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Paper 23

Finite Element Analysis of Walking Vibration Problems for Tubular Steel-Concrete Composite Footbridges

G.L. Debona[1], J.G. Santos da Silva[2], A.C.C.F. Sieira[2]
P.C.G. da S. Vellasco[2] and L.R.O. de Lima[2]
[1]Civil Engineering Post-Graduate Programme, PGECIV
[2]Structural Engineering Department
State University of Rio de Janeiro, UERJ, Brazil

Abstract

The main objective of this investigation is to present the finite element modelling of the dynamic behaviour of tubular composite (steel-concrete) footbridges subjected to human walking vibrations. The investigated structural system was based on a tubular composite (steel-concrete) footbridge, spanning 82.5 m. The structural model consists of tubular steel sections and a concrete slab. This investigation is carried out based on correlations between the experimental results related to the footbridge dynamic response and those obtained with finite element modelling. The finite element model enabled a complete dynamic evaluation of the tubular footbridge in terms of human comfort and its associated vibration serviceability limit states. The peak accelerations found in the present analysis indicated that the investigated tubular footbridge presented problems related with human comfort. Hence it was detected that this type of structure can reach high vibration levels that can compromise the footbridge user's comfort.

Keywords: dynamic analysis, fatigue analysis, structural dynamics, tubular steel-concrete composite footbridges, design codes, computational modelling.

1 Introduction

Tubular hollow sections are increasingly used in off-shore structures, highway bridges, pedestrian foot-bridges, large-span roofs and multi-storey buildings due to their excellent properties and the associated advances in fabrication technology.

The intensive use of tubular structural elements in Brazil, such as the example depicted in Figure 1, mainly due to its associated aesthetical and structural advantages, led designers to be focused on their technologic and design issues.

Nowadays in Brazil, there is still a lack of code that deals specifically with tubular design. This fact induces designers to use other international tubular design codes. Consequently, their design methods accuracy plays a fundamental role when economical and safety points of view are considered. Additionally, recent tubular joint studies indicate that further research is needed, especially for particular geometries. This is even more significant for some failure modes where the collapse load predictions lead to unsafe or uneconomical solutions.

Figure 1. Example of a tubular steel pedestrian footbridge in Rio de Janeiro, Brazil.

Steel and composite tubular footbridges are currently subjected to dynamic actions with variable magnitudes due to the pedestrian crossing on the concrete deck. These dynamic actions can generate the initiation of fractures or even their propagation in the structure. Depending on the magnitude and intensity, these adverse effects can compromise the structural system response and the reliability which may also lead to a reduction of the expected footbridge service life.

Generally, fatigue assessment procedures are usually based on S-N curves which relate a nominal or geometric stress range S to the corresponding number N of load cycles to fatigue failure. In this situation fatigue assessment refers to the nominal stress range $\Delta\sigma$ in a tubular structural member.

The fatigue resistance is given according to a classification catalogue in the form of standardized S-N curves. Structural details classified in this catalogue [1], correspond specifically to a situation of stress range, direction, crack position, detail dimension and weld quality which had been characteristic for the tests on which the classification is based [2, 3].

The use of circular hollow section members as part of the structure of pedestrian footbridges is a relatively new constructional concept. During the last couple years several steel-concrete composite footbridges had been constructed in Brazil, as illustrated in Figure 1.

The typical cross-section of this type of pedestrian footbridge generally consists of a tubular spatial truss girder carrying the concrete deck slab, as presented in Figure 1. The deck slab is connected directly to the steel structure by either shear studs, concrete dowels or in some cases where no top chord exists. At the bottom chord of the tubular space truss four brace members have to be connected to the continuous bottom chord. This type of joint is usually named K-joint, as depicted in Figure 2 [2].

