Contributions for experimental and numerical characterization of the structural behaviour of stone arch bridges

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Abstract

This paper reports on methodologies for experimental and numerical characterization of the structural behaviour of stone arch bridges based on several studies of bridges existing in the Portuguese network. The main contributions are focused on results of technical inspections, experimental testing and numerical simulation. The objectives and achievements of the selected case studies are presented and discussed aiming for a general overview of the methodologies carried out to assess the bridge structural behaviour.

Keywords: Stone arch bridges, Experimental characterization, Numerical modelling, Vehicle-bridge interaction, Load-carrying capacity

1. Introduction

Stone arch bridges in Portugal represent a significant part of the bridge stock in the national road and rail infrastructures. According to the bridge inventory, about 33 % of the railway bridges under the administration of IP - Infraestruturas de Portugal are masonry arch bridges [1]. The representativeness of this bridge typology is an indicator of their importance but other aspects have to be considered. In fact, many of these bridges are more than 100 years old, which on the one hand endorses the need to evaluate the bridges' damage condition and, on the other hand, emphasises the need to increase knowledge about their structural behaviour that, in many cases, corresponds to several decades (or centuries) of evolution.

The structural system of stone arch bridges is constituted by arches, spandrels, piers and abutments usually made of regular stone masonry and infill materials of different nature placed above the arches and between the spandrels. For the most common loads, self-weight and traffic overload, the structural behaviour can be distinguished according to the two principal bridge directions and their main elements. In the bridge longitudinal direction, the structural behaviour is mainly determined by the arch response to provide strength and transmission of loads and by the arch interaction with other structural components. The formation of arch hinges by joint opening, with the development of arch hinges' failure mechanisms, is commonly associated with the load carrying capacity of this type of bridges. Both the spandrels and the infill placed above the arch extrados (when in good condition) have a determinant role, thanks to passive effect, in preventing the formation of arch hinges (joint opening in the arch extrados zones) and corresponding failure modes.

In the bridge transverse direction, the structural behaviour is determined by the transmission of horizontal pressures through the infill to the spandrels and arches. The most frequent damages found in this type of bridges arise from transverse effects, namely out of plan deformation and sliding of the spandrel walls and transversal joint opening of the arch joints in the longitudinal direction.

2. Case studies

Lagoncinha and Lázaro bridges (Figure 1) are two study cases of old masonry arch bridges made of granite stone in the north of Portugal, dating back to the Middle Age, and classified by the Portuguese heritage administration body. The objectives of the studies were focused on the assessment of the above mentioned bridges' structural condition and on the identification of the causes of damages found in both bridges, particularly related with cracking and deformation in the arches. The broad studies carried out in both bridges covered visual inspections, geometric surveys, material and structural experimental characterisation and numerical simulations of the bridges' behaviour under the road traffic loading and the bridge weight [2]. Another case, the Zameiro bridge, was also studied for which it was possible to test its infill material.

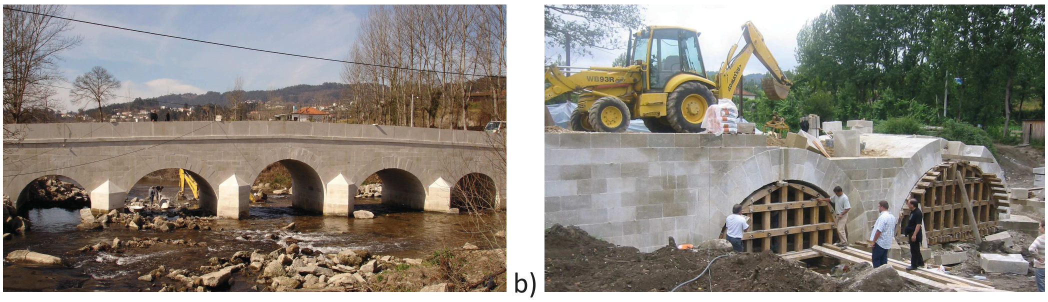
a)

b)


Figure 1. Case studies of old road bridges:
a) Lagoncinha and b) Lázaro

Another case study is the Vila Fria road bridge (Figure 2) that was built in 2005 using traditional construction techniques. The project framework comprised the objective of studying traditional construction techniques and characterising, numerically and experimentally, the structural behaviour of this type of bridges [3]. A large monitoring system was installed during the bridge construction [4] and detailed structural models were used to evaluate the structural response to bridge gravity loads and traffic loading [2].

