Damping identification in a stress-ribbon footbridge

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ABSTRACT: This paper describes the different types of dynamic tests (hammer, shaker, free and ambient vibration tests) recently performed on the stress-ribbon footbridge of FEUP Campus, with the purpose of achieving an accurate identification of the most significant modal parameters, getting better sensitivity with regard to the advantages and drawbacks associated to the application of the alternative identification techniques employed. Due to the enormous influence that damping has on the structural simulated response under pedestrian loads, particular attention has been dedicated to the identification of modal damping factors.

1 INTRODUCTION

The Laboratory of Vibrations and Monitoring (ViBest, www.fe.up.pt/vibest) of FEUP is presently involved in the development of the European research project "Advanced Load Models for Synchronous Pedestrian Excitation and Optimized Design Guidelines for Steel Footbridges (SYNPEX)", coordinated by RWTH Aachen.

One of the ongoing tasks of this project is the development of dynamic tests in existing lively footbridges, in Portugal and Germany, in order to obtain accurate estimates of their most significant dynamic properties, characterize the corresponding dynamic response due to the passage of a single pedestrian or groups of pedestrians and evaluate the level of importance of the human induced vibrations, from the human comfort point of view.

The stress-ribbon footbridge of FEUP, whose lively behaviour was early detected, was selected as an example for this research.

In this context, the present paper describes the different types of dynamic tests (hammer, shaker, free and ambient vibration tests) recently performed on that bridge with the purpose of achieving an accurate identification of the most significant modal parameters, getting better sensitivity with regard to the advantages and drawbacks associated to the application of the alternative identification techniques employed.

Due to the paramount influence that damping has on the structural response, particular attention has been dedicated to the identification of modal damping factors.

2 THE BRIDGE

The bridge, which establishes a link between the main buildings and the students' canteen, was designed by ENCIL (1998) and its deck is a very slender stress-ribbon concrete slab, continuous over two spans (Figure 1). The slab embeds all four prestressing cables and it takes a catenary shape over the two spans, with a circular curve over the intermediate support. Figure 2 presents the elevation of the deck. The two spans 28m and 30m long and the 2m rise from the abutments to the intermediate pier were the starting points for the definition of the bridge structural geometry. The constant cross-section is approximately rectangular with external design dimensions of 3.80mx0.15m.

Figure 1. View of the footbridge.

The construction method suggested by the bridge designer sets the following steps:
(i) installation and progressive prestressing of all cables to about 750kN each; (ii) hanging of 1m long precast segments from the cables, starting from the abutments and ending at the external limits of the deviating saddle over the intermediate support; (iii)

casting of the concrete slab, with formwork provided by the precast segments; casting should be made continuously in an approximately symmetric fashion with respect to the intermediate support, and it should be followed by an injection of the joints between precast segments; (iv) eventual modification of final prestressing in all cables, for correction of geometry; (v) injection of all prestressing ducts with cement grout.
The intermediate support is made of four steel pipes forming an inverted pyramid hinged at the base, with horizontal resistance provided only by the prestressing cables. Therefore, the structure was supported longitudinally during the construction phase.

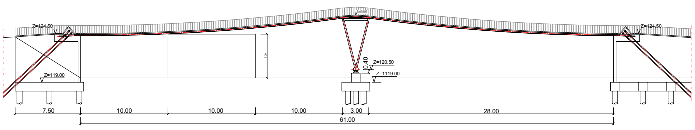

Figure 2. Elevation of the footbridge.

