Self-control of a lively footbridge under pedestrian flow

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ABSTRACT

In this paper, a case study about a lively footbridge is developed; the vibration levels caused by the pedestrian action are controlled by the change of the modal parameters of the structure due to the pedestrian-structure interaction. A detailed finite element model of the structure has been updated from an operational modal analysis. The updated model has been used to obtain the numerical acceleration at the mid-span of the footbridge under different pedestrian flows. A relation between the maximum acceleration and the pedestrian density on the deck has been obtained numerically, pointing out an improvement in the comfort level of the structure when the number of pedestrians increases. This result validates a design rule for cable-stayed footbridges in order to avoid vibratory problems, since the first vertical natural frequency of the structure remains below the range that characterizes the pedestrian walking action.

Keywords: lively footbridge, self-control, pedestrians, operational modal analysis, model updating.

1. INTRODUCTION

At the design stage of every footbridge it is an advisable practice to ensure that the natural frequencies of the structure are outside the range of frequencies that characterizes the pedestrian walking activity and, therefore, to check the comfort level of the structure under its service conditions.

The *Malecón footbridge*, designed by the Spanish engineer Javier Manterola [1], is the most emblematic structure of the city of Murcia (Spain). This footbridge crosses the Segura River and connects the Carmen neighbourhood with the historical centre (Fig. 1), being one of the most journeyed pedestrian bridges of the city. The experimental first natural frequency of the structure is within the range that characterizes the walking action, 1.25-2.30 Hz [2], so as it is expected, the footbridge undergoes a lively dynamic behaviour under its service conditions. However, the footbridge checks the comfort level established by international standards [3]; moreover, even when the pedestrian flow increases, the vertical acceleration of the footbridge does not exceed from comfort limits.

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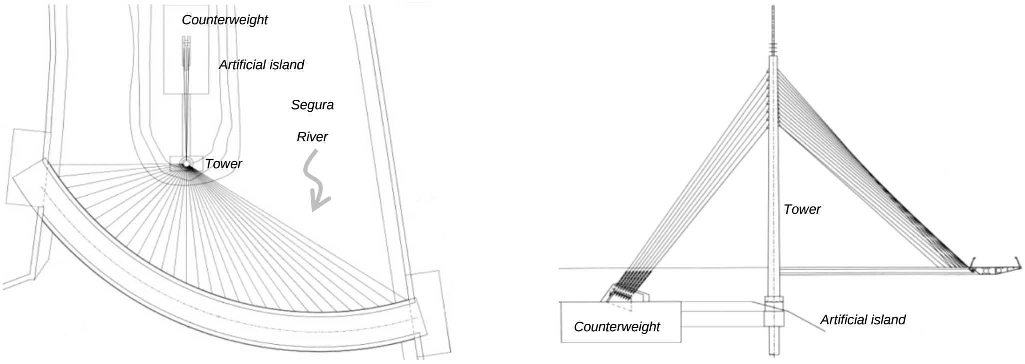
The objective of this work is to analyse the relation between the vibrational self-control of the footbridge and the modification of its modal parameters due to the action of the pedestrians. To this aim, an operational modal analysis of the footbridge has been performed; from the experimental results, a detailed updated 3D finite element model of the structure has been developed comparing the experimental and numerical dynamic parameters of the system. Finally, a dynamic transient analysis of the footbridge has been performed for different pedestrian densities using the updated model, and the maximum vertical accelerations of the structure for different pedestrian flows have been estimated.

Figure 1. *The Malecón Footbridge.*



a) b)

Figure 2. *a) Plan view. b) Lateral view*

2. BRIEF DESCRIPTION OF THE STRUCTURE

The structure is a cable-stayed deck with an eccentric tower. The deck is a pinned-pinned beam with a radius of 45 m and a width of 5.13 m that spans over a distance of 54.7 m (Fig 2a). The cross section of the deck has a trapezoidal shape, with a uniform thickness of 0.7m, and is composed by steel plates with a thickness of 12 mm; the cable-stayed sections of the deck are reinforced using steel diaphragms with a thickness of 15 mm (Fig. 2b).

The tower has a height of 25 m and is founded in an artificial island using reinforced concrete piles with a diameter of 1 m and a depth of 20 m. The cross section of the tower is also composed by steel plates with a thickness of 15 mm. The link between the tower and the deck is performed through 30 pre-stressed steel cables; at the same time, the tower is linked to a reinforced concrete counterweight through 15 pre-stressed steel cables. The diameter of all the cables is 20 mm.

