Modelling crowd-structure interaction on an ultra-lightweight FRP footbridge

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ABSTRACT

Human-Structure Interaction (HSI) may influence the dynamic behaviour of Fibre Reinforced Polymer (FRP) footbridges due to the lightweight nature of composite materials. Hence, load models that account for HSI should be applied to accurately predict vibration levels on these pedestrian structures. This paper proposes a model to assess the structural response of a simply supported footbridge subjected to a weak traffic scenario (0.2 pedestrians/m^2), considering HSI and higher harmonics of pedestrians walking. The dynamic parameters of a single pedestrian, depicted as a Mass-Spring-Damper-Actuator (MSDA) system, and the modal parameters of the structure are employed to construct a coupled time-invariant crowd-structure system. The frequency-domain approach, based on a closed-loop Transfer Function (TF), considered in this study leads to a good agreement between numerical results and experimental outcomes obtained on an ultra-lightweight FRP footbridge. Thus, the proposed HSI model may be used as a first approximation to correctly estimate the dynamic response of other lightweight structures subjected to crowd-induced loads.

Keywords: FRP footbridge, dynamic response, crowd-induced load, human-structure interaction.

1. INTRODUCTION

Guidelines and codes often define non-interacting load models to represent pedestrian actions in the assessment of lightweight pedestrian structures at Vibration Serviceability Limit State (VSLS) [1–3]. Nevertheless, an unreal high estimation of the response of Fibre Reinforced Polymer (FRP) footbridges may be obtained using these load models since Human-Structure Interaction (HSI) is neglected. Moreover, higher harmonics of human actions, which are not considered in design recommendations, may excite significantly FRP structures due to the lightweight nature of composite materials [4].

A pedestrian has been usually modelled as a mechanical Mass-Spring-Damper (MSD) system together with an external harmonic force to account for interaction phenomenon on the dynamic analysis of lightweight structures [5]. Based on this idea, several approaches are available to represent a stream of pedestrians acting on a lively footbridge. For example, a HSI sub-model and a crowd sub-model, based on social forces among humans, were adopted in Ref. [6] to analyse a cable-stayed footbridge. Recently, a simplified methodology to consider vertical interaction between crowds and footbridges has been

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proposed in Ref. [7], obtaining charts in terms of the modal parameters of the empty structure to define a system with effective natural frequency and damping ratio. A pedestrian-to-structure mass ratio up to 30% was assumed, so the procedure may be just valid for structures made of traditional construction materials, such as concrete or steel.

The effects of HSI increases with the crowd-to-structure mass ratio [8], and human mass may easily surpass 30% of the mass associated to a specific vibration mode of an FRP footbridge. This is the case when three people, whose total mass is 218.8 kg, walked over the structure constructed at the Laboratory of Structures at *ETSI Caminos, Canales y Puertos – UPM* (see Fig. 1). As the laboratory footbridge presents a natural frequency of 7.62 Hz and modal mass of 405 kg associated to the first vertical vibration mode [4], the pedestrian-to-structure ratio is around 54%.

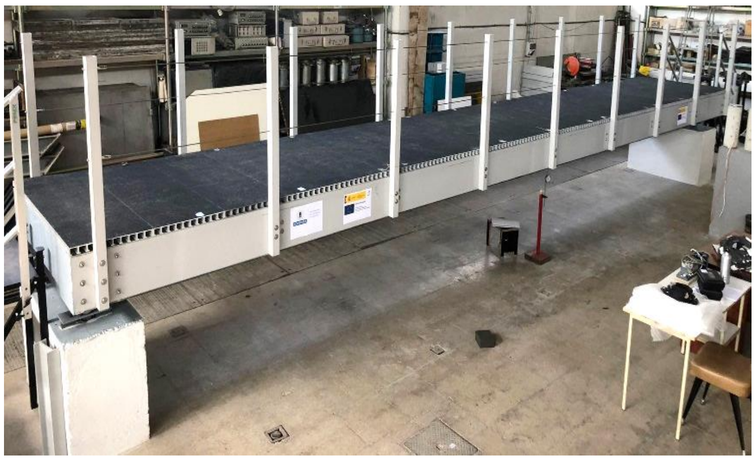


Figure 1. *FRP footbridge.*

This paper proposes a model to predict the structural response of a simply supported FRP footbridge subjected to weak traffic scenario, accounting for HSI and higher harmonics of pedestrians walking. After this introduction, experimental results from a test considering three pedestrians walking freely over the bridge deck are presented. Following, the model of the coupled crowd-structure system is described, and the results are compared with those obtained from the test. Finally, results from sensitivity analyses are discussed, and some conclusions of the work are drawn.

