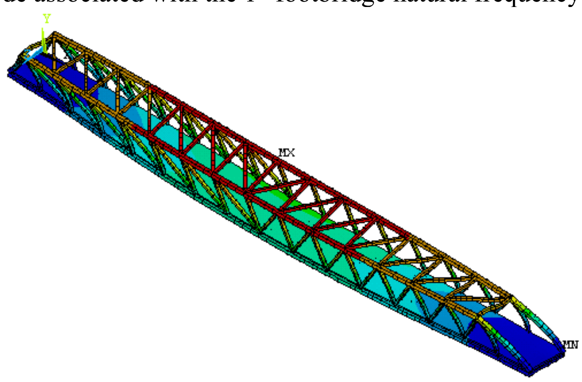
Initially, the (steel-concrete) composite footbridge natural frequencies vibration modes and peak accelerations were determined with the aid of the numerical simulations, based on the finite element method using the ANSYS program [6]. The peak acceleration values were obtained considering a step frequency equal to 2.4 Hz (f_s = 2.4 Hz), corresponding to a fast walking (see Table 1) and simulating a resonance situation. Table 3 presents the footbridge natural frequencies and Figure 4 illustrates a few vibration modes of the investigated structure.

Natural Frequencies (Hz)					
f_{01}	f_{02}	f_{03}	f_{04}	f_{05}	f_{06}
4.80	6.13	8.33	12.29	13.40	18.80

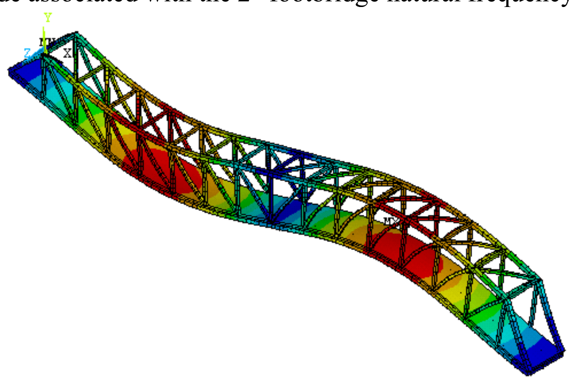
Table 3: Stee-concrete composite footbridge natural frequencies.



a) Vibration mode associated with the 1st footbridge natural frequency (f_{01} = 4.83 Hz).



b) Vibration mode associated with the 2st footbridge natural frequency (f_{02} = 6.13 Hz).



c) Vibration mode associated with the 5st footbridge natural frequency (f_{05} = 13.40 Hz).

Figure 4: Investigated footbridge vibration modes.

The finite element modelling follows with the evaluation of the footbridge performance in terms of vibration serviceability due to dynamic forces induced by people walking. The first step of this investigation concerned the determination of the tubular footbridge peak accelerations, based on a linear time-domain dynamic analysis, as presented in Table 4.

The dynamic loading model, see Equation (1), Tables 1 to 2 and Figure 1, related to one pedestrian crossing the footbridge on the concrete slab centre, in fast walking, were applied on the investigated footbridge over 13s (t = 13s), see Figure 5. A resonance situation was simulated in this analysis, based on a step frequency equal to 2.4 Hz, corresponding to a fast walking (f_s = 2.4 Hz => 2^{nd} harmonic: 2 x 2.4 Hz = 4.8 Hz => f_{01} = 4.8 Hz).

The maximum accelerations (peak accelerations) were obtained adopting an integration time step equal to 2 x 10^{-3} s (Δt = 2 x 10^{-3} s). The structural damping coefficient adopted in this investigation was equal to 0.01 (ξ=1%) [2-3]. In this investigation the central section of the structural model was analysed, see Figure 5. These maximum accelerations were compared to the limits recommended by several authors and design standards [3-4], see Table 4.