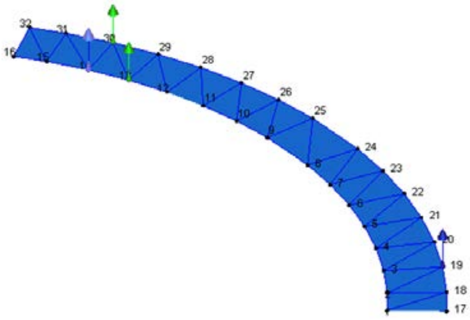


Figure 3. *Registered points during the ambient vibration test.*

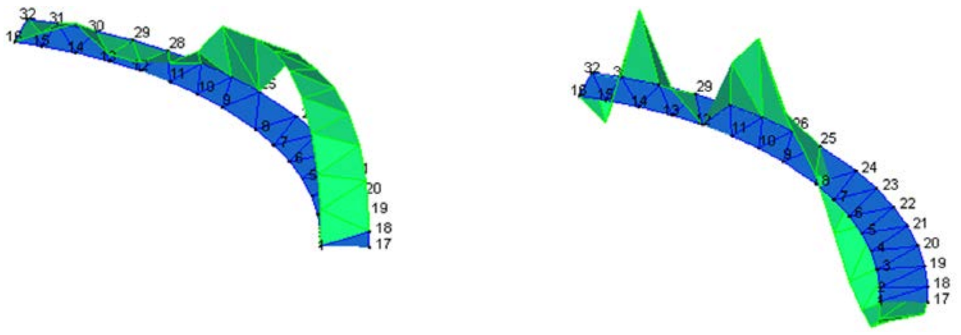
3. AMBIENT TEST

In order to identify experimentally the dynamic properties of the footbridge, an ambient vibration test was performed on 27th November 2014 under normal conditions of use induced by the wind and the pedestrians. To this aim, a preliminary dynamic finite element model of the structure was developed in order to predict the natural frequencies and vibration modes of the footbridge, and then, to design the experimental test. The test was performed using 4 uniaxial accelerometers connected to a portable datacentre; the deck was discretized in 16 sections and 32 points and the reference accelerometers were fixed at the points 14 and 19 (blue narrows at Figure 3). The other two accelerometers were successively placed along the rest of sections. At each position, ambient vertical accelerations were recorded at 100 Hz for 1000 seconds [4].

Table 1. Experimental modal parameters

Mode (Description)	Modal parameter	
	Frequency	Damping
Mode 1 (Vertical)	1.677 Hz	0.6%
Mode 2 (Torsion + Vertical)	2.580 Hz	1.3%

From the recorded accelerations, the dynamic properties of the footbridge were determined using an operational modal analysis; in this particular case, a frequency domain technique (the so-called *Enhanced frequency domain decomposition*, EFDD) was applied. The identification of the modal parameters was performed using the software ARTEMIS Extractor Pro 2012 developed by SVS A/S [5]. The natural frequency and the percent of damping corresponding to each vibration mode have been summarized in Table 1; the two first experimental vibration modes are represented in Figure 4. As seen, the natural frequency of the first vertical vibration mode is equal to 1.677 Hz and belongs to the range associated to the walking action of the pedestrians.



