Conference Proceedings 4th ICTB (2022)
https://doi.org/10.24451/02es-hd44

ICTB 2021 PLUS
4th International Conference on Timber Bridges
Biel/Bienne, Switzerland, 9 -12 May 2022

Innovative large timber foodbridges and dynamic testing in Spain

Julio Vivas[1]*, Álvaro Magdaleno*[2]*, Juan Carlos Santos*[1]*, Soledad Rodríguez*[3]*, Antolín Lorenzana*[2]

1 Summary

This work shows the practical methodology used for the dynamic testing and identification of a timber pedestrian walkway located in the *Anillo Verde* trail, upon the N-102 road in Vitoria, Spain. The footbridge is 61 meters long and 3 meters wide and consists of arched glulam structural beams, wood deck and steel cross bracings, designed by Media Madera Ingenieros Consultores. The experimental campaign was carried out in December 2019, just after its erection process. Useful data was collected to estimate its modal properties and to calibrate the corresponding computational model. Also, some serviceability tests were carried out to quantify the vibrations induced when a lone pedestrian transits at different paces. Although there may be some other works with similar objectives and methodology, the peculiarity of this structure is the building material, its large size and the challenging one-step erection process, resulting in a fully functional structural typology with attractive advantages from construction and environmental points of view.

2 Introduction

Fig. 1. Walkers on the Guadalhorce footbridge

With a total length of 270 meters spread and a central span of 70 meters, the Guadalhorce footbridge is one of the largest timber footbridges in Europe and has become a new attraction of the city of Malaga, since its inauguration in October 2020, with thousands of walkers, cyclists and pictures shared on social networks.

This bridge is an excellent example of the latest works carried out by the company Media Madera, a company specialized in the design, calculation an construction of timber bridges for more than 20 years. Taking

[1] Media Madera Ingenieros Consultores, Asturias, Spain
[2] ITAP, Universidad de Valladolid, Valladolid, Spain
[3] CETEMAS, Centro Tecnológico de la Madera de Asturias, Asturias, Spain

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into account the existing background of the brightest timber footbridges built, the structural arch typology constitutes the most immediate and adequate solution for the resistant characteristics of the glue-laminated timber, allowing a high range of economically effective lights between 30 and 80 meters, with which the minimun number of necessary supports is defined.

Fig. 2. The Guadalhorce footbridge during its construction

3 Dynamic testing

Fig. 3. Dynamic testing of Guadalhorce footbridge

Pedestrian footbridges, like many other building and civil engineering structures, must meet a number of criteria prescribed in standards. Most of the criteria refer to safety conditions. It is also desirable to comply with serviceability conditions, sometimes included as recommendations in the standards and design guidelines [1, 2, 3]. When both the actions and the behaviour of the material are well known, the criteria fulfilment can be check by simulation. This is usually the case with the ultimate strength criteria undergoing overloads, often considered to be quasi-static loading. However, if the behaviour is not so well defined (as in the case of structural timber [4]) or the actions are dynamic ones (as in the case of pedestrian transits) the evaluation by simulation may present serious deficiencies, mainly due to the lack of knowledge of the damping coefficient. Furthermore, with this type of material, the parameters that define the behaviour (both static and dynamic) significantly depend on environmental factors such as humidity and temperature. It is therefore necessary to evaluate on the basis of estimates and to check, once the footbridge has been built, that the estimates are correct or at least conservative. Otherwise, corrective action may be required. Dynamic tests such as those described in this paper are necessary for these checks. Another application of these tests, which is not covered in this work, would be the calibration of the computational model in order to simulate the behaviour in situations that are difficult to experiment with, such as the case of a crowded footbridge.

