Human structure interaction: approaches to consider crowd effects

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Abstract. Pedestrians walking in slender footbridges may lead to dynamic behavior that does not satisfy the serviceability limits proposed in codes. On the other hand, the presence of pedestrians may bring beneficial effects to the structural behavior by providing damping to the coupled system structure plus pedestrians. In this work, three approaches are assessed to evaluate the response of a footbridge in a crowd situation: (i) pedestrians represented by a moving load model (MLM) applied to an equivalent single degree of freedom model (SDoFM) of the empty structure (ii) pedestrians represented by MLM applied to an equivalent (SDoFM) of the occupied structure whose modal properties are obtained from free vibration analyses and, (iii) pedestrians represented as biodynamic models (BM) walking along the footbridge deck. Comparisons between the results in terms of the maximum midspan acceleration of a composite footbridge using the three formulations evaluated herein are performed.

Keywords: Structural dynamic, footbridges, human-structure-interaction; Monte Carlo simulation; crowd loads.

1 Introduction

Footbridges may exhibit dynamic behavior when subjected to crowd induced loads, in particular lightweight structures, whose behavior may be affected by human-structure interaction (HSI), such as in composite GFRP structures [1]. The analysis procedure recommended by some design guides consists in applying to the structure a uniformly distributed harmonic load in the form of the moving load model expressing the ground reaction force of one pedestrian [2, 3]. The random movement generated by pedestrians that depends of ifs physical characteristcs and gait is accounted for by means of the factor known as equivalent pedestrian number as indicated in codes and guides [3, 4]. Nevertheless, the effects of HSI are not considered in this kind of analysis.

According to Shahabpoor *et al*. [5], the HSI is defined as the dynamic effect that the pedestrian introduce on the structure and the structure acts on the pedestrian. Consequently, the occupied footbridge is represented by a new mechanical system composed by the empty structure plus pedestrians [6].

Brownjohn [7] performed tests in a prestressed concrete slab under the presence of a single person in different positions and report the following changes on modal properties of the structure in relation to the empty one: increase in the damping ratio and a slight reduction in the natural frequency.

This paper applies three different formulations to consider the effects of crowd in footbridges using probabilistic load model with Monte Carlo simulations. In the first approach the pedestrians are represented according to the moving load model (MLM) with randomly generated characteristics. The other two formulations address the effects of HSI in different ways: (i) pedestrians are represented as MLM applied to the footbridge model whose modal properties account for the presence of persons and (ii) pedestrians are modelled as moving biodynamic models (MBM) applied to the model of the isolated structure, yielding a coupled system structure plus pedestrians.

2 Moving load model (MLM)

Pedestrians walking generate forces in the vertical direction due to the acelerating and decelerating of the human body mass. These forces are commonly presented in the literature [2, 4] as an deterministic load that depends of the weight (G) and natural frequency (f_p) of the pedestrian. Zivanovic *et al*. [8] carried out a numerical simulation to reproduce the experimental tests conducted in Podgorica Footbridge under a crowd event, the authors adopted the probabilistic moving load model (MLM) approach to represent crowd induced loads.

The equivalent effect giving by the crowd as MLM may be determined by summing the individual force that each pedestrian on the structure acts, as indicated in Eq. (1):

$$F(t) = \sum_{i=1}^{N_{ped}} \phi_{p,i}(x)\{G_i + \sum_{j=1}^{nh} G_{i,j}\alpha_{i,j}sen(2\pi f_p t - \varphi_{i,j})\} \quad (1)$$

where: nh is the number of harmonics considered in the analysis, take herein as $nh = 1$; α_i is the dynamic load factor ($\alpha_1 = 0.4$, [4]); φ_i is the phase angle in relation to the first harmonic ($\varphi_1 = 0°$) and $\phi_{p,i}$ is the vertical amplitude of the vibration mode of the footbridge at the instantaneous position of the i-th pedestrian.

3 Human structure interaction (HSI) model

To consider the effects of HSI, the pedestrians are commonly represented as a single degree of freedom (SDoF) spring (k_p) - mass (m_p) - damper (c_p) called biodynamic model (BM) whose the dynamic properties are equivalent to the human body walking [1,5,9].