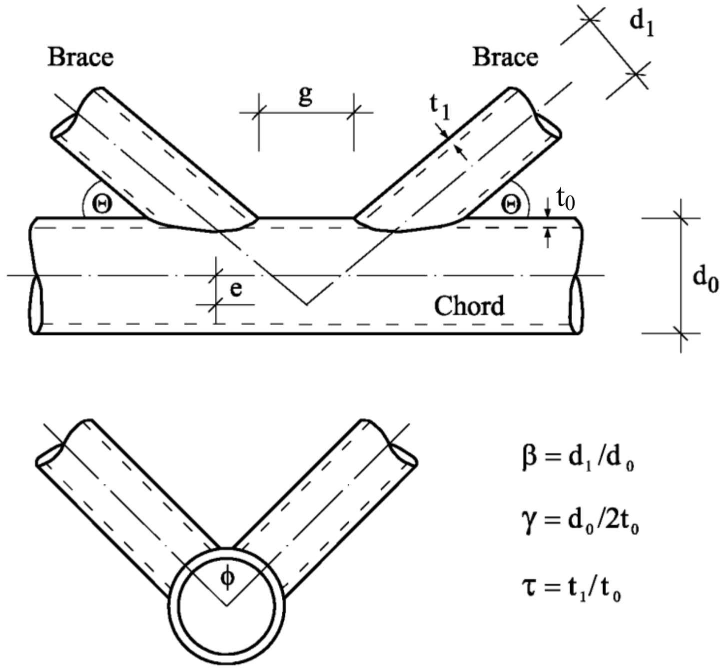

Figure 2. Typical multiplanar K-joint with notations.

Steel and composite tubular footbridges can be subjected to the material imperfections of its structural elements, such as mechanical and metallurgic discontinuities. Such defects lead to cracking in these structural elements. When these elements are subjected to dynamic actions, the fatigue phenomenon occurs and produces stress concentrations and possible fractures. These fractures are directly responsible for reducing the local or global footbridge stabilities or even its life service [3].

On the other hand, the structural engineers experience and knowledge allied by the use newly developed materials and technologies have produced tubular steel and composite (steel-concrete) foot-bridges with daring structures.

This fact have generated very slender tubular steel and composite (steel-concrete) pedestrian foot-bridges and consequently changed the serviceability and ultimate limit states associated to their design. A direct consequence of this design trend is a considerable increase of structural vibrations [3-12].

Considering all aspects mentioned before, the main objective of this investigation is to present the finite element modelling of the dynamic behaviour of tubular composite (steel-concrete) footbridges subjected to human walking vibration. Based on the results obtained in this study, a fatigue assessment will be performed, in order to evaluate the tubular footbridges service life. Further research in this area is currently being carried out.

The investigated structural model was based on a tubular composite (steel-concrete) footbridge, spanning 82.5 m. The structure is composed by three spans (32.5 m, 17.5 m and 20.0 m, respectively) and two overhangs (7.50 m and 5.0 m, respectively). The structural system consists of tubular steel sections and a concrete slab and is currently used for pedestrian crossing [6, 12].

The proposed computational model adopted the usual mesh refinement techniques present in finite element method simulations, based on the ANSYS program [13].

The finite element model has been developed and validated with the experimental results. 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 [6, 12].

This investigation is carried out based on correlations between the experimental results related to the footbridge dynamic response and those obtained with finite element models. The proposed computational model adopted the usual mesh refinement techniques present in finite element method simulations.

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 [8, 14].

The peak acceleration values found in the present investigation indicated that the analysed tubular footbridge presented problems related with human comfort. Hence it was detected that this type of structure can reach high vibration levels that can compromise the footbridge user's comfort and especially its safety.

2 Human Walking Modelling

The present investigation was carried out based on a more realistic loading model developed to incorporate the dynamic effects induced by people walking. The loading model considered the ascent and descending movement of the human body effective mass at each step and the position of the dynamic load (human walking load) was also changed according to the individual position.