3 FINITE ELEMENT MODELLING AND UPDATING

The performance of different types of modal identification tests was preceded by the development of a finite element model of the bridge, which was conveniently updated on the basis of an initial ambient vibration test (performed on the 28th March 2003 – Test 1) using a sensitivity analysis. This work, extensively described in (Caetano & Cunha 2004), involved the construction of the following numerical models:
Model 1: Modelling the bridge deck as a series of beam elements with the geometry corresponding to the design configuration;
Model 2: Modelling the bridge deck as a series of beam elements with the geometry corresponding to the real measured profile;
Model 3: Discretization of the deck in truss finite elements with the cables' axial stiffness (neglecting bending stiffness), adjusting the initial cables tension so as to obtain the measured longitudinal profile after progressive application of the loads;
Model 4: Discretization of the deck in truss finite elements, with progressive loading and activation of beam elements connecting the nodes of the truss elements, to take into account the bending stiffness of the concrete slab;
Final Model: Discretization of the deck in truss finite elements, with progressive loading and activation of beam elements; Consideration of partial rotations between beam elements to simulate the lack of sealing of the joints; Reduction of the area and inertia of the beam elements to simulate the effects of cracking and lack of adherence between precast and in situ concrete.

Table 1 summarizes the values of natural frequencies calculated on the basis of these models, allowing a comparison with the corresponding identified frequencies. Inspection of this table shows that the several iterations of the finite element updating procedure led to very good correlation between identified and calculated natural frequencies in the *Final Model*. Similar conclusion can also be drawn in terms of comparison of identified and calculated mode shapes (Caetano & Cunha 2004), as shown in next section.

Table 1. Calculated *vs* identified natural frequencies (Test 1).

Mode no.	Id. Freq. f (Hz)	Mod. 1 f (Hz)	Mod. 2 f (Hz)	Mod. 3 f (Hz)	Mod. 4 f (Hz)	Fin. Mod. f (Hz)
1	0.990	0.849	0.794	0.724	1.096	0.949
2	2.083	2.448	2.654	0.937	2.442	1.990
3	2.178	1.902	1.822	1.446	3.813	2.143
4	2.423	2.096	2.002	1.547	3.895	2.417
5	3.753	-	-	2.217	7.496	3.334
6	3.857	3.415	3.401	3.376	7.569	3.869
7	4.229	3.782	3.630	3.034	12.4	4.381

4 INPUT-OUTPUT / OUTPUT-ONLY MODAL IDENTIFICATION

In a subsequent stage of research, additional modal identification tests were developed in order to compare the performance and estimates obtained using both input-output and output-only identification techniques. These tests were performed on the 5th October (Test 2) and complemented by some additional measurements on the 6th November 2004 (Test 3).

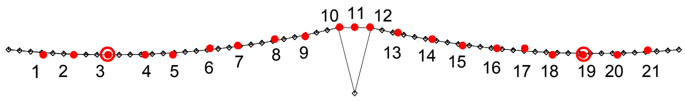

Figure 3. Measurement points in modal identification tests.

4.1 *Hammer test*

Test 2 comprehended a conventional modal analysis test performed using an impact hammer, a set of four piezoelectric accelerometers and an eight-channel Fourier analyzer (Figure 4).

(a) (b)

Figure 4. (a) Application of hammer impulse; (b) Data acquisition system.

The impact hammer has a force sensor at the tip with a sensitivity of 1V/0.23kN, which allows the measurement of the applied force. The piezoelectric accelerometers have a sensitivity of 1V/g. These devices are connected to signal conditioners for further amplification of the signal. The impulsive loads were always applied at a fixed point at each span (nodes 3 or 19), and the corresponding response was measured at four different points in each setup. The evaluation of frequency response functions (FRFs) relating the input force and the output accelerations was performed in the frequency range 0-200Hz, considering an individual time of acquisition of 16s and the average over 8 spectral estimates, which led to a frequency resolution of 0.0625Hz.

