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# ANALYSIS OF THE "PONTE DO ARCO" STONE MASONRY ARCH BRIDGE

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## SUMMARY

The "Ponte do Arco" stone masonry arch bridge is located in the north of Portugal, in the municipality of Marco de Canaveses, district of Porto. The bridge is immersed in a remote natural environment and is part of the Romanesque Route, which links buildings and structures built in the area during the Romanesque Period. The "Ponte do Arco" bridge is a fine example of this type of architecture and, therefore, it deserves devoted conservation and maintenance works. The geometry of the bridge, the internal structure of the pavement and the damage state were characterised by using two non-destructive techniques, photogrammetry and ground penetrating radar, and by performing a damage survey. The data collected was used to perform limit and finite element analyses in order to estimate the structural safety level of the structure. The paper presents the structural appraisal, resulting from the non-destructive surveys and the numerical analyses.

**Keywords:** *Arch bridge; stone masonry; NDT, non-destructive techniques; structural assessment.*

## 1. INTRODUCTION

An important number of historic masonry arch bridges can still be found in the north of Portugal. Most of these infrastructures belong to the mediaeval period and represent an important part of the built cultural heritage. The "Ponte do Arco" stone masonry arch bridge is located in the north of Portugal [1], in the district of Porto (Fig. 1). It is built over the river Ovelha and connects the banks of two parishes of the municipality of Marco de Canaveses. The bridge is located in the natural environment of Tâmega Valley (Fig. 2) far away from the villages and between the hills of Tâmega and Douro rivers.

The "Ponte do Arco" belongs to the Romanesque Route (www.rotadoromanico.com) [1]. The Romanesque Route constitutes a very interesting project that is supported by several municipalities and is devoted to the conservation and promotion of local Romanesque historical and cultural legacy. The Route is placed at the heart of north of Portugal within the Sousa, Tâmega and Douro valleys (Fig. 1 and Fig. 2). The Romanesque Route created a built heritage network, made by several buildings (e.g. churches, towers, monastery etc.) and bridges, in which each monument is strategically linked to the others, thus providing a structured inspiring excursion through places, which promotes the growth of local and sustainable tourism and related economic activities.

The "Ponte do Arco" appears as a possible fine example of the Portuguese Romanesque architecture. In fact, a precise dating of the bridge is very difficult due to the lack of documents and any builder marks on stones. To assess the Romanesque character of the bridge, the topic of the medieval communication and transport network was discussed in [1]. This bridge, together with the downstream bridge of Aliviada, was part of a municipal or inter-parish network of roads that connected relatively close villages since the medieval period [1]. However, the first official document of the "Ponte do Arco" is from the abbot José Franco Bravo in 1758 [1], which described its architecture and included the bridge in the same abovementioned communication and transport network. Therefore, even though the bridge complies with the usual Romanesque construction rules and it might likely belong to the late Middle Ages, it is not viable to rule out the possibility that this infrastructure might have been built in the Modern Period.

Nonetheless, the “Ponte do Arco” bridge constitutes an interesting structural case study concerning a slightly pointed granite stone masonry arch bridge, which received little or no attention in the past. Modelling and assessing the performance of these specific arched structures continues to be a challenging exercise [2, 3] due to the inherent complexity of their historic materials, three-dimensional behaviour and the interaction among different structural components. The approach for existing and historical structures outlined by the Italian technical regulations for constructions [4], the Italian Guidelines for evaluation and mitigation of seismic risk to Cultural Heritage [5] and the Guidelines for the structural safety evaluation of masonry road bridges [3] was used. The geometry of the bridge, the internal structure of the pavement and the damage state were characterised by using two non-destructive techniques (NDTs), namely photogrammetry and ground penetrating radar, and by performing a damage survey. The data collected was used to perform preliminary limit and finite element analyses to estimate the structural safety of the structure [6]. This paper presents a preliminary structural appraisal, resulting from the non-destructive surveys and the numerical analyses.