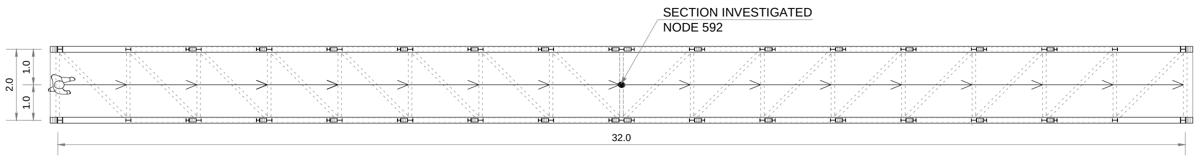


Figure 5: One person walking on the footbridge (f_s = 2.4 Hz). Dimensions in (m).

Amplitude Response to Resonance Situation		Limiting Acceleration a_{lim}= 5%g (m/s^2)
Displacement (mm)	Acceleration (m/s²)	**0.49**
0.36	**0.64**	

Table 4: Composite floor dynamic response (central node).

6 VIBRATION CONTROL

With the main objective of control the excessive footbridge vibration response (a_{max} = 0.64 m/s^2 > a_{lim} = 0.49 m/s^2, see Table 4), an absorber which dissipates part of the main system energy is needed. In other words, such dispositive attached to the structure counteracts the forces applied to it and then less work is done on the structural system. This type of absorber (also known as Tuned Mass Damper: TMD) is made up in general of a mass-spring-damper assemble. It is important to emphasize that this device is a passive system, i.e. the absorber does not apply any external force to the main structure.

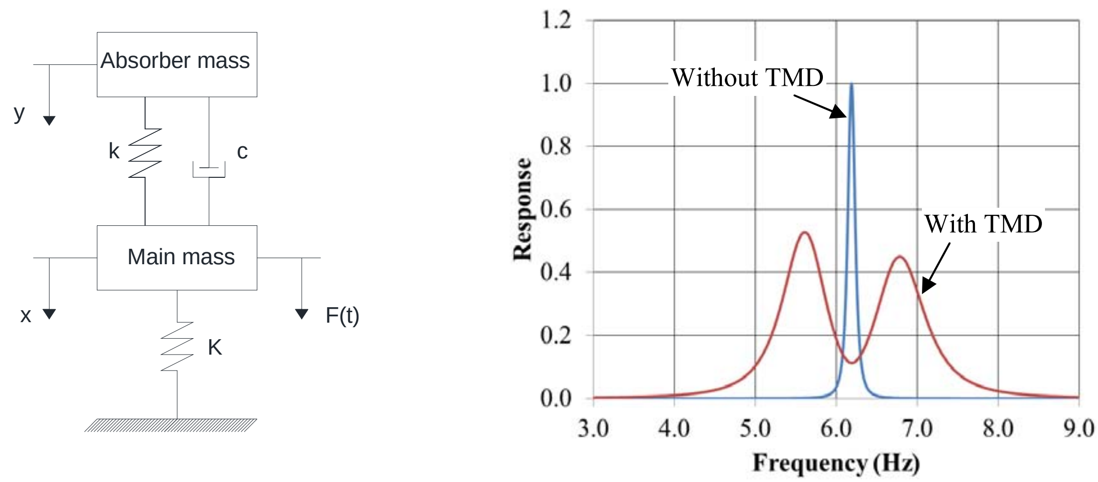
Another important point is that the TMD is more effective if tuned close to the main structure natural frequency. In addition, the absorber splits the natural frequency of the main system in two others frequencies, see Figure 6. The energy associated to these frequencies will depend on the absorber damping value.

Several authors have developed similar devices concerning optimum parameters to minimize the structural system dynamic response. The formulation developed by Den Hartog [7] has considered optimum parameters based on a two degrees of freedom system, see Figure 6. In this investigation the TMD system was developed based on Den Hartog's formulation [7].