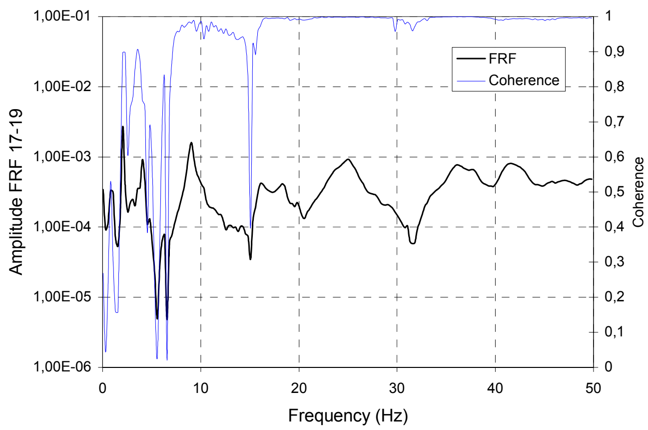

Figure 5. FRF and coherence relating force applied at node 19 with acceleration measured at node 17.

Figure 5 shows one the FRFs obtained, relating the input force and output acceleration at nodes 19 and 17, respectively, as well as the respective coherence function. Inspection of all the FRFs obtained shows that their peaks allow to easily identify the fundamental natural frequencies of the footbridge, whose values (0.979, 2.050, 2.446, 3.629, 4.104 and 5.374 Hz) agree rather well with the identified frequencies at the initial ambient vibration test (Caetano & Cunha 2004). However, the relatively short time of each acquisition (16s), associated to the application of each impulsive load, led to a relatively low frequency resolution (0.0625Hz) of the spectral estimates, whose peaks became wider. Accordingly, the separation of close modes and the accurate identification of modal damping factors (clearly overestimated) became impossible.

On the other hand, despite the very high values of the coherence functions in the frequency range 10-200 Hz, their values fall drastically in the frequency range (0-10Hz), evidencing the difficulty of the hammer to excite significantly the most relevant modes of vibration in that range, with regard to the level of noise induced by ambient factors, like wind. These aspects also precluded the obtainment of reliable estimates of modal components.

4.2 *Electrodynamic shaker test (random excitation)*

Test 2 was simultaneously used to perform a conventional modal analysis test using, as alternative excitation technique, an electrodynamic shaker controled by the Fourier analyzer (Figure 6).

(a) (b)

Figure 6. (a) Application of random shaker load;
(b) Detail of the shaker and load cells.

In a first instance, the shaker was placed in the longer span (at nodes 3 or 5), applying a random load in the frequency range 0-6.25Hz, the corresponding structural response being measured by the piezoelectric accelerometers at four different points in each setup. The evaluation of frequency response functions (FRFs) relating the input force and the output accelerations was performed, in this case, in the frequency range 0-6.25Hz, considering an individual time of acquisition of 128s, an average over 8 spectral estimates (with 50% overlapping), and applying a Hanning window, which led to a higher frequency resolution (0.01563Hz).

As some of the modes of vibration only involve the motion of one of the spans, the shaker was subsequently placed (Test 3) in the shorter span (at nodes 19 or17).

Figure 7 shows a comparison of two estimates of a FRF, obtained through the application of the shaker and the hammer. This plot shows two interesting aspects: (i) the much better definition of the peaks of the FRFs allowed by the higher frequency resolution of the spectral estimates associated to the shaker; (ii) the higher capacity of the shaker to excite the fundamental modes of vibration of the footbridge, with frequencies below 10Hz.

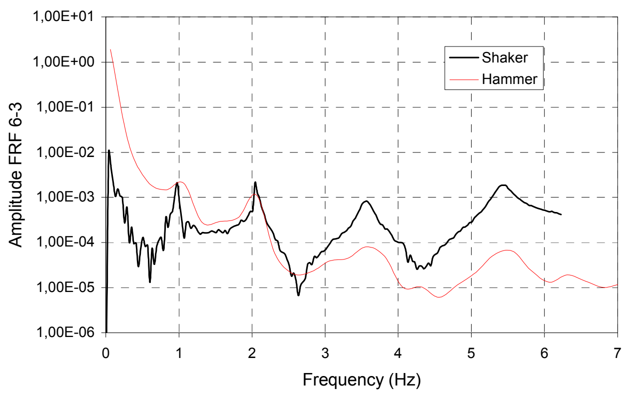

Figure 7. Comparison of FRFs (shaker *vs* hammer).

