Moving Toward Smart, Resilient and Sustainable Bridges – Catbas, Frangopol & Yun (Eds)
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In-service vibration analysis of steel pedestrian bridges

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ABSTRACT: Serviceability is a critical design criterion for modern footbridges, particularly lightweight and slender decks that are sensitive to pedestrian-induced vibrations. Excessive accelerations can compromise user comfort and, in extreme cases, trigger crowd-induced synchronization. While Eurocode 0 and Eurocode 1 provide guidance on pedestrian loads and acceleration limits, simplified models may be insufficient for modern, optimized designs. The EUR 23984 EN Technical Report addresses these challenges by integrating theory, experimental evidence, and practical verification procedures, emphasizing modal identification, damping estimation, comfort criteria, and step-by-step experimental testing. This paper presents an extensive experimental campaign conducted on a newly constructed 200 m pedestrian bridge over the Cesano River in Central Italy. The campaign included Ambient Vibration Tests to determine modal properties and Human-Induced Vibration Tests to measure response under controlled pedestrian loading. The results assessed serviceability according to recommended acceleration thresholds, confirming EUR 23984 EN as the main reference for pedestrian bridge design and testing in Europe.

1 INTRODUCTION

Serviceability has become a governing design criterion for modern footbridges, often exceeding ultimate limit state requirements in terms of practical relevance and public perception (Bayat et al, 2022; Varzaneh et al, 2026). Due to their typically slender decks, low mass, and limited structural damping, footbridges are particularly sensitive to vibrations induced by pedestrian traffic. Excessive accelerations can compromise user comfort, lead to serviceability concerns, and in extreme cases trigger crowd-induced synchronization phenomena (Drygala et al, 2019; Gong et al, 2022). For these reasons, European design standards place increasing emphasis on vibration performance verification under operational conditions.

Within the European regulatory framework, serviceability verification is primarily addressed through the Eurocode 0 (EN 1990, 2023) and Eurocode 1 (EN 1991-2, 2003), complemented by specific national annexes and technical background documents. These documents define load models for pedestrian-induced actions, limit acceleration thresholds for comfort assessment, and provide guidance for both numerical and experimental verification procedures. However, the growing architectural ambition and structural optimization of contemporary footbridges often push designs toward the boundaries of these simplified predictive models (Tadeu et al, 2022).

In this context, experimental serviceability testing represents a crucial tool for validating design assumptions, calibrating numerical models, and ensuring compliance with European prescriptions. Full-scale dynamic tests allow for the identification of modal parameters (natural frequencies, damping ratios, and mode shapes) and enable the direct measurement of structural response under controlled pedestrian loading scenarios (Nicoletti et al, 2023).

This paper investigates serviceability testing methodologies applied to footbridges in accordance with current European standards, highlighting practical procedures, interpretative

DOI: 10.1201/9781003778677-131
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criteria, and implications for design verification. The study is based on application on a real footbridge case study experimentally tested after the construction.

2 SERVICEABILITY TESTING ON FOOTBRIDGES FOLLOWING EUROPEAN PRESCRIPTIONS

The European framework for footbridge serviceability is treated in Eurocode 0 and 1, where pedestrian actions are classified as variable loads and comfort is evaluated through acceleration limits, with EN 1991-2 providing more specific provisions for bridges. Nevertheless, the simplified formulations in the Eurocodes often prove insufficient to capture complex effects such as crowd–structure interaction and synchronization, particularly in lightweight and slender decks (Van Nimmen et al, 2016). In this context, the technical report called "*Design of Lightweight Footbridges for Human-Induced Vibrations*" (EUR 23984 EN, 2009), developed by the Joint Research Centre (JRC) and based on the outcomes of the HIVOSS (Research Fund for Coal and Steel, 2008) and SYNPEX (Butz et al, 2007) research projects, represents a cornerstone in European practice. The report integrates theoretical background, experimental evidence, and practical verification procedures, covering pedestrian load modelling in both time and frequency domains, dynamic characterization of footbridges (natural frequencies, mode shapes, damping), and comfort classes defined through recommended acceleration thresholds.

A core part of the document is dedicated to comfort criteria and acceleration limits. Here comfort classes associated with recommended acceleration thresholds are introduced. These limits are linked to intended usage scenarios (e.g., low-density pedestrian traffic versus crowded conditions), thereby establishing a performance-based framework.

