Estimation of the damping ratio of composite arch footbridges considering human-structure interaction

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Abstract: The footbridge dynamic analysis under the action of human walking involves many variables that influence the structure. With this in mind, this article analyzes the dynamic responses of composite material footbridge with different spans submitted to the action of human walking in order to measure the increase of damping ratio on footbridge caused by the human-structure interaction. Two models used to represent the action of human walking: the moving biodynamic model (MBM) and the moving force model (MFM). Analyzing the difference between the results obtained from each of the models it is possible to find the increase of the damping ratio of the structure in the presence of pedestrians.

Keywords: Damping Ratio, Human-Structure Interaction, Biomechanical Model, Fourier Series Model and Composite Material.

1 Introduction

Several factors must be considered in the dynamic analysis of a structure, such as the structural stiffness, modal mass and damping ratio, and the dynamic loading. One parameter that greatly influences the amplitudes of vibration responses of a structure is its damping ratio, that is associated with a dissipation of mechanical energy, usually by conversion into thermal energy. According to Bachmann et al. [1], the overall damping of a structural system is related to the damping of the bare structure, the non-structural elements and the radiation to the soil. The damping of the bare structure is mostly influenced by its material and the structure type. Althought there are many indications of damping ratios in the literature according to the structure type and material of construction [1-3], each structure is different from the other and the most reliable method to determine its damping ratio is experimentally.

In the case of footbridges, where the dynamic loading is human walking, the human-structure interaction (HSI) can modify some parameters of the structure, including its damping. This was experimentally noticed in the studies by Pedersen [4] and Zivanovic et al. [5]. As the footbridge and the people walking on it can both be considered dynamic systems, the human-structure coupled system presents dynamic properties that differs from the bare structure or from people walking separately. The damping of the human-structure coupled system is higher than the damping of the bare structure [6,7]. Therefore, not considering this addition of damping in theoretical models can lead to dynamic responses that are very different from reality.

There are some models to represent human walking on footbridges. One of them is a movable load mathematically represented by a Fourier Series [1]. For light footbridges, in which the human-interaction effect is of great importance on the dynamic behaviour of the structure, it is also used the biodynamic model [8-12], where people walking are represented by a single degree of freedom system with a spring, a mass and a damper. The methodology used in international guidelines [2,3] to estabilish a comfort criteria in terms of vibrations, uses human walking loading described by Fourier Series to estimate the vibration amplitudes of a footbridge. This is done because it is much simplier to calculate and it presents good results for the majority of footbridges, but not for the lighter ones, as the composite footbridges.

In this paper, a methodology to find the damping of composite footbridges that can be used in dynamic analyses using the movable load model is proposed using computational simulations of people walking represented by biodynamic model. The analyses are performed in arch footbridges with spans of 20, 30, 40 and 50 meters made of pultruded profiles of glass fiber reinforced polymers (GFRP).

2 Human walk modelling

The Fourier series function is widely used in footbridge design to represent the force x time of people walking [1] (see Eq. 1). This is the model chosen to describe a crowd load in the SÉTRA [2], for example.

$$F(t) = G + \sum_{j=1}^{n} G\alpha_j sen(2j\pi f_p t \; + \; \phi_j \,) \tag{1}$$

Where F(t) is the vertical force applied to the ground by a pedestrian or a crowd, G is the person´s or crowd weight, f_p is the step frequency of the pedestrians, α_j is the jth dynamic load factor, ϕ_j is the jth phase angle between the jth and the first harmonic of the load, and *t* is the time. In this paper will be used the first or the second harmonic, depending on the possibility of resonance with the analysed footbridge.

Moreover, it will be used the biomechanical model proposed by Silva and Pimentel [13]. In this model, each pedestrian is represented by a one degree of freedom mass-spring-damper system and is coupled to the structural system alongwith the Fourier series force described before. The mass (m_p), damping (c_p) and stiffness (k_p) of the pedestrian are obtained as follows [13], where *M* is the total mass of the pedestrian:

$$m_p = 97.082 + 0.275M - 37.518f_p \tag{2}$$

$$c_p = 29.041\, {m_p}^{0.883} \tag{3}$$

$$k_p = 30351.744 - 50.261\, c_p + 0.035\, {c_p}^2 \tag{4}$$

3 Methodology

For the computer simulation, pairs of pedestrians weighing 700 N each walk side by side along the entire footbridge in resonance with one of the vibration modes of the structure. The pairs of pedestrians distance each other one meter apart. Thus, analyzes were carried out for 2, 4, 6, 8, ... n_p being n_p the number of people that fulfills the entire length of the footbridge. In this work it is used a deterministic approach to the characteristics of human walking. This means that it is considered that all pedestrians walks in resonance with the one of the vibartion modes of the footbridge, with the same step frequency, stride length and body mass.