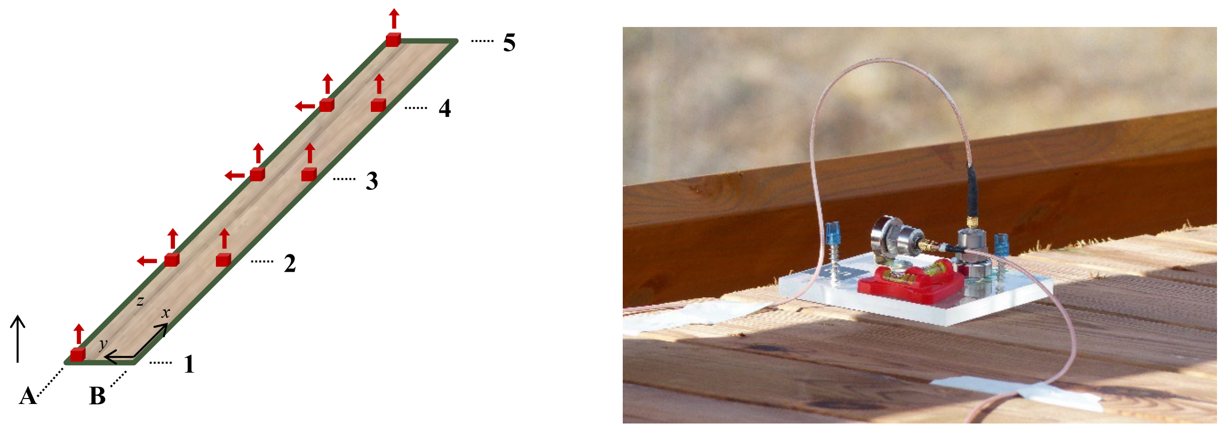
4 Case study: Dynamic Testing of a 61 meters span timber footbridge

Fig. 4. Green Ring footbridge in Vitoria

In December 2019, the Green Ring (*Anillo Verde*) of Vitoria was completed by placing a footbridge over the N-102 at km 347. The footbridge is designed as a three-hinged arch of 61 m. The width is 3 m and a maximum height above the road is 6 m. Figure 1(a) shows an overview of the whole structure. At the time of its construction, it was the longest single-span footbridge on the iberian peninsula, although in February 2020 it was surpassed by the central span of the footbridge over the Guadalhorce River in Málaga, which is 70 m long. The assembly (Figure 1(b)) was carried out in only 6 hours, the abutments had already been built previously.

The properties of structural class GL28h wood according to EN 14080:2013, density 425 kg/m^3 and bending modulus of elasticity 12600 MPa were taken into account in its project. The total weight is 39.3 tons. To the structural wood are added functional parts (deck and railings) and steel bracing and fittings that can mean about 3 additional tons.

5 Modal testing and identification



(a) (b)

Fig. 5. (a) Layout; (b) detail of the biaxial configuration of the accelerometers

Modal analysis techniques are well established in the literature [5, 6, 7, 8]. Obviously, some instrumental equipment is needed to perform any full-scale tests. This work shows how these means can be reduced to a lightweight and autonomous equipment easily handled by two people. Figure 5(a) shows the layout of the footbridge projected on a horizontal plane where the simplest 5 equidistant measurement sections have been selected along the length of the footbridge. Accelerometers (Figure 5(b)) are placed at these points and oriented in the indicated directions to measure vertical and transversal accelerations. The excitation force required to conduct the experimental modal analysis is induced by a person bouncing on a homemade force plate. This bouncing is applied in two different locations, with the force plate located on point 2A (case I) and with the force plate located on point 3A (case II).

Once the input (bouncing, Figure 6) and the outputs (accelerations) are synchronously registered by means of a proficient and battery-powered datalogger, the frequency response functions (FRFs) relating them, also known as accelerances, can be calculated by means of an estimator such as H_v [5, 6].

Fig. 6. Bouncing on a forceplate.

The modal properties of the structure that constitute the expression shown in Eq. (1), which permits to calculate the frequency response function relating an input (i) and an output (k), can be found by means of a curve fitting procedure. Note that this is performed simultaneously for all the FRFs of each case. In that expression, s_r accounts for the eigenvalues of the structure, closely related to the natural frequencies (ω_r) and damping ratios (ζ_r) through Eq. (2). The i-th coordinate of the r-th mode shape is denoted as ϕ_{ri} and n accounts for the order of the modal model, which is the number of modes it is composed of. Finally, j stands for the imaginary unit ($\mathrm{j}^2 = -1$) and the symbol $*$ represents the complex conjugate.

$$h_{ik}(\omega) = \sum_{r=1}^{n} \left(\frac{\phi_{ri}\phi_{rk}}{\mathrm{j}\omega - s_r} + \frac{\phi_{ri}^{*}\phi_{rk}^{*}}{\mathrm{j}\omega - s_r^{*}} \right) \quad (1)$$

$$s_r = -\omega_r \zeta_r + \mathrm{j}\,\omega_r \sqrt{1 - \zeta_r^2} \quad (2)$$

Note that the total amount of modes in the measured frequency range is unknown *a priori*. For this reason, the curve fitting process is repeated several times for each case assuming different orders n. The found modes for each order are plotted together in the known as the stability diagrams shown in Figure 4, which are carefully studied to choose the best model order, i.e., the one which best represents the dynamic behaviour of the structure in the frequency range of interest with the least number of modes. In this case, in the range of interest (between 1 and 8 Hz), an order 8 was considered appropriate in both cases.