In Chapter 5 of the EUR 23984 EN, the experimental evaluation of pedestrian-induced vibrations is presented as a key component of serviceability verification for lightweight footbridges. The chapter outlines procedures for identifying modal parameters through ambient and forced vibration tests, followed by controlled pedestrian load tests in which individuals or groups walk at frequencies close to resonance. Acceleration time histories are measured at critical locations, processed to obtain peak or Root Mean Square (RMS) values, and compared with the recommended comfort thresholds defined in the technical report. Experimental testing is thus framed as a tool for model validation, damping calibration, and final acceptance verification, particularly when analytical predictions are affected by significant uncertainties. A workflow highlighting the procedure to experimentally test such type of structures is reported in Figure 1.

Overall, the structure of the document reflects its dual nature: it is both a scientific synthesis of research findings and a practical design manual supporting the European normative framework for footbridge serviceability. To this day, the EUR 23984 EN remains the most widely adopted technical reference for the dynamic design and testing of pedestrian bridges in Europe.

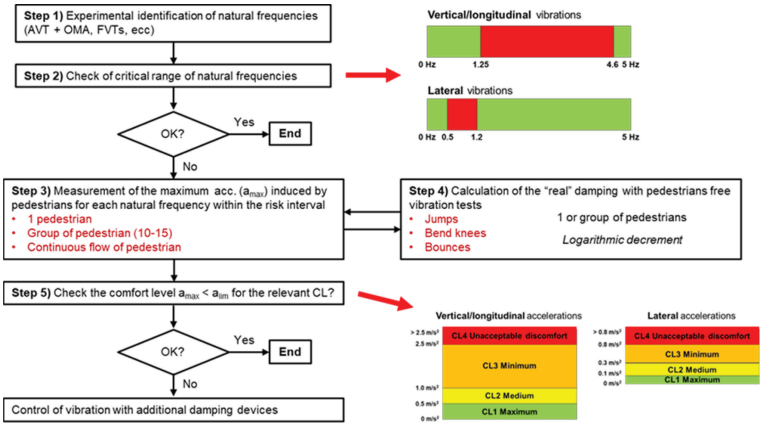


Figure 1. Flowchart for the experimental serviceability assessment of footbridges following EUR 23984 EN technical report prescriptions.

3 DESCRIPTION OF CASE STUDY

The examined case study is a newly constructed pedestrian bridge over the Cesano River in Central Italy (Figure 2). The bridge has 3 spans of 55, 86, and 55 m each, for a total length of about 200 m. The deck accommodates a 5.00-meter-wide pedestrian and cyclist path.

The central span features an inclined arch aligned on one side of the deck (the upstream side) that is continuous with the two box-girders supporting the side spans, located on the same side. The deck has a hybrid cross-section, combining a partially box-shaped and partially open design: the box section has a trapezoidal shape, while on the opposite side, a tubular element runs along the length of the bridge, connected to the box section by solid-web transverse members (Figure 2). In the central span, the deck is supported by the arch through stays composed by steel profiles; in the side spans, the deck is supported in an eccentric position by a tubular structure that is continuous with the arch, assisted by a secondary, smaller tubular beam on the opposite side. The arch suspension system comprises 19 stays made of I-shaped steel profiles welded directly to the deck and the arch. Both the central and side spans are supported by reinforced concrete piers, which have rectangular cross-section with variable width. As for the support configuration, the superstructure is connected to the piers through fixed devices, while unidirectional bearings are used at the abutments allowing longitudinal thermal distortions.



Figure 2. Footbridge case study: (a) cross-section deck blueprint; (b) picture showing the overview of the complete structure.

4 EXPERIMENTAL CAMPAIGN

The experimental campaign was extensive and carried out over several days, aiming to thoroughly characterize the dynamic behavior of the footbridge. It included two main tasks: Ambient Vibration Tests (AVTs), conducted to identify the structure's natural frequencies, mode shapes, and damping ratios under minimal external excitation (ambient noise), and Human-Induced Vibration Tests, designed to assess the bridge's response to controlled pedestrian loads and verify compliance with comfort criteria. This comprehensive approach allowed both the validation of the design numerical model and a direct evaluation of serviceability under realistic operational conditions.