This dynamic loading model considers a space and time variation of the dynamic action over the structure that is evaluated. Additionally, also incorporates the transient effect due to the human heel impact, see Equations 1 to 4 [11].

$$F(t) = \begin{cases} \left(\dfrac{f_{mi}\,F_m - P}{0.04\,T_p}\right)t + P & \text{if } 0 \le t < 0.04\,T_p \\ f_{mi}\,F_m\left[\dfrac{C_1\left(t - 0.04\,T_p\right)}{0.02\,T_p} + 1\right] & \text{if } 0.04\,T_p \le t < 0.06\,T_p \\ F_m & \text{if } 0.06\,T_p \le t < 0.15\,T_p \\ P + \sum_{i=1}^{nh} P\,\alpha\,\text{sen}\left[2\pi i f_p\left(t + 0.1T_p\right) + \phi_i\right] & \text{if } 0.15\,T_p \le t < 0.90\,T_p \\ 10\left(P - C_2\right)\left(\dfrac{t}{T_p} - 1\right) + P & \text{if } 0.90\,T_p \le t < T_p \end{cases} \quad (1)$$

$$F_m = P\left(1+\sum_{i=1}^{nh}\alpha_i\right) \tag{2}$$

$$C_1 = \left(\frac{1}{f_{mi}}-1\right) \tag{3}$$

$$C_2 = \begin{cases} P(1-\alpha_2) & \text{if } nh = 3 \\ P(1-\alpha_2+\alpha_4) & \text{if } nh = 4 \end{cases} \tag{4}$$

Where:

F_m : maximum Fourier series value, given by Equation 2;
f_{mi} : human heel impact factor;
T_p : step period;
f_s : step frequency;
Φ : harmonic phase angle;
P : person's weight;
α_i : dynamic coefficient for the harmonic force;
i : harmonic multiple (i = 1,2,3…,n);
t : time;
C_1 and C2 : coefficients given by Equations 3 and 4.

The proposed mathematical model used to represent the dynamical actions produced by people walking on the floor slabs is not simply a Fourier series, due to the fact that the mentioned equations also incorporate the human heel impact effect [10, 11]. The present investigation used a heel impact factor equal to 1.12 (f_{mi} = 1.12). However, it must be emphasized that this value can vary substantially from person-to-person [6, 10].

The pedestrian motion on the tubular footbridge was modelled based on the Equations 1 to 4 and four harmonics were used to generate the dynamic forces produced by human walking. Figure 3 illustrates the dynamic load function for an individual walking at a step frequency of 2.0 Hz (f_s = 2.0 Hz).

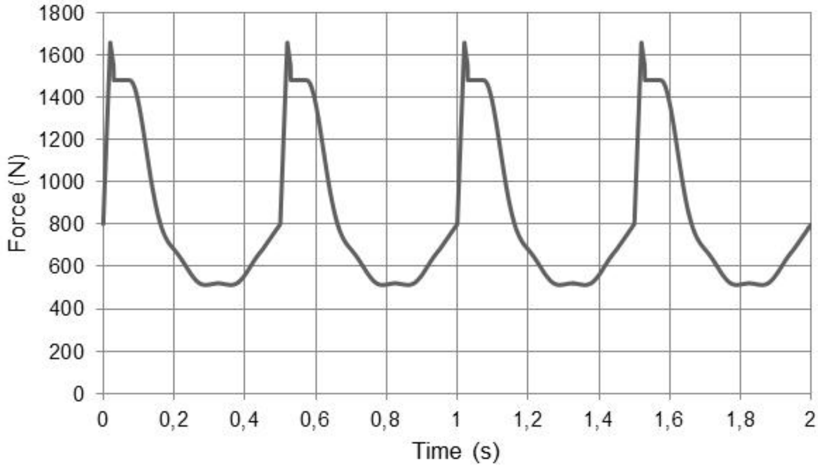

Figure 3. Dynamic load function for one person walking (f_s = 2.0 Hz). Resonant harmonic of the walking load (3rd harmonic: 3 x 2.0 Hz = 6.0 Hz).

Considering the investigated tubular footbridge, the third harmonic with step frequency equal to 2.0Hz (f_s = 2.0 Hz) was considered the resonant harmonic of the walking load (3 x 2.0 Hz = 6.0 Hz). In this situation, the finite element mesh has to be very refined and the contact time of application of the dynamic load over the structure depends of the step distance and step frequency, see Table 1.