Costa [9] performed an experimental campaign with 53 pedestrians walking in a laboratory footbridge aiming to calibrate dynamic properties of a BM formulated as a SDoF system subjected to base excitation. Equations (2) to (4) express the modal properties of the MB as functions of the mass (m) and walking frequency (f_p) of the pedestrians:

$$m_p = 12.940 + 0.874m - 9.142f_p \quad (2)$$

$$k_p = 360.30m_p - 1282.50 \quad (3)$$

$$\xi_p = -20.818f_{ma} + 87.513 \quad (4)$$

where f_{ma} and ξ_p are the damped frequency and damping ratio of the BM, respectively.

Pfeil *et al*. [1] presented an analytic-numerical model of the coupled system represented by the equivalent single degree of freedom model (SDoFM) of the footbridge-structure and the SDoFM of the BM of a pedestrian walking. The model proposed was applied in a lively footbridge and the results show to be in good agreement with experimental measurements performed under the passage of a single pedestrian.

To consider crowd effects, Gonzaga [10] adapted the mathematical model proposed by Pfeil *et al*. [1]. Numerical analysis were carried out using this model and the results were correlated with experimental campaign performed in two different structures: (i) a concrete slab footbridge located in the Structure and Materials Laboratory of the Universidade Federal da Paraíba/UFPB [11] and (ii) the Podgorica Footbridge's located in the capital of Montenegro [12].

The pedestrians-structure mathematical model presented by Gonzaga [10] is indicated in Eq. (5). This model consists in ($N_{ped} + 1$) coupled differential equations: one representing the generalized SDoF of the footbridge system model and N_{ped} representing the total number of pedestrians on footbridge deck, as illustrated in Figure 1.

$$
\begin{bmatrix} m_s & 0 & 0 & \dots & 0 \\ 0 & m_{p,1} & 0 & \dots & 0 \\ 0 & 0 & m_{p,2} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & m_{p,N_{ped}} \end{bmatrix} \begin{Bmatrix} \ddot{y} \\ \ddot{u}_{p,1} \\ \ddot{u}_{p,2} \\ \vdots \\ \ddot{u}_{p,N_{ped}} \end{Bmatrix} + \begin{bmatrix} c_s + \sum_{i=1}^{n} c_{p,i}\phi_{p,i}^2 & -c_{p,1}\phi_{p,1} & -c_{p,2}\phi_{p,2} & \dots & -c_{p,N_{ped}}\phi_{p,N_{ped}} \\ -c_{p,1}\phi_{p,1} & c_{p,1} & 0 & \dots & 0 \\ -c_{p,2}\phi_{p,2} & 0 & c_{p,2} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -c_{p,N_{ped}}\phi_{p,N_{ped}} & 0 & 0 & \dots & c_{p,N_{ped}} \end{bmatrix} \begin{Bmatrix} \dot{y} \\ \dot{u}_{p,1} \\ \dot{u}_{p,2} \\ \vdots \\ \dot{u}_{p,N_{ped}} \end{Bmatrix} +
$$

$$
\begin{bmatrix} k_s + \sum_{i=1}^{n} k_{p,i,}\phi_{p,i}^2 & -k_{p,1}\phi_{p,1} & -k_{p,2}\phi_{p,2} & \dots & -k_{p,}\phi_{p,N_{ped}} \\ -k_{p,1}\phi_{p,1} & k_{p,1} & 0 & \dots & 0 \\ -k_{p,2}\phi_{p,2} & 0 & k_{p,2} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -k_{pn}\phi_{p,Nped} & 0 & 0 & \dots & k_{p,N_{ped}} \end{bmatrix} \begin{Bmatrix} y \\ u_{p,1} \\ u_{p,2} \\ \vdots \\ u_{p,N_{ped}} \end{Bmatrix} = \begin{Bmatrix} \sum_{i=1}^{Nped} \phi_{p,i}(x)F_i(t) \\ 0 \\ 0 \\ \vdots \\ 0 \end{Bmatrix} \quad (5)
$$

in which: m_s, c_s and k_s are the generalized mass, damping coefficient and stiffness of the footbridge, respectively; y is the generalized coordinate of the structure and u_{pi} is the vertical displacement of the i-th pedestrian.