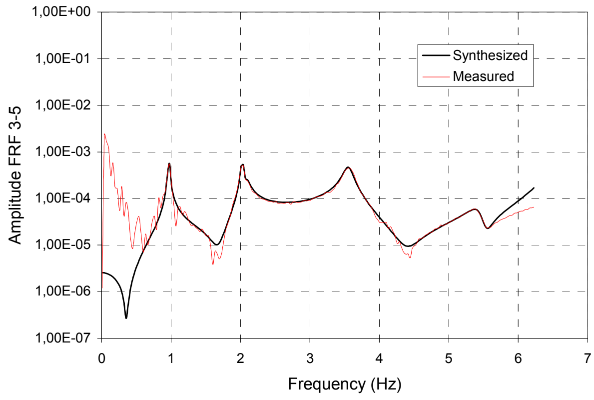

Figure 8. Measured *vs* synthesized FRFs.

The identification of the modal parameters of the bridge was done by applying a multi-degree-of-freedom identification algorithm in the frequency domain (RFP method) (Han & Wicks 1989) to the FRFs obtained. Figure 8 shows, for instance, a comparison between amplitudes of one of the measured FRFs and the corresponding synthetized FRF, on the basis of the identified modal parameters, showing the good agreement achieved.

Table 2. Identified frequencies and modal damping ratios.

Natural freq. (Hz)		Damping factors (%)	
Mean	St. deviation	Mean	St. deviation
0.972	0.005	1.07	0.24
2.043	0.013	1.40	0.53
2.072	0.020	1.51	0.79
2.382	0.005	1.72	0.14
3.590	0.039	1.77	0.25
4.165	0.023	2.00	0.17
5.461	0.036	1.92	0.24

Table 2 resumes mean values and standard deviations of estimates of natural frequencies and modal damping factors obtained by this approach. It's worth noting that the difference between modal estimates achieved in Tests 2 and 3 were irrelevant.

Figure 9 presents the identified modes of vibration, as well as the corresponding calculated modes and the identified modes at the initial ambient vibration test (Test 1).

4.3 *Electrodynamic shaker test (resonant / free vibration response)*

The electrodynamic shaker was also used to induce modal resonance, by applying sinusoidal excitations with frequencies in correspondence with some of the previously identified natural frequencies. By stopping suddenly that excitation, it was possible to measure the corresponding free vibration response (Figure 10) at several points, and extract some accurate estimates of modal damping factors.