2. DYNAMIC TEST

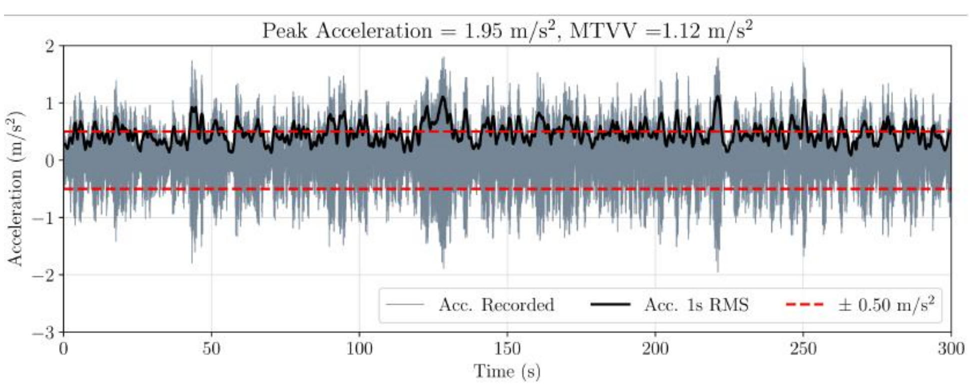
The structure studied herein is a 10 m long simply supported footbridge (see Fig. 1), comprised of glass-FRP profiles and carbon-FRP strips manufactured by Fiberline Composites A/S [9]. The pedestrian structure was designed to meet requirements for Deflection Serviceability Limit State (SLS) and Ultimate Limit State (ULS), as reported in Ref. [10]. Due to the adopted design approach, an ultra-lightweight footbridge was obtained and excessive vertical vibrations under human actions were expected.

Three pedestrians, whose total mass was 218.8 kg, were asked to walk freely and comfortably for five minutes in a closed-loop path over the bridge deck (see Fig. 2). During the test, the acceleration response of the FRP footbridge was recorded at midspan with a sampling frequency of 1000 Hz using a high-sensitivity accelerometer attached at the bottom of the central stringer (see Fig. 3a). The collected signal was processed using a low pass filter with a cut-off frequency of 10 Hz to account only for the contribution of the first vibration mode.

Figure 2. *Dynamic test: three pedestrians walking.*

In Fig. 3b, it is observed that the obtained maximum acceleration was 1.95 m/s^2, whereas the Maximum Transient Vibration Value (MTVV) was 1.12 m/s^2. The former is the peak value from the 1s running-root-mean square (RMS) acceleration. Multiplying the MTVV by $\sqrt{2}$, which led to 1.58 m/s^2, a minimum degree of comfort at VSLS was assigned to the FRP footbridge according to *HIVOSS* guideline [1] $(1.0\ \mathrm{m/s^2} \leq \mathrm{a_{lim}} \leq 2.5\ \mathrm{m/s^2})$.

(a)



(b)

Figure 3. *Dynamic test: (a) Accelerometer at midspan, (b) Bridge response due to a weak traffic scenario.*

2.1. Numerical model neglecting interaction phenomenon

According to *prEN 1991-2* [3], the load model for a crowd of n pedestrians without considering the interaction phenomenon is

$$q_a(t) = W \cdot \cos(2\pi f_{as} t) \cdot n' \cdot \psi_w \quad (1)$$

with f_{as} being the step frequency which is assumed equal to the natural frequency of the structure, ψ_w the reduction coefficient and n' the synchronised number of pedestrians ($n' < n$) which can be calculated as

$$n' = \frac{10.8\sqrt{\zeta_s \cdot n}}{S} \quad (2)$$

where ζ_s is the damping ratio of the structure and S is the area of the deck.

