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Calibration of the numerical model of a stone masonry railway bridge based on experimentally identified modal parameters

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ABSTRACT

This paper focuses on the calibration of a numerical model of a stone masonry arch railway bridge using dynamic modal parameters estimated from an ambient vibration test. The developed 3D numerical model is based on the finite element method, featuring a realistic representation of the bridge structural components and materials. The calibration methodology relied on a genetic algorithm strategy which allowed estimating and updating numerical model parameters, particularly the elastic properties of materials. The validation of the updated bridge material properties' parameters was based on the results of material testing, on existing bridge design data and on observations resulting from *in situ* visual inspections.

1. Introduction

The need to identify exploitation limits and conditioning effects of regular traffic operation on stone masonry arch railway bridges led to the development of the StonArcRail research project.

This study comprised experimental and numerical research activities on the effects of rail traffic in the structural behaviour of bridges. It includes identifying the vibration effects caused by traffic action and the influence of its parameters (speed, type of train and track irregularities) on the dynamic response of the bridge, track and train subsystems, aiming at assessing the structure and the track safety as well as the passenger comfort.

The large number of existing and in operation masonry arch bridges on the rail network across Europe justifies the need to study this type of bridges. According to data reported in UIC [1], which several European have contributed to, about 60% of railway bridges are arched ones or culverts. In Portugal there are about 11 746 such cases which amount to 90% of the total existing railway bridges. The report also concludes that 80% of these Portuguese bridges have spans lower than 5 m and 70% are aged between 100 and 150 years. The European project "Sustainable Bridges" [2] which involved about 220 000 bridges in Europe, also concluded that about 41% are arched bridges, of which 35% are over 100 years old and 62% have small span.

Due to their age, the characterization of these bridges' conservation status is essential to allow assessing their structural behaviour and identifying the exploitation limits for future rail networks. For this purpose, experimental campaigns on these bridges should be made, mainly involving non-destructive testing, as presented by McCann and Forde [3] in a review of such type of experimental methods applicable to and used on concrete and masonry structures. Orbán and Gutermann [4], refer the UIC project results relative to methods of inspection and testing of railway bridges in arched masonry. Also, Olofsson et al. [2], present the results of the European project "Sustainable Bridges" describing methods to upgrade existing railway bridges in the European network. Roberts and Hughes [5] introduce a monitoring task through the use of accelerometers in the upper part of the superstructure. Brencich and Sabia [6,7] investigated masonry bridges both in service conditions and in various demolition stages, having developed an experimental program involving lab tests on material samples, as well as *in situ* activities, namely flat jack and sonic tests to characterize material properties and dynamic tests for the identification of modal shapes and frequencies. Arêde et al. [8] presented the results of a project which involved the implementation of an instrumentation system on a stone arch bridge during the construction (2004–2005) and its structural response monitoring

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during a load test. This project also included ambient vibration [9] and lab testing of the materials used in the bridge construction, namely classic tests for material strength characterization in stone specimens and mortar, triaxial tests on filling material samples and shear-compression test on samples representative of the joints [10]. Srinivas et al. [11] present experimental methodologies using flat jacks to assess the longitudinal internal forces on the bridge due to the increased weight of freight wagons.

The evaluation of structural operation and load capacity of masonry arch bridges always lacked appropriate numerical tools for their analyses. The first scientific approaches were based on the concepts of static and failure mechanisms experimentally observed, such as the works of Philippe de la Hire [12], Pippard [13] and Heyman [14]. Later on, thanks to the rapid evolution of computational technologies, new methodologies based on the finite element method (FEM) and the discrete elements methods (DEM) are developed and increasingly used, some of which are addressed in the following paragraphs.

