EXPERIMENTAL AND NUMERICAL ASSESSMENT OF THE UNEXPECTED DAMPING IN A SLENDER FOOTBRIDGE AT MURCIA (SPAIN)

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ABSTRACT

In this paper an experimental and numerical study has been carried out in order to analyse the dynamic behaviour of the ‘Jorge Manrique’ footbridge at Murcia (Spain). In this sense, an operational modal analysis, based on the measures made during an ambient test, has been performed in order to assess the modal parameters of the structure. The correlation between the experimental and numerical modal parameters is adequate; however unexpected high values of the damping ratios of the first two identified vibration modes, in lateral and vertical direction, have been detected. As the main cause of such unexpected values the presence of a thick carpet situated on the deck has been considered. In order to assess the effect of this non-structural element on the dynamic behaviour of the structure, a double strategy has been followed. First, an estimation of the damping of the carpet has been obtained from a free vibration test. Second, a simplified carpet-structure interaction model has been used to estimate the original structural damping ratio without the effect of the carpet. These later values are inside the range established by international standards. Finally, a numerical study of the sensibility of the footbridge to the lateral lock-in phenomenon under two situations, with and without carpet, reflects the importance of the carpet as passive control device that avoids the occurrence of this phenomenon.

Keywords: slender footbridge, ambient test, operational modal analysis, unexpected damping.

1. INTRODUCTION

The city of Murcia (at southeast of Spain) is currently divided in two parts by the Segura River. In the last years, the population increase and the urban expansion have promoted the construction of several structures that cross the river and connect both sectors of the city (Fig. 1a). One of this structures is the footbridge ‘Jorge Manrique’ (Fig. 1b), which links Vistabella neighborhood to the urban center of Murcia. This footbridge was designed by the architect Santiago Calatrava [1] and constructed by the Agroman Corporation in 1999.
A singular feature of the above footbridge, from a dynamic point of view, is that although the natural frequencies of the structure, in the lateral and vertical direction, predicted during the design phase of the structure, were inside the range that characterizes the human walking action [2, 3]; the current dynamic response of the structure is adequate under its service conditions, satisfying the comfort level established during its design phase [2]. This fact motivated the assessment of the dynamic behaviour of the structure from the identification of its experimental modal parameters. During the identification process, high values of the damping ratios of the first two vibration modes of the structure have been detected. The cause of the high (and unusual) value for the damping of the structure may be the presence of some non-estructural elements on the deck, namely a thick carpet.

![Figure 1](image1.png) a) Segura River (Murcia, Spain) b) Jorge Manrique footbridge.

The objective of this work is to analyze the origin and nature of the unexpected damping of the footbridge. To this aim, a 3D finite element model of the structure has been developed and several characterization tests of the structural and non-structural elements of the footbridge have been performed.

![Figure 2](image2.png) a) Plan view b) Lateral view.
2. BRIEF DESCRIPTION OF THE STRUCTURE

The ‘Jorge Manrique’ footbridge represents one of the most emblematic constructions of Murcia. The structure is a symmetric and upper arch bridge with a roller-pinned deck configured by a steel truss solution and supported by inclined hangers. The structure extends over a distance of 54 m and its width varies from 12.9 m at the supports to 6.4 m at the midspan (Fig. 2a). The thickness of the deck is also variable from 0.6 m at the supports to 1.2 m at the apex (Fig. 2b). The upper arch is a steel tubular profile with a diameter of 350 mm and a thickness of 40 mm; this arch is connected to the deck through 48 steel hangers with a diameter of 24 mm.

The cross section of the deck is composed by a grid of beams, composed by ½IPE-100 and HEA-100 profiles, supported on a space truss of steel tubular profiles with diameters between 89 and 140 mm. The material of the floor is a STADIP tempered glass. Due to the frequent falls of the pedestrians, an antiskid carpet was put on the glass covering all the surface of the deck. The carpet is made from a vinyl non-woven material with a thickness of 18 mm and a weight of 8.2 Kg/m2.