4.1 *Ambient vibration tests*

A comprehensive dynamic characterization of the bridge was performed to determine its modal properties in terms of resonant frequencies, damping ratios, and mode shapes. This initial characterization is essential to detect modes falling into critical frequency ranges. High-sensitivity, low-noise wired accelerometers were used to measure bridge vibrations induced by ambient excitation. Overall, 70 1-axial measurement points were adopted in order to have a refined spatial resolution of the mode shapes; each cross-section was instrumented with three accelerometers, two measuring in the vertical direction (bending and torsional modes) and one in the transverse direction. In addition, a sensor measuring in the longitudinal direction was added at one cross-section. The layout of sensors was designed to capture the flexural, transverse, longitudinal, and torsional dynamics of the entire bridge deck. Measurements were carried out using six distinct non-simultaneous

configurations and using 4 reference (fixed) sensors. Dynamic identification of modal parameters was performed by using the well-known Subspace Stochastic Identification - Principal Component (SSI-PC) technique. To merge modal displacements obtained from each measurement configuration, the Post Separate Estimation Re-scaling (PoSER) method was employed (Brincker et al, 2014). This involves performing modal identification separately for each configuration, followed by a posteriori scaling of the modal shapes. The identified vibration modes of the footbridge in the 0-5 Hz frequency range are reported in Table 1, together with a description of the mode shapes. The modal shapes are not reported herein due to the maximum length constraints of the manuscript.

Table 1. Modal parameters of the footbridge identified from AVTs.

Mode	Frequency [Hz]	Damping ratio [%]	Mode shape description
1	1.30	1.83	Bending with 4 half waves
2	1.38	0.29	1st Torsional of the arch span
3	1.64	1.28	Bending with 5 half waves
4	1.94	0.13	Bending with 6 half waves
5	2.30	0.23	1st Bending + Torsional of the arch span
6	2.89	0.33	2nd Torsional of arch span + bending of approaching spans
7	3.15	0.32	Bending with 7 half waves
8	4.07	0.24	Torsional + bending of arch span + bending approaching spans
9	4.35	0.38	Bending with 8 half waves
10	4.94	0.34	Bending with 7 half waves (counterphase arch span and approaching spans)

4.2 *Human induced vibration tests*

Following the EUR 23984 EN prescriptions, if natural frequencies fall within the critical frequency ranges, pedestrian-induced vibration tests must be performed to assess user comfort.

In the present case study, the first 9 modes fall within the critical frequency interval relevant to vertical and torsional modes; therefore, pedestrian tests involving walking and running were conducted to excite these frequencies. The adopted testing procedure (walking or running) depends on the target frequency to be excited — lower frequencies being typically excited by walking and higher frequencies by running — and the corresponding test configurations are reported in the Table 2. The investigation was limited to the 6th mode, as excitation above 3 Hz proved impractical due to synchronization and human physical effort limitations, despite the higher critical frequency range. The technical report prescribes different test configurations involving a single pedestrian, a small group of pedestrians (15 in this case study), and a continuous pedestrian flow. In the present work, intermediate group sizes were included to assess how pedestrian number affects the structural response and to inform a more appropriate choice for testing, beyond fixed deterministic values provided by the report. For this purpose, additional configurations involving groups of 3, 6, and 9 pedestrians were also considered for walking and running, while 8, 9, and 10 pedestrians for jumping tests. The continuous flow configuration was not tested due to limited participants and its low relevance to this low-traffic case study. The load ratio for each pedestrian configuration (pedestrian weight to bridge weight, estimated from the design model) is reported to indicate the ratio between the excitation mass and the structural mass. The walking tests for the 2nd mode were excluded, as it could not be effectively excited—likely due to its predominant arch motion and the difficulty of maintaining the required unnatural walking frequency.

The identified modes are predominantly bending or torsional, with minor transverse components; consequently, the frequency risk intervals for transverse modes were not investigated.

In parallel, additional tests were conducted to estimate the actual structural damping by having pedestrians perform jumps, knee bending, and bouncing at locations corresponding to the maximum modal displacement and at the target frequency of the investigated mode. In this case, the 2nd mode was excited due to the fixed excitation setup, which facilitated its activation. A summary of such types of tests is reported in Table 3.

Table 2. Summary of the pedestrian load tests performed to assess comfort criteria (walking/running).

