EXPERIMENTAL CHARACTERIZATION OF THE STRUCTURAL BEHAVIOUR OF STONE ARCH RAILWAY BRIDGES

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SUMMARY

This paper reports on a comprehensive experimental campaign performed on stone masonry railway bridges aiming to obtain a realistic characterization of the component and materials of the bridges as well as the bridge response under the railway traffic. The experimental campaign comprised in-situ testing carried out with Ménard Pressuremeter for the infill material and flat jack testing for the masonry components. In-situ testing also included dynamic tests to identify mode shapes and natural frequencies of the bridges, as well as DPSH penetrometer tests and GPR tests to complement information about bridge foundations and structural components' geometry. Laboratory tests were performed using masonry samples collected from the bridges, including material testing for granite stone characterization and interfaces between stone blocks characterized by performing shear and compression tests.

Keywords: *Masonry arch bridges; experimental assessment; Ménard pressuremeter, flat jack testing; DPSH; GPR; modal identification.*

1. INTRODUCTION

The study of the structural behaviour of masonry arch bridges has shown that material characterisation of structural components is a key step for a better understanding of this type of construction [1]. Due to the heterogeneity of materials (masonry and infill) and construction techniques used in this type of structures, conducting laboratory tests on samples taken from the bridges and in-situ tests for structural characterisation is an essential step for the numerical simulation of such structures using duly calibrated models [2].

The present paper presents some results obtained in testing campaigns in three railway bridges composed of granite masonry arches and includes in-situ tests for the geometric characterisation with experimental data obtained from GPR (Ground Penetrating Radar) and DPSH (Dynamic Probing Super Heavy) tests and for mechanical characterisation with flat-jack and pressuremeter tests as well as laboratory tests on samples of materials collected from the bridges. The flat-jack testing is a less intrusive option which provides information about in-situ stress and deformability characteristics of masonry, namely estimations of elastic modulus and the in-situ vertical stress. The Ménard pressuremeter tests (developed in 1954 by Louis Ménard in France), have a good application in soils and soft rocks or hard surfaces, and in this study are used for estimating the deformability parameters of the infill material. Dynamic tests were also performed including free vibration and forced vibration tests to evaluate the structural behaviour aiming for the identification of the modal characteristics of the bridges.

These studies were conducted under the scope of the *StonArcRail* project aimed at the experimental and numerical characterization of the structural behaviour of existing stone arch bridges in Portugal under rail traffic loading. The interest in this structural system relates to the fact that currently there are a considerable number of cases of stone masonry arch bridges in operation in the rail and road infrastructures and many of them with several years of age [1]. The study cases comprises a bridge with just one arch about 8 m span (Fig. 1a), which is a common masonry structure found in the Portuguese railway network, located at PK124 of the Minho line, near São Pedro da Torre (next to the North Portugal-Spain border, close to Valença), and it has a total length of 11.2 m, and a maximum height of about 11 m. Another case study is an overpass in Durrães, also at the Minho line, namely the Durrães bridge (Fig. 1b), with an extension over 178 m, 5.3 m wide and with a maximum gap of 22 m between the bridge deck and the ground. It consists of 16 arches and a span of 9 m supported by 15 piers and 2 abutments. Finally, the Côa bridge (Fig. 1c) in the Beira Alta Line towards the Vilar Formoso, near the Portugal-Spain border, with about 238 m total length and 4.8 m width. The bridge is formed by eight arches with spans ranging between 20 m and 38 m, which are supported onto seven piers and two abutments. The maximum height difference between the foundation and the pavement is approximately 56 m. In a companion paper [3] the numerical study is also presented in this conference.

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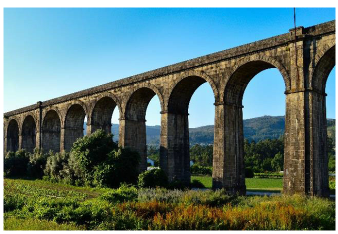
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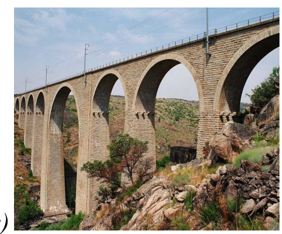

Fig. 1. *Case studies: a) PK124 bridge; b) Durrães bridge; c) Côa bridge.*

2. EXPERIMENTAL ASSESSMENT

The experimental component of the project comprised testing activity in-situ and in laboratory and the corresponding result analysis. Tests were made on the three case study bridges and on corresponding material samples extracted thereof (stone, infill and joint materials). One freight railway vehicle was also tested aiming for the identification of vehicle modal parameters.