Durrães, PK124 and Côa bridges are railway bridges in operation in the Portuguese railway infrastructure. Durrães and PK124 were built in the late 19th century during the construction of the Minho line (Porto-Valença) while Côa bridge was built in the 1940's to replace an existing metallic bridge. The studies were included in the framework of the StonArcRail R&D Project [5] focused on the numerical and experimental characterisation the bridge response under traffic loading with the objective of identifying limits of exploitation of this type of bridges.



a) b)

Figure 2. Vila Fria road bridge: a) general overview and b) construction phase

a) b) c)

Figure 3. Case studies of railway bridges: a) Durrães, b) PK124 and c) Côa

3. Experimental characterization

The experimental characterization comprised laboratory and in-situ testing to identify material parameters for numerical simulation structural models and to assess the current state of bridge components and constituent materials. The in-situ structural characterization of the global bridge behaviour was another essential component of the experimental campaign. The complementary use of lab and in-situ testing allowed merging results from lab sample tests with those drawn from in-situ material tests and global structure testing.

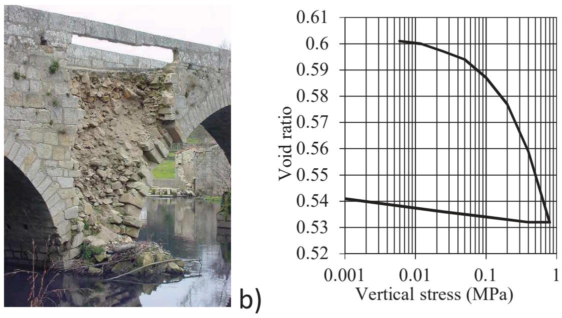
3.1 Lab material testing

Lab testing for material characterization using samples taken from the bridges was performed in both material components: masonry and infill. Standard tests for granite stone characterization were carried out in four bridge cases ([6], [7]), for which the estimated values of the elastic modulus and unit weight are summarised in Table 1.

The infill material of an old roadway Zameiro bridge case was characterized by lab oedometer testing of granular material taken from the bridge backfill exposed after partial collapse of the spandrel (see Figure 4). The obtained experimental values for the elastic modulus range from 7.7 to 15.2 MPa [6].

Table 1. Granite stone experimental parameters

Bridge	Elastic modulus [GPa]	Unit weight [kN/m^3]
Lagoncinha	22.5 - 58.2	26.2 - 26.7
Vila Fria	15.5 - 29.4	23.7 - 24.1
Durrães	20.0 - 23.5	25.9 - 26.5
PK124	6.8 - 10.9	25.2 – 25.7



a) b)

Figure 4. Zameiro bridge: a) view of the infill material and b) oedometer test plot

Standard triaxial tests were carried out with infill materials used in the Vila Fria bridge construction in order to evaluate the mechanical properties [6]. Two type of materials were taken: a simple granular material and a mix of granular material with a small percentage of cement. The deviatoric stress *versus* axial deformation plots are shown in Figure 5, while shear-strength parameters were evaluated in terms of the Mohr-Coulomb failure envelopes which provided the frictional angle and the cohesion of both materials: 41.6° and 13.1 kPa, respectively, for the simple granular material and 32.9° and 1054.7 kPa for the mixed material.

