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Experimental and numerical serviceability assessment of a steel suspension footbridge

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A B S T R A C T

The paper summarizes the main results of the serviceability assessment of a steel suspension footbridge, performed through dynamic testing and numerical simulations.
The experimental part of the study involved both operational modal testing and measurement of the structural response under the crossing of different groups of pedestrians. The footbridge exhibited quite complex dynamic characteristics (i.e. two couples of closely spaced modes and five modes in the frequency range 1.9–3.0 Hz) and the maximum accelerations induced by pedestrians and joggers turned out to be in the range of discomfort. An accurate FE model, based on the design drawings, was then developed and a general procedure is proposed to tackle the crucial issue of assigning the design tension forces to the suspension elements.
Since the comparison between numerical and experimental results generally shows a good agreement, the model is adopted to perform a numerical assessment of vibration serviceability according to the European guideline HiVoSS. A minor shortcoming of HiVoSS and the unusual relevance of the 2nd harmonic of pedestrian-induced load are highlighted for the investigated footbridge.

1. Introduction

The design of recent footbridges is often inspired by aesthetics requirements for greater slenderness and results in longer spans, low ratio between permanent and live loads, and low damping [1]. This trend has been also favoured by the economic demand of efficiency, the increasing strength of materials and the relatively small service loads (as the structural design of footbridges is traditionally governed by the Ultimate Limit State, i.e. the load carrying capacity of the structural elements).

Consequently, the structural systems adopted on modern footbridges might exhibit dynamic behaviour marked by closely-spaced natural frequencies and/or frequencies very close to the values perceived by human beings [2–10], so that the design requires a greater care regarding vibration phenomena [11–12]. Well known examples of steel footbridges, that experienced serviceability problems associated to vibrations or required the design of tuned mass dampers to prevent this issue, include the Millennium bridge in London, UK [3], the Solférino bridge in Paris, France [4] and the Pedro e Inês footbridge in Coimbra, Portugal [7–8] (where the efficiency of the vibration control devices is also permanently assessed by a long-term dynamic monitoring system [13]).

Therefore, predicting the performance of footbridges to human-induced vibration has become a critical aspect of the structural design (see e.g. [1,7], [10–12]) so that different practical design methodologies have been developed, such as the French guideline Sétra [14] and the European guideline HiVoSS [15], that enable the designer to check the vibration serviceability of the footbridge for different pedestrian densities, based on a prediction of the maximum acceleration levels in vertical and lateral directions.

The paper presents the experimental and numerical vibration serviceability assessment of a slender steel suspension footbridge, overpassing the Serio River near Seriate, Italy. The investigated footbridge (Figs. 1–2) includes: (a) the deck, very slender and about 64.0 m long; (b) one main spatial system of suspension cables and hangers; (c) two steel frames supporting the suspension cables and the backstays.

Within the proof tests carried out before the bridge opening, dynamic tests were performed by the Laboratory of Vibration and Dynamic Monitoring of Structures (VibLab), Politecnico di Milano. Firstly, operational modal testing (with the excitation being mainly provided by micro-tremors and wind) was performed and 14 vibration modes were identified in the frequency range 0–10 Hz using different output-only techniques [16–17]: the frequency of the

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Fig. 1. Footbridge crossing the Serio river (Seriate, Italy): (a) General view; (b) Underside view of the deck.

fundamental mode was 1.03 Hz and five modes turned out to fall in the frequency range 1.9–3.0 Hz. Subsequently, groups of volunteers (up to 32 adults) simulated normal walking and running along the deck. The human-induced vibrations were measured and the results clearly indicated that, especially in the vertical direction, the maximum acceleration values violate the human comfort serviceability conditions, when compared to limit acceleration targets present in references and design codes [14–15].

The numerical investigation relies on the development of a FE model, based on the as-built design data and implemented within the ANSYS [18] framework. A non-linear static analysis was performed to take into account the pre-tension forces in the suspension system, since the pre-tension in cables is crucial in determining the modal properties correctly. In order to assign the target (design) tensile forces to the suspension elements through fictitious thermal loads, a numerical procedure has been developed. The procedure is quite general and can be applied without any restriction to structural systems similar to the one at study.

