Numerical Investigation of a Medieval Masonry Arch Bridge Based on a Discrete Macro-element Modeling Approach

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Abstract. Since ancient times masonry arch bridges have been used to cross natural obstacles. Many examples are still present and under service, particularly in European countries. Due to the historical and cultural value of these bridges, together with their important role in the transportation network system, it is necessary to have numerical tools suitable for an accurate structural assessment of their conditions, both under vertical and horizontal loading, including extreme events. In this study, the structural assessment of Barcelos Bridge, a medieval stone masonry arch bridge in northern Portugal, was carried out comparing two different numerical approaches: the Finite Element Method (FEM) and the Discrete Macro-Element Method (DMEM). In previous studies, the FEM Diana software has already demonstrated its validity in the structural assessment of this bridge, but the computational costs and the time required for the analysis are hardly compatible with the usual professional practice outside the research activity. As a matter of fact, the importance of precise yet simple assessment methods is well established today, since they provide useful means to the professionals who perform the structural analysis of this type of bridges. Pushdown and pushover analysis were performed to assess the structural performance of the bridge under vertical and horizontal loads.

Keywords: Masonry arch bridges · Nonlinear analysis · Discrete macro-element method · Historical constructions

1 Introduction

Masonry arch bridges are one of the most ancient types of structures used to cross natural obstacles and still today there are many examples within the road and railway infrastructures in Europe. They are gravity structures whose behaviour highly depends on the geometry of structural elements and material properties, especially of masonry, mortar and fill materials.

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Several parameters and related uncertainties affect the structural assessment of masonry arch bridges both regarding the materials characterization and the possible failure modes of the structure. They are particular types of bridges composed of many elements that significantly affect their structural behaviour, making in-depth studies necessary on the case in question [1–3]. In addition to the difficulties inherent to the material properties definition, the safety assessment is still nowadays a complex challenge from several aspects that characterize existing bridges and in particular masonry arch bridges [4–7]. Therefore, so many uncertainties require adequate tools for the safety assessment of this specific type of structures, to be adopted both for researches and practical applications.

Two main types of materials are used in the construction of masonry arch bridges: masonry and soil-type (fill material). The principal characteristics of masonry are its heterogeneity, anisotropy, moderate compressive strength and reduced or null tensile strength. The fill material consists of agglomerates of various particle size materials placed over the masonry vaults, typically a soil that has undergone an anthropic process and therefore cannot be considered undisturbed as in the usual case of a soil interacting with structural and geotechnical works [8, 9]. For these reasons, suitable models are needed to define the mechanical properties of the infill material. Theoretical formulations for the adoption of the Mohr-Coulomb criterion for characterizing the fill material in terms of cohesion and friction coefficient are available in literature [10, 11].

It is fundamental to take into account all these aspects, also in the development and improvement of methods for the study of masonry arch bridges [12]. The structural assessment of existing bridges is important and actual even today, as evidenced by recent events regarding the collapse of this type of structures.

This study focuses on the specific case represented by Barcelos Bridge, a Medieval granite masonry arch bridge located in the north of Portugal between Barcelos and Barcelinhos crossing Cávado river (Fig. 1). Constructed between 1325 and 1330 by Pedro Afonso, count of Barcelos, it was an important crossing point for pilgrims on the Portuguese Way of Santiago and for merchants given the relevance of Barcelos as a trade centre since the High Middle Age. The bridge consists of five unequal arches with a maximum span of about 19 m, the largest and the highest covering the middle of the river. The bridge is 100 m long, 18 m high in the middle and it has an average width of 5 m.

In a previous study, Barcelos Bridge was considered to investigate the application of the non-destructive testing methodologies accompanied by advanced numerical modeling in safety assessment of historical bridges, using the Finite Element Method (FEM) approach implemented in the Diana software [13]. In this work, the main objective is to apply a different, simpler and faster method for the assessment of masonry arch bridges, in order to obtain a suitable numerical tool for the professionals who study this type of structures. The approach used is the Discrete Macro-Element Method (DMEM) introduced by Caliò et al. [14–17].

A parametric geometry has been used for the numerical model; after a comparison in the linear field with a modal analysis, pushdown and pushover analysis were performed in order to assess the safety of the bridge concerning the gravity and seismic loads.

Fig. 1. Barcelos Bridge (downstream view).

Further developments in the use of this method may however allow the study of typical problems of this type of bridges, which until now have been less considered.

2 Numerical Modeling

2.1 The DMEM Approach

As mentioned above, in this study a Discrete Macro-Element Method developed by Caliò et al. [14–17] has been used for the assessment of the structural response of Barcelos Bridge.

The DMEM is a particular approach at a “macro-scale” within the more general category of Discrete Macro-Element Methods. With the analysis strategies based on macro-elements the structure is divided into macro-portions (macro-elements) whose behaviour is simulated by an equivalent mechanical element. Differently from the classical Discrete Element Method approach, in which each element is typically considered as a rigid body, in this Discrete Macro-Element strategy each macro-element possesses an in-plane shear deformability, related to a single degree of freedom for each macro-element, and it is applied at the macro-scale. The mechanical interaction among adjacent macro-elements is concentrated in zero-thickness interfaces obtained as a uniform distribution of nonlinear links incorporating the nonlinear behaviour of masonry according to a straightforward fibre strategy (see Fig. 2). The computational cost of the proposed numerical approach is greatly reduced in comparison to that involved in nonlinear finite element simulations or discrete element strategies based on a meso-scale discretisation.

2.2 The DMEM Model

Barcelos Bridge has been modeled with the HiStrA Bridges software, which incorporates the proposed DMEM. The software allows to model masonry arch bridges with the aid of a powerful parametric graphical user interface that facilitates the input of the geometry, the mechanical properties of the materials and loading conditions (Fig. 3a).

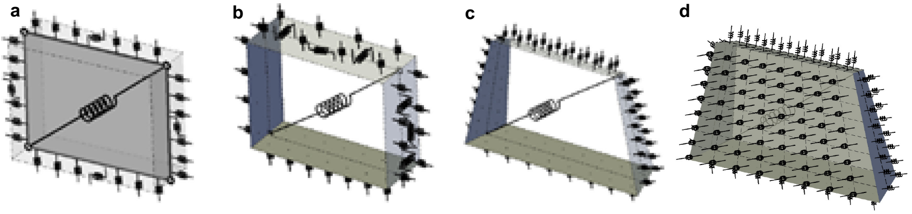

Fig. 2. Mechanical scheme adopted in the proposed macro-element approach: (a) plane element; (b) regular three-dimensional element; (c) irregular 3D element; (d) irregular 3D element with interfaces on all faces.

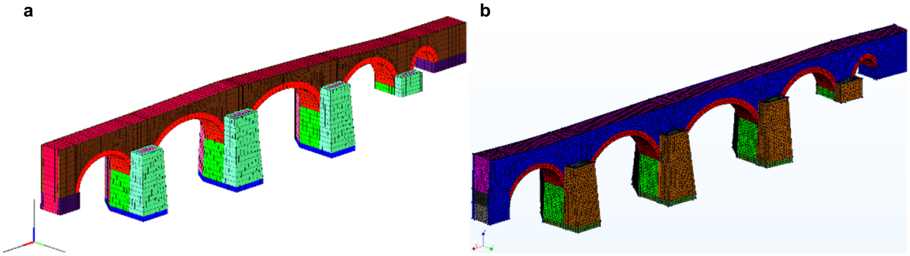

Fig. 3. Barcelos Bridge model: (a) HiStrA model; (b) Diana model.

The material properties adopted in this work are reported in Table 1 according to those adopted in [13]. It is worthwhile to note that the linear properties (i.e. Young's modulus) were obtained in the previous study by a calibration in the linear range, comparing the numerical frequencies derived from a modal analysis with those obtained with an ambient dynamic identification test. The constitutive law adopted in the Diana model (see Fig. 3b) for the backing and the infill materials requires only the definition of the cohesion and the friction angle since the plastic yielding surface is a function of these parameters. On the contrary, in the HiStrA model flexural and shear behaviours are uncoupled, so it is required to define the compressive and tensile strengths to properly describe the plastic yielding domain, while the plastic shear domain is a function of cohesion and friction ratio according to Mohr-Coulomb criterion.

A great challenge for the modeling of Barcelos Bridge was represented by the presence of the cutwaters. These elements play a key role in the structural response of the bridge, especially as regards horizontal actions in the transversal direction, but it is equally true that their adequate representation in a numerical model must take into account several aspects.

Referring to the case in question, it is likely that these elements are subsequent to the construction of the piers. Not having carried out internal inspections, it is not possible to define with certainty the type of constraint of the connection. It is plausible that the cutwaters constitute nonlinear restraints to the bridge as they are not ideal bilateral ones. The different response in compression and tension is evident since in the case of compression there is a physical contact that gives greater stiffness to the piers of the bridge, while in tension this is significantly lower and difficult to evaluate.

Table 1. Assigned nonlinear material properties.

Material	ρ (kg/m^3)	E (MPa)	$f_c^{'}$ (MPa)	G_c (N/mm)	f_t (MPa)	G_t (N/mm)	C (kPa)	μ $(-)$
Arches	2300	1970	3.28	5.25	0.15	0.025	250	0.4
Piers and cutwaters	2300	1710	2.85	4.56	0.10	0.020	250	0.2
Spandrel walls and abutments	2300	1490	2.48	3.97	0.10	0.020	250	0.4
Pier nucleus and backing	2000	980	1.20	–	0.06	–	5.5	0.2
Infill	1700	450	0.80	–	0.04	–	5.5	0.2

For this reason, it is necessary to evaluate well the approach used for the modeling of the cutwaters. Several strategies are possible and there are different responses for each one. In this study, cutwaters have been modeled explicitly, assuming a structural continuity between them and the piers and arches.

3 Numerical Analysis

3.1 Validation of the Model in the Linear Field

A validation of the HiStrA model in the linear field has been performed comparing the modal properties with those obtained by Diana software. In the Diana model, four-node iso-parametric solid pyramid elements have been adopted for linear and nonlinear simulations; the model has about 1574000, 295000 and 885000 elements, nodes and degrees of freedom, respectively. For the numerical simulation of the HiStrA model, 14486 macro-elements with a total number of 101678 degrees of freedom are considered. Figure 4 reports the first four vibration mode shapes and the corresponding frequencies. A good comparison has been obtained for the investigated vibration modes with the HiStrA model despite the lower number of degrees of freedom with respect to the Diana model.

It should be noted that a simplified parametric geometry has been adopted in HiStrA compared to that implemented in Diana, the latter reconstructed using point cloud geometrical data. Furthermore, it is a comparison between two approaches that presents very different computational costs, also in terms of implementation time. The higher difference has been obtained in terms of frequency for the third longitudinal mode which is probably due to the irregular layout of the bridge in the longitudinal direction. While in the Diana model the curvilinear course has been reproduced, a straight path has been adopted in HiStrA as a simplification.

3.2 Pushdown Analysis

Masonry arch bridges usually have good structural behaviour under vertical loads. Anyway, it is of interest to assess the safety level of the bridge against gravity loading. To

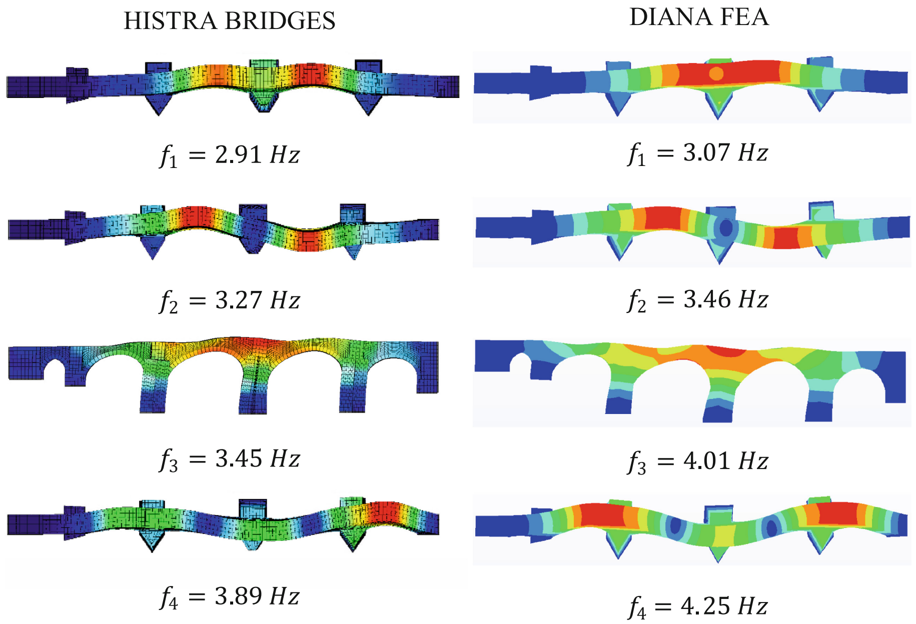

Fig. 4. HiStrA Bridges versus Diana FEA. Comparison between the first four vibration frequencies and the corresponding vibration modes.

do this, its self-weight is monotonically increased up to failure. Figure 5a presents the curves for the self-weight load factor λ versus the vertical displacement obtained using the two numerical approaches. The difference in terms of stiffness between the two models is due to the different modeling approach, since in HiStrA the possible confinement Poisson's effect given by the spandrel walls to the fill material is neglected. This effect increases the stiffness of the inner material.

The higher value of the ultimate load factor obtained with HiStrA is due to the fact that the analysis with the FEM model does not proceed further as numerical instability phenomena are activated. On the other hand, the DMEM approach allows to obtain further increases in displacement since the interfaces, on which the deformability depends, allow the non-localization of the plasticization and therefore avoid the loss of convergence of the numerical solution.