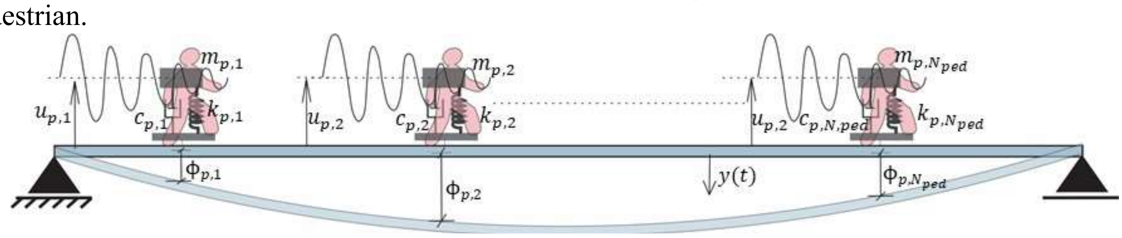
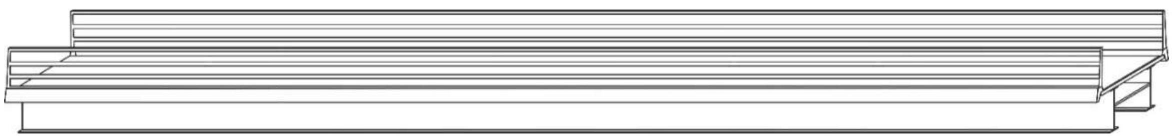


Figure 1. Pedestrians as SDoF BMs walking on the footbridge deck

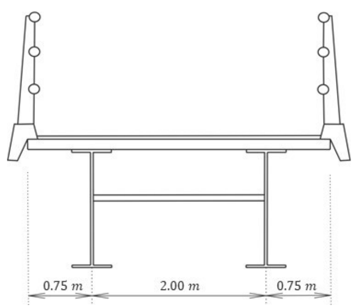
4 Brief description of the structure

4.1 Empty footbridge

The structure used in this work is a composite concrete-steel simple supported footbridge. Figure 2 shows the lateral view and the cross section of the structure, while Table 1 provides its modal and physical properties.



(a) Lateral view



(b) Cross section

Figure 2: Composite steel-concrete footbridge

Table 1. Physical/modal properties of the empty composite footbridge [13]

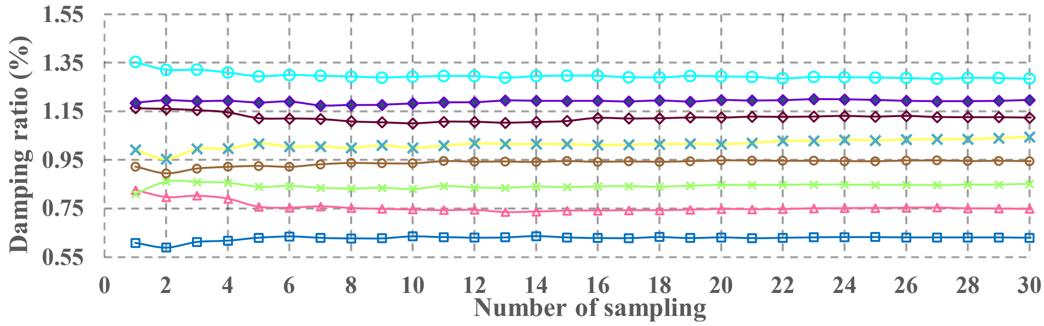
Length (L)	35.00 m
Width of the deck (B)	3.00 m
Modal mass (m_s)	32.02 t
Natural frequency (f_s)	2.0 Hz
Damping ratio (ξ_e)	0.50%

4.2 Occupied footbridge

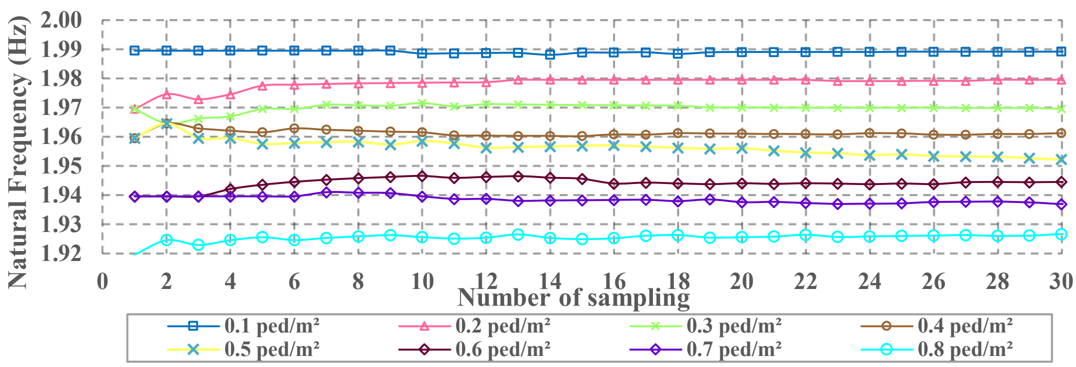
In order to obtain the modal properties (damping ratio and natural frequency) of the occupied composite footbridge, that is, the modal properties of the system composed by the empty structure plus pedestrians on the crowd, free vibration analyses were performed using the mathematical model indicated in Eq. (5). For this purpose, a Monte Carlo Algorithm was used to simulate different scenarios of crowd following the steps:

(i) firstly, the position of each pedestrian is randomly assigned on the footbridge deck;
(ii) the mass (m) and natural frequency (f_p) of the pedestrians are generated by sampling using normal distribution with mean and standard deviation given by: $m\,[71.4; 15.3]\,kg$ [12] and $f_p[2.000; 0.175]\,Hz$ [14];
(iii) The modal properties (m_p, c_p and k_p) of the BM are obtained using the regression equations proposed by Costa [9] and shown in Eqs. (2)-(4);
(iv) An instantaneous pulse load equivalent to the sum of the weight of all pedestrians on the crowd is applied on the SDoFM of the footbridge (see Eq. 5) and the coupled system (footbridge model plus BMs) oscillates in free vibration;
(v) The damping ratio of the coupled system is determined using logarithmic decrement and the natural frequency is obtained applying the Fast Fourier Transform algorithm to the free vibration signals;

It was considered different rates of occupancy (ρ) on footbridge deck varying from 0.1 ped/m² to 0.8 ped/m². The results of the modal properties of the occupied structure in the Monte Carlo simulations are indicated in Figure 3:



(a) damping ratio of the occupied structure



(b) Natural frequency of the occupied structure

Figure 3: Modal properties of the occupied structure

The modal properties of the occupied composite footbridge as function of the crowd density are show in Figure 4:

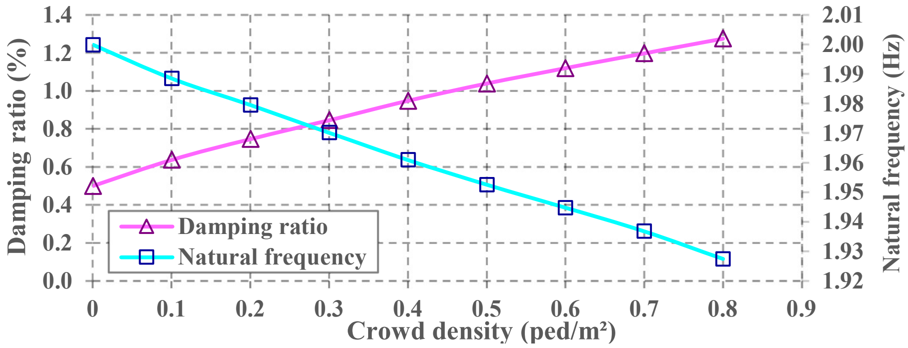


Figure 4: Modal properties of the occupied structure as function of crowd densitity

5 Crowd induced loads

The induced loads generated by pedestrians crossing the footbridge deck is addressed in this work as a probabilistic moving load (see Eq. 1), in which, the variables that compose or influence this load are sampled generating random numbers from its probability distribution that are shown in Table 2, where λ is mean value of the Poisson distribution as:

$$\lambda = \frac{1}{\rho W v_{p,m}} \tag{6}$$

which depends on the crowd density (ρ), width of the footbridge's deck (B) and the mean value of the walking speed ($v_{p,m}$) of the persons in the crowd.