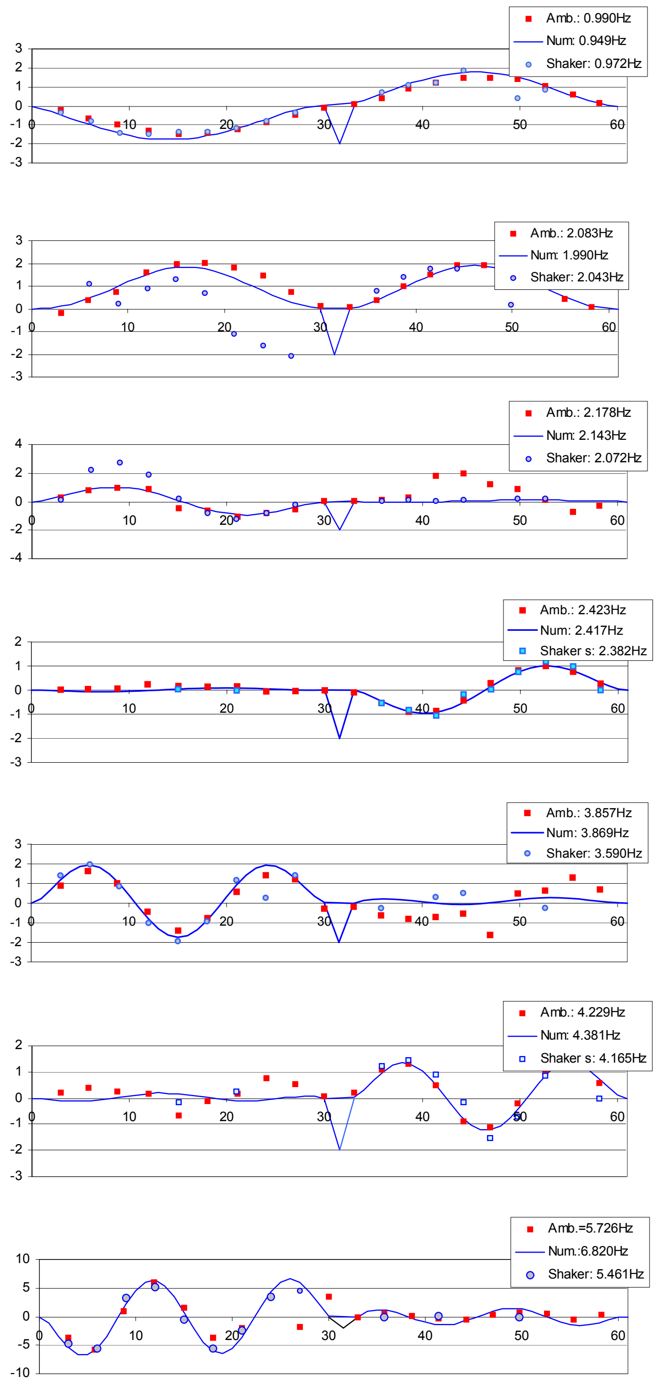

Figure 9. Identified *vs* calculated modes of vibration.

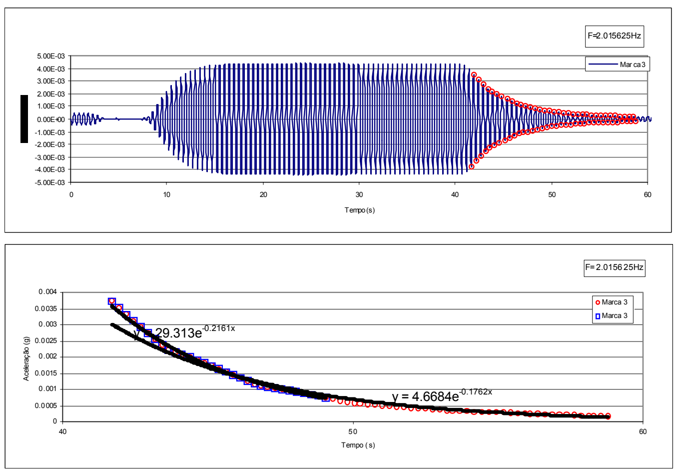

Figure 10. Free vibration modal response and fitting of the free decay response envelope.

Table 3 shows the estimates obtained following this procedure with regard to four different modes of vibration. Observing the decay of the response envelopes, one can see that certain modal factors increase significantly with the amplitude of oscillation. Therefore, Table III presents both the estimate of damping at the beginning of the decay and an average value.

Table 3. Modal damping factors identified from the measured free vibration responses.

Identified	Modal damping factor (%)	
frequency (Hz)	initial	average
0.972	1.26	1.22
2.043	1.20	1.09
2.072	1.80	1.24
3.590	1.89	1.81

The increase of damping with the amplitude of oscillation could be still better evidenced by analyzing the free vibration response of the bridge excited at resonance with one person skipping at a fixed position, with an adequate pacing rate and stopping its movement suddenly. Figure 11 shows some records obtained by this procedure, as well as the significantly higher modal damping estimates achieved.