Harmonic i	f_s	α_i	ϕ_i
1	1.6 - 2.2	0.50	0
2	3.2 - 4.4	0.20	$\pi/2$
3	4.8 - 6.6	0.10	π
4	6.4 - 8.8	0.05	$3\pi/2$

Table 1. Forcing frequencies (f_s), dynamic coefficients (α_i) and phase angles ϕ_i [4,8].

The following strategy was adopted in this study: a step distance equal to 0.75 m corresponding to the third harmonic with a step frequency of 2.0 Hz was used, see Table 1. The step period is equal to $1/f_s$ = 1/2.0 Hz = 0.50 s, corresponding to a distance of 0.75 m. This way, the adopted strategy considered three forces to model one human step and each of the dynamic loads P1, P2 and P3 were applied to the footbridge structure during 0.50/3 = 0.1667 s, corresponding to the contact time of each dynamic load.

However, the dynamic forces were not simultaneously applied. The load application begins with the first human step where the first load, P1 is applied for 0.1667 s, see Equations 1 to 4. At the end of this time period, the load P1 becomes zero while the load P2 is subsequently applied for 0.1667 s. The process continues with the application of the other load P3, based on the same procedure previously described, until the end of the first step. At this point, the load P3 from the first step is made equal to the load P1 of the second step. The process continues with subsequent step applications until all dynamic loads are applied along the entire structure length. It can be concluded that all the dynamic actions associated will be applied over the structure.

3 Investigated Structural Model

The structural model consists of tubular steel sections and a 100 mm concrete slab and is currently subjected to human walking loads. The structure was based on a tubular composite (steel-concrete) footbridge, spanning 82.5 m. The structure is com-posed by three spans (32.5 m, 17.5 m and 20.0 m, respectively) and two overhangs (7.50 m and 5.0 m, respectively), see Figure 4.

The steel sections used were welded wide flanges (WWF) made with a 300 MPa yield stress steel grade. A 2.05 x 105 MPa Young's modulus was adopted for the tubular footbridge steel beams and columns. The concrete slab has a 20 MPa specified compression strength and a 2.13 x 104 MPa Young's Modulus.

Figure 4. Investigated structural model.

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 (ANSYS, 2003). The finite element model has been developed and validated with the experimental results. This model enabled a complete dynamic evaluation of the investigated tubular footbridge especially in terms of human comfort and its associated vibration serviceability limit states [6], as presented in Figure 5.

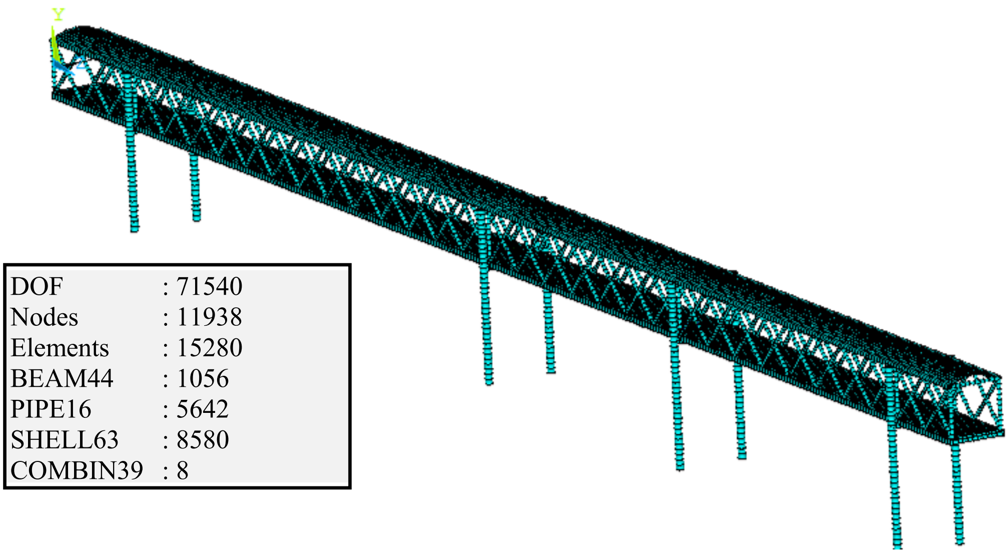

Figure 5. Tubular footbridge finite element model.