The most extensive experimental campaign was performed on the bridge case study with one arch, PK124 bridge, to be complemented with detailed numerical modelling. The Durrães bridge, a larger one with several arches, was also object of a broad experimental campaign, though with less detail in the numerical modelling due to its dimension. Finally, for the Côa bridge, also with of several arches, the experimental characterization and numerical modelling was more restricted, focusing on modal identification and using simplified modelling which is more appropriate and feasible for large bridge cases. Based on this strategy and case studies' outputs, the objective was to obtain realistic data from in-situ and lab tests, feeding numerical models, both detailed and more simplified ones, all duly calibrated based on experimental measurements.

2.1. Geometric survey

The geometric characterization of the bridges was based on laser scanning survey and Ground Penetrating Radar (GPR) tests performed on two of the bridge cases, namely the Durrães and PK124 bridges, as well as visual inspections and details from the design drawings available for all bridge cases.

GPR tests were made in order to deeply understand the bridge geometry, including the facing stones' thickness in piers, abutments and spandrel walls, and study the properties of foundations. The geometry of the cross section of pier P8 of the Durrães bridge, which has a rectangular shape with 6.72x1.58 meters, has been simulated through a GPR simulation software, and synthetic radargrams have been generated, revealing to be consistent with the in-situ obtained radargrams. In addition, four penetrometer Dynamic Probing Super Heavy (DPSH) tests were performed at ground level of Durrães bridge at the same locations where GPR tests were done in order to correlate the results from both test types (Fig. 2a). GPR radargrams and DPSH evolution of the number of blows (N_{20}) against depth are shown in Fig. 2b [4]. The results of both GPR and DPSH tests shown good correlation allowing estimating the depth of the firm of the Durrães bridge [5] which is close to 10 m in location of tests 1-to-3 (corresponding to the zones of the arches 3, 6 and 8) and close to 4 m in the location of test 4 (corresponding to the zone of the arch 13).

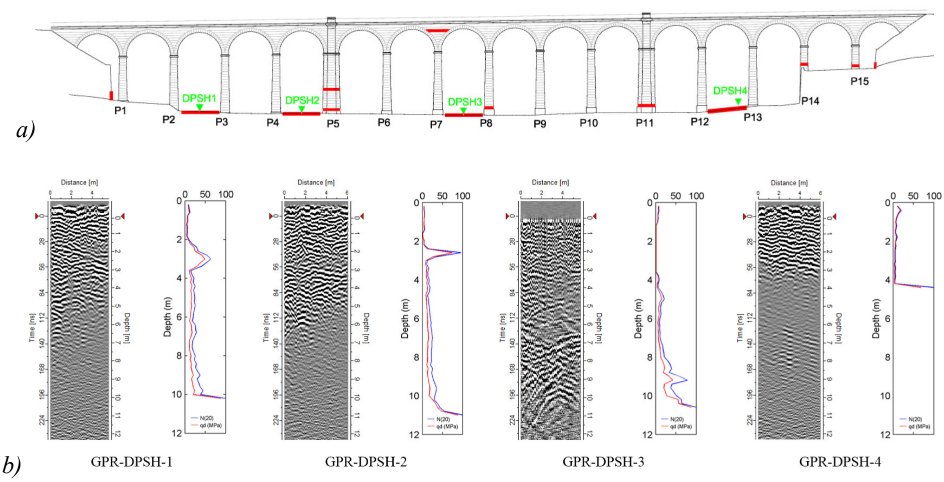

Fig. 2. *a) Locations of GPR (in red) and DPSH tests (in green); b) GPR radargrams and DPSH test results obtained at the ground level of Durrães bridge.*

2.2. Dynamic tests

For all case studies, dynamic tests were made which allowed identifying modal properties of the bridges, particularly, natural frequencies, vibration modes and damping coefficients. For Durrães and Côa bridge ambient vibration tests were made, while for the PK124 bridge forced vibration tests were adopted due to the reduced acceleration levels in the bridge under ambient vibration conditions. Forced vibration was induced using a structural exciter materialized by a mechanical device, provided with a mass of approximately 130 kg suddenly released at 1.50 m high. Fig. 3 shows some perspectives of the accelerometers and the exciter used in the forced vibration tests in PK124 bridge.