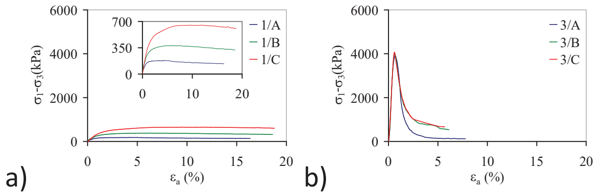


Figure 5. Triaxial test plots: a) granular material and b) mixture with 7% of cement

Shear and compression tests were carried out for samples of masonry interfaces in order to identify mechanical properties of stone-to-stone and stone-to-infill interfaces of the Vila Fria, Durrães and PK124 bridges. Table 2 provides a summary of experimental normal and shear estimates of interface stiffness of the referred bridges masonry, where all cases the stone-to-stone interfaces were filled with mortar [6].

Table 2. Masonry joints experimental proprieties

Bridge	**Normal stiffness [MPa/mm]**	**Shear stiffness [MPa/mm]**
Vila Fria	42 - 116	0.2 - 0.7
Durrães	1.6 - 6	0.63 - 2.58
PK124	0.5 – 2.5	0.07 - 0.63

The nonlinear parameters were also estimated in terms of stresses *versus* displacements plots for both joint normal and shear directions, as well as the Mohr-Coulomb failure envelope in the shear domain. Those results were essential to define the interfaces' material parameters used in the bridge discrete models (FE and DE) and to calibrate the continuous material parameters of bridge global FE models.

3.2 In-situ material testing

In-situ testing using flat-jacks on masonry elements and Mènard pressuremeter tests on infill materials (Figure 6) can provide valuable information for local characterisation of the material mechanical parameters. Both tests were part of the in-situ experimental campaigns of the Durrães and PK124 bridges [7] to characterise the elastic modulus of both bridge materials, for which the range of estimated values are summarised in Table 3.

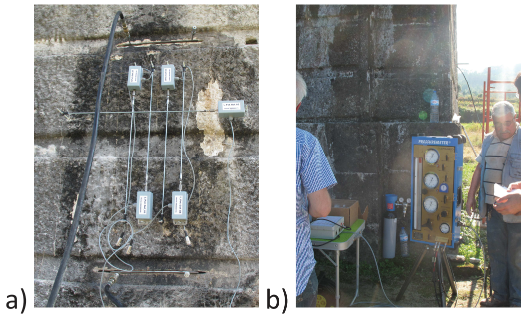


Figure 6. In-situ material testing: a) double flat-jack and b) pressuremeter tests

Table 3. In-situ elastic modulus

Bridge	**Masonry [MPa]**	**Infill [MPa]**
Durrães	7 - 23	190 - 680
PK124	0.9 - 1.3	130 - 370

These tests can be considered slightly-destructive techniques since the size of the devices introduced in the bridge components are small (comparatively to the size of the bridge elements cross sections), they can be easily removed and similar bridge materials can be reintegrated after the test.

3.3 In-situ testing for dynamic identification

Global dynamic identification tests of bridges were carried out in six of the above referred bridge cases, to obtain their natural vibration frequencies, mode shapes and damping coefficients. The bridge responses to ambient vibration were measured in terms of acceleration using two types of device sets, namely macro seismographs and uniaxial accelerometers, allowing to configure testing setups with simultaneous measurements in several locations of the bridge elements, particularly on the deck (Figure 7).

The dynamic identification was made by the EFDD (Enhanced Frequency Domain Decomposition) method implemented in the ARTeMIS software [8].

Table 4 shows the values of the identified frequencies associated with the first mode shape involving vibration components along the bridge transverse direction [2] and [5].