![Figure 3. 3D finite elements model of Jorge Manrique footbridge.](image)

3. NUMERICAL FINITE ELEMENT MODEL

The singularity of the footbridge motivated the development of a finite element model of the structure in order to support both the experimental tests and the subsequent interpretation of results. The numerical model was developed using the software MIDAS FEA; in particular, the steel truss and the grid of beams of the deck were modelled using 3D steel beam elements; the railing of the footbridge and the upper arch were also modelled using 3D steel beam elements, whereas the lateral hangers were modelled using 3D steel truss elements in tension. Finally, the tempered glass floor and the antiskid carpet were implemented as additional nodal mass. Figure 3 contains two snapshots of the proposed discretization and the corresponding mesh.

The calculation of the natural frequencies has been made assuming two load hypotheses: 1) empty footbridge (H1) and 2) high pedestrian flow corresponding to a density of 0.60 pedestrians/m² (H2). Table 1 shows the values of the two first natural frequencies corresponding to the two load hypotheses defined above; the main characteristics of the relevant vibration modes (T: transverse; V: vertical; To: torsion) are indicated.

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>H1(empty) [Hz]</th>
<th>H2 (full) [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.674 (T+To)</td>
<td>0.673 (T+To)</td>
</tr>
<tr>
<td>2</td>
<td>1.590 (V)</td>
<td>1.584 (V)</td>
</tr>
</tbody>
</table>

![Table 1. Numerical natural frequencies for full and empty deck](image)
4. EXPERIMENTAL IDENTIFICATION OF THE MODAL PROPERTIES

In order to identify experimentally the modal properties of the footbridge, an ambient vibration test was performed on 9th July 2014 under service conditions. To this aim, the deck was discretized in 11 sections and 22 points (each section is defined by a pair of points; see Figure 4). The test was performed using 4 uniaxial accelerometers connected to a portable datacenter; two of them were fixed at the sections 4-15 and 6-19 (blue narrows at Figure 4). The other two accelerometers were successively placed along the rest of sections. In each position, ambient vertical and horizontal accelerations have been recorded at 100 Hz for 1000 seconds.

![Registered points during the ambient vibration test.](image)

The recorded accelerations allowed determining the dynamic properties of the footbridge using an operational modal analysis [4]. In particular, two different techniques, based on time-domain (SSI) and frequency-domain (EFDD), were applied. In order to verify the goodness of the identification, the MAC ratio has been calculated; values of such ratio higher than 0.90 are considered as acceptable. The natural frequency ($f$), the percent of damping ($\xi$) and the MAC ratio corresponding to each vibration mode are summarized in Table 2; the two first experimental vibration modes are represented in Figure 5. The natural frequency of the first horizontal vibration mode is equal to 0.833 Hz and belongs to the range corresponding to the pedestrian action; nevertheless, the registered damping ratio for each vibration mode, between 2% and 3%, is considerably higher than the standard one proposed by technical codes. In the next paragraph, the origin of such damping and its effect on the lateral vibration of the structure are discussed.

![Numerical versus experimental (EFDD) vibration modes.](image)

![Numerical versus experimental (EFDD) vibration modes.](image)
### Table 2. Experimental vibration modes.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$f$ [Hz]</th>
<th>$\xi$ [%]</th>
<th>$f$ [Hz]</th>
<th>$\xi$ [%]</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.8288</td>
<td>2.683</td>
<td>0.833</td>
<td>2.72</td>
<td>0.999</td>
</tr>
<tr>
<td>2</td>
<td>1.663</td>
<td>2.04</td>
<td>1.659</td>
<td>2.04</td>
<td>0.998</td>
</tr>
</tbody>
</table>

A reasonably good correlation has been obtained between the experimental and numerical modal parameters. However, the unexpected damping values [5] obtained from both identification techniques and its influence in the dynamic behaviour of the structure have motivated the analysis of the cause of nature of this magnitude.