To solve the differential equations of dynamics equilibrium, a program in Python was developed that finds the maximum acceleration of the structure for the two loading scenarios: (i) moving biomechanical model (MBM); (ii) moving force model (MFM). The methodology to determine the added damping of people on footbridge is based on the comparison of the responses of the midspan of the footbridge with the two models. The value of the dynamic responses of the footbridge for the biodynamic model is determined only one time for each number of pedestrians. The damping ratio of the foobridge with the moving force model is increased iteratively so as to reach an amplitude of maxixum acceleration suffiently near to the result obtained with the biodynamic model (less than 1%).

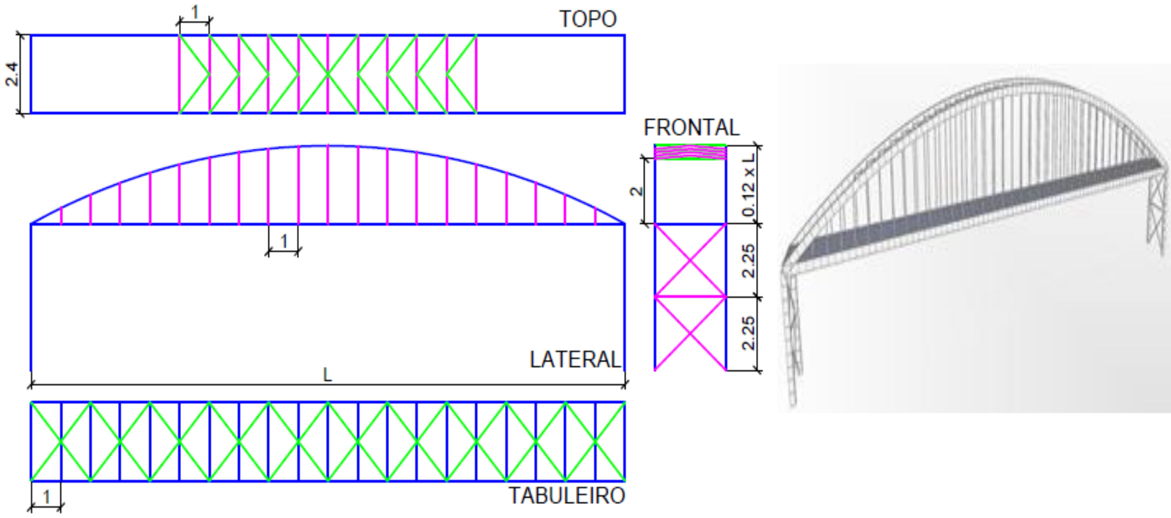
4 Description of the structural models

4.1 Brief description of the structures

The most common structural types of composite footbridges are trusses, arches and cable-stayed. In this work the arch footbridges will be analysed for spans of 20 to 50 meters. Figure 1 illustrates the structural system and Table 1 presents the GFRP pultruded profiles used in the model. The material and profile properties were extracted from Cardoso and Togashi [14] and by Vieira et al [15]. The profiles are all tube shaped. Some of them are square tubes and the others are tubes formed by the welding of two “C” profiles.

The profiles were chosen and checked to static verification according to EUROCOMP [16] that is an European standard. Nowadays, there is no standards on the subject in Brazil. The profiles were optimized in terms of weight. It is worthy to notice that the limitation in composite structures is usually in terms of serviceability limit state.

The composite material was chosen because of its physical charactheristics, including lightweight and noncorrosive properties, which leads to an easy and fast installation and savings in foundation and low maintenance costs. On the other hand, it presents high flexibility.



