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Rehabilitation assessment of a centenary steel bridge based on modal analysis

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ABSTRACT

Modal testing through ambient vibration holds unique advantages over other experimental techniques, including static load tests, for the measurement of global parameters that characterize the bridges' behaviour, among which are the fastness of execution, low cost, non-compulsory restriction of the traffic during the test, and the ability of simultaneous evaluation of different directions. Moreover, quantities that decisively influence the structural safety, such as damping for the fatigue resistance in old steel bridges, can only be measured through appropriate dynamic testing.

On the other hand, the use of this non-destructive testing technique to assess the changes in rehabilitated structures and to enable the evaluation of the actual effectiveness of different rehabilitation strategies emerge as extremely important, since the current knowledge in this field is short and therefore demands an improvement in order to achieve more cost-effective designs without lowering the required safety levels.

This paper presents the ambient vibration tests conducted on a centenary through-truss steel bridge before and after its rehabilitation, with the purpose of evaluating the changes in its dynamic properties as a result of the adopted strengthening strategy. The implemented testing program, experimental setup, data processing and modal identification technique are described. Field data validated numerical models for the analysis of the structural changes produced by the strengthening process are presented. Significant conclusions were drawn by comparing the experimental and numerical results between the pre and post-rehabilitation conditions, namely in what concerns the vibration level experienced by the structure, its stiffness variation and suitability of the adopted modelling methodology. Furthermore, an unexpected coupled behaviour of the simply supported spans that constitute the bridge, translated by a global vibration mode, could even be detected and validated.

1. Introduction

The recent emergence of rehabilitation, repair and upgrading projects on old steel bridges has been driven by the profitability of the economic potential inherent to the existing infrastructures but also targeted a better management of available funds for their maintenance and operation. It brought a renewed need for non-destructive testing and evaluation techniques either in objective decision-making, validation of numerical models or assessment of the implemented solutions. In this context, the paper reports a case study of a centenary steel bridge recently rehabilitated on which field dynamic testing was performed before and after the completion of the construction works.

Modal testing, besides the characterization of the vibration level, aims at determining the most relevant modal parameters of the structural system, i.e. natural frequencies, mode shapes and damping ratios [1], or in other words, deals with the performance of an experimental modal analysis. Modal testing presents several advantages over other experimental techniques, particularly in relation to static load tests, one of which is the ability to provide global mechanical characteristics of a structure-foundation-soil system by direct measurement [2,3], as is the case of the flexibility coefficients of a structure associated to a coordinate system with a fine spatial resolution.

The experimental modal analysis can be accomplished with three major testing procedures: ambient vibration, forced vibration and free vibration. This classification is based on two criteria, which are the excitation source that induces the vibration of the structure and the type of response to be measured and/or analyzed. Further details about the three alternatives can be found elsewhere

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[4], being the work presented in this paper focused in ambient vibration testing. For ambient vibration testing different sources may be used, such as wind, traffic, seismic activity, waves or tidal fluctuations [2,5]. Some advantages in its adoption are the little or no interference with the normal operation of the structure [6], its fastness, easiness and low cost [7], long-term nature of the excitation and frequency content suitable for long-span and flexible bridges [5]. On the other hand some inherent drawbacks are the variable nature of the excitation in terms of amplitude, direction, duration, as well as the difficulty in measuring it [5]. In order to extract the modal properties from the recorded data output-only identification techniques are used [8], both on the frequency and time domains, usually regarding the excitation as being stationary with a flat frequency spectrum around the bandwidth of interest [7,9].

The main reasons for conducting full-scale dynamic tests have been listed by Salawu and Williams [9]. Firstly, the vibration field tests supply information to experimental databases from which analytical methods adopted in the design of new similar structures can be improved or evaluated. Secondly, dynamic measurements can assist in the evaluation of the structure integrity after the occurrence of an extreme event, being also useful in determining the effectiveness of retrofit works. Thirdly, data provided by these tests are invaluable for the validation and upgrading of theoretical models of structures, ultimately leading to more economical designs by preserving suitable feasible safety levels. Fourthly, field dynamic tests can accurately quantify some structural parameters that play a decisive role in the safety evaluation, as is the case of dynamic amplification factors when an increase of live loading is envisaged. Fifthly, structural damage detection can be enabled if the dynamic response of a structure is followed up on a regular basis, for instance through a structural health monitoring system. Sixthly, vibration testing can be used to prove that the structure's performance is within the expectations. The uncertainty in the fatigue evaluation associated with the structural damping dependency can also be mitigated by reliable modal damping estimates mined through proper identification methods. At last but not least, results obtained by the dynamic tests supplement data collected through controlled static and quasi-static diagnostic loadings and are very useful to validate some of their findings.