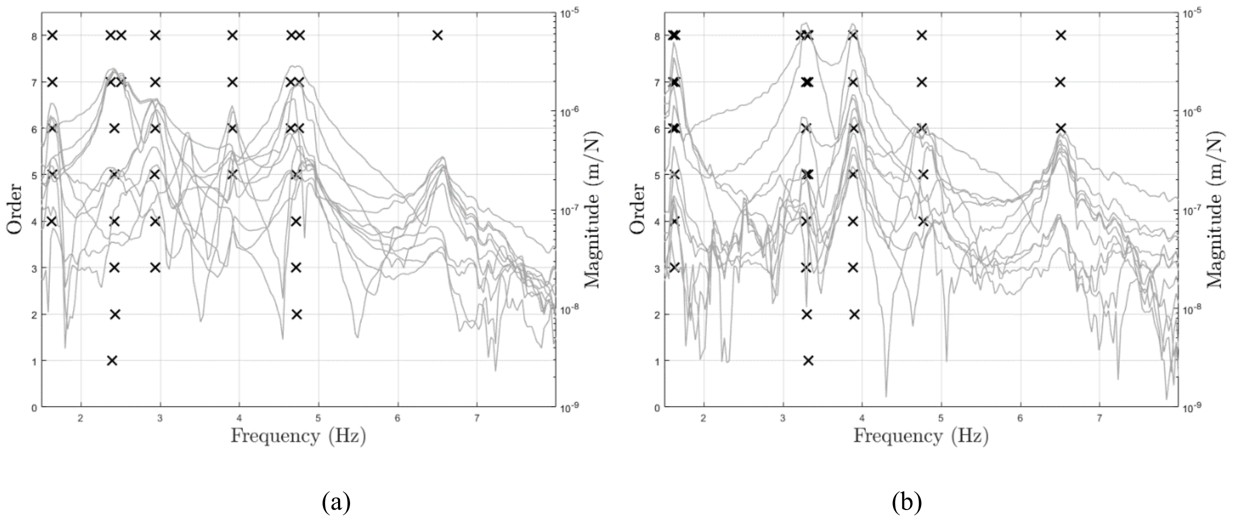


Fig. 7. Stability charts of (a) case I and (b) case II

Figure 5 shows two examples of FRF fitting: Figure 7(a) corresponds to the case I and Figure 8(b), to the case II. In both cases, the FRF corresponding to the point 3A (Z axis) has been plotted. As can be seen, the fitted curve (in solid black), computed from Eq. (1), accurately represents the same dynamic behaviour than the experimental FRF (in solid gray).