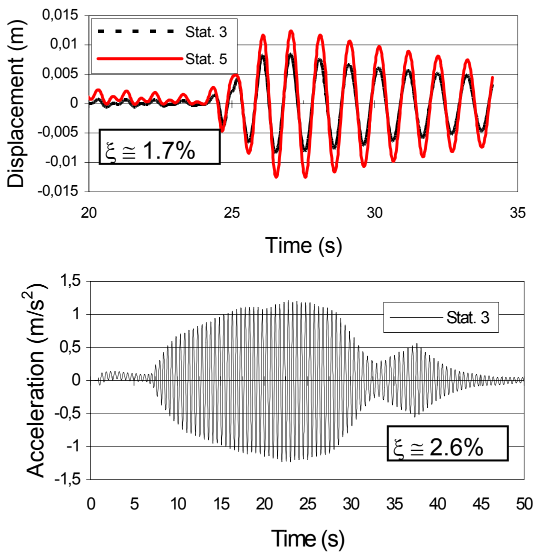

Figure 11. Free vibration response: skipping at 1Hz, station 16 (top); skipping at 2Hz, station 3 (bottom).

4.4 *Ambient vibration tests*

During the present research, two ambient vibrations tests were performed. The first one took place in March 2003 (Test 1), with the aim of achieving estimates of the most relevant modal parameters of the bridge, so as to update the respective finite element modeling (Caetano & Cunha 2004). The second measurement campaign (Test 2) was developed in October 2004, in parallel with the hammer and shaker tests, in order to enable coherent comparison of estimates extracted through the different identification techniques. Both ambient vibration tests were based on the use of 4 triaxial seismographs duly synchronized by GPS, provided with 18 bit A/D converters. Two of them were placed at fixed positions (reference points at 1/3 span), while the other two were successively placed at the other measurement points indicated in Figure 3. The sampling frequency was 100Hz and the time of acquisition was at least 10 minutes in each setup, in order to obtain sufficiently high frequency resolution spectral estimates. The extraction of modal parameters was done using the classical Peak-Picking (PP) (Felber 1993), the Frequency Domain Decomposition (FDD) (Brincker *et al.* 2000) and the Data Driven Stochastic Subspace Identification (SSI-DATA) (Van Overschee & De Moor 1996).

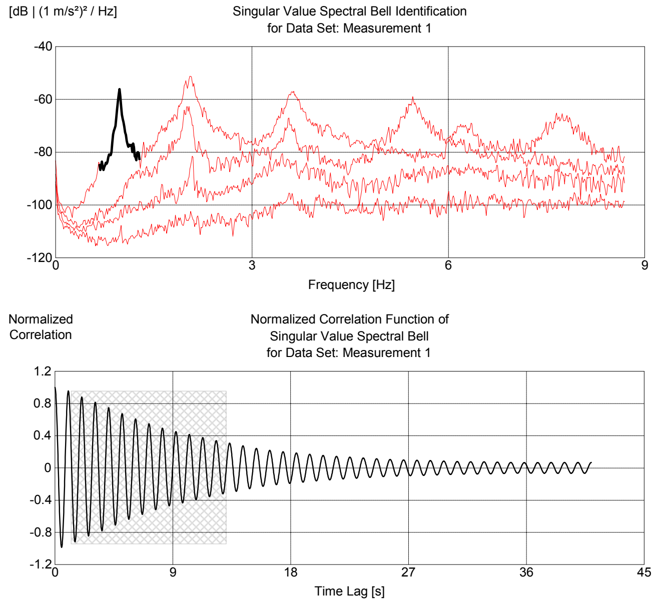

Figure 12. Singular values spectra (FDD) and normalized correlation function (mode 1).

Table 4. Identified natural frequencies (Hz).

Test 1			Test 2
PP	FDD	SSI-DATA	FDD
0.990	0.984	0.983	0.965
2.083	2.093	2.083	2.018
2.178	2.101	2.136	2.023
2.423	2.411	2.408	2.341
3.857*	3.745	3.743	3.594
4.229	4.239	4.241	4.092
5.726	5.547	5.705	5.407

(*) – coupled mode (weakly defined) around 3.753Hz.