### 5. ANALYSIS OF THE UNEXPECTED NON-STRUCTURAL DAMPING

In order to study the nature of the structural damping obtained from the previous operational modal analysis, a double strategy has been followed. First, a free vibration test has been performed on a piece of the antiskid carpet in order to obtain a preliminary estimation of its equivalent viscous damping. Second, a carpet-footbridge interaction model has been developed in order to estimate the original damping of the footbridge.

#### 5.1. Estimation of the equivalent viscous damping of the carpet.

A piece of carpet has been fixed at its four corners and a free vibration test has been performed. An initial displacement has been applied to the middle of the element and the dynamic response (accelerations) during the free vibration movement has been measured. The experimental response (Figure 6) has been used to identify the first natural frequency of the laboratory structure and to adjust a logarithmic decrement curve. A first natural frequency of 4.33 Hz has been estimated. The obtained envelope curve allows [6] the estimation of the damping ratio of the carpet, a medium value of 7.52 % has been determined.

![Damping estimation. Free vibration test](image)

#### 5.2. Estimation of the initial damping of the footbridge.

The estimation of the original value of the structural damping of the footbridge has been obtained from the implementation of a carpet-footbridge interaction model, where the dynamic equilibrium has
been applied to a system with two degrees of freedom [6]. In Figure 7 a scheme of the model is shown.

The equations that govern the interaction between the structural and non-structural elements are the following:

\[
m_f \ddot{u}_f + c_f \dot{u}_f + c_c \dot{u}_c \left( u_f - u_c \right) + k_f u_f + k_c \left( u_c - u_f \right) = p^*(t)\]

\[
m_c \ddot{u}_c + c_c \dot{u}_c \left( u_c - u_f \right) + k_c \left( u_c - u_f \right) = 0\]

\[
p^*(t) = p(t) \cdot \phi(x) = G \cdot \cos(w_f \cdot t) \cdot n' \psi \cdot \phi(x)\]

where:

- \( m_f \) and \( m_c \) are the modal masses of the footbridge and the carpet, respectively [kg].
- \( c_f = 2 \cdot m_f \cdot w_f \cdot \zeta_f \) is the modal damping of the footbridge [Ns/m].
- \( k_f = m_f \cdot w_f^2 \) is the modal stiffness of the footbridge [N/m].
- \( w_f \) is the natural frequency of the vibration mode of the footbridge [rad/s].
- \( \zeta_f \) and \( \zeta_c \) are the modal damping ratios of the footbridge and the carpet [%].
- \( c_c = 2 \cdot m_c \cdot w_c \cdot \zeta_c \) is the modal damping of the carpet [Ns/m].
- \( k_c = m_c \cdot w_c^2 \) is the modal stiffness of the carpet [N/m].
- \( w_c \) is the natural frequency of the vibration mode of the carpet [rad/s].
- \( p^*(t) \) is the modal projection of the equivalent pedestrian load [2].
- \( G \) is the dynamic component of the pedestrian step load, 280 N for vertical and 35 N for lateral direction.
- \( n' = 1.85 \cdot \sqrt{n} \) is the equivalent number of the \( n \) pedestrians on the footbridge for pedestrian density \( d > 1 \) P/m² (Person/m²) [2].
- \( \psi \) is the reduction coefficient to take into account the probability that the footfall frequency approaches the natural frequency under consideration [2], considering in this paper a fixed value \( \psi = 1 \).
- \( \phi(x) \) is the considered vibration mode.