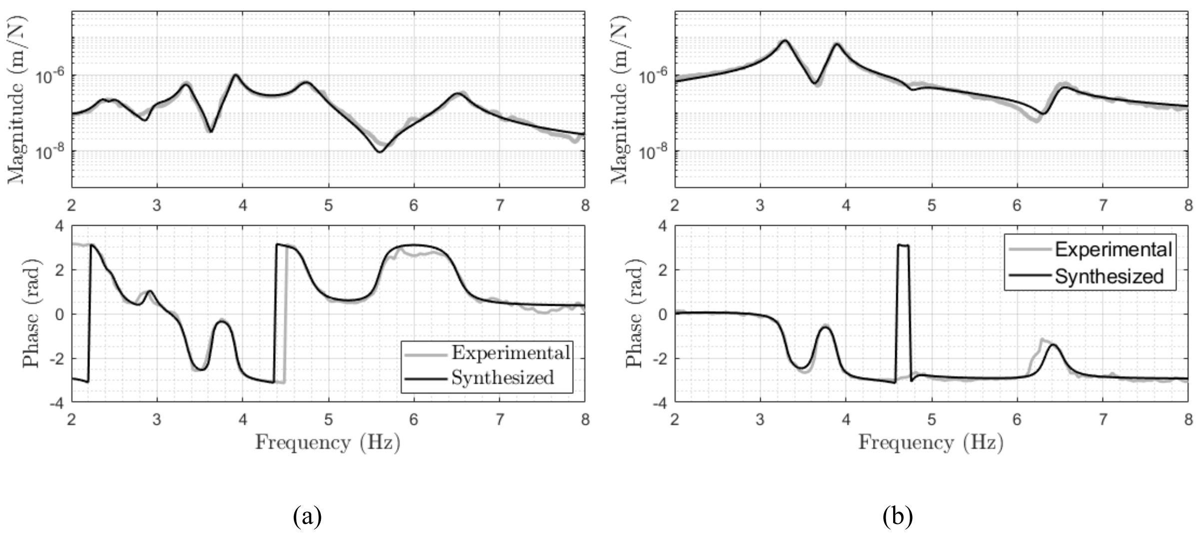


Fig. 8. Examples of A3Z receptance fit of (a) case I and (b) case II

After the visual interpretation of the resulting modes, it is possible to sum up the main results in Table 1, where the last column shows a rough description of the corresponding mode shapes by comparing them to the classical mode shapes of a simple supported beam. Note that the actual mode shapes of the timber structure do not correspond exactly to the ones found in a simple supported beam, but they share similar topological features, like the general shape (bending or torsion) and the number of vibration nodes (points with a null mode shape coordinate). In this sense, the mode shapes described as “1” do not contain any internal vibration node (only the ones associated to the supports), those marked as “2” contain one vibration node located approximately at the middle section, etc.

Table 1. Identified natural frequencies and description of the corresponding mode shapes

Freq. (case I) [Hz]	Freq. (case II) [Hz]	Damping ratio (%)	Mode shape
1.64	1.64	2.91	Lateral Bending 1
2.38	–	2.85	Vertical Bending 2
3.35	3.29	1.90	Vertical Bending 1
3.91	3.89	1.14	Torsion 1
4.65	–	1.95	Torsion 2
4.74	4.75	1.68	Vertical Bending 3
6.51	6.51	2.38	Torsion 3

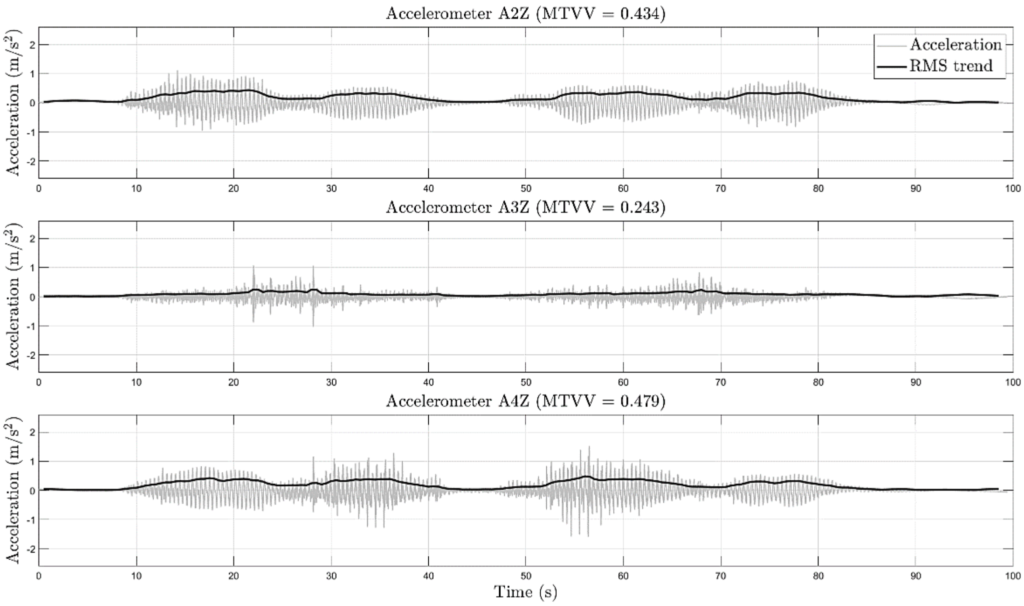
6 Serviceability assessment

Once the modes have been identified (mode shapes, natural frequencies and damping ratio), determining if any of them is prone to be excited by human locomotion is relatively easy. Usual walking and running are in the range from 95 bpm to 256 bpm (1.58 to 4.26 Hz), which covers the 1st to 4th identified modes. Experimental results are presented by crossing (figure 9) the footbridge at paces matching modes 2 and 3, that are the ones likely to resonate with normal walking and running activities. After the corresponding round-trip transits (90 kg pedestrian with the help of a metronome) the vertical accelerations shown in figures 10 are obtained.