Using the following values of the parameters: $f_{as} = 7.63\ \mathrm{Hz}$, $n = 3$ pedestrians, $\zeta_s = 0.0155$, $S = 15\ \mathrm{m}^2$ and $\psi_w = 0.15$, the acceleration shown in Fig. 4 was obtained employing the calibrated FE model of the structure, described in Ref. [4]. The value $\psi_w = 0.15$ is chosen in order to define the load using the fourth harmonic set in *ISO-10137* [11] ($DLF_4 = 0.06$).

Neglecting the interaction between the structure and the pedestrians, the dynamic response is very far from the actual value obtained experimentally. For this reason, the inclusion of a human model becomes essential for lightweight structures under pedestrian loads.

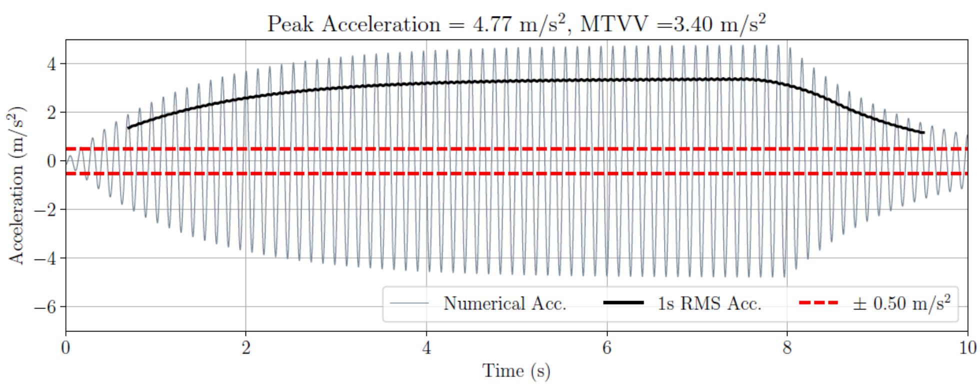


Figure 4. *Numerical dynamic response at midspan of the footbridge for a crowd load neglecting the interaction phenomenon.*

3. CROWD-STRUCTURE INTERACTION

In this section, the crowd-structure interaction model is described and implemented to obtain the acceleration of the structure under crowd loads.

3.1. Modelling

A walking pedestrian can be represented as a Mass-Spring-Damper-Actuator (MSDA) system based on the dynamic properties of the human body to account for HSI [4]. The person is defined using his/her mass (m_h), natural frequency (f_h), and damping ratio (ζ_h). Also, a harmonic force (F_a) generated by the human legs is considered in this model as a pair of action-reaction forces acting simultaneously on both the footbridge and the human. The most intuitive approach to represent a crowd of pedestrians may be employing several MSDA systems.

Another alternative to model the crowd may be through an equivalent single-degree-of-freedom (SDOF) system defined by the parameters of a MSDA system and the number of pedestrians on a footbridge. The transfer function (TF) of this crowd-structure system between the footbridge acceleration at midspan ($\ddot{x}_s$) and the equivalent crowd driving force (F_a^{eq}) is denoted herein as GH_{CL}^{eq}. The TF is characterized by a feedback loop associated to the interaction phenomenon, and it is defined as follows for the case of a simply supported structure

$$GH_{CL}^{eq}(s) = \frac{2/\pi \cdot G_H^{eq} \cdot G_S}{1 - (2/\pi)^2 \cdot G_{HSI}^{eq} \cdot G_S} \tag{3}$$

where $s = j\omega$ is the Laplace variable, ω is the angular frequency in rad/s, $G_S(s)$ is the TF of the structural system, $G_H^{eq}(s)$ is the TF between the equivalent crowd driving force and the contact force of the pedestrians with the structure, and $G_{HSI}^{eq}(s)$ is the TF related to HSI.