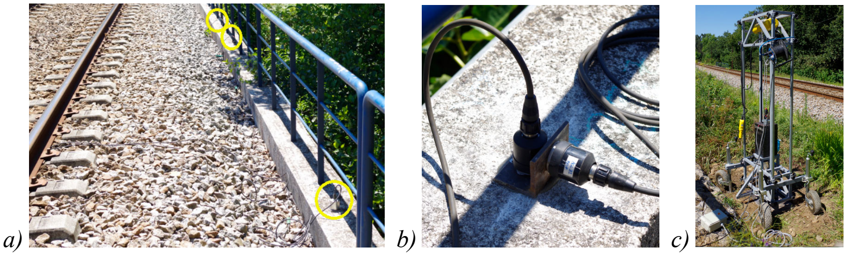

Fig. 3. *Dynamic test on PK124 bridge: a), b) views of the accelerometers in the deck of the bridge; c) excitation system.*

The dynamic tests on Durrães bridge involved 32 points of measurement (Fig. 4a), located in the deck and in the piers' faces, allowed identifying eleven vibration modes, characterized by their frequencies (from 1.851 Hz to 5.916 Hz), damping ratio and mode shapes (the first four of them are shown in Fig. 4b, [6]), obtained by the enhanced frequency domain decomposition method (EFDD) available in ARTeMIS commercial software [7]. The same was done for the Côa bridge, totalizing 25 measurement points located on the deck, and allowing characterizing seven vibration modes in the frequency range between 1.14 Hz and 7.75 Hz [8, 9]. For the PK124 bridge, thirteen measurement points located on both sides of the deck and two located in the wing walls were considered and eight vibration modes were obtained with frequencies from 10.45 Hz to 32.12 Hz, using both output-only and input-output data analysis methods [10]. Tab. 1 summarises the frequencies and respective damping coefficients for the identified vibration modes of the bridges.

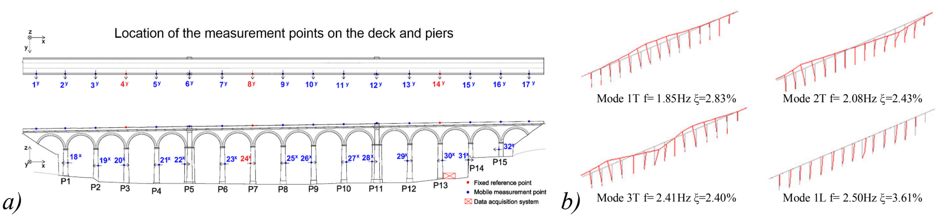

Fig. 4. *Modal identification of Durrães bridge: a) test setup; b) first four modes shapes and respective modal parameters.*

Table 1. *Frequencies and damping coefficients of the experimental vibration modes of the bridges.*

PK124 Bridge		Durrães Bridge		Côa Bridge	
Frequency [Hz]	**Damping coef. [%]**	**Frequency [Hz]**	**Damping coef. [%]**	**Frequency [Hz]**	**Damping coef. [%]**
10.45	4.91	1.85	2.83	1.14	3.64
12.75	4.47	2.08	2.43	1.56	3.16
15.08	4.56	2.41	2.40	2.12	2.32
19.75	3.35	2.50	3.61	2.74	1.75
21.97	2.88	2.79	3.37	3.39	1.36
24.33	2.61	3.31	2.23	7.01	1.38
26.88	2.77	3.83	1.67	7.75	0.87
32.12	2.73	4.11	1.94		
		4.33	1.72		
		5.17	1.00		
		5.92			

The forced vibration tests on the freight railway vehicle provided acceleration outputs from which the identification of vehicle modal parameters was carried out through the EFDD method, both in unloaded and loaded vehicle conditions. It was evaluated in terms of the accelerations in the transverse and vertical directions in one measurement setup totalizing 14 measurement points (Fig. 5a). For the former, 6 natural vibration modes were obtained (2.69 Hz to 8.11 Hz) while for the later condition (unloaded) 11 modal parameters were captured with frequencies between 3.42 Hz and 26.49 Hz. In Fig. 5b is illustrated the first four modal shapes and frequencies in unloaded and loaded conditions.