Test	Freq. [Hz]	Activity	N. People	Load ratio [%]	Duration [s]	Speed [m/s]
TA 1	1.30 Mode 1	Synchronized walking from one end to the other	1	0.01	280	0.70
TA 2			3	0.04		
TA 3						
TA 4			6	0.08		
TA 5						
TA 6			9	0.12		
TA 7						
TA 8						
TA 9			15	0.19		
TA 10						
TA 11	1.64 Mode 3	Synchronized walking from one end to the other	1	0.01	250	0.78
TA 12						
TA 13			3	0.04		
TA 14						
TA 15						
TA 16			6	0.08		
TA 17						
TA 18						
TA 19			9	0.12		
TA 20						
TA 21			15	0.19		
TA 22	1.94 Mode 4	Synchronized walking from one end to the other	1	0.01	180	1.08
TA 23						
TA 24			3	0.04		
TA 25						
TA 26						
TA 27			6	0.08		
TA 28						
TA 29						
TA 30			9	0.12		
TA 31			15	0.19		
TA 32	2.30 Mode 5	Synchronized running from one end to the other	1	0.01	120	1.63
TA 33						
TA 34			3	0.04		
TA 35						
TA 36						
TA 37			6	0.08		
TA 38						
TA 39						
TA 40			9	0.12		
TA 41			15	0.19		
TA 42	2.89 Mode 6	Synchronized running from one end to the other	1	0.01	100	1.95
TA 43						
TA 44			3	0.04		
TA 45						
TA 46			6	0.08		
TA 47						
TA 48						
TA 49			9	0.12		
TA 50			15	0.19		

All tests were conducted using a single measurement configuration consisting of accelerometers (the same type used for AVTs), albeit in a reduced number. For the bending and torsional dynamics, 7 measurement sections were distributed along the deck at locations

Table 3. Summary of the pedestrian load tests performed to investigate damping properties (jumping tests).

Test	Freq. [Hz]	Activity	N. People	Load ratio [%]
TD 1	1.30 (Mode 1)	Synchronized jumping at mid-length of the approaching span	8	0.10
TD 2			9	0.12
TD 3			10	0.13
TD 4	1.38 (Mode 2)	Synchronized jumping at the mid-length of the central span (eccentrically, downstream)	8	0.10
TD 5				
TD 6			9	0.12
TD 7	1.64 (Mode 3)	Synchronized jumping at mid-length of the central span		
TD 8			8	0.10
TD 9				
TD 10			9	0.12
TD 11			10	0.13
TD 12	1.94 (Mode 4)	Synchronized jumping at mid-length of the approaching span		
TD 13			8	0.10
TD 14				
TD 15			9	0.12
TD 16	2.30 (Mode 5)	Synchronized jumping at mid-length of the central span		
TD 17			8	0.10
TD 18				
TD 19			9	0.12
TD 20	2.89 (Mode 6)	Synchronized jumping at a quarter of the central span		
TD 21			8	0.10

previously tested during the AVTs, with two sensors per section: one on the upstream side (B) and one on the downstream side (A), following the layout reported in the Figure 3 schematics.

The results obtained with 3, 6, and 9 pedestrians walking and running were considered, as the single-pedestrian configuration was deemed not representative for this case study and the 15-pedestrian configuration was based on a limited number of tests. The selected configurations provided the most reliable and meaningful results. In Figure 3, the average of the peak accelerations measured at each sensor location (averaged over tests with the same number of pedestrians) are reported for all performed tests and for the same excited mode. These values

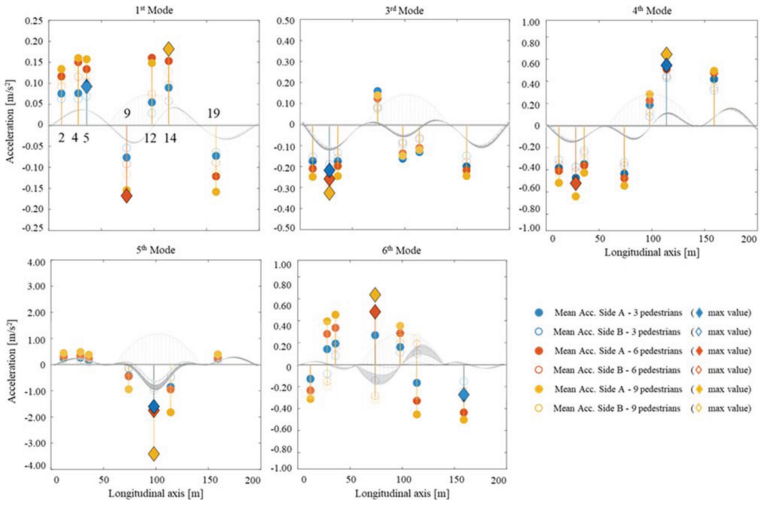


Figure 3. Mean accelerations along the footbridge for each load configuration and vibration mode.