In this computational model, all steel tubular sections were represented by three-dimensional beam elements (PIPE16 and BEAM44) with tension, compression, torsion and bending capabilities. These elements have six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about x, y, and z axes.

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

The footbridge pier bearings were represented by a non-linear rotational spring element (COMBIN39). This element is a unidirectional element with nonlinear generalized force-deflection capability that can be used in any analysis.

The finite element model presented 71540 degrees of freedom, 11938 nodes and 15280 finite elements (BEAM44: 1056; PIPE16: 5642; SHELL63: 8580 and COMBIN39: 8), see Figure 5. It was considered that both structural elements (steel tubular sections and concrete slab) have total interaction with an elastic behaviour.

5 Dynamic Analysis

Initially, the tubular composite (steel-concrete) foot-bridge natural frequencies, vibration modes and peak accelerations were determined based on experimental tests [12]. The peak acceleration values were obtained considering three types of human walking: slow walking, regular walking and fast walking [12].

In a second phase, the tubular composite (steel-concrete) 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 [13].

It can be clearly noticed that there is a very good agreement between the structural model natural frequency values calculated using finite element simulations and the experimental results, see Table 2. Such fact validates the finite element model here presented, as well as the results and conclusions obtained throughout this investigation. The vibration modes of the tubular footbridge are depicted in Figures 6 to 8.

Natural frequencies (Hz)	f_{01}	f_{02}	f_{03}
Finite element modelling	1.61	2.12	5.39
Experimental results	1.56	2.34	5.08
Error (%)	3.20	9.40	6.10

Table 2. Tubular footbridge natural frequencies.

When the tubular footbridge freely vibrates in a particular mode, it moves up and down with a certain configuration or mode shape. Each footbridge natural frequency has an associated mode shape.

It was verified that longitudinal amplitudes were predominant in the fundamental vibration mode (f_{01} = 1.61 Hz), see Figure 6. In the second mode shape lateral displacements were predominant (f_{02} = 2.12 Hz), as presented in Figure 7. On the other hand, in the third vibration mode (f_{03} = 5.39 Hz), the flexural effects were predominant, as illustrated in Figure 8.

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 in the determination of the tubular footbridge peak accelerations, based on a linear time-domain dynamic analysis.

The dynamic loading related to one person crossing the tubular footbridge on the concrete slab centre, as presented in Figure 3, was applied over 55.0 s and an integration time step of $2x10^{-3}$ s ($\Delta t = 2x10^{-3}$ s) was adopted in this investigation.

The peak accelerations were obtained at seven sections of the analysed structural model, as presented in Figure 9. These maximum accelerations were compared to the limits recommended by design codes [8, 14].

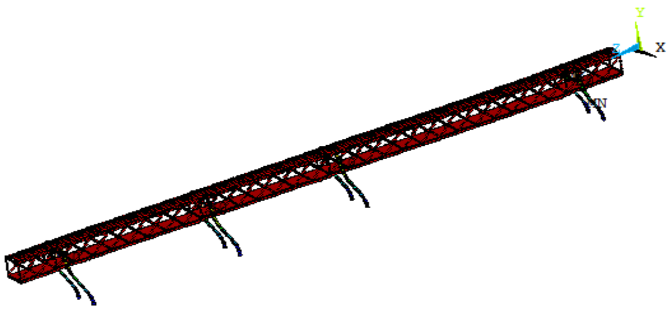

Figure 6. Vibration mode associated with the 1st footbridge natural frequency (f_{01}=1.61 Hz).