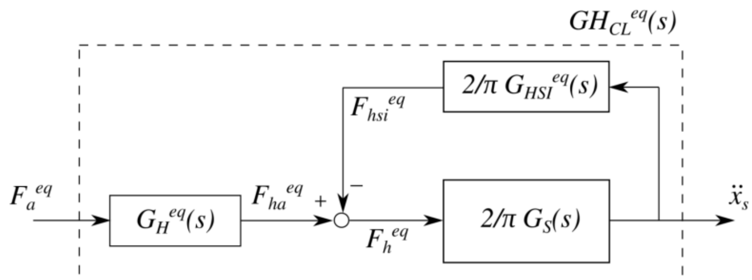


Figure 5. *Block diagram of the crowd-structure system.*

Considering the modal parameters of the first vertical vibration mode of a simply supported structure, the TF between the structure acceleration at midspan and the equivalent external force in the Laplace domain is

$$G_S(s) = \frac{s^2}{m_s\, s^2 + c_s\, s + k_s} \tag{4}$$

where m_s (kg) is the equivalent mass, $k_s = \omega_s^2 m_s$ (N/m) is the equivalent stiffness, and $c_s = 2\omega_s m_s \zeta_s$ (Ns/m) is the equivalent viscous damping of the fundamental vibration mode.

The TF between the force generated by the equivalent crowd without including the force transmitted to them due to the structure movement, and the driving force from the flow of pedestrians is as follows

$$G_H^{eq}(s) = \frac{m_h^{eq}\, s^2}{m_h^{eq}\, s^2 + c_h^{eq}\, s + k_h^{eq}} \tag{5}$$

being m_h^{eq} the equivalent mass of the crowd, and k_h^{eq} and c_h^{eq} the equivalent stiffness and viscous damping of the flow of pedestrians, respectively. These parameters are obtained as follows

$$m_h^{eq} = \sum_{i=1}^{n} m_{hi} \tag{6}$$

$$k_h^{eq} = \sum_{i=1}^{n} k_{hi} \tag{7}$$

$$c_h^{eq} = \sum_{i=1}^{n} c_{hi} \tag{8}$$

with $i = 1, 2, \cdots, n$, where n is the number of individuals within the crowd, $k_h = \omega_h^2 m_h$ (N/m) is the person stiffness, $\omega_h = 2\pi f_h$ (rad/s) is the angular natural frequency of the human, $c_s = 2\omega_s m_s \zeta_s$ (Ns/m) is the viscous damping of the pedestrian body.

Similarly to the non-interacting load models for pedestrian flows provided in *prEn 1991-2* [3], the equivalent crowd force applied at midspan of a simply supported structure is

$$F_a^{eq} = W_h \cdot GLF_r \cdot cos(2\pi f_{as}) \cdot n' \cdot S \tag{9}$$

being L the span of the footbridge, b the width of the structure, $W_h = m_h \cdot g$ (N) the weight of a person, GLF_r the generalised load factor associated to the *r*th harmonic of the walking action.

Finally, the TF between the crowd interacting force, which is the force transmitted due to the structure movement, and the structure acceleration is

$$G_{HSI}^{eq}(s) = \frac{m_h^{eq}(c_h^{eq}\, s + k_h^{eq})}{m_h^{eq}\, s^2 + c_h^{eq}\, s + k_h^{eq}} \tag{10}$$

3.2. Case study

To validate the proposed crowd-structure interaction model, the dynamic response of the FRP footbridge is obtained herein. Based on Ref. [4] and the experiment described in Section 2, the following information was employed: $m_s = 405$ kg, $f_s = 7.66$ Hz, $\zeta_s = 1.55\%$, $L = 10$ m, $b = 1.50$ m, $m_h = 0.93 \cdot 72.9$ kg, $f_h = 1.88$ Hz, $\zeta_h = 23.4\%$, $n = 3$ pedestrians, and $GLF_4 = 0.032$. Fig. 6 shows the acceleration at midspan. A clear good agreement between the MTVVs obtained via the experimental test and the numerical simulation is achieved. However, the peak value of the response presents a significant difference. This is explained by the definition of the load (see Eq. (9)), which only accounts for the fourth harmonic of the human action. Whereas for the experimental result shown in Fig. 3b, the contribution of the first three harmonics are also consider due to the low-pass filter (at 10 Hz) employed.