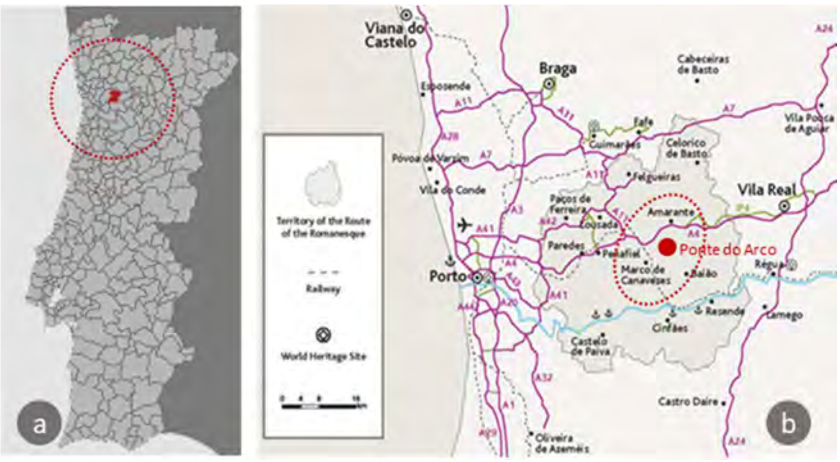

*Fig. 1.* *“Ponte do Arco” Bridge: (a) administrative map of Portugal; (b) Romanesque Route map [1].*

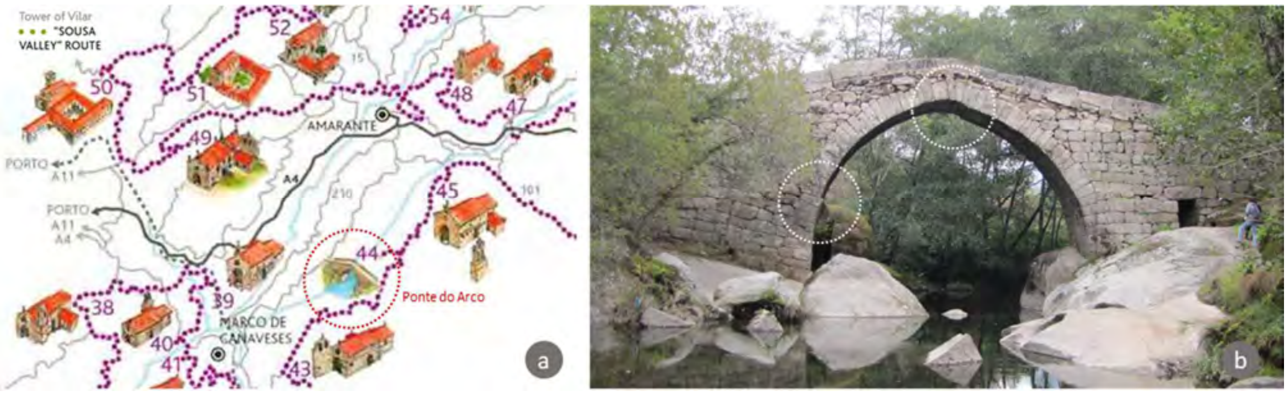

*Fig. 2.* *“Ponte do Arco” Bridge: (a) extract of the Tâmega Valley Romanesque Route map [1], with the location of the bridge highlighted in red; (b) downstream view of the bridge with geometrical deviation of the arch profile highlighted.*

## 2. GEOMETRICAL SURVEY, NDTs AND DAMAGE SURVEY

No geometrical data was available for the “Ponte do Arco” bridge. Therefore, the geometry of the arch was derived from an onsite survey where traditional methods (e.g. ruler, measuring tape, laser measuring tool and plumb line) were combined with two NDTs (close-range photogrammetry and ground penetrating radar, i.e. GPR). Photogrammetry and GPR were already successfully used for the geometrical survey of road bridges

[7, 9]. The plan, sections and elevations of the bridge were obtained through the application of these measuring tools and NDTs. The close-range photogrammetry was very useful for the construction of the 3D model (Fig. 3a) via the Agisoft PhotoScan software [10].

The GPR test was very helpful for the detection of the thickness and shape of the stone arch and of the backfill material. Looking at the radargram in Fig. 3b, it seems to exist a shallow cover in the bridge deck (the original pavement seems to be at a depth of about 15 cm from the current bridge deck surface). There were quite a few signals that were scattered from inside the bridge and they probably represent areas with a higher proportion of voids, or some sort of material heterogeneity. The GPR transversal profiles confirmed the former assumptions and shallow covering over stone pavement. In particular, it was possible to discern, right below the signals from the stone original pavement, an arch thickness that slightly increases from the centre towards the sides from about 35 cm (at the crown) to approximatively 55 cm close to the springing.