Based on an absorber system proposed and experimentally tested by Varela [5], a similar system was developed in this investigation. The TMD was tuned to the footbridge first modal frequency (f_{01} = 4.80 Hz) to control the resonant motion. Table 5 presents all the Tuned Mass Damper (TMD) system parameters proposed in this work.

It can be seen from Table 5 that practically 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 2).

Besides, the actual TMD was proportionally divided in three TMDs with the same tuning to make it lighter and consequently easier to install (see Figure 2). The TMDs were symmetrically arranged at the investigated steel-concrete composite footbridge mid-span (concrete slab centre) and properly attached to the floor bottom. The TMDs location and details are presented in Figure 2.



a) Schematic of a two DOF system

b) TMD response in frequency domain

Figure 6: Theoretical TMD characteristics.

Absorber Parameters	Optimum TMD	Actual TMD
f_{opt}	0.956	0.957
f_a (Hz)	4.617	4.623
ζ_a (%)	12.1	1.5
k_a (N/m)	403934	406440
m_a (kg)	481	481
c_a (Ns/m)	3347	418

Table 5: Absorber parameters.

The work proceeds with the simulation of the three (optimum and actual) TMDs as they were installed to the investigated steel-concrete composite footbridge mid-span, see Figure 2. In sequence, Figures 7 to 9 and Table 6 show the footbridge steady-state displacement and acceleration amplitude responses relative to the central node of the structural model and their respective effectiveness.

Based on Table 6 results, a good percentage reduction equal to 29.68% (optimum TMDs) and 34.37% (actual TMDs) was obtained for the resonance condition. Thus, it can be seen that the TMD system is effective in resonance situations, see Figures 9 to 11. It must be emphasized that the blue and red lines illustrated in Figures 7 to 9 are related to the footbridge uncontrolled and controlled dynamic response, respectively.

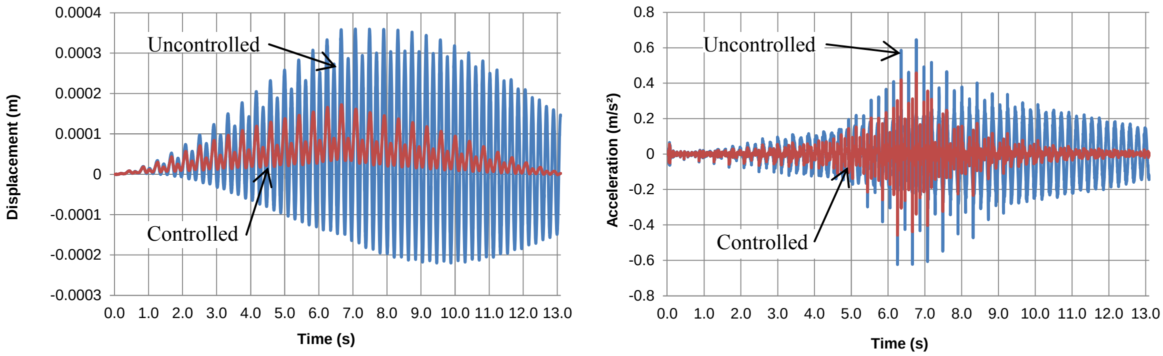


Figure 7: Footbridge dynamic response in time domain. Optimum TMDs.