Fanning et al. [15] used a 3D FEM model in which masonry, filling and pavement were discretized with continuous solid elements using commercial software ANSYS [16]. Frunzio et al. [17] studied a Roman arch bridge adopting a 3D FEM model developed also in ANSYS, wherein the nonlinear material behaviour was considered using the Drucker-Prager criterion for all materials. Cavicchi and Gambarotta [18] used a 2D FEM where the arch and backfill interaction was considered, the arches and piers were modelled with 1D elements with perfect elasto-plastic material behaviour, ductile in compression and with no tensile strength. The backfill was simulated by 2D triangular finite elements interconnected by interface elements ruled by a modified Mohr-Coulomb criterion with tension "cut-off". Arani and Zandi [19] also studied the conditions of a three span railway bridge, using a FEM based model with SOLID-2D plain strain elements. Detailed FEM modelling strategies were adopted by Costa et al. [20] for simulating the structural response of stone arch bridges under road traffic loading, resorting to the computer code CAST3M [21]. In the adopted models the bridges' masonry components are represented by FEM micro modelling strategies using solid elements, to define the individualized blocks, and zero thickness joint elements at their interfaces. The backfill is also modelled with solid elements connected to zero thickness joint elements in the interfaces between the infill and blocks of the masonry structure. Nonlinear constitutive models supported by experimental calibration were considered assuming a nonlinear Mohr-Coulomb friction model without dilatancy for the joint elements and using the Drucker-Prager model for the infill material. In the sequence of this work, DEM models were also used for comparative purposes to evaluate the load-carrying capacity of one of the case studies [22]. Anderson [23] developed a comprehensive 2D model of a railway concrete arch bridge and a 3D model of the three spans on the north side of the bridge, using the SOLVIA03 program [24]. For the structural modelling, the concrete was considered as a continuous nonlinear distributed cracking material and the backfill behaving the Drucker-Prager criterion. The 3D model involved the separation between the various constituent elements, namely arches, spandrel walls, backfill, piers and foundations. Domede et al. [25] studied an arched masonry railway bridge using a 3D FEM based damage model developed in CAST3M [21]. The masonry was simulated as a nonlinear homogenized solid material by means of a damage model in which the masonry behaviour in compression and tension is handled separately. The backfill was modelled with a nonlinear homogeneous material following the Drucker-Prager criterion.

Comparing the numerical results with the experimental ones, it is normal to have differences that should be minimized by optimizing the bridge numerical models [26]. Bayraktar et al. [27,28] present the numerical modelling and calibration of roadway stone masonry arch bridges for which people walking was adopted as the dynamic excitation during vibration testing; in this case the numerical model calibration only involved changes of the bridge boundary conditions.

In line with previous studies, this paper presents the outcome of a very recent work involving 3D FEM modelling of a stone masonry arch railway bridge over 100 years old. The model was generated in ANSYS [16], with refined individualization of the various bridge components in order to allow assigning different material parameters to each of them. These parameters were considered on the basis of an extensive experimental campaign involving *in situ* and laboratory tests. Aiming at assessing the bridge response, ambient vibration tests were performed from which natural frequencies, vibration modes and damping coefficients were obtained. A good correlation was obtained between the numerical and experimental results, for which an optimization procedure was adopted to improve the numerical model based on data obtained from the ambient vibration tests. The calibrated model was developed to allow performing analyses involving the bridge-train interaction, from which the response of both can be obtained.

2. Durrães railway bridge

2.1. Description

The Durrães bridge (Fig. 1) dates back to late 19th century and is located at km + 64.344 of the Minho line which constitutes the rail link between the Porto and Valença cities. The bridge presents a structural system made of granite masonry arches and is part of a single-track section in Iberian gauge currently allowing the circulation of freight and passenger trains with maximum speeds of 100 km/h and 120 km/h, respectively.

The bridge length is about 178 m, having a longitudinal rectilinear profile deck with 1.45% slope and 5.3 m width. It consists of 16 arches with approximately 9 m span, supported by 15 piers and two abutments. The spandrel walls, vertically supported on the outer faces of arches and piers, are formed by horizontal rows of carved stone. The maximum gap between the bridge ground level and the railroad is approximately 22 m. Fig. 2 shows the west view of Durrães Bridge obtained from a topographical survey made within the StonArcRail project activities.

The arches have 0.7 m uniform thickness and the piers' height, measured between the top face of the foundations' blocks and the arches' bases, range from 11 m to 12 m. The two piers located at about 1/3 and 2/3 of the total length of the bridge (between arches A5 and A6 and arches A11 and A12) have about twice the cross section area of the other piers. The shallow foundations are based on a rocky base at a variable depth between 5 m and 10 m.

The railway line consists of bi-block type sleepers and UIC60 rails, laid on a ballast layer approximately 0.50 m thick. The side guards are made of granite stone blocks.

2.2. Preliminary experimental campaign

An experimental campaign was carried out aiming at studying and evaluating the physical and mechanical parameters of the structural components of two stone masonry bridges, including the herein addressed Durrães bridge, described at length (including presentation of results) in another paper prepared by some of the present paper authors [29].

The characterization of the Durrães bridge materials consisted of *in situ* tests, namely, flat jack (FJ) and Ménard Pressuremeter (PMT) tests, and laboratory tests on samples of stone blocks and joints extracted from the bridge. Tests with Ground Penetrating Radar (GPR) were also carried out in order to study the geometric