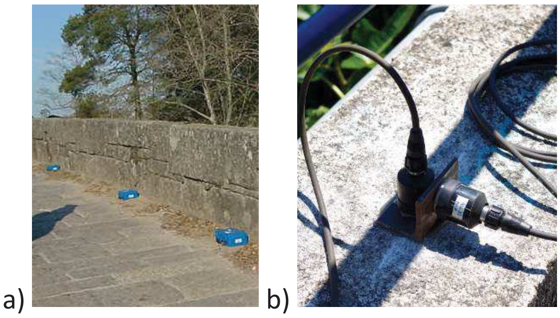


Figure 7. In-situ vibration testing: a) macro seismographs and b) uniaxial accelerometers

Table 4. Experimental fundamental frequencies

Bridge	Frequency [Hz]	Bridge	Frequency [Hz]
Vila Fria	6.0	Durrães	1.8
Lagoncinha	3.9	PK124	12.8
Lázaro	7.7	Côa	1.1

3.4 Monitoring the bridge response

Another component of some experimental campaigns was focused on monitoring the bridge response under traffic loading.

Load tests were performed in the Vila Fria bridge by considering several cases of static loading positions of real trucks on the deck (Figure 8a). The bridge was extensively instrumented during its construction allowing to monitor the bridge response in each testing setup. Flat pressure cells were placed on the arch ring and on the base of the backfill to estimate in-situ stresses; LPDSs (Linear Position Displacement Sensors) based on optical fibre Bragg gratings were used to measure relative displacements between arch blocks and opposite spandrel walls; level sensors (ultra-low differential electrical pressure sensors) and topographic survey were adopted to monitor global displacements of the bridge [4]. Figure 8b shows a plot of the arch crown vertical displacements monitored with level sensors, where the diamond marks (in red) refer to the sensor near the bridge axis and negative values refer to downwards displacements.

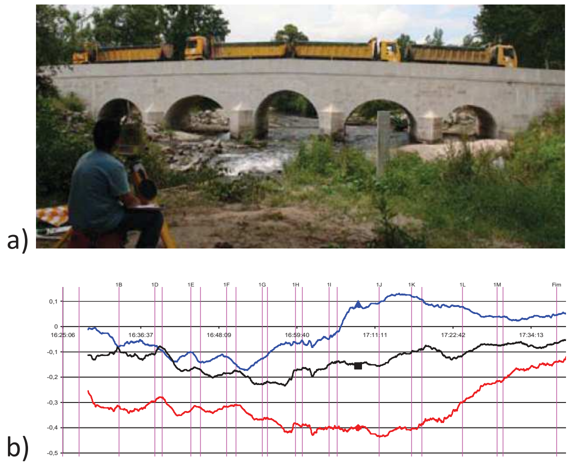


Figure 8. Vila Fria load testing: a) general view and b) vertical displacements of the arch crown

Load testing under dynamic conditions were also carried out in the Durrães, Côa and PK124 bridges by measuring the bridges' responses in terms of acceleration with the test setup used for dynamic identification of the bridges referred in the previous section [5]. The vertical acceleration recorded on each bridge deck due to freight trains presented peak values during locomotives passage, with values between 0.5 m/s^2 and 1.5 m/s^2. The records of accelerations associated with the passage of wagons present a regular pattern with peak values generally lower than 0.5 m/s^2. Figure 9 shows the vertical acceleration record due to the passage of a freight train at a point on the bridge deck. Overall, the acceleration levels recorded on the PK124 bridge are lower than those recorded on the other two bridges.

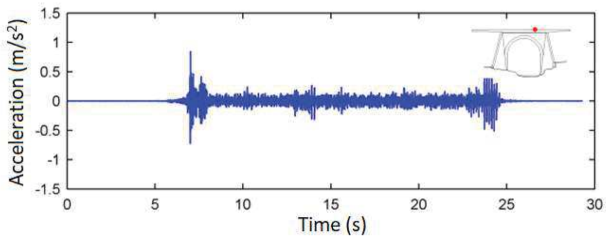


Figure 9. Vertical accelerations on PK124 bridge

In both cases the tests were simulated and the numerical results were compared with the corresponding experimental results thus allowing validating the bridges' structural models.