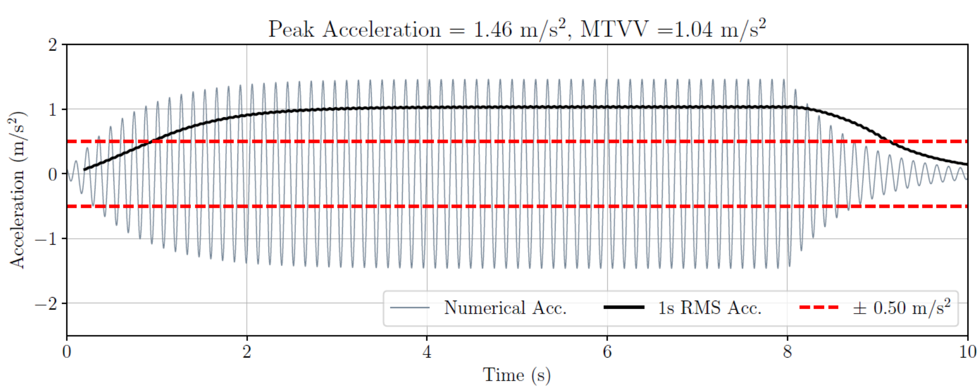


Figure 6. Numerical response of the footbridge.

4. DISCUSSION OF RESULTS

Employing the crowd-structure interaction model obtained in Section 3, two parametric analyses varying both the dynamic properties of the human body and the footbridge are conducted. The influence of every parameter on the numerical dynamic response of the FRP footbridge was investigated by considering 1000 stochastic samples generated from the following distributions:

- Uniform distributions for the three parameters of the human body (factor of the mass, frequency and damping ratio).
- Normal distribution for the mass of the footbridge.
- Weibull distribution for the frequency and damping ratio of the footbridge.

Fig. 7 shows the results of the sensitivity analysis regarding the dynamic parameters of the human body, where the most influential property on the numerical response is the damping ratio of the body, whereas the factor of the mass has the less impact.