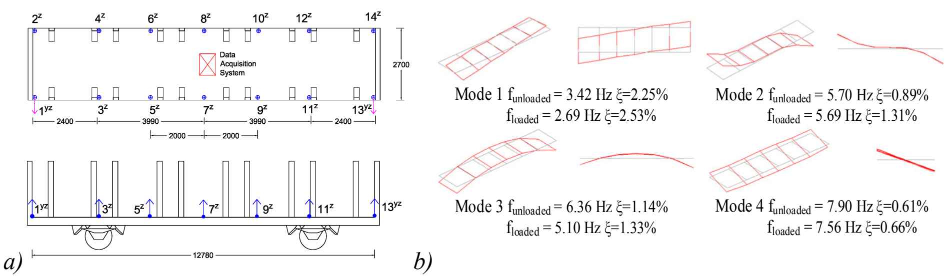

Fig. 5. *Modal identification of a freight vehicle: a) test setup; b) first four modes shapes and respective modal parameters for unloaded and loaded conditions.*

2.3. Material testing

Concerning the physical and mechanical parameters' characterization of structural components, as already mentioned, the experimental campaign was carried out for the PK124 and Durrães bridges. This involved in-situ activities, including flat-jack and Ménard pressuremeter tests, and laboratory tests performed on the collected samples, [4, 5]. For the mechanical tests, cores were drilled and samples were extracted from points that wouldn't compromise the bridge aesthetics and resistance, yet allowing a good characterization of the different components. Stone and stone-to-stone block joint samples were taken at the surface of piers, on spandrel walls over pier and on the abutments. The corresponding boreholes were used for the pressuremeter tests. Fig. 6 shows examples of cored samples extracted from granite stone blocks, joints and infills of both bridges.

a)  *b)* 

Fig. 6. *Materials extracted in coring (stone, joint and infill) from the bridges: a) Durrães and b) PK124.*

For component and material in-situ testing, the flat-jack technique was successfully used as a non-destructive option to characterize in-situ vertical stress and deformation of the masonry structure. However, the difficulties found in applying this technique to large masonry blocks (0.5 m high, see Fig. 7a) and joints of reduced thickness (1-2 mm) involving high axial loads, allowed exploring the very limits of this type of test (which is not usual for the tested masonry type) thus yielding results that must be carefully explored. The tests with Ménard pressuremeter led to good results for mechanical parameters of the bridges' infills. The adoption of this technique in horizontal boreholes (Fig. 7b), with materials stronger than common soils, was a challenging alternative use of this type of equipment; nevertheless, the results have shown good applicability of this technique to the study of these materials.

a)  *b)* 

Fig. 7. *In-situ material testing: a) two flat-jack tests in masonry components; b) pressuremeter test in the infill.*

In Fig. 8a is showed the type of graph containing the results for one of the two-flat jack tests performed for Durrães bridge. Based on the analysis of loading/unloading cycles obtained from the tests and on the calculation of the slope on the stress/strain plot in each vertical alignment, it is possible to estimate the elastic modulus of the tested masonry area consisting of stone blocks and respective joints. In Fig. 8b is showed one pressuremeter curve for one of the pressuremeter tests performed in Durrães bridge. Based on the pressuremeter curves it is possible to obtain the deformability parameters, the so-called pressuremeter (or Ménard) modulus (E_{PMT}). These parameters are calculated by an empirical method, using the values of the pseudo-elastic phase of the corrected stress-strain curve. In Table 2 is given the experimental results in terms of the range of average values of masonry and infill deformability obtained in situ with two flat-jacks and pressuremeter tests.