Table 5. Identified modal damping factors (%).

Freq. (Hz)	Test 1		Test 2
PP	FDD	SSI	FDD
0.990	1.65	1.56	1.51
2.083	1.11	1.27	1.31
2.178	1.37	2.10	1.98
2.423	1.97	1.84	1.09
3.857	1.84	2.12	2.37
4.229	2.19	2.21	2.13
5.726	2.04	2.82	1.74

Figure 12 shows, for instance, spectra of the first singular values associated to the application of the FDD method to data captured at Test 2. This figure shows clearly the location of the most significant natural frequencies and, in particular, the existence of two close modes around 2Hz, which could be better separated than using the Peak-Picking method. This figure shows also the normalized correlation function associated to the first modal response.

Tables 4 and 5 resume the estimates of natural frequencies and corresponding modal damping factors identified on the basis of the two ambient vibration tests performed.

4.5 *Comparison of modal estimates*

Tables 6 and 7 summarize estimates of natural frequencies and modal damping factors achieved by application of different input-output or output-only modal identification techniques.

With regard to the natural frequencies, one can easily observe in general a very good agreement of estimates. Notwithstanding, one can notice that the hammer technique was not able to detect the two close modes around 2Hz. Moreover, some slight decrease of frequencies from Test 1 (March 2003) to Tests 2 and 3 (Oct./Nov. 2004) is also detected, probably due to some structural degradation and temperature effects.

With regard to the modal damping factors, one can also observe a reasonable agreement of results provided by the output-only techniques with regard to the shaker tests, despite the considerably higher scatter of estimates.

Table 6. Identified natural frequencies (Hz).

Test 1			Tests 2 / 3		
PP	FDD	SSI	Hammer	Shaker	FDD
0.990	0.984	0.983	0.979	0.972	0.965
2.083	2.093	2.083	2.051	2.043	2.018
2.178	2.101	2.136	-	2.072	2.023
2.423	2.411	2.408	2.446	2.382	2.341
3.857	3.745	3.743	3.630	3.590	3.594
4.229	4.239	4.241	4.100	4.165	4.092
5.726	5.547	5.705	5.374	5.461	5.407

Table 7. Identified modal damping factors (%).

Test 1		Tests 2 / 3		
FDD	SSI	Shaker (RFP)	Shaker (free)	FDD
1.65	1.56	1.07	1.22/1.26	1.51
1.11	1.27	1.40	1.09/1.20	1.31
1.37	2.10	1.51	1.24/1.80	1.98
1.97	1.84	1.72	-	1.09
1.84	2.12	1.78	1.81/1.89	2.37
2.19	2.21	2.00	-	2.13
2.04	2.82	1.92	-	1.74

5 CONCLUSION

The modal identification tests described in this paper were performed to obtain accurate estimates of the most relevant modal parameters of the footbridge, allowing the convenient calibration of the corresponding finite element modeling used to simulate the passage of pedestrians on the bridge, as well as a comparison of the performance of alternative identification techniques.

As the influence of damping properties on the structural dynamic response is paramount, special attention has been given to the identification of modal damping factors. From this point of view, the results obtained permit, in particular, to draw the following conclusions:

a) The hammer technique looks inappropriate to accurately identify modal damping factors in this type of slender structures, due to some difficulty of exciting the fundamental modes of vibrations and to the low frequency resolution associated to the corresponding spectral estimates;

b) The electrodynamic shaker, though relatively heavy and difficult to transport, provides much better estimates by using multi-degree-of-freedom input-output identification techniques;

c) Moreover, this equipment permits to obtain the free vibration response of the bridge after inducing modal resonance, which is in fact the best procedure to extract accurate modal damping estimates;

d) Despite some more significant scatter of the damping estimates, the application of output-only modal identification techniques (FDD and SSI) seems to provide identified values with a reasonable agreement with regard to those obtained with the shaker (relative errors inferior to 20%, in general).

ACKOWLEDGEMENTS

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