A linear modal analysis was performed at the end of the non-linear static analysis, and the correlation between experimental and numerical modal parameters turned out to be fully satisfactory. It is worth underlining that no tuning procedures (see e.g. [2,5,19]) were adopted in the FE model of the footbridge, as in the typical situation at the design stage. Subsequently, the assessment of serviceability conditions was performed according to the European guideline HiVoSS [15].

After a brief description (Section 2) of the investigated footbridge, the paper describes the experimental procedures (Section 3) and the FE model development (Section 4). Subsequently, the numerical serviceability assessment is presented (Section 5) and conclusions are drawn.

2. The STEEL suspension footbridge

The investigated steel footbridge (Figs. 1–2) crosses the Serio River in the neighborhood of the town of Seriate (about 50 km far from Milan, Italy) and connects two cycle routes in the "Serio Park".

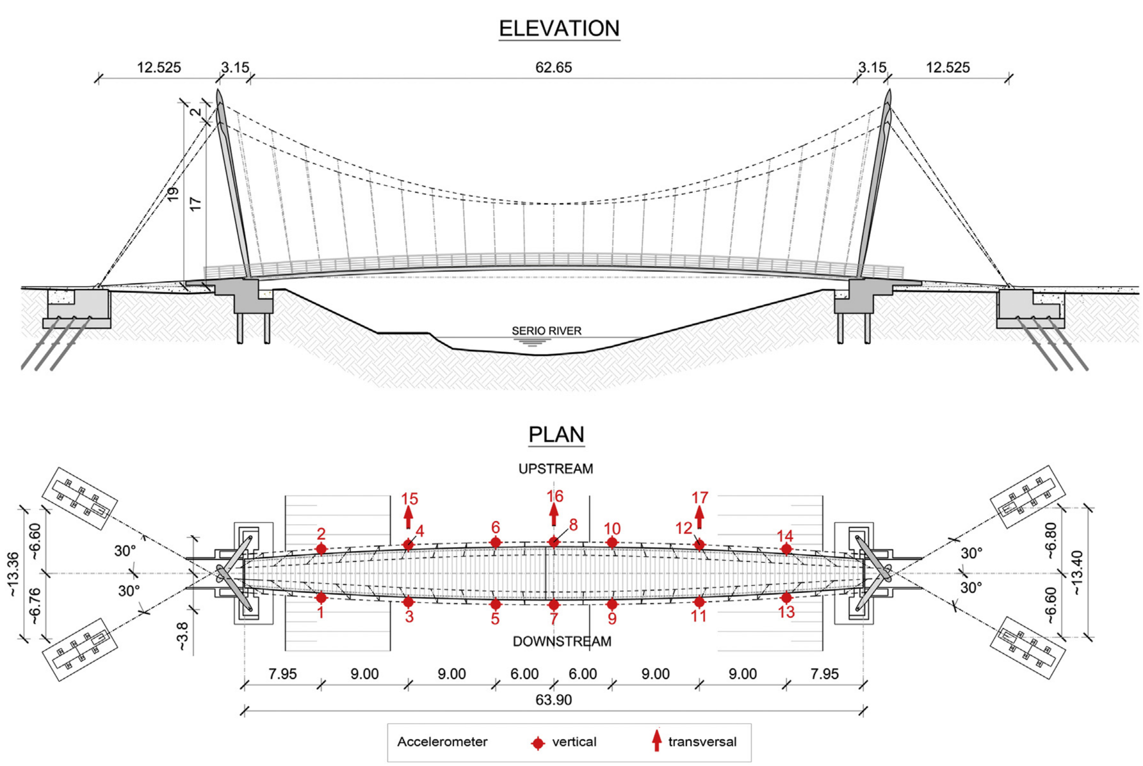

Fig. 2. Elevation and plan of the footbridge (dimensions in m). Accelerometer layout during the field tests.