4. Numerical simulation

4.1 FE and DE modelling strategies

Concerning structural behaviour simulation, numerical models using finite elements (FE) and/or discrete elements (DE) were adopted to evaluate the dynamic effects of vehicle-bridge interaction as well as load factors of the vehicle loading.

FE global modelling with equivalent homogeneous materials and FE micro modelling strategies to simulate the masonry components were used to represent the bridge structural behaviour both in the elastic and plastic domains. Due to limitations of computational time consuming and available RAM, global modelling is more suitable for cases of large bridges, as the Durrães and Côa bridges. Particular attention has to be put on defining suitable homogenised material proprieties of each bridge component, for which model updating and validation procedures based on experimental data are essential [9] and [10]. Figure 10 shows, for example, the FE global model of Côa bridge where each bridge element is discretised using continuous materials. Similar FEM discretizations were made for the Durrães and PK124 bridges using the software packages ANSYS [11] and CAST3M [12].

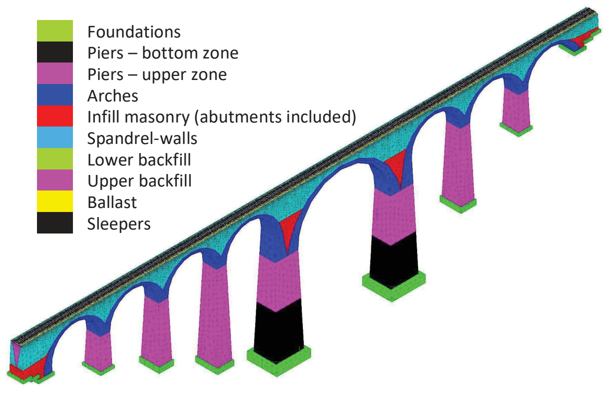


Figure 10. FE global model of Côa bridge

Micro modelling strategies allow representing the block-to-block assembly and its interfaces with the corresponding material proprieties for stone blocks and for stone-to-stone or stone-to-mortar joints. Both FE and DE methods can be used for detailed simulations of the linear and nonlinear masonry behaviour. Due to their high level modelling detail, these strategies require large computational time for thee analysis and therefore are more suitable for cases of small bridges. Examples of this are the FE discrete models used to simulate the structural behaviour of the Lagoncinha, Lázaro and Vila Fria road bridges [12] and the PK124 railway bridge [5] resorting to CAST3M software [12]. For the Lázaro and PK124 bridges, DE models were also defined using UDEC and 3DEC codes [14] and [15]. In both cases the infill material was modelled using continuous elements along with infill-to-masonry interface elements [16].

The definition of bridge discrete models was based on experimental data for geometric and material characterization, further supported on modal updating and calibration by comparing numerically obtained vibration frequencies and mode shapes with those experimentally identified [12]. Historical data and observations from visual inspections were also taken in account in all bridge cases.

4.2 Dynamic analysis

Dynamic analyses of the vehicle-bridge systems subjected to moving loads representing the traffic loading were made to evaluate the effects of interaction between vehicles and bridge structural components, resorting to iterative procedures to simulate the dynamic behaviour of the bridge and the vehicle separately [2] and [19]. The influence of the path/track irregularities in the vehicle-bridge dynamic response was also assessed by considering irregularity profiles measured on each bridge.

The assessment was performed in terms of the bridges' structural safety by considering the linear behaviour of railway bridge cases subjected to real train loads' simulations [5]. The results allowed to identify the influence of a range of train speeds on the bridges' dynamic response in terms of stresses, displacements and accelerations. Figure 11 shows as an example of the vertical response at the mid-span of the principal arch of Côa bridge in terms of displacements and accelerations [17], allowing also to assess the effects of real track irregularities.

The material nonlinear behaviour was considered in the analyses of the Lagoncinha, Lázaro and Vila Fria road bridges [2]. Figure 12 shows the influence lines of the mid-span vertical displacement of the principal arch of Lázaro bridge for a vehicle speed of 30km/h.