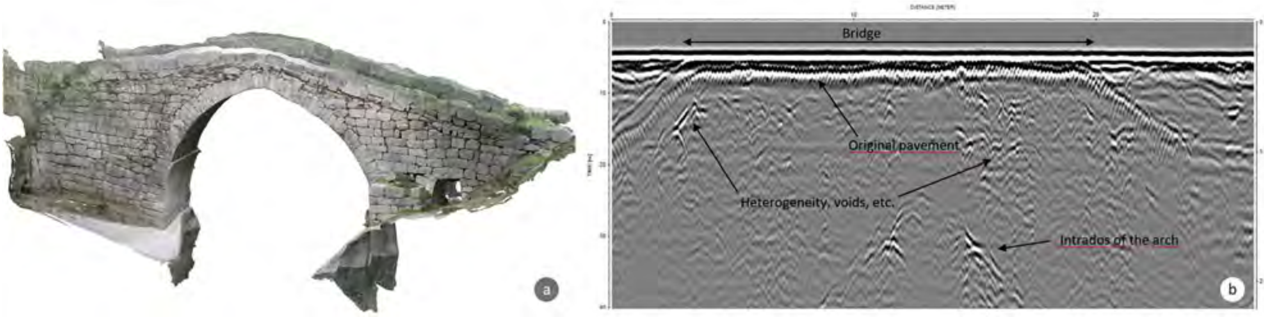

***Fig. 3.*** *NDTs: (a) 3D model constructed using close-range photogrammetry; (b) radargram carried out along the longitudinal central axis the bridge (frequency of 800 MHz).*

The "Ponte do Arco" is a single and slightly pointed arch with a trestle-shaped structure. The bridge structure is about 28 m long. The bridge is 9 m tall from the lower level of springing to the upper part of the parapet. The arch rest on the terrain profile following the emerging bedrock (Fig. 2b). On the upstream left side, the bridge is provided with cutwaters and a rectangular opening that serves as drainage channel. The arch resembles an imperfect vault with a span of 11 m, a rise in between 7.2 and 5.6 m, a width of about 3.5 m and a variable thickness depending on the 62 voussoirs composing the profile, as also pointed out by the GPR data. The average rise/span ratio of 0.6, thus the "Ponte do Arco" can be classified as a deep arch according to [2]. The arch is slightly pointed and presents two main geometrical deviations that constitute an interesting question about the historical constructive phases not yet solved (Fig. 2). The voussoirs constituting the arch have a length in between 0.4 to 0.2 m, decreasing from the springing to the crown, a width from 1.1 to 0.2 m and a thickness from 1.1 to 0.5 m. The "Ponte do Arco" bridge is made by dry joint stone masonry made with granite units, which is a common material in the north of Portugal [11]. The final geometry of the bridge is presented in Fig. 4a.

The surveyed damage was divided into two main categories according to [12]: damages affecting structural resistance and damages affecting durability. The sources of damage can be natural (e.g. floods, earthquakes, environmental) or anthropogenic (e.g. excessive moving loads). Damages affecting the structural resistance are those related to geometrical imperfections/dislocations, broken elements (i.e. cracks). The reported damages affecting the structural resistance were loss and dislocation of arch material, ashlar sliding, joint opening. Damages affecting the durability are mainly related with the environmental degradation of the material and lack of maintenance, such as biological colonization, overgrowing vegetation, wet spot, graffiti. The final damage survey of the "Ponte do Arco" bridge is shown in Fig. 4b.