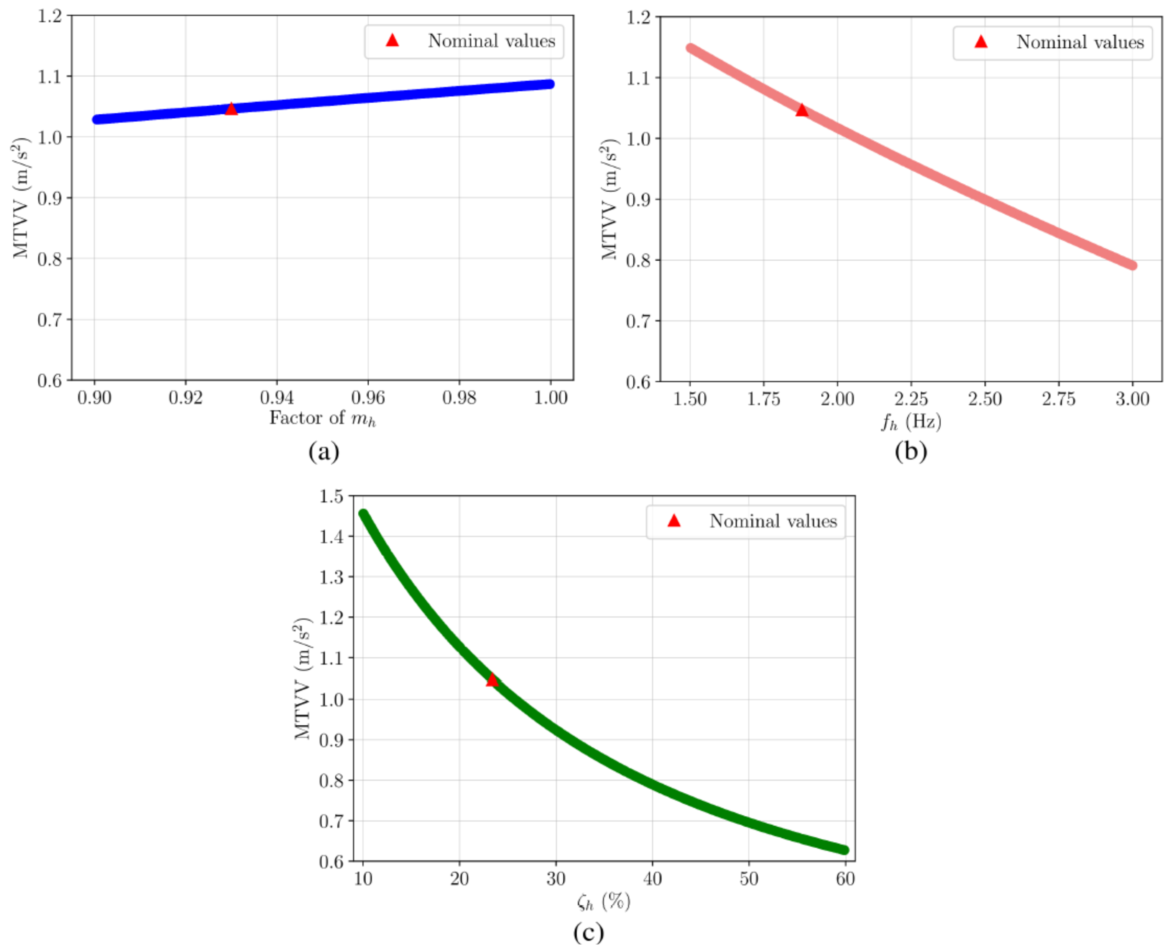


Figure 7. *Sensitivity analysis for the human body parameters: (a) factor of the m_h, (b) f_h, and (c) ζ_h.*

Regarding the footbridge parameters, it can be observed in Fig. 8 two main results. First, in contrast to the previous analysis, the damping ratio remains as the less influential parameter and, second, both mass and frequency have similar but inverse relevance. The first result is due to the large difference between the damping ratio of the human and the structure, being the first one at least ten times the second one. The second result was the expected as more mass produces a reduction of the natural frequency when the stiffness remains constant.