Figure 7. Carpet-footbridge interaction model.
Substituting these relations in the overall dynamic equilibrium equation of the structure and organizing information in a matrix form, the following model of interaction is obtained:

$$\mathbf{M} \cdot \ddot{\mathbf{u}}(t) + \mathbf{C} \cdot \dot{\mathbf{u}}(t) + \mathbf{K} \cdot \mathbf{u}(t) = \mathbf{F}(t)$$

$$\mathbf{M} = \begin{bmatrix} m_f & 0 \\ 0 & m_c \end{bmatrix} ; \mathbf{C} = \begin{bmatrix} c_f + c_c & -c_c \\ -c_c & c_c \end{bmatrix} ; \mathbf{K} = \begin{bmatrix} k_f + k_c & -k_c \\ -k_c & k_c \end{bmatrix} ; \mathbf{F}(t) = \begin{bmatrix} p^*(t) \\ 0 \end{bmatrix}$$

$$\ddot{\mathbf{u}}(t) = \begin{bmatrix} \ddot{u}_f(t) \\ \ddot{u}_c(t) \end{bmatrix} ; \dot{\mathbf{u}}(t) = \begin{bmatrix} \dot{u}_f(t) \\ \dot{u}_c(t) \end{bmatrix} ; \mathbf{u}(t) = \begin{bmatrix} u_f(t) \\ u_c(t) \end{bmatrix}$$

Considering the nature of the resulting system, the use of a method of $\beta$-Newmark integration family is proposed, with parameters $\beta=1/4$ and $\gamma=1/2$, thus ensuring an unconditionally stable system.

The above formulation allows, through the application of an inverse dynamic problem, the estimation of the value of the original damping ratio of the footbridge before the placement of the carpet. In this sense, several simulations has been carried out, where the above system has been forced to vibrate, modifying iteratively the value of the structural damping ratio in order to adjust the damping ratio of the system $\zeta_{sys}$ with the experimental values obtained from operational modal analysis. This methodology has been applied to the two affected vibration modes. Table 3 summarizes the estimation process.

**Table 3. Estimation of the structural damping ratios of the footbridge.**

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\zeta_{sys}$ [%]</th>
<th>$m_c$ [kg]</th>
<th>$\zeta_c$ [%]</th>
<th>$m_f$ [kg]</th>
<th>$\zeta_f$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral</td>
<td>2.72</td>
<td>708.00</td>
<td>7.52</td>
<td>57500.00</td>
<td>0.55</td>
</tr>
<tr>
<td>Vertical</td>
<td>2.04</td>
<td>885.00</td>
<td>7.52</td>
<td>72857.00</td>
<td>0.40</td>
</tr>
</tbody>
</table>

The estimated values are inside the usual range for this kind of structures according to the international standards [2].

6. EFFECTS OF THE UNEXPECTED DAMPING IN THE FOOTBRIDGE BEHAVIOUR

Finally, in order to validate the effect of the high non-structural damping in the behaviour of the structure a numerical comparison between the dynamic responses of the footbridge under a pedestrian flow (with a pedestrian density of 1.00 P/m$^2$) considering two scenarios (with and without carpet) has been performed. The effect of the pedestrian flow has been considered according to the methodology reported in the French code [3]. The maximum numerical acceleration in lateral direction has been obtained for the mentioned scenarios. In Figure 8 the results of the analysis are shown, comparing the maximum lateral acceleration on the deck of footbridge for both hypotheses. The increase in the value of the damping associated with the non-structural elements avoids the occurrence of comfort problems, even controlling the occurrence of the lateral lock-in phenomenon according to the criterion of the French code [3].
7. CONCLUSIONS

Although the first lateral vibration mode of the ‘Jorge Manrique’ footbridge is inside the range that characterizes the walking human action, the footbridge satisfies the comfort limit established by international standards due mainly to the high damping modal ratio observed in this direction. A carpet-structure interaction model has been developed and validated in order to justify the cause of this unexpected high damping value. A thick carpet situated on the deck is set as the main cause for this unusual phenomenon. This non-structural element acts as a control passive device of the dynamic behaviour of the footbridge under the pedestrians flows.

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