Mode 1: f=1.677 Hz

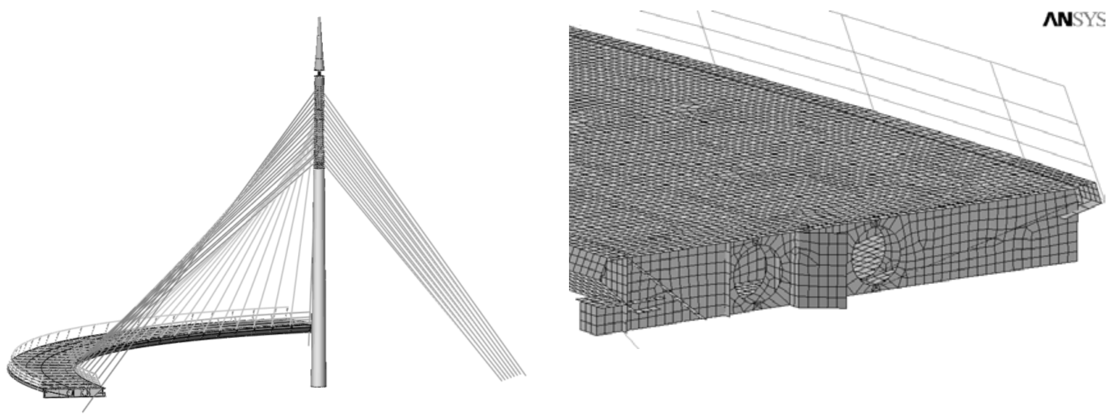
Mode 2: f=2.580 Hz

Figure 4. *Operational modal analysis: experimental modal shapes.*

4. MODEL UPDATING

4.1. Detailed finite element model

As support for the experimental tests and the subsequent interpretation of results, a finite element model of the structure has been developed. The numerical model was performed using the software ANSYS; in particular, the steel plates and the diaphragms of the curved deck, as well as the steel plates of the tower, were modelled using 2D-shell (SHELL181) elements; the longitudinal stiffeners of the deck and the railing of the footbridge were modelled using 3D-beam (BEAM4) elements, whereas the front and rear cables were modelled using 3D-truss (LINK180) elements. Figure 5 contains two snapshots of the proposed discretization and the corresponding mesh.



a)

b)

Figure 5. *3D Finite element model: a) global view b) detail*

4.2. Model updating

In order to characterize adequately the dynamic behaviour of the footbridge, a model updating of the above finite element model has been performed using the experimental results of the operational modal analysis [6]. A sensitivity study of the main physical parameters of the structural model has pointed out the great influence of the axial stiffness of the cables in the dynamic behaviour of the footbridge. Therefore, the 45 cables of the structure have been divided into 9 groups of 5 cables; the Young's modulus of each group have been modified in order to minimize, via genetic algorithm, the mean square error between the experimental and numerical modal parameters (natural frequencies and modal coordinates). In this case, the objective function was defined as the sum of the relative differences between the numerical and experimental values of the natural frequencies and the modal coordinates. Figure 6 shows the results of the adjustment made on the first two vibration modes; as seen, after the adjustment above described, a good correlation between experimental and numerical modal shapes (M.A.C. between 75% and 95%) have been reached in the two modes identified. Finally, in Figure 7 the updated two first vibration modes are shown.

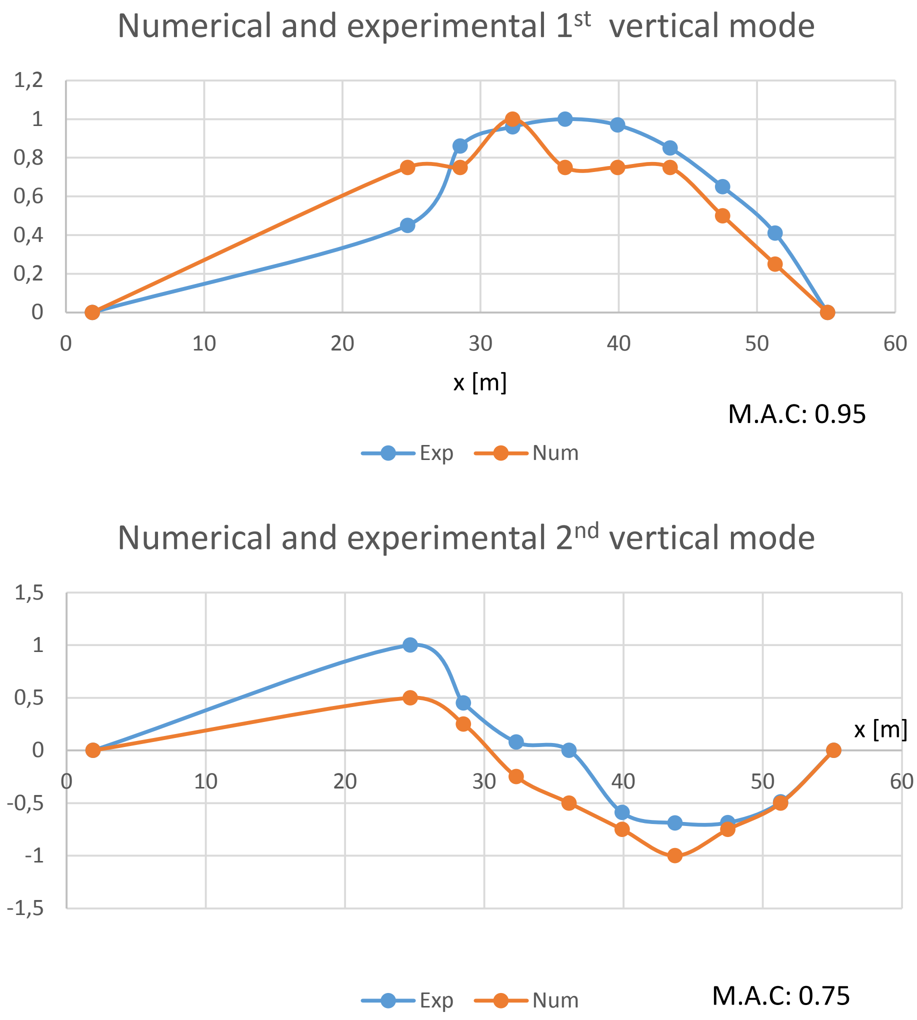
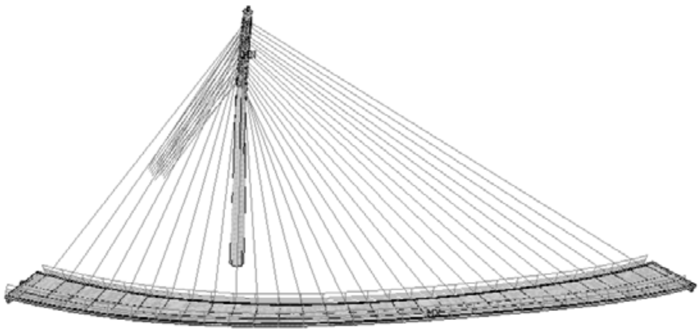
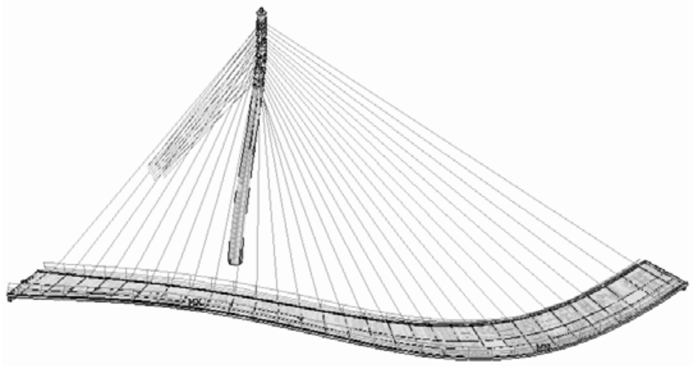


