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Structural assessment of masonry arch bridges by combination of non-destructive testing techniques and three-dimensional numerical modelling: Application to Vilanova bridge

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ABSTRACT

In this work a multidisciplinary approach for the structural assessment of masonry arch bridges is presented. The Vilanova Bridge, located in Galicia, northwest of Spain, is considered for the implementation of the methodology. A comprehensive field survey fully based on non-destructive testing techniques, which integrates laser scanning, ground penetration radar, sonic tests and ambient vibration testing, is proposed. It provides all the necessary geometric data to build an accurate and detailed three-dimensional finite element model. The calibration of the model is then carried out through the coupling with an optimization algorithm, which minimizes the discrepancies with respect to the experimentally obtained modal properties. The structural analysis of the bridge is addressed in the last stage. A sensitivity analysis involving different loading scenarios and the plausible variation of the masonry and soil material properties is performed. The results demonstrate the significant influence of tensile non-linear properties of masonry, but also the key role played by fill materials on the arch bridge performance. Lastly, the advantages of adopting a three-dimensional modelling approach are also pointed out, since the apparition of critical transverse effects in the response of the structure is successfully captured by the developed numerical model.

1. Introduction

Nowadays a great number of masonry arch bridges can still be found in the northwest of Spain and Portugal [1]. Many of these constructions date to the Roman and Mediaeval periods, and without any doubt represent a very important part of our built cultural heritage. Furthermore, a large proportion of them still play an important role within the railway and roadway networks. This scenario is easily generalizable to many other countries in Europe [2], and highlights the importance of assessing their actual structural performance in order to guarantee the required safety level as well as the preservation of their historical value.

However, modelling and assessing the performance of these ancient structures is a quite challenging exercise. Masonry arch bridges are complex three-dimensional systems whose structural behavior is greatly influenced by the interaction between its different components [3]. When developing numerical models for assessment purposes, a detailed information about the structural system is crucial for an accurate estimation, but this information is not readily obtainable due to the large uncertainties associated to this kind of constructions. The lack of geometrical and material data are the main drawbacks, among others.

Concerning its geometry, masonry arch bridges are usually materialized in complex and irregular shapes. In most situations, drawings about the original design either does not exist or, even if they exist, might not actually represent the final construction aspect due to damage and permanent deformations that might have happened during its service life [4]. Furthermore, the inner morphology of the bridge such as information about the spandrel walls and fill material, which plays a key role in the overall stiffness and ultimate strength of the bridge [5], is very difficult to assess.

As for mechanical properties, which are essential for a reliable definition of appropriate constitutive laws within numerical models, they are hardly measurable in historic arch structures [6]. Large

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variability due to the use of natural materials, the effect of past interventions, mechanical degradation processes due to environmental effects and past loading events are, among others, the causes of this difficult characterization. Lastly, and as long as possible, all of these data should be acquired preferably using non-destructive testing methods, since the non-intrusion is one of the main requirements in any type of testing or intervention procedure over the architectural heritage [7].

In this paper a multidisciplinary approach fully based on non-destructive testing techniques, and aimed to solve most of the difficulties listed above, is proposed and applied to a real case study, the Vilanova masonry arch bridge located in the village of Allariz, Spain.

For the geometric characterization both a detailed laser scanning and ground penetrating radar survey were conducted. Through their use, precise information about the external geometry of the bridge (including permanent deformations) as well as an estimation of the inner morphology (presence of backing, distribution of fill material and thickness of the spandrel walls) were achieved. A dynamic identification campaign based on the operational modal analysis was also carried out, which allowed to characterize the dynamic behavior of the bridge, namely their natural frequencies, mode shapes and damping coefficients. Finally, an estimation of the elastic modulus of masonry was obtained through indirect sonic testing.

The overall information was collected and later used for developing a three-dimensional non-linear finite element model. Masonry was treated in the context of the macro-modelling strategy, and it was modelled adopting a total strain rotating crack model that accounts for the possibility of development of cracks in tension and crushing in compression. Fill materials were modelled according to the classical Mohr-Coulomb yield criterion. The finite element model was calibrated resorting to an optimization procedure and on the basis of the experimental modal properties. Posteriorly, a comprehensive set of analysis were conducted to evaluate the structural performance of the bridge, with particular emphasis on the maximum load carrying capacity and collapse mechanisms developed. Three different loading scenarios were analyzed, namely a vertical loading case, the application of a live loading and a transversal pushover analysis. All loading scenarios were studied within the framework of a baseline analysis as well as a sensitivity analysis.