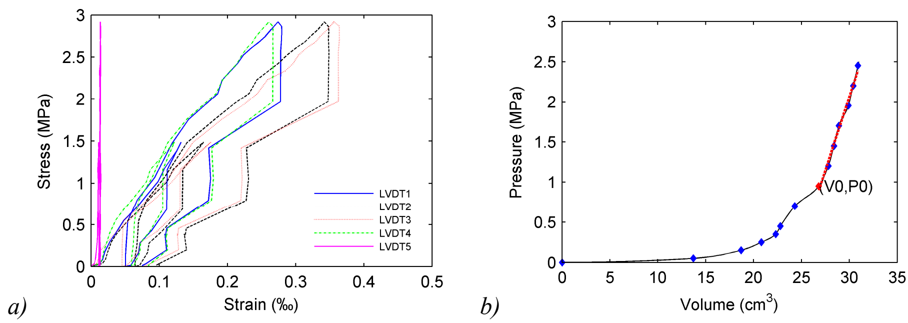

Fig. 8. *Experimental curves for Durrães bridge: a) two flat-jack test curves; b) pressiometric curve.*

Table 2. *Masonry and infill deformability range of average values obtained with flat-jacks and pressuremeter tests.*

	In-situ stress state [MPa]	**In-situ deformability of masonry, E [GPa]**	**In-situ deformability of infill, E_{PMT} [MPa]**
Durrães	1.53-1.54	7-23	336-542
PK124	0.2-1.0	0.9-1.3	228-264

The characterization of the behaviour of joints to be used in numerical modelling is based on the definition of strength and deformability parameters obtained from compression and shear tests carried out on samples extracted from the bridges. The samples featured very different initial conditions (before testing). Some samples were intact (bonded) and others were split, for this reason regarding the state of preservation they were separated in different groups.

In order to characterize the behaviour of masonry joints in the normal direction, cyclic compression tests were carried out, which enabled to record the evolution of compressive stress with the vertical displacement and evaluate the variation of normal stiffness of the joint caused by successive loading-unloading cycles (see Fig. 9a). As for behaviour of masonry joints in the tangential direction, shear tests were made in a shear-test box machine, by applying a normal constant pressure at three different levels (0.2, 0.6 and 1.2 MPa), from which results were obtained in terms of peak and residual shear strength and elastic stiffness (see Fig. 9b). Based on normal and shear peak and residual strength values, Mohr-Coulomb envelopes were determined for both peak and residual conditions (see Fig. 9c). Fig. 9 shows the experimental behaviour recorded in samples of stone-to-stone joints collected from Durrães bridge.