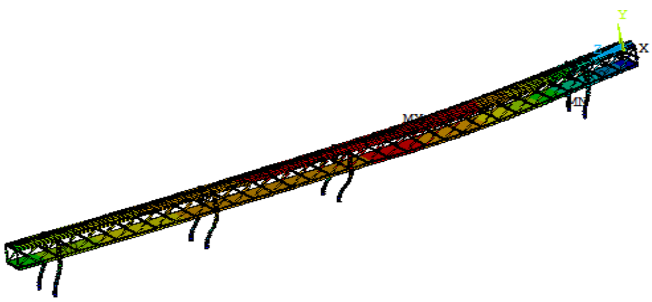

Figure 7. Vibration mode associated with the 2nd footbridge natural frequency (f_{02} = 2.12 Hz).

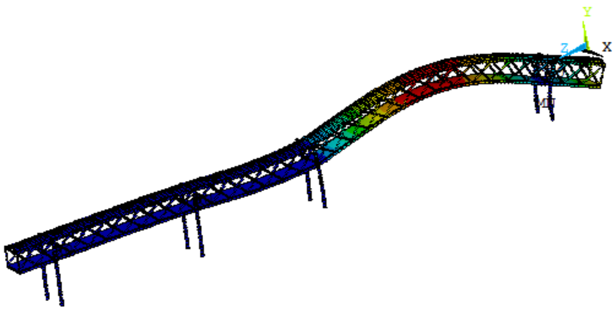

Figure 8. Vibration mode associated with the 3rd footbridge natural frequency (f_{03} = 5.39Hz).

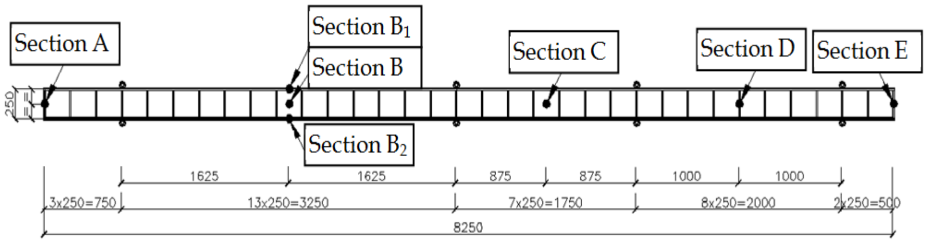

Figure 9. Tubular composite (steel-concrete) footbridge investigated sections.

In sequence, Figure 10 illustrates the tubular footbridge dynamic response, along the time, related to the section B (see Figure 9), when one pedestrian crosses the footbridge in regular walking (resonance condition).

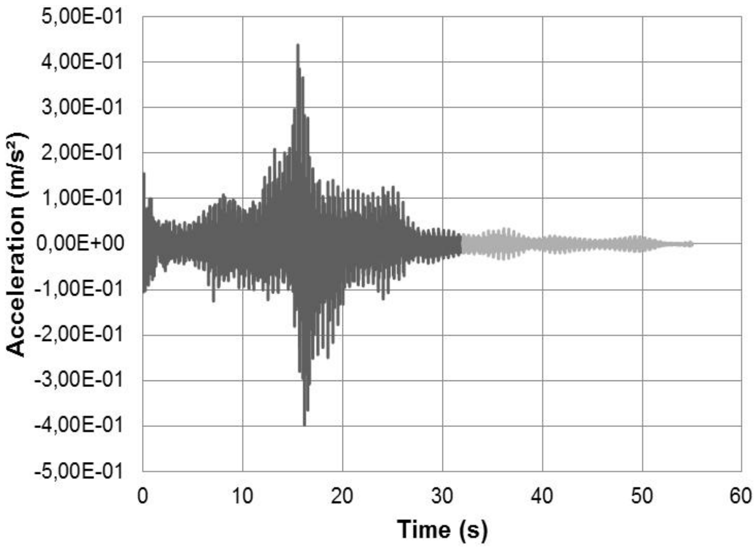

Figure 10. Tubular footbridge acceleration response at section B. One pedestrian crossing the concrete slab centre at resonance. Regular walking.