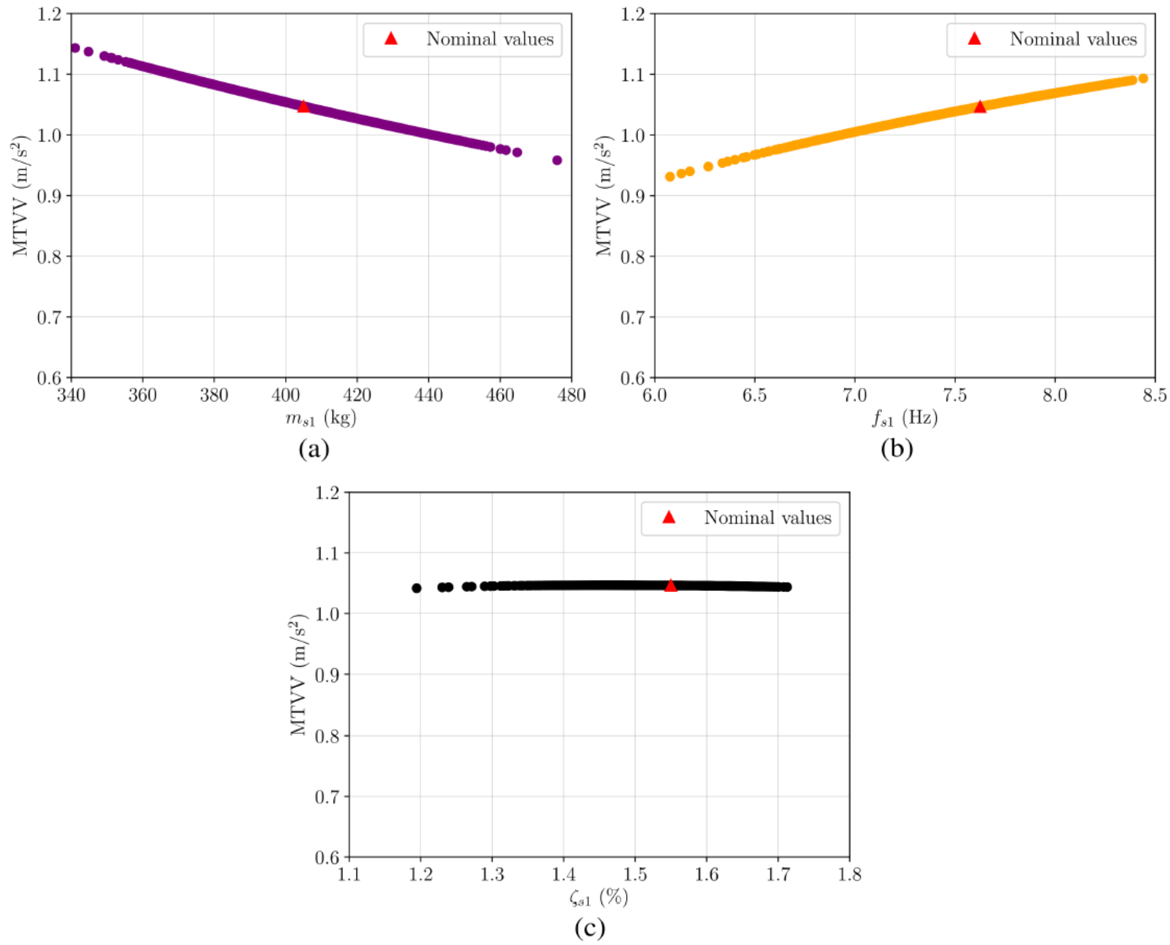


Figure 8. *Sensitivity analysis for the fundamental mode parameters: (a) m_{s1}, (b) f_{s1}, and (c) ζ_{s1}.*

4.1. Comparison of the crowd-structure interaction model with a time-domain model

The results are compared herein with a time-domain-based pedestrian-structure interaction model implemented in a modified version of the software CALDINTAV [12]. This software, developed by the Computational Mechanics Group of the Technical University of Madrid, considers the interaction phenomenon through the modification of the mass, damping and stiffness matrices of the pedestrian-structure system. Also, it accounts for a moving MSD system plus an external harmonic force (F_{ha}) to represent a walking pedestrian. The dynamic force exerted by the pedestrian is defined as follows

$$F_h(t) = W_h \sum_{r}^{n_r} VDLF_r \sin(r2\pi f_a t + \varphi_r) \quad (11)$$

with $r = 1, 2, \dots n_r$, where n_r is the total number of harmonics considered, r is the harmonic number, $VDLF_r$ is the vertical dynamic load factor associated to the rth harmonic, and φ_r is the corresponding phase angle.

For the analysis, the parameters given in Section 3.2 were employed to define both, the structure and the pedestrians. Also, $VDLF_1 = 0.229, VDLF_3 = 0.218, VDLF_3 = 0.112, VDLF_4 = 0.034$, $\varphi_1 = 0$ rad, and $\varphi_2 = \varphi_3 = \varphi_4 = \pi/2$ rad [4]. The crowd of 3 pedestrians walking on the footbridge was simulated considering the MSD systems separated 3.30 m. Hence, it was ensured that only 3 of 10 systems were on the footbridge at a given time to obtain a stationary response.

It is observed in Fig. 9 that the MTVV is very close to the obtained using the proposed interaction model ($1.04\ \mathrm{m/s^2}$) and the peak acceleration is higher due to the contribution of the first three harmonics of the human action.

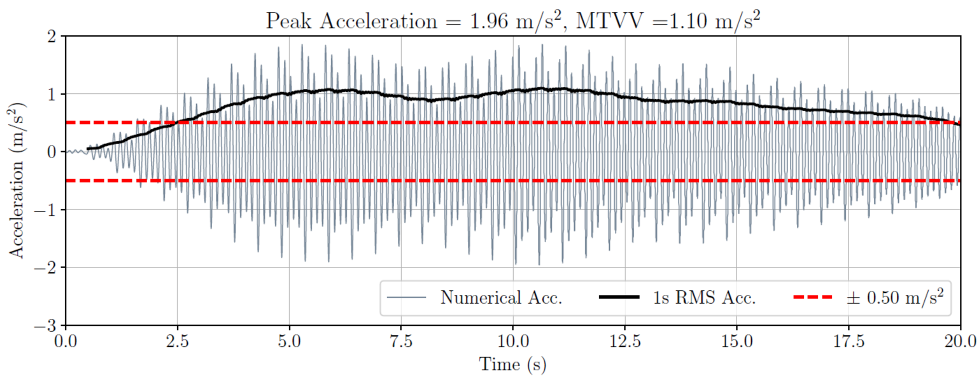


Figure 9. *Dynamic response at midspan of the footbridge using a time domain interaction model.*

Table 1 presents a summary of the MTVVs calculated using both approaches. Although good results have been obtained using the time-domain approach, to depict each person within a large crowd may not be practical in engineering offices. The modification of the mass, damping and stiffness matrices due to HSI is not straightforward and time-variant models with a very high number of DOFs may be obtained, leading to an expensive computational problem. In general, this requires expertise and advance modelling skills from the users. In this context, the frequency-domain approach considered in this study seems to be simpler to implement without excessive loss of accuracy in the results.