The present paper is organized as follows: Section 1 is the introduction where the motivation and the methodology is presented. Section 2 presents the Vilanova Bridge followed by Section 3 where all the non-destructive tests carried out on the bridge and their results are presented. From Section 4 to Section 5 the numerical studies are presented, starting by the description of the modelling strategies and calibration, till the sensitivity analysis, passing through the structural assessment. Finally, the conclusions are presented in Section 7.

2. The Vilanova bridge

The Vilanova Bridge is located in the municipality of Allariz in the northwest region of Galicia, Spain (see Fig. 1). Built to span the Arnoia river, it is believed that its origin dates back to the 13th-14th centuries, although it is certainly difficult to establish precisely the date due to the numerous processes of restauration that this bridge has experienced through time [8]. The last historical evidences come from 1600, when the two arches of the bridge were completely reconstructed after having suffered a partial collapse due to the great avenues of the river. The signs of these repair works are still present, and can be easily observed at an ashlar located in the parapet, at the road level, where the date of the restoration was registered. Indeed, as indicated in [8], this intervention established the definitive and current shape of the bridge.

At present, the bridge still conserves the use for it was originally conceived, giving support to the local road network of the village and indeed, registering a relatively high traffic due to the natural connection that it represents with the historical center of the village of Allariz; an important touristic place in the region of Galicia.

Following the classical pattern of medieval bridges, the Vilanova Bridge presents a slightly sloped profile in elevation with a nearly rectangular-straight shape in plan. The river is spanned with two arches that rest over a unique central pier. Attached to this pier, but not connected, both a cutwater at upstream as well as a kind of buttress at downstream can be found. The cutwater presents a triangular shape and ends approximately at the mid-rise of the arches. On the other side, the buttress reaches the roadway level and disposes a small sidetrack over the river.

The bridge presents a total length of approximately 63 m, with spans of 11.15 m and 10.94 m, viewing the bridge from downstream and from left to right (arches A1 and A2, hereafter). The corresponding rises are 5.32 m and 5.63 m, respectively. These dimensions result in a rise to span ratios (r/s) of 0.48 and 0.52, which enable to classify the arches as deep or semi-circular ones [1]. The arches are constituted with a quite regular arrangement of voussoirs with dry joints. The average arch thickness is about 0.70 m in both spans.

The width of the bridge, measured along the intrados of the arches in transversal direction, is equal to 5.00 m. The parapets are disposed at both sides of the bridge and present an average thickness of about 0.30 m. This renders a free width of the road surface of 4.40 m. The height of the parapets is rather significant, with values ranging from approximately 0.50 m up to 1.10 m.

3. Experimental campaign

3.1. Visual inspection

Prior to the in-situ non-destructive tests, a visual inspection of Vilanova Bridge was carried out with the aim of assessing its current state. The presence of damage, defects and past restauration works was examined and corresponding maps were elaborated.

It was observed that both arches and spandrel walls are constituted with (in general) ashlars of good quality and quite regular disposition. On the contrary, the abutments present a lower masonry quality, which might be the result of any of the repair works performed in the past (Fig. 2(a)). Similarly, the cutwater and the buttress attached to the central pier seem to have been added after its erection, since a connection to the main structure was not found (Fig. 2(b) and Fig. 2(e)). This judgment is ratified by the presence of several cracks in both constructive elements (Fig. 1(a) and (b)), which typically arise due to the inability of moving solidary with the main body of the bridge and the subsequent experienced differential displacements.

At the crown of both arches, but more severely on arch A2, deterioration of several stones was observed, probably caused by long-term exposition to environmental actions (Fig. 2(c) and (d)). Out-of-plane deformations together with the opening of the joints at the upstream spandrel wall (Fig. 2(f)), and in-plane deformations on arch A2 were also noticed during the survey (Fig. 2(d)), which might be related to the mechanical actions of past loading events. Finally, at the road level and over the original pathway of the bridge, a mixture of granitic slabs and weak concrete is currently disposed (Fig. 2(g)), which shows degradation in some areas due to the continuous crossing of cars and its poor consistency.