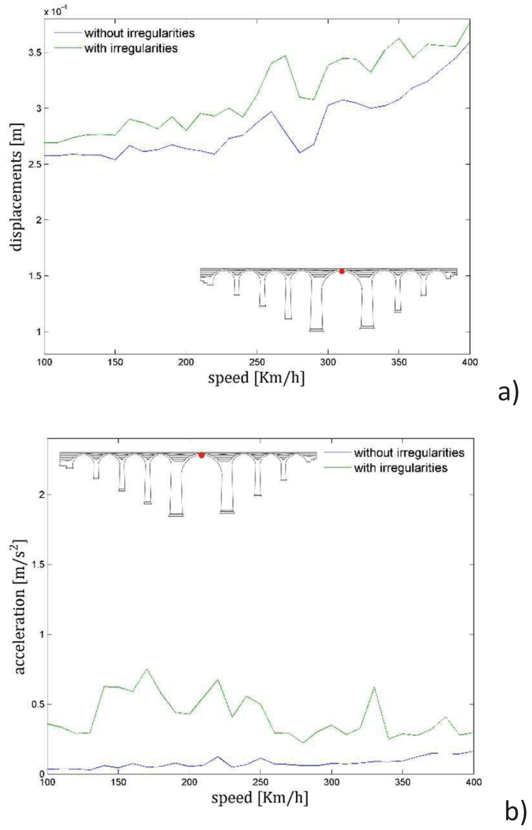


Figure 11. Côa bridge: a) vertical displacements and b) accelerations in the principal arch

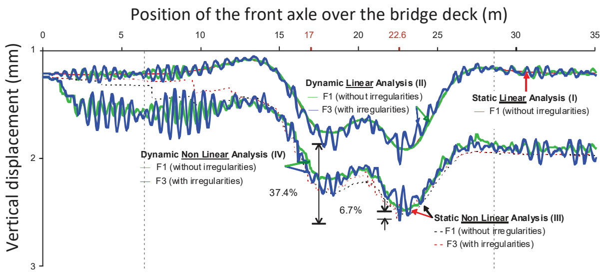


Figure 12. Lázaro bridge: Influence lines of the vertical displacement of the principal arch.

The study allowed concluding that the activation of the nonlinear behaviour has significant influence on the bridge effects and the dynamic effects are mainly due to the vehicle dynamic response.

The assessment of the passenger comfort was also carried out in the cases of railway bridge analyses, by considering real models of trains (calibrated also using modal identification) and computing the associated vertical accelerations for comparison with code standard prescribed limits.

4.3 Load carrying capacity

The nonlinear analyses using nonlinear detailed bridge models under incremental static loading allowed simulating the development of arch hinge mechanisms and identifying vehicle loadings associated with the load-carrying capacity of the bridge models. Lázaro and PK124 bridges were analysed by means of FE and DE discrete models referred in section 4.1 [16] and [17]. FE global modelling strategies were also adopted for the Côa bridge [18]. It was found that very high values are required for the load factor of the nominal vehicle loading to develop bridge collapse mechanisms. Figure 13 shows as a deformed shape example of the Lázaro bridge DE model due to dead load plus vehicle load with the maximum intensity level of a standard vehicle applied near the arch ¼ span, wherein it is possible to identify that four hinges are formed in the arch ring (A, B, C and D marks).

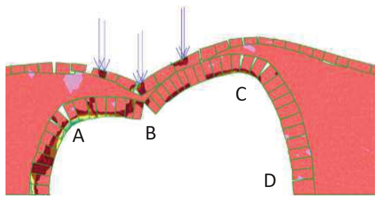


Figure 13. Deformed configuration of Lázaro bridge DE model

5. Conclusions

A general overview was provided concerning the use and real case application of experimental and numerical strategies for the assessment of stone masonry arch bridges. The presented cases have highlighted that different levels of detail can be adopted to accomplish several types of objectives subjacent to different structural analysis types. The feasibility and applicability of each modelling and analysis strategy were also discussed.

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