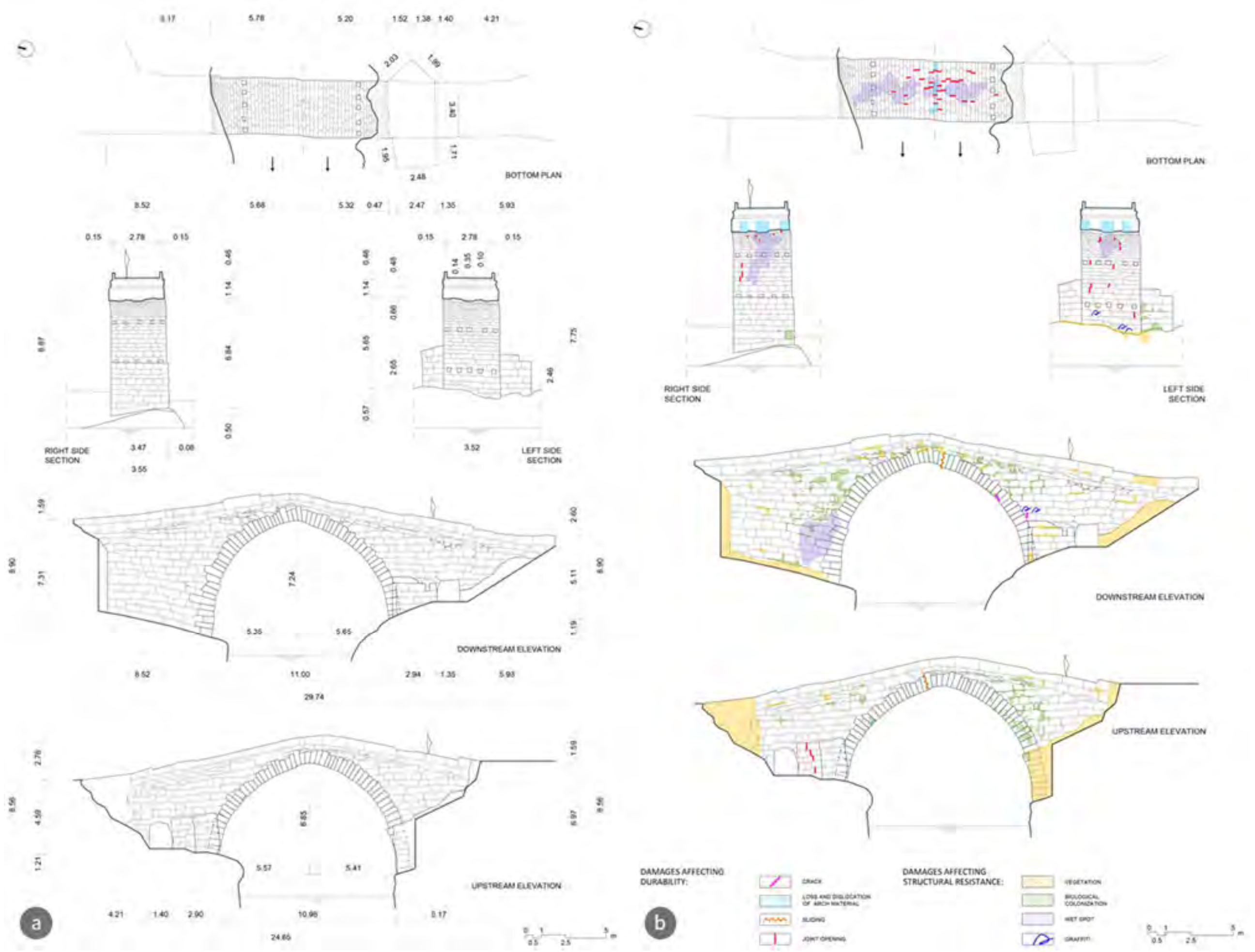

***Fig. 4.*** *"Ponte do Arco" bridge: (a) geometry; (b) damage survey in 2016.*

## 3. LIMIT ANALYSIS

The structural behaviour of the "Ponte do Arco" bridge under vertical forces was firstly evaluated via the limit analysis approach. This approach, developed by Heyman [13], is largely used for masonry arches and adopted by several researchers [2, 7, 9], also with the use of dedicated software (e.g. LimiteState Ring3, originally developed in the 1990s [14]).

The geometry of the models was constructed according to the data retrieved from the geometrical survey. The arch was subdivided in 100 voussoirs. Some simplifications were adopted to adapt the geometrical data to the features of LimiteState Ring3. Three models were constructed having the same common intrados profile, but increasing geometrical detailing of the arch (Fig. 5.) as follows: Model 1 with an arch minimum constant thickness of 0.50 m, Model 2 with a variable thickness of the arch according to the surveyed geometry (Fig. **4**a), and Model 3 having an initial maximum constant thickness of 0.85 m later locally reduced to the same profile of Model 2 via the diminution of the contact between voussoirs via the joint reduction tool of the software.

The structural analyses were performed using average values for the material properties collected from a literature survey [2, 6, 7, 9, 11] and on the basis of the bridge typology. The adopted values for the relevant material properties are listed in Table 1 and were used within the models without partial safety factors. The arch was loaded with a point load of 1 kN corresponding to a single-axle load having a width of 1.8 m and a length of 0.3 m. The point load was moved along the entire longitudinal length of the bridge in order to determine the position of minimum capacity for the three models implemented. The results are shown in Fig. **6**. As conceivable, the capacity curves presented minimum values approximatively close the one-quarter of the arch span. The minimum load capacities were 482 kN, 812 kN and 763 kN for Model 1, Model 2 and Model 3, respectively.

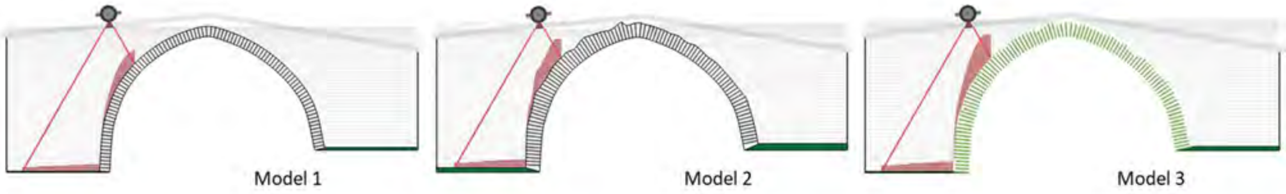

***Fig. 5**. Three models used for the limit analyses.*

The “Ponte do Arco” bridge was also assessed under practical design vertical loads, excluding any dynamic load factor thanks to the vehicle speed restriction enforced on the transit over this infrastructure [3]. The approach for existing and historical structures outlined by the Italian technical regulations for constructions [4] and the Guidelines for the structural safety evaluation of masonry road bridges [3] was used. From the Italian technical regulations for constructions, a double-axle concentrated load with axle distance of 1.2 m and a width of 2 m was selected. A partial safety factor of 3 and a confidence factor of 1.35 (limited knowledge level) were used for the existing stone masonry of the bridge. Model 1 and the former material properties were used. The minimum design load for the double-axle concentrated load was of $Q_d$ = 84.6 kN that activated the mechanism shown in Fig. 7. This capacity is reasonably sufficient for safely covering for the transit of light vehicles.

***Table 1**. Material properties used in the limit analysis models.*

| Material | Property | Adopted value |
|---|---|---|
| Masonry | Unit weight | 25 kN/m$^3$ |
| | Friction coefficient | 0.7 |
| | Compressive strength | 8 N/mm$^2$ |
| Backfill | Unit weight | 22 kN/m$^3$ |
| | Friction angle | 40° |
| | Cohesion | 0.05 N/mm$^2$ |

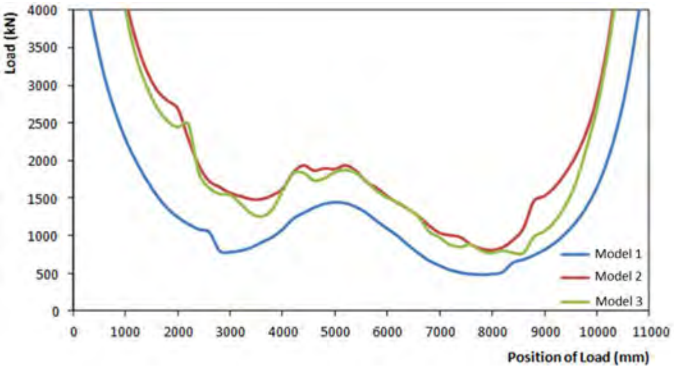

***Fig. 6**. Capacity curves under moving vertical point load.*

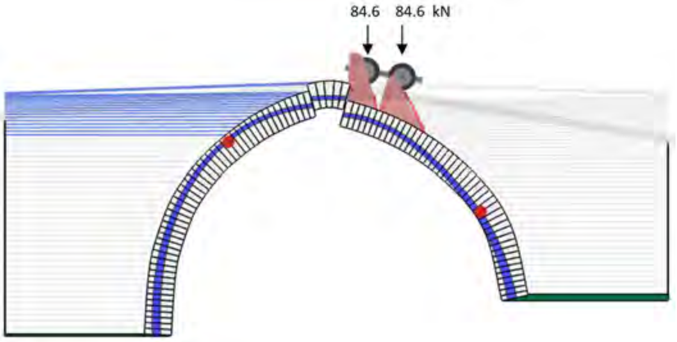

***Fig. 7**. Collapse mechanism and design load under vertical forces.*

## 4. PRELIMINARY FINITE ELEMENT SEISMIC ASSESSMENT

The preliminary structural assessment of the “Ponte do Arco” bridge was completed with the evaluation of the performance of the structure under seismic actions. Mainland Portugal is divided in several seismic areas, with different seismic hazard, according to Eurocode 8 [15], which covers type 1 (far-field) and type 2 (near-field) seismic actions. According to the geographical location of the bridge, the two design relevant elastic response spectra for a return period of 475 years are shown in Fig. 8.

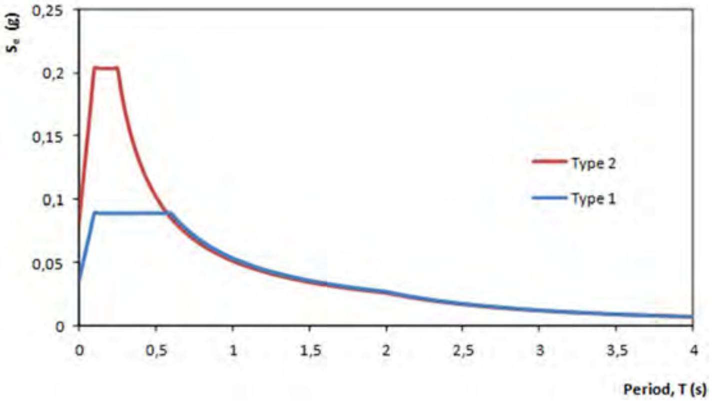

***Fig. 8***. *Elastic response spectra.*

The dynamic properties of the bridge were estimated via Finite Element Analysis (FEA). A dedicate Finite Element Model (FEM) was built starting from the data collected in the geometrical survey. A commercial finite element program available as educational version at the Laboratory of the Department of Civil, Environmental and Architectural Engineering of the University of Padova was used [16]. The FEM was constructed by using the volumes derived from the 3D photogrammetric model and using 16-nodes prismatic solid elements. The contact with the soil was simulated via linear elastic springs according to the Winkler’s model and having an axial stiffness of 0.160 N/mm$^3$ corresponding to dense sands [6]. The average values for the material properties collected from literature [2, 6, 7, 9, 11] are reported in Table 2. All the materials were treated as elastic [6]. The FEM used for the analyses is shown in Fig. 9.

As preliminary step for the spectral response analysis, the first 15 numerical frequencies of the “Ponte do Arco” bridge were calculated. The first two principal vibrating modes correspond to mode 1 and mode 3 (Fig. **10**) with a participating mass of 41% and 45%, respectively. The natural frequencies and the participating masses of the remaining modes are reported in Table 3.

The data of Table 3 together with the response spectra of Fig. 8 were used to carry out an elastic response spectrum analysis useful for a preliminary assessment of the seismic behaviour of the bridge under lateral actions. The analyses showed that the bridge under design seismic actions behaves within the linear range since the principal tensile stresses retrieved from the models are smaller than 0.015 N/mm$^2$ (Fig. 11).

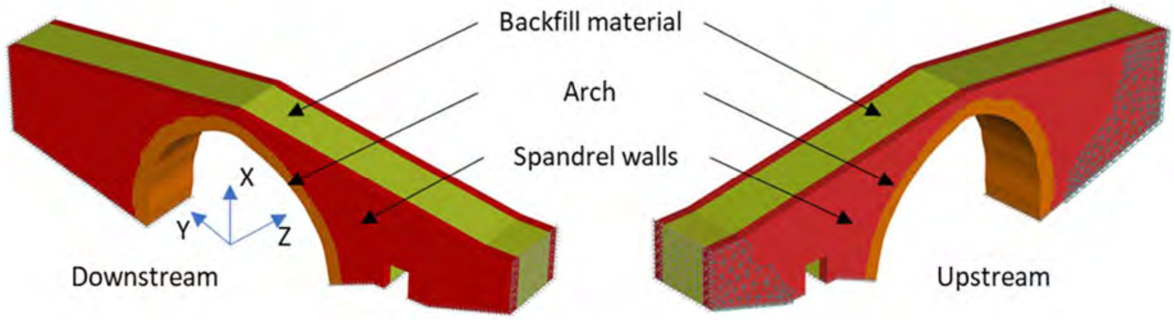

***Fig. 9***. *Finite element model adopted for the analyses.*

***Table 2**. Material properties used in the FEA.*

| Part of the model | Property | Adopted value |
|---|---|---|
| Arch | Unit weight | 25 kN/m$^3$ |
| | Friction angle | 50° |
| | Cohesion | 0.5 N/mm$^2$ |
| | Modulus of elasticity | 5000 N/mm$^2$ |
| | Poisson's ratio | 0.2 |
| Spandrel walls | Unit weight | 24 kN/m$^3$ |
| | Friction angle | 50° |
| | Cohesion | 0.3 N/mm$^2$ |
| | Modulus of elasticity | 3000 N/mm$^2$ |
| | Poisson's ratio | 0.2 |
| Backfill material | Unit weight | 22 kN/m$^3$ |
| | Friction angle | 40° |
| | Cohesion | 0.05 N/mm$^2$ |
| | Modulus of elasticity | 1000 N/mm$^2$ |
| | Poisson's ratio | 0.2 |

***Table 3**. Natural modal frequencies and related participating masses.*

| Mode | Frequency [Hz] | Participating mass [%] | | |
|---|---|---|---|---|
| | | X | Y | Z |
| **1** | **8.6** | 0.0 | 0.0 | **41.3** |
| 2 | 14.7 | 0.0 | 0.0 | 0.0 |
| **3** | **18.0** | **44.8** | 0.0 | 0.0 |
| 4 | 20.6 | 0.0 | 0.0 | 22.3 |
| 5 | 21.6 | 0.2 | 23.5 | 0.0 |
| 6 | 25.8 | 0.2 | 10.7 | 0.0 |
| 7 | 27.9 | 0.0 | 0.0 | 0.1 |
| 8 | 30.4 | 22.8 | 1.0 | 0.0 |
| 9 | 30.8 | 0.0 | 0.0 | 1.7 |
| 10 | 34.8 | 4.3 | 3.3 | 0.0 |
| 11 | 35.5 | 0.0 | 0.0 | 2.3 |
| 12 | 36.9 | 0.0 | 0.0 | 8.1 |
| 13 | 39.0 | 0.1 | 34.5 | 0.0 |
| 14 | 43.3 | 0.0 | 0.0 | 1.1 |
| 15 | 43.9 | 0.0 | 0.1 | 0.0 |
| Cumulative participating mass: | | 72.3 | 73.2 | 76.9 |

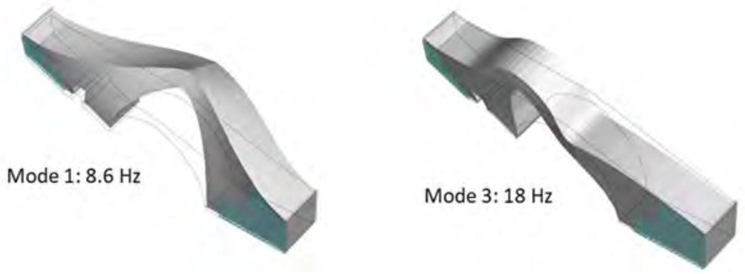

***Fig. 10.** First two principal vibration modes of the "Ponte do Arco" bridge.*

***Fig. 11**. Principal tensile stress contour for the elastic response spectrum analysis.*

## 5. MAIN CONCLUSIONS

The paper presents the survey and a first structural analysis of the “Ponte do Arco” bridge, which is a very interesting example of the Romanesque architecture from the North of Portugal. Its geometry and conservation state were retrieved using two non-destructive techniques, photogrammetry and GPR, and by performing a damage survey. The bridge requires a devoted conservation and maintenance for a better preservation within the Romanesque Route. Moreover, the structural appraisal, based on limit and finite element numerical analyses, estimates an acceptable safety level, although the existing damage state has not been considered in the model. Future detailed studies can be directed toward material characterization and the use of more refined numerical analyses, including the modelling of the existing damage level.

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