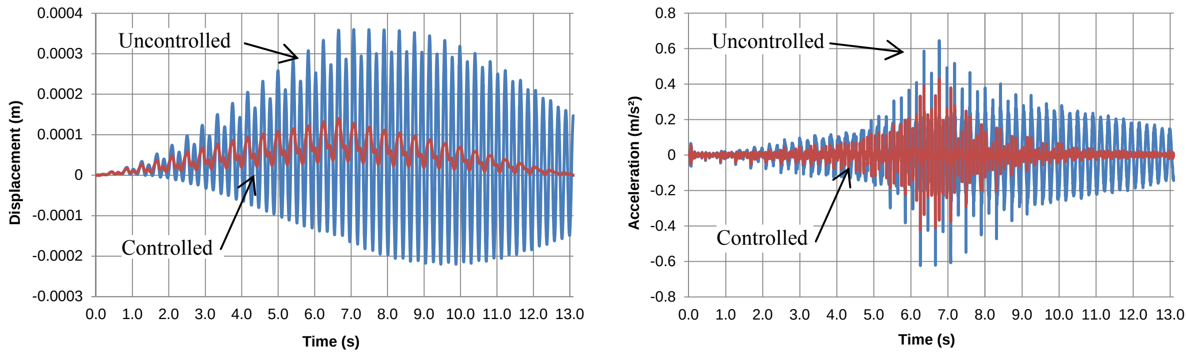
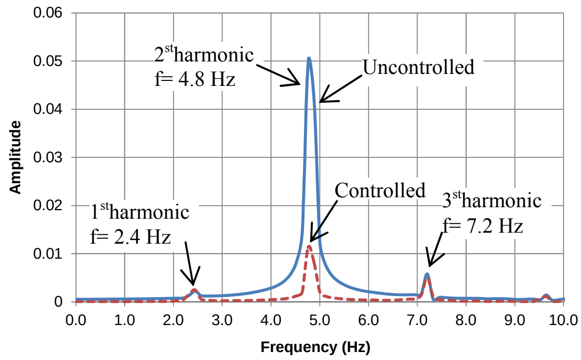
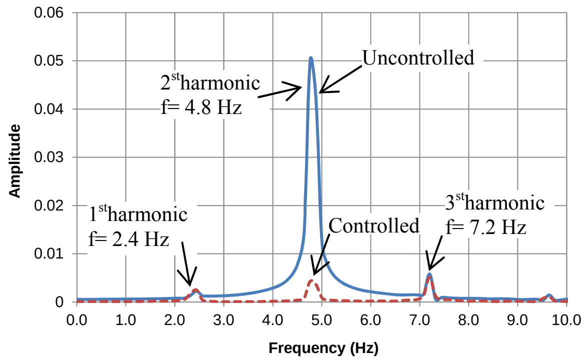


Figure 8: Footbridge dynamic response in time domain. Actual TMDs.



a) Optimum TMDs.



b) Actual TMDs.

Figure 9: Footbridge dynamic response in frequency domain.

Without TMDs / With TMDs / Reduction	Peak Acceleration (m/s²)	
	Optimum TMDs	Actual TMDs
Uncontrolled	0.64	0.64
Controlled	**0.45**	**0.42**
Reduction (%)	29.68	34.37

Table 6: TMDs effectiveness comparison: resonance situation.

7 CONCLUSIONS

This work analysed the dynamic behaviour of a steel-concrete composite pedestrian footbridge spanning 32m and located at the mountain region of Rio de Janeiro. 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 footbridge fundamental frequency was equal to 4.80Hz (f_{01} = 4.80Hz). This frequency value lies in the frequency range of pedestrian walking (fast walking), which may lead the structural model to a resonant situation. The dynamic analysis carried out shown that the peak accelerations obtained from the footbridge model were higher than the recommended limit ($a_{max} = 0.64$ m/s^2 $> a_{lim} = 0.49$ m/s^2). This situation led to human discomfort for the individuals walking on the composite footbridge.

Aiming to reduce such excessive vibrations, the use of three passive TMDs were simulated as they were attached to footbridge mid-span at the concrete slab centre. The maximum reduction obtained in resonant motion (the worst case to design) was equal to 34.37%, which resulted in a peak acceleration of 0.42m/s^2 and thus lower than the limit of 0.49m/s^2. It can be concluded that the use of tuned mass damper systems has shown to be a low-cost alternative to respect the intended human comfort criteria for steel-concrete composite pedestrian footbridges when submitted to human walking.

8 ACKNOWLEDGEMENTS

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