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E. Torroja's bridge: Tailored experimental setup for SHM of a historical bridge with a reduced number of sensors

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ABSTRACT

This paper presents the design of an experimental setup with a reduced number of sensors for the structural health monitoring of the historical bridge of Posadas (Córdoba, Spain), designed by the eminent engineer Eduardo Torroja in 1957. The motivation of this study stems from the need for safeguarding this piece of cultural heritage. In particular, the singularity of this historical construction, a steel–concrete composite typology consisting of a concrete deck slab and inverted bowstring steel trusses, makes continuous in-service condition assessment essential for its maintenance. Nevertheless, the application of existing continuous monitoring systems to such large-scale structures entails considerable investments as well as complex signal processing algorithms. Whereby the optimization of the number of sensors and their location is of the utmost interest. In this line, this work presents the application of an Optimal Sensor Placement (OSP) methodology to tailor an experimental setup for a cost-efficient continuous monitoring of the E. Torroja's bridge. Due to the fact that most OSP approaches are model-based, it is essential to count on a sufficiently accurate numerical model. To this aim, an extensive vibration-based operational modal analysis is first conducted with a large number of accelerometers. Afterward, a three-dimensional finite element model of the E. Torroja's bridge is updated on the basis of the experimentally identified dynamic properties with a genetic optimization algorithm. Finally, an optimal sensor placement methodology is utilized to design an experimental setup with a limited number of sensors for long-term monitoring purposes. The results demonstrate that few sensors are needed to accurately assess the main resonant frequencies and mode shapes.

1. Introduction

Historical bridges constitute a key piece of cultural heritage, inasmuch as they bear witness to the course of history and hold an important social, cultural, and artistic value. There exists a great concern about their conservation and, therefore, the assessment of their health condition is absolutely crucial. Structural Health Monitoring (SHM) encompasses the application of Non-Destructive Testing (NDT) and damage detection in order to extend the life-cycle of structures. In particular, Operational Modal Analysis (OMA) is considered one of the most suitable methods to assess the condition of structures through their vibrational properties [1,2]. OMA is performed under conditions of service without the need for artificial excitations, feature that is essential to monitor historical structures where the use of stronger modal exciters, such as instrumented hammers or shakers, is often inadmissible. Nevertheless, OMA usually requires a large number of sensors to properly characterize the dynamic properties, fact that limits the scalability of long-term OMA-based SHM to large-scale structures. Given the high cost of such systems, it is essential to count on techniques that allow for tailoring experimental setups in such a way that only a reduced number of sensors can accurately identify the vibrational properties of structures.

Plenty of studies on Finite Element Modeling (FEM) and experimental investigation of historical bridges can be found in the literature. A noteworthy contribution was done by Chiara Pepi et al. [3] who studied the structural performance of an ancient bridge located in Todi (Umbria, Italy), through the integration of geometric survey procedures, dynamic testing and numerical modeling. Conde et al. [4] conducted ambient vibration tests on the Vilanova bridge, a masonry structure located in Galicia (Spain), and whose origin dates back to the 13–14th centuries. Those authors presented a multidisciplinary approach for the structural assessment of masonry arch bridges by using

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Fig. 1. E. Torroja's bridge in Posadas, Córdoba (Spain).

NDT techniques and three-dimensional numerical modeling. Gentile and Saisi [5] conducted the dynamic characterization of two historic structures, namely the Collegiata of San Vittore bell tower (Arcisate, Italy), and the San Michele bridge (Milan, Italy), an arch bridge built in 1889. In the latter case, those authors investigated the variation of the dynamic characteristics of the bridge under different traffic conditions. Finally, it is also worth noting the work done by Altunisik et al. [6] on a mid-nineteenth century bridge in Turkey, the Mikron arch. Those authors reported about the definition of a three-dimensional FEM of the bridge, an OMA campaign, and the updating of the FEM on the basis of the experimentally identified modal properties. Overall, despite great efforts have been put into the implementation of these techniques to the conservation of historical constructions, the elevated costs of these systems still remain an important obstacle.

This paper is aimed at presenting a methodology to tailor a cost-efficient experimental set-up with a reduced number of sensors for the long-term SHM of the E. Torroja's bridge. This bridge was constructed in 1951 over the Guadalquivir river by the renowned civil engineer Eduardo Torroja (Fig. 1). The cultural and historical importance of this bridge justifies the implementation of a long-term SHM system, so that preventive actions can be taken in order to prevent or mitigate structural aging and accidental damages. Following the previous discussions, the present methodology proposes the use of a limited number of sensors which are placed at optimal locations determined by means of an OSP algorithm. OSP algorithms, which are typically based on a numerical model of the structure, maximize the modal information with a reduced number of degrees of freedom and, therefore, a limited number of sensors. Hence, the suitability of the tailored experimental set-up is critically determined by the accuracy of the numerical model. A thorough ambient-vibration test with a large number of sensors is first conducted to assess the vibrational properties of the structure and to serve as a basis for the updating of the preliminary numerical model. Afterward, the discrepancies between the theoretical and experimental results are minimized by updating different variables of the numerical model through a genetic optimization algorithm. Once the numerical model is properly tuned, the optimal locations of a reduced set of sensors are determined by an OSP algorithm. The results demonstrate that few sensors are needed to accurately assess the main resonant frequencies and mode shapes.

The remainder of this paper is organized as follows. Section 2 concisely describes the historical evolution of the bridge and its geometric configuration. Section 3 introduces the preliminary FE model of the bridge. Section 4 presents the dynamic characterization of the bridge by means of an experimental OMA campaign. Section 5 details the updating process of the preliminary FE model. Section 6 overviews the theoretical formulation of the utilized OSP technique and reports the proposed optimal set-up for a long-term SHM of the E. Torroja's bridge. Finally, Section 7 draws the main conclusions of this study.

2. E. Torroja's bridge: Construction and evolution

Eduardo Torroja Miret (1899–1961) is considered one of the major figures of Spanish civil engineering, with a fundamental contribution to the design of thin-shell concrete structures. In his book *"Razón y Ser de tipos estructurales"* [7], his oeuvre is conceived as a quest for structural truth, a concept through which E. Torroja advocates that beauty lies in rationality and not in artificial ornamentation. With this in mind, E. Torroja developed new ways of designing structures whereby aesthetics

(a) (b)

Fig. 2. Views of (a) Muga bridge, 1939 (Girona, Spain), and (b) Tordera bridge, 1939 (Barcelona, Spain).