(a) 2D views (b) 3D view

Figure 1: Arch footbridge structural model

Table 1: Geometric description of the GRFP pultruted profiles

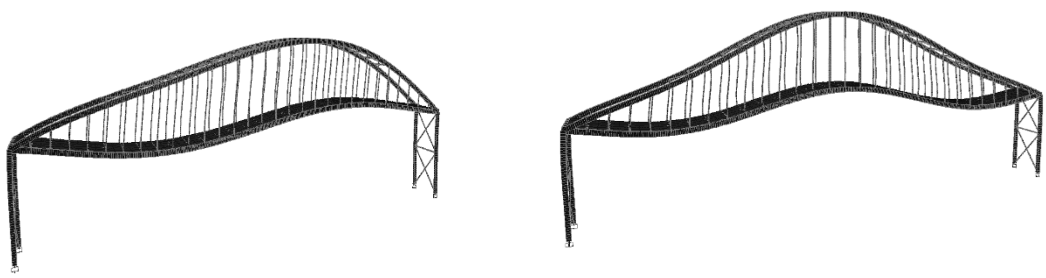
Profile Type	Footbridge span (m)			
	20	30	40	50
Square Tube (*b* x *t*)	25.4x3.2	25.4x3.2	25.4x3.2	25.40x3.2
Square Tube (*b* x *t*)	38.1x6.4	50.8x3.2	50.8x3.2	76.2x 6.4
2C (*bf* x *bw* x *t*)	101.6x203.2x9.5	152.4x228.6x7.9	200.0x360.0x7.0	152.4x304.8x12.7

Notes: (1) profile dimensions in milimeters (mm); (2) *b* is the width of the square tube, *bf* is the width of the flange of the "C" profile, *bw* is the width of the web of the "C" profile and *t* is the thickness of the profiles

4.2 Modal analysis of the footbridges

The dynamics properties of the footbridges were obtained from free vibrations analyses of 3D models using SAP2000 software, which is based on Finite Element Method (FEM). The first two bending vertical vibration modes are shown in Figure 2.

The vibration induced by uniformely distributed crowds in antisymmetric vibration modes of structures as illustraded in Figure 2a is zero all along the structure because of the modal force is null. Thus, the second vibration mode of the arch footbridge illustrated in Figure 2b is the one to be analysed herein.



(a) First vertical vibration mode (b) Second vertical vibration mode

Figura 2: Vibration modes of the structure

According to the SÉTRA [2], the resonance between people walking and the vibrations modes of a footbridge may occur in a range between 1.0 and 2.6 Hz. Footbridges with natural frequencies in the range between 2.6 to 5.0 Hz also can also be in resonance with the second harmonic of people walking, but with less intensity. Table 2 shows the frequencies of the second vertical vibration mode of the analysed footbridge. Table 1 also shows the total mass and modal mass for each footbridge. The highlighted cells indicate the values of natural frequencies with a possibility of resonance with people walking. For this reason, the 20m span arch footbridge was discarded from further analyses. It was considered a damping ratio of 0.8% for composite footbridges.

Table 2: Dynamics properties of the second vertical bending modes of the footbridges

Property of the footbridge	Un.	20 meters	30 meters	40 meters	50 meters
Natural frequency	Hz	5.75	3.42	2.99	1.97
Total mass	kg	2775.1	4189.6	6561.1	11534.8
Modal mass	kg	664.5	1039.7	1606.7	2905.1

GFRP pultruded profiles are lightweight materials. Due to this characteristic, the mass of pedestrians is relevant compared to the mass of composite footbridges, which indicates that the coupled dynamic properties of the pedestrians-footbridge system is different from the footbridge alone. In these cases, the effect of human structure interation (HSI) highly influences the dynamic responses of the structure. Table 3 shows the mass ratio between crowd mass (70 kg/m²) and the structure mass for the footbridges with spans of 30, 40 and 50 meters analysed herein.

Table 3: Crowd-footbridge mass ratio

Mass ratio	30 meters	40 meters	50 meters
Crowd mass / footbridge mass	1.2	1.0	0.7

5 Results and analysis

Figure 3 shows the normalized acceleration graphs of the moving force model (MFM) and moving biodynamic model (MBM). m_p represents the modal mass of pedestrians extracted from the biomechanical model of Silva and Pimentel [13] while m_s is the modal mass of the structure represented previously in Table 2. As can be seen in Figure 3, the MBM presents much lower accelerations than MFM due to the human structure interaction (HSI) effect mentioned before.

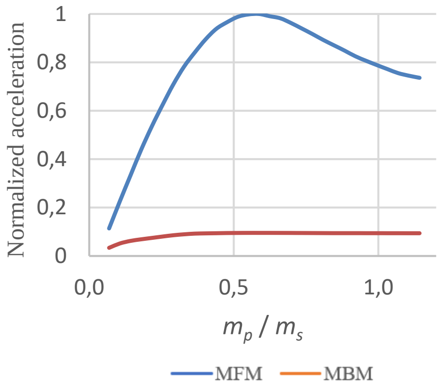
As described in methodology section, the goal is to overlap the curves adding damping to the footbridge in the MFM scenario. Figure 4 shows the pedestrians-footbridge coupled system damping ratios obtained with this methodology. The graphs in Figure 4 demonstrate a large addition of damping to the structure in the MFM scenario to reach the same results obtained with MBM.

6 Conclusions

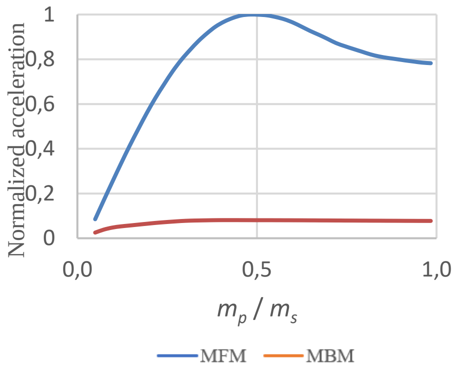
In this paper it was analysed the influence of pedestrians in the damping ratio of composite arch footbridges. It was studied footbridges with spans of 20 to 50m. Two approaches were used to determine the maximum accelerations at the midspan of the structure. The first one represented each pedestrian as a moving force mathemathically described by a Fourier series, here named moving force model (MFM). The second one represented each pedestrian as a moving mass-spring-damper plus the Fourier series force described before, here named moving biodynamic model (MBM).

The analyses consisted in using this two models for analysing the dynamic response of the 30m to 50m arch footbridges for different number of pedestrians. The pedestrians were considered in resonance with one of the vibration modes of the structure and uniformily distributed over the footdridge. The results pointed out the difference obtained with the two models. Moreover, as it is expected that MBM presents more realistic results, the damping ratio of the coupled pedestrians-footbridge was obtained using a MFM that resulted in the same maximum acceleration of the analyses with MBM. Damping ratios of up to 17% were obtained, compared to 0.8% of the bare structure.

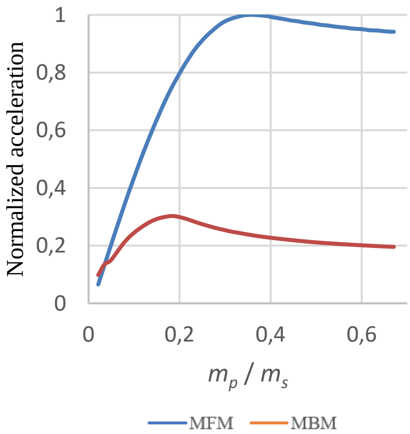
It can be concluded that human-structure interaction (HSI) can change the dynamic properties of the structure, especially in the case of lightweigh footbridges such as those made of composite materials. In the case discussed in this article, not considering the human structure interaction (HSI), represented here by modelling the pedestrians as moving mass-spring-damper biodynamic systems, can lead to unrealistic acceleration responses.



(a) 30 meters footbridge

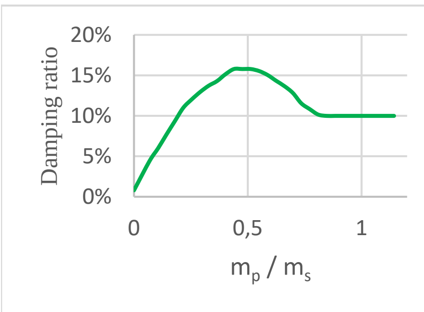


(b) 40 meters footbridge

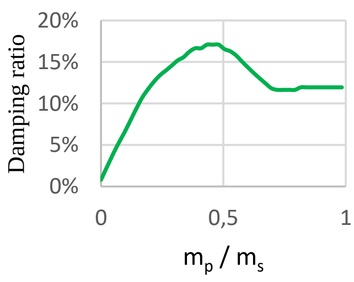


(c) 50 meters footbridge

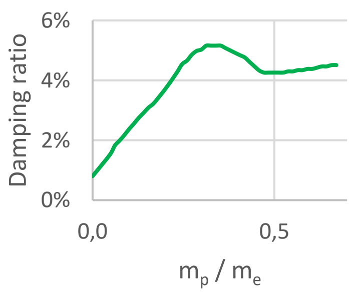
Figure 3: Normalized acceleration of the arch footbridge for different spans, number of pedestrians and pedestrian load models



(a) 30 meters footbridge



(b) 40 meters footbridge



(c) 50 meters footbridge

Figure 4: Pedestrians-footbridge coupled system damping ratios

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