Figure 6. *Comparison between the experimental (exp) and numerical (num) vibration modes.*



1st updated vertical mode: f=1.45 Hz



2nd updated vertical mode: f=2.42 Hz

Figure 7. *Updated two first vibration modes.*

5. SELF-CONTROL OF THE FOOTBRIDGE

According to the numerical and experimental results above presented, the first vertical vibration mode of the structure is within the range that characterizes the walking action of the pedestrians; although a certain level of vibrations is reached continuously on the footbridge under pedestrian flows, the maximum acceleration experienced by the users never exceeds the limits associated with an adequate comfort level. Moreover, from several measurements of the dynamic response of the structure under service conditions, it is reflected even a reduction of the value of the vertical accelerations according to the increasing of the number of pedestrians on the deck. Two factors emerge as possible causes of this phenomenon:

I. The modification of the modal parameters of the structure due to the presence of the pedestrians (i.e., pedestrian-structure interaction)
II. The modification of the stiffness of the structure due to the change of the stress level of the cables.

In this work, the first factor has been considered through the methodology proposed by international standards, considering only the effect of the pedestrian flow on the modal mass of the structure. In consonance with the research developed by different authors, the walking forces may be determined from Fourier series decomposition in the three space components [2]; in particular, the vertical component of the walking force may be approximated as

$$F_{p,vert} = P\left[1+\sum_{i=1}^{n_f}\alpha_{i,vert}\sin 2\pi i f_s t-\varphi_i\right] \tag{1}$$

where $F_{p,vert}$ is the vertical periodic force due to walking, P is the medium pedestrian weight (internationally considered as P=700000 N), $\alpha_{i,vert}$ is the Fourier coefficient of the ith harmonic for vertical force, f_s is the step frequency (in this work an average value equal to 1.9 Hz has been considered), φ_i is the phase shift of the ith harmonic and, finally, n_f is the number of contributing harmonics. The vertical dynamic load factors proposed by SYNPEX [2] have been adopted; the velocity (v) of the pedestrian moving load has been determined from the empirical relationship proposed by Bertram and Ruina [7]:

$$f_s = 0.35v^3 - 1.59v^2 + 2.93v \tag{2}$$

From the updated finite element model above presented, a transient dynamic analysis of the footbridge for different pedestrian flows is possible [8, 9]. According to international codes, such analysis has been developed for the equivalent number of pedestrians (i.e., pedestrians moving in phase with the structure) corresponding to the following pedestrian densities: 0.2, 0.5, 0.8 and 1.0 pedestrian/m^2; the equivalent number of pedestrians (n') may be estimated as:

$$n' = 10.8\sqrt{n_p \cdot \zeta} \tag{3}$$

where n_p is the real number of pedestrians on the loaded surface and ζ is the structural damping ratio. Figure 8 shows the numerical vertical acceleration at the mid-span of the footbridge for an equivalent pedestrian flow, uniformly distributed over the span length, corresponding to a pedestrian density of 1 person/m^2; the maximum predicted value is below of the maximum registered vertical acceleration (0.3 m/s^2) under normal conditions of use.

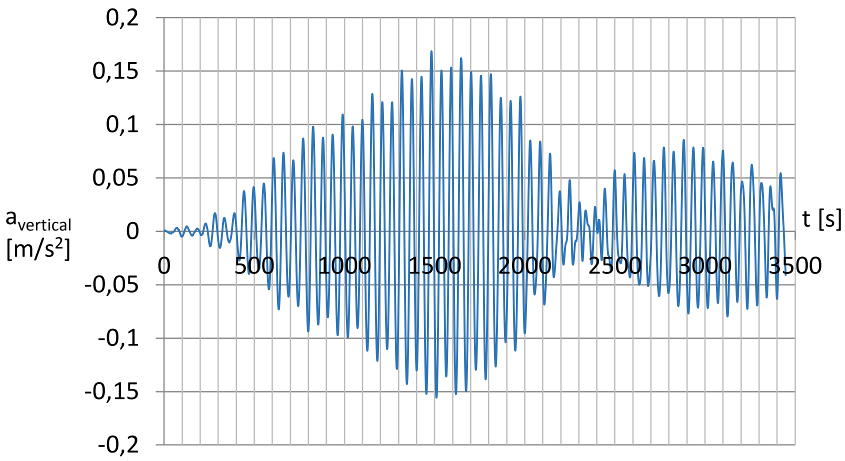


Figure 8. *Numerical vertical acceleration at mid-span for the maximum pedestrian flow*

Figure 9 shows the maximum vertical acceleration of the footbridge at mid-span section as a function of the number of pedestrians crossing the footbridge. As seen, until a *critical density* of 0.3 pedestrians/m^2 (160 pedestrians on the load surface), the vertical acceleration grows up, and then decreases; for densities higher than this critical value the modification (by the pedestrians) of the modal mass of the footbridge places the first natural frequency of the system below the range of the pedestrian walking action and, therefore, the vertical acceleration of the footbridge diminishes as than the pedestrian flow increases.

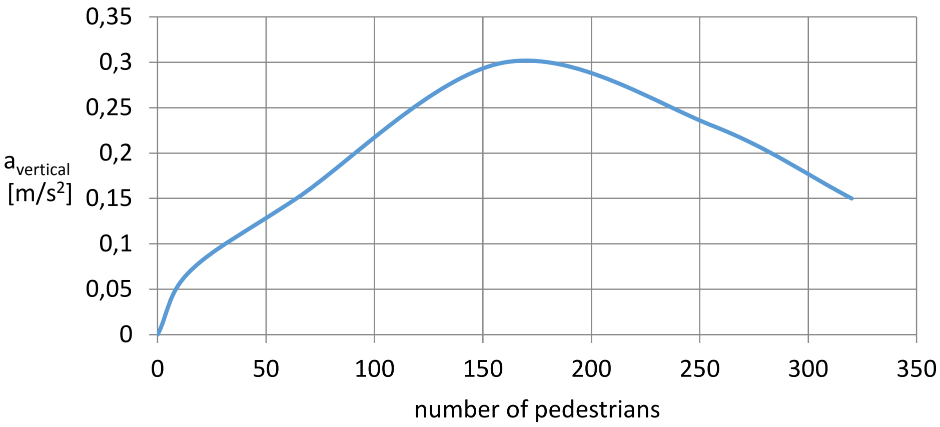


Figure 9. *Numerical relation between the vertical acceleration and the pedestrian density*

6. CONCLUSIONS

In this paper, the change of the dynamic behaviour of a slender footbridge due to the pedestrian flow has been numerically estimated from an updated finite element model. The maximum vertical acceleration of the footbridge under different pedestrian flows has been obtained. The relation obtained shows an increasing of the comfort level with the number of pedestrians due to the modification of the modal mass of the footbridge. This result may be used as criterion to establish a design rule for this type of structures.

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