Figure 10 presents the vertical acceleration versus time graph for the tubular footbridge at section B (see Figure 9). This figure shows that the vertical acceleration gradually increase with time. In this particular case, the third harmonic with a 2.0 Hz step frequency (f_s = 2.0 Hz), was the walking load resonant harmonic.

The maximum acceleration value found at section B (see Figure 9) was equal to 0.44 m/s^2. Figure 10 also indicates that from the moment that the pedestrian leaves the footbridge span (Section B, see Figure 9), when the time is approximately equal to 26 s, the structural damping minimises the dynamic structural model response, as presented in Figure 10. This assertive occurs in dynamic loading models that consider the load spatial variation.

The peak acceleration analysis was focused in three types of human walking: slow walking, regular walking and fast walking. Table 7 presents the maximum accelerations (peak accelerations: a_p in m/s^2), related to seven sections of the investigated footbridge (A, B, B_1, B_2, C, D and E), as illustrated in Figure 9.

Tubular footbridge peak accelerations (a_p in m/s^2) S slow walking R regular walking F fast walking							
Walking	A	B_1	B	B_2	C	D	E
S	1.15	0.22	0.57	0.22	0.67	0.54	0.94
R	1.00	0.16	0.44	0.16	0.38	0.33	0.78
F	**1.41**	0.18	**0.62**	0.18	**0.75**	**0.54**	**1.58**
*a_{lim} = 1.5%g = 0.15 m/s^2: indoor footbridges *a_{lim} = 5.0%g = 0.49 m/s^2: outdoor footbridges							

Table 7. Structural model peak accelerations corresponding to individual walking.

The maximum acceleration values (peak accelerations) are respectively equal to 1.41 m/s^2 (Section A), 0.62 m/s^2 (Section B), 0.75 m/s^2 (Section C), 0.54 m/s^2 (Section D) and 1.58 m/s^2 (Section E), see Table 7. These peak accelerations presented in Table 7 are related to a pedestrian fast walking situation. It must be emphasized that the limit acceleration value is equal to 0.49 m/s^2, when outdoor footbridges are considered in the analysis [8, 14].

Based on the finite element modelling of the tubular composite (steel-concrete) footbridge dynamic behaviour, the numerical results presented in Table 7 indicated that the dynamic actions produced by human walking led to peak accelerations higher than the limiting values present in design code recommendations (Outdoor footbridges: 5%g = 0.49 m/s^2), [8, 14], as depicted in Table 7.

6 Conclusions

This contribution covers the application of tubular structural elements in pedestrian footbridge design and tries to give an overview about the evaluation of tubular footbridges dynamic behaviour, objectifying to help practical structural engineers to deal with this kind of problem and to allow for a further application of tubular structural elements in pedestrian footbridge design.

The present study was carried out based on a more realistic loading model developed to incorporate the dynamic effects induced by people walking. The loading model considered the ascent and descending movement of the human body effective mass at each step and the position of the dynamic load (human walking load) was also changed ac-cording to the individual position. Additionally, also incorporates the transient effect due to the human heel impact.

The proposed analysis methodology considered the investigation of the dynamic behaviour, in terms of serviceability limit states, of a tubular composite (steel-concrete) footbridge, spanning 82.5 m. The structure is composed by three spans (32.5 m, 17.5 m and 20.0 m, respectively) and two overhangs (7.50 m and 5.0 m, respectively). The structural system consists of tubular steel sections and a concrete slab and is currently used for pedestrian crossing.

A computational model, based on the finite element method, was developed using the ANSYS program. This 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 results found throughout this investigation have indicated that the dynamic actions produced by human walking could generate peak accelerations that surpass design criteria limits developed for ensuring human comfort. Hence it was detected that this type of structure can reach high vibration levels that can compromise the footbridge user's comfort and especially its safety.

The analysis methodology presented in this paper is completely general and is the author's intention to use this solution strategy on other pedestrian footbridge types and to investigate the fatigue problem. The fatigue problem is a relevant issue and certainly much more complicated and is influenced by several design parameters and footbridge types. Further research in this area is currently being carried out.

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