Dynamic testing on steel bridges with the purpose of collecting field data to address one or more of the aforementioned challenges has been reported in scientific and technical literature over the years, and some representative examples are herein presented. In 1969 Marécos et al. [10] have described the dynamic measurements carried out on the Tagus River Suspension Bridge during its construction and after the completion of the structure. Aiming at developing a structural dynamics based integrity monitoring system for a long span bridge, Wang et al. [11] have established a baseline model validated by experimental modal data. Fu and DeWolf [12] have presented the results of a study performed to assess the behaviour of a bridge with partial restrained movements at the roller supports. Zhao and DeWolf [13] made an effort to detect the alterations in the dynamic properties of the same bridge induced by temperature. A combined field ambient vibration experiment and a computational modelling study were accomplished by Shama et al. [14] on a cantilever truss bridge. Another cantilever truss bridge has been subjected to an ambient vibration test by Catbas et al. [2]. Dynamic field tests were carried out by Conte et al. [15] on the Alfred Zampa Memorial Bridge, known as the New Carquinez Bridge, located in the San Francisco Bay.

This paper firstly presents the objectives to be accomplished by conducting the tests, as well as the adopted experimental procedures and data processing. Then, the 3D numerical models constructed for simulating the pre and post-rehabilitation behaviours of the structure are also described. Finally, the correlation of the experimental data and the validation of the models led to significant conclusions concerning the changes produced in the structure performance and the viability of using modal information in their detection.

2. Objectives and scope

The Pinhão Bridge was commissioned in 1907 and since then it has been in continuous operation, still representing a vital link in the road infrastructure that serves the Douro vineyard region where the Porto wine is produced (see Fig. 1). An in-depth rehabilitation of the bridge was undertaken following a viability study pushed forward by the tragic collapse in 2001 of an older bridge that crossed the same river [16].

During the conducted surveys the most relevant problems were the widespread corrosion of steel due to lack of proper maintenance and the excessive vibration of some elements. Additionally, the safety level of the structure to carry the current loads and the evaluation of the need of a strengthening scheme to meet the contemporary standards were issues of concern. In this context, a first dynamic test was mandatory to support the rehabilitation project by enabling the bridge condition assessment and by supplying in situ data for the validation of the numerical model to be used in the evaluation of alternative strengthening strategies.

After the completion of the construction works, a second field test sought to determine the changes introduced in the structure's dynamic behaviour. It was also targeted the appraisal of the effectiveness of the implemented strengthening in terms of stiffness variation, not only associated with vertical displacements but also with transverse and torsional motion of the deck. Furthermore, the update of the model would enable its use in the simulation of the structure response under dynamic loadings in the new service stage, and consequently would turn possible its integration into a health monitoring system to detect alterations in the bridge behaviour over the time.

3. Pinhão Bridge

3.1. Description

The superstructure is constituted by three simple through truss spans of about 68.60 m between supports and a skewed deck plate girder span measuring no more than 10 m in length (see Fig. 2). The main girders of the longer spans have a semi-parabolic arch shape at the upper level, varying its height from 2.67 m at the supports to 8.86 m at the centre of the span. Each of the main spans comprises 16 panels, 4.20 m long at the ends and the remaining with a length of 4.30 m. Before the rehabilitation the bridge deck was formed by an orthotropic concrete-steel composite slab lying on a steel grid of stringers and crossbeams, serving two 2.30 m wide roadway lanes. After the rehabilitation the deck is accomplished by a 0.17 m thick concrete slab resting on an orthotropic steel grid, materialized by 5 stringers 0.67 m high and 17 crossbeams with a minimum height of 0.89 m. It carries a single roadway lane and two side walkways, 4.60 m and 0.62 m wide, respectively. The girders were originally supported by pin bearings in the north side and roller bearings in the south side, which were replaced by pot and disk bearings, respectively. Therefore, for both conditions (pre and post) the longitudinal displacements were blocked in one support line and allowed in the other (simply supported spans).

The original elements of the bridge are built-up members fabricated by assembling various plates and angles through riveted connections. The girders chords are U-type sections whereas the stringers and crossbeams are I-shaped. Pairs of double angles