Table 1. Comparison of MTVVs (m/s^2)

Traffic class	**Experimental**	**Proposed model**	**Time-domain model**
Weak	1,12	1,04	1,10

5. CONCLUSIONS

An experiment consisting in three pedestrians walking freely has been performed in a lightweight FRP footbridge and the acceleration at midspan has been collected. Through the comparison of the results from the test with the numerical outcomes using the provisions stated in the *prEN 1991-2* [3], a poor estimation of the real behaviour was obtained as HSI was disregarded.

Hence, in the study a load model that considers HSI and a higher harmonic of walking action has been proposed to improve the prediction of the response of the lively FRP pedestrian structure subjected to a weak traffic scenario (0.2 pedestrians/m^2). The proposal is based on a closed-loop TF that uses equivalent parameters to define a flow of pedestrians, working with a linear time invariant coupled system. The results have demonstrated that the equivalent crowd-structure interaction model gives a good assessment of the dynamic response of the footbridge at VSLS, what allows concluding that the inclusion of the dynamic properties of the human body is essential to an accurate evaluation of the dynamic behaviour of lightweight structures.

Besides, by considering HSI at the design stage of composite footbridges may be beneficial to meet vibration serviceability requirements and avoid oversizing the structural elements.

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REFERENCES

[1] Butz C, Heinemeyer C, Keil A, Schlaich M, Goldack A, Trometer S, et al. HIVOSS: Design of footbridges guideline. Joint Research Center; 2008.

[2] CEN. Draft prEN 1990 Basis of Structural and Geotechnical Design, Annex A.2. Applications for Bridges. European Committee for Standardisation; September 2021.

[3] CEN. Draft prEN 1991-2:2021: Actions on Structures - Part 2: Traffic loads on Bridges and other Civil Engineering Works. European Committee for Standardization; September 2021.

[4] Gallegos-Calderón C, Naranjo-Pérez J, Díaz IM, Goicolea JM. Identification of a human-structure interaction model on an ultra-lightweight FRP footbridge. Appl Sci 2021;11:6654.

[5] Shahabpoor E, Pavic A, Racic V. Interaction between Walking Humans and Structures in Vertical Direction: A Literature Review. Shock Vib 2016;2016:1–22.

[6] Jiménez-Alonso JF, Sáez A, Caetano E, Magalhães F. Vertical Crowd–Structure Interaction Model to Analyze the Change of the Modal Properties of a Footbridge. J Bridg Eng 2016;21.

[7] Van Nimmen K, Pavic A, Van den Broeck P. A simplified method to account for vertical human-structure interaction. Structures 2021;32:2004–19.

[8] Živanović S, Díaz IM, Pavić A. Influence of walking and standing crowds on structural dynamic properties. IMAC XXVII Conf. Expo. Struct. Dyn., Orlando, FL: The Society for Experimental Mechanics, Inc.; 2009.

[9] Fiberline Composites A/S. General Design Certification. Middelfart, Denmark: Fiberline Composites A/S; 2018.

[10] Gallegos-Calderón C, Naranjo-Pérez J, Pulido MDG, Díaz IM. Design, construction and structural response of a lightweight FRP footbridge. IABSE Congr. Struct. Eng. Futur. Soc. Needs, Ghent, Belgium: 2021, p. 2053–61.

[11] ISO. ISO 10137 - Bases for design of structures - Serviceability of buildings and walkways against vibrations. vol. 10137. International Organization for Standardization; 2007.

[12] Goicolea JM, Nguyen K. CALDINTAV Version D1.0 Tutorial. Madrid: 2017.