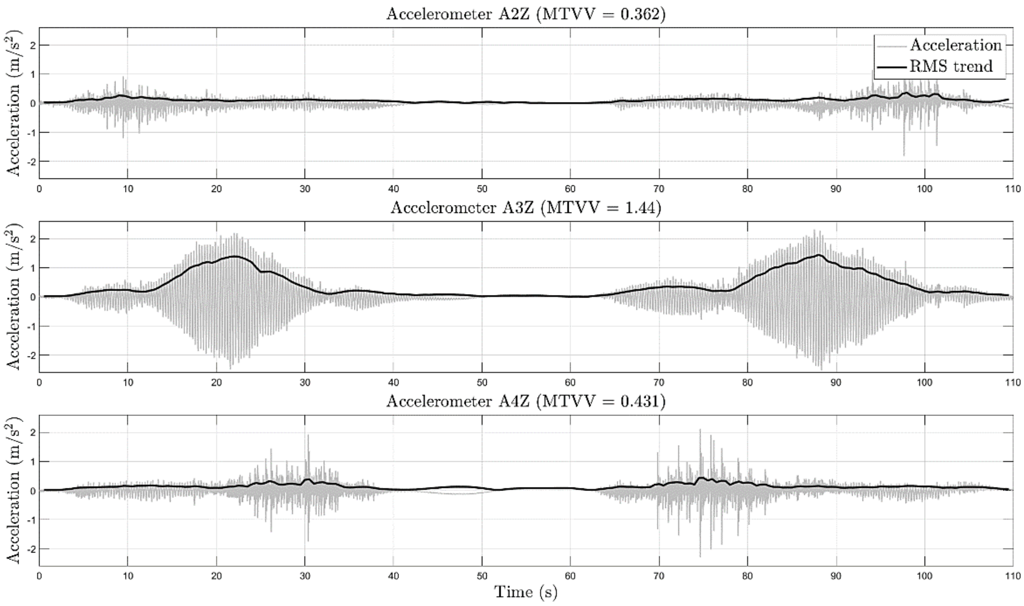
Fig. 9. Transits on the footbridge. A single pedestrian walking test.

In the first case, peak effective values about 1 m/s^2 and maximum transient vibration values (MTVV) less than 0.5 m/s^2 are obtained.

For the transits at 200 bpm, the processed values are 2.4 m/s^2 peak and 1.44 m/s^2 MTVV. Overall, these values exceed the range of "comfortable footbridge" [9, 10] but given the use of the bridge (immersed in a green trail) the installation of dissipation systems were not prescribed.



(a)



(b)

Fig. 10. Time responses of certain locations. (a) Walking at 143 bpm (VB2). (b) Running at 200 bpm (VB1)

7 Conclusions

When the interest is focused on identifying structures prone to vibrate under pedestrian actions, it has been demonstrated that with portable instrumental equipment and without an external energy supply, modal identification tests can be satisfactorily performed.

Seven modes below 7 Hz have been easily identified in the footbridge under study. Beyond that frequency the task is more difficult without the instrumental support of a mechanical shaker. However, from the serviceability point of view, it is pointless to identify modes at higher frequencies.

Although the design guidelines and the limits they set with regard to comfortability are varied, after the obtained values of MTVV for isolated transits, the footbridge can be classified within the normal comfort range for the intended use.

The MTVV values could be increased in case of synchronized groups of pedestrians [12, 13] or synchronized pedestrian flow. However, the high mass of the structure and the damping of more than 1.5% will make interaction effect difficult to appear. In addition, under high occupancy conditions the damping will increase significantly, making synchronisation even difficult. These ends could be estimated by simulation once the computer model has been calibrated with the results obtained from the modal analysis.

8 Acknowledgement

The authors wish to acknowledge IDEPA and the Ministerio de Economía y Competitividad, Spanish Government, for the partial support through the RTI 2018-098425 Research Project

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