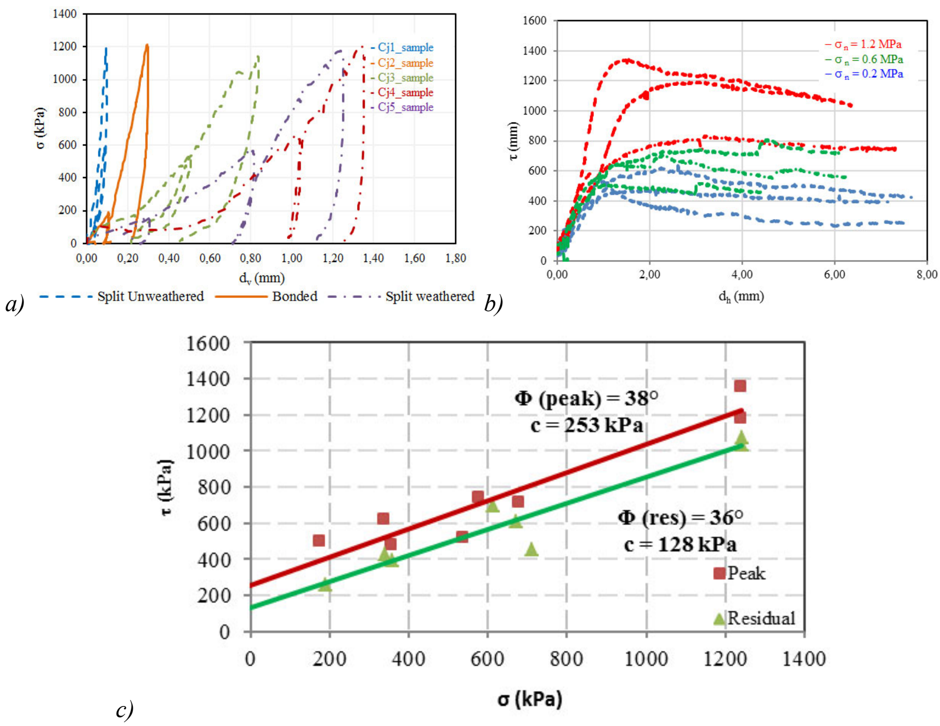

Fig. 9. *Stone-to-stone joints behaviour of Durrães bridge samples: a) normal stress vs. vertical displacement; b) shear stress vs. horizontal displacement; c) Mohr-Coulomb failure envelope.*

By analysing the curves in Fig. 9a, with the exception of sample Cj1, as the joint degradation increases there is a decrease in the average normal stiffness. For the split samples the average value is 1.6 MPa/mm. The shear stress *vs.* horizontal displacement curves from Fig. 9b are characterised by different phases, starting with a nearly linear elastic phase until reaching a maximum value of shear stress, followed by a strain-softening phase with reduction of this stress, only noticeable with high normal stresses, ending at residual phase corresponding to a residual strength. From the test results it appears that, in general, the initial elastic stiffness, peak shear strength and the residual shear strength increased with the installed normal stress. For the Durrães samples the initial stiffness has an average value of 0.73 MPa/mm.

The normal and shear stiffness obtained for PK124 and Durrães bridge joint samples are shown in Table 3. It also includes the values obtained for the mechanical characterization of the granite stone collected in both bridges, which comprised the determination of the compressive strength and deformability modulus as well as the tensile strength, using standard testing.

Table 3. *Physical and mechanical parameters of granite stone blocks and masonry joints.*

	Stone blocks				Masonry joints			
	Unit weight [kN/m^3]	Compressive strength [MPa]	Tensile strength [MPa]	Young modulus [GPa]	Normal stiffness [MPa/mm]	Shear stiffness [MPa/mm]	Residual friction angle [°]	Residual cohesion [kPa]
Durrães	25.9-26.5	34.8-59.4	3.7-5.4	20.0-23.5	1.652	0.728	36.0	128
PK124	25.2-25.7	35.9-81.4	2.3-5.2	6.8-10.9	1.730	0.665	32.5	38

3. CONCLUSIONS

This paper presents the experimental campaign conducted to study and characterise the structural components of three stone masonry railway bridges. It describes the different types of in-situ tests carried out on the bridges and the main results obtained. The dynamic identification tests were made in the bridges and in one of the freight train vehicle foreseen to be used in the load tests. Ambient vibration was mainly adopted, complemented with forced vibration in one bridge due to the difficulties found in appropriately measuring a good signal level. Vibration frequencies and mode shapes were obtained for all the three bridges, thus providing required input for the numerical modelling.

The testing campaign allowed evaluating the strength and deformability parameters of the constituent materials of the bridges by testing samples of granite stone, as well as samples representing the masonry interfaces existing between stone blocks. The flat-jack technique was successfully used as a non-destructive option to characterize in-situ vertical stress and deformation of the masonry structure, although difficulties found in applying this technique to large masonry blocks and with high axial loads. The tests with Ménard pressuremeter led to good results for mechanical parameters of infills. The adoption of this technique in horizontal boreholes, with materials stronger than common soils, was a challenging alternative use of this type of equipment; nevertheless, the results have shown good applicability of this technique to the study of these materials.

The results obtained with in-situ and laboratory tests permitted a detailed characterization of the constituent materials of both bridges and thus the values obtained for the mechanical properties have been used in numerical simulation models of their structural behaviour.

ACKNOWLEDGEMENTS

This work includes research conducted with the financial support of FCT through the PTDC project/ECM-EST_1691/2012-Experimental and Numerical Characterisation of the Structural Behaviour of Arch Stone Masonry Bridges under the Action of Railway Traffic - Application to Portuguese Existing Bridges (StonArcRail). The authors thank engineers Ana Silva, Hugo Patrício and Nuno Lopes from IP-Infrastructures of Portugal for all their collaboration and the information provided on the bridges.

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