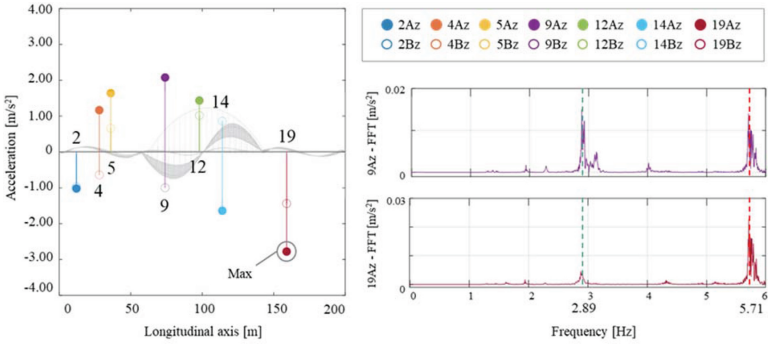


Figure 4. Effects associated with the second harmonic of human walking excitation.

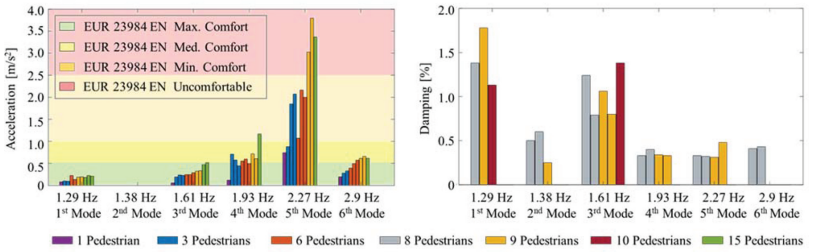


Figure 5. Human induced vibration test results: (a) maximum accelerations and (b) estimated damping.

are superimposed on the longitudinal modal deformation profile of the corresponding mode, highlighting the average peak responses. As expected, the highest acceleration values occur at the modal antinodes and nodes of mode shape, confirming the recommendations of the technical report, which prescribes measurements at locations corresponding to the maximum modal amplitude. Only for the 6th mode is it possible to observe a maximum measured acceleration at a point that is nearly a node of the modal shape. This can be explained by the fact that, at this frequency, the bridge mode with approximately twice the frequency (5.71 Hz) is excited through the second harmonic of the excitation (Figure 4).

Finally, Figure 5 shows the maximum absolute accelerations measured during the various walking and running tests for the different modes. It can be observed that the highest accelerations were recorded for the 5th mode, with an increasing trend from the 3rd to the 5th mode. Moreover, tests involving a larger number of participants generally exhibit higher acceleration amplitudes. The damping ratios for all six modes are also reported, with values ranging approximately from 0.5% to 1.7%.

5 CONCLUSIONS

This study demonstrated the effectiveness of an experimental-based approach for assessing the serviceability performance of modern pedestrian bridges. The combined use of ambient and human-induced vibration testing enabled reliable dynamic characterization and comfort verification, confirming the applicability of the framework proposed in EUR 23984 EN for practical design and assessment. The procedures were applied with reference to a case study (steel arch footbridge). The main findings about human induced vibration tests can be summarized as follows:

- Although the critical frequency range specified in the EUR 23984 EN extends up to 4.6 Hz — which would require excitation and testing up to the 9th mode for the case study— the investigation was limited to the 6th mode, since exciting frequencies above 3 Hz with pedestrians becomes increasingly difficult, both in terms of synchronization control and physical effort.
- The extended testing configurations, including intermediate pedestrian group sizes (3, 6, 8, 9, and 10), enabled a more detailed investigation of the influence of the number of pedestrians on the structural response, providing useful insights into the selection of appropriate and structure-specific testing procedures.
- The maximum acceleration values were recorded for the 5th mode across all pedestrian configurations, showing a significantly higher response compared to the other modes. Further investigations are required to better understand the causes of this behavior.

ACKNOWLEDGEMENTS

This work was developed within the scientific consultancy provided by the DICEA (Università Politecnica delle Marche) and the Marche Region (Italy) on the "*Analysis of the dynamic and vibration characteristics of the pedestrian bridges over the Cesano and Chienti rivers for the assessment of pedestrian comfort*", related to the two new footbridges under construction.

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