Table 2: Probability distribution of the variables

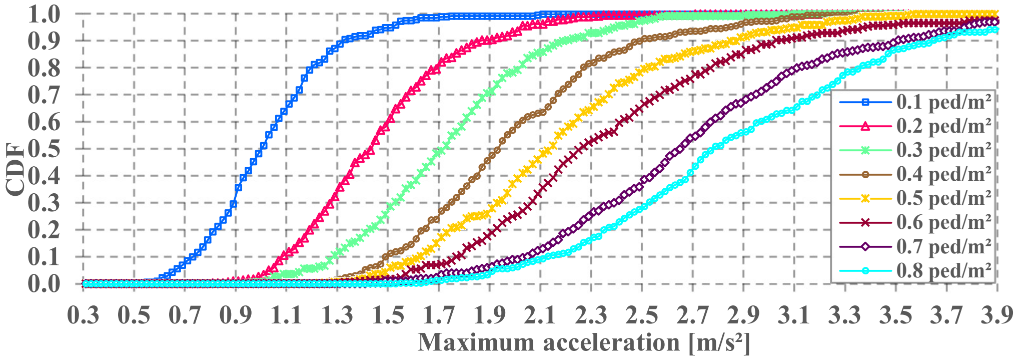
Variable	Distribution	Mean value	Std. deviation	Reference
Weight of pedestrians (P)	Normal	700	150	Sètra [4], Živanović *et al.* [12]
Walking frequency (f_p)	Normal	2.000	0.175	Sètra [4]
Step lenght (λ)	Normal	0.750	0.080	Živanović *et al.* [12]
Entrance time (T_{entr})	Poisson	λ*	-	Matsumoto *et al.* [14]

Three hundred different scenarios of pedestrian configuration were generated for each crowd density evaluated and the response of the structure in terms of its maximum midspan acceleration was assessed using the three approaches considered herein: (a) pedestrians modelled as MLM applied to a model of the empty structure; (b) pedestrians as MLM applied to a model of the occupied structure; and (c) pedestrians as MBMs. Whereas in (a) and (b) the problem consists in solve numerically a one second order differential equation, in (c) the system is composed by ($N_{ped} + 1$) second order differential equations.

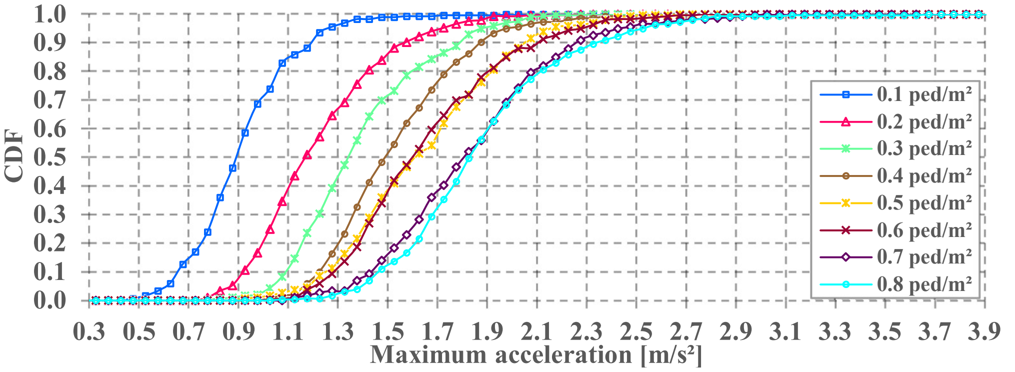
The results achieved in the Monte Carlo simulations are illustrated in Figures 5a to 5c by the cumulative distribution function (CDF) respectively for the crowd approaches (a), (b) and (c).

As may be observed, the CDF of the maximum midspan acceleration of the footbridge decreases significatively from Fig. 5a in relation to the Fig. 5b and 5c. Furthermore, these last two Figures show that the amplitudes of vibration due to crowd action tends to stabilize with the increase of the crowd density because of the damping ratio provided on the system, that is one of the most important aspect addressed in HSI not contemplated in MLM indicated in Fig. 5a.

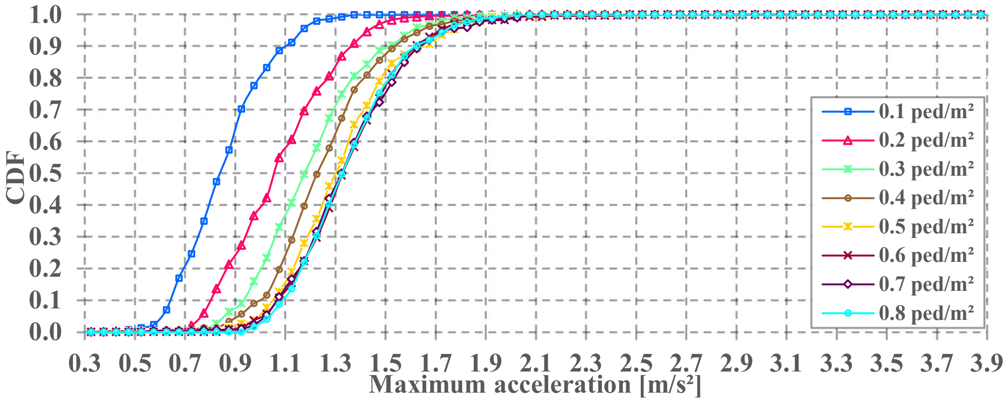
The characteristic acceleration of the composite footbridge for each crowd density was designated as the value of the maximum acceleration with 95% non-exceedance probability [14]. Figure 6 shows these characteristic accelerations for diferent crowd density values considering the three approaches assessed herein.



(a) Pedestrians modelled as MLM: modal properties of the empty structure



(b) Pedestrians modelled as MLM: modal properties of the occupied structure



(c) Pedestrian modelled as MBMs.

Figure 5: CDF of the midspan acceleration using the different approaches proposed

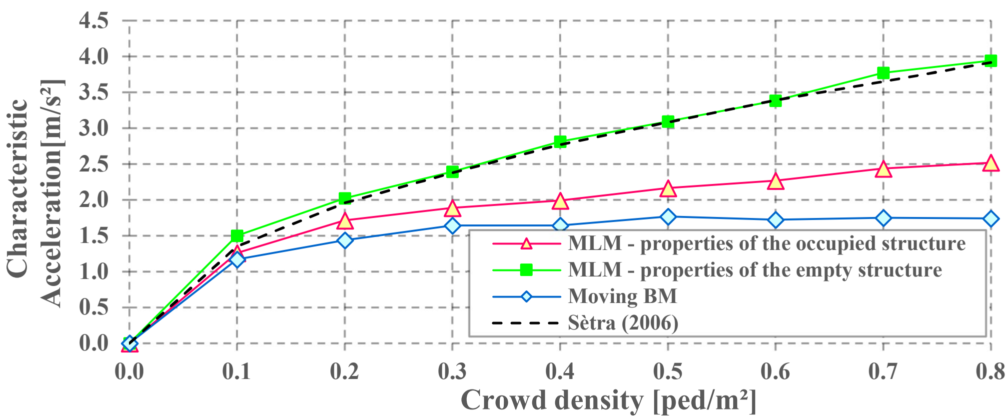


Figure 6: Characteristic acceleration of the footbridge for the different approaches considered

As observed in Figure 6, the characteristic acceleration determined when the pedestrians are represented as moving load model (MLM) and applied to the isolated bridge is higher than the other two approaches that consider the effects of human-structure interaction (HSI).

This results was expected because the presence of the pedestrians leads to an increase in the damping ratio of the structure as reported in the analysis presented herein (see Figure 4) and by numerous experimental evidences pointed out in the literature [3,6,7,8,11,12]. In spite of that, codes and practical guidelines, in general, still adopt the MLM without taking into account the modal properties of the coupled system as indicated in dashed line that presents the response of the composite footbridge using the procedure recommend by Sètra guideline [4].

Moreover, the pedestrians modelled as moving biodynamic models (MBM) results in the lowest amplitudes of vibration among the other approach to consider crowd assessed herein. However, the performance of this methodology in relation to the others is difficult to verify without experimental results.

The approach considering the pedestrians as MLM applied to the SDoFM of the footbridge with altered properties seems to be an interesting alternative procedure to the full HSI approach because it is is a simple strategy that may be easy implemented and used by designers to account the effects of HSI while giving less conservative results than the MLM applied to the isolated structure addressed in codes: attaching spring-mass-damper elements whose the modal properties is equivalent to the human body on the finite element model (FEM) of the footbridge and applying a MLM in this model, such as the proposed in Sètra [4], for example.

6 Conclusions

This paper presented a comparison between three different methodologies to represent crowd actions and provide necessary information to encourage searches and designers to account the effects of HSI, especially in slender footbridges.

The results achieved in this work show that the (a) simple MLM applied on the SDoFM of the empty structure is relatively more simple but it does not account effects of (HSI) that are responsible by changes on the modal properties of the footbridge, reported herein with the increase in damping ratio and a slighty reduction in the natural frequency of the composite footbridge evaluated. Nevertheless, (b) MLM applied on the SDoFM of the structure, whose the modal properties include pedestrians is an interesting alternative because it account the effects of HSI not contemplated in codes. Moreover, it is more simple and more allowance in comparision to the (c) moving BM strategy.

Acknowledgements. The authors of this work are grateful to the financial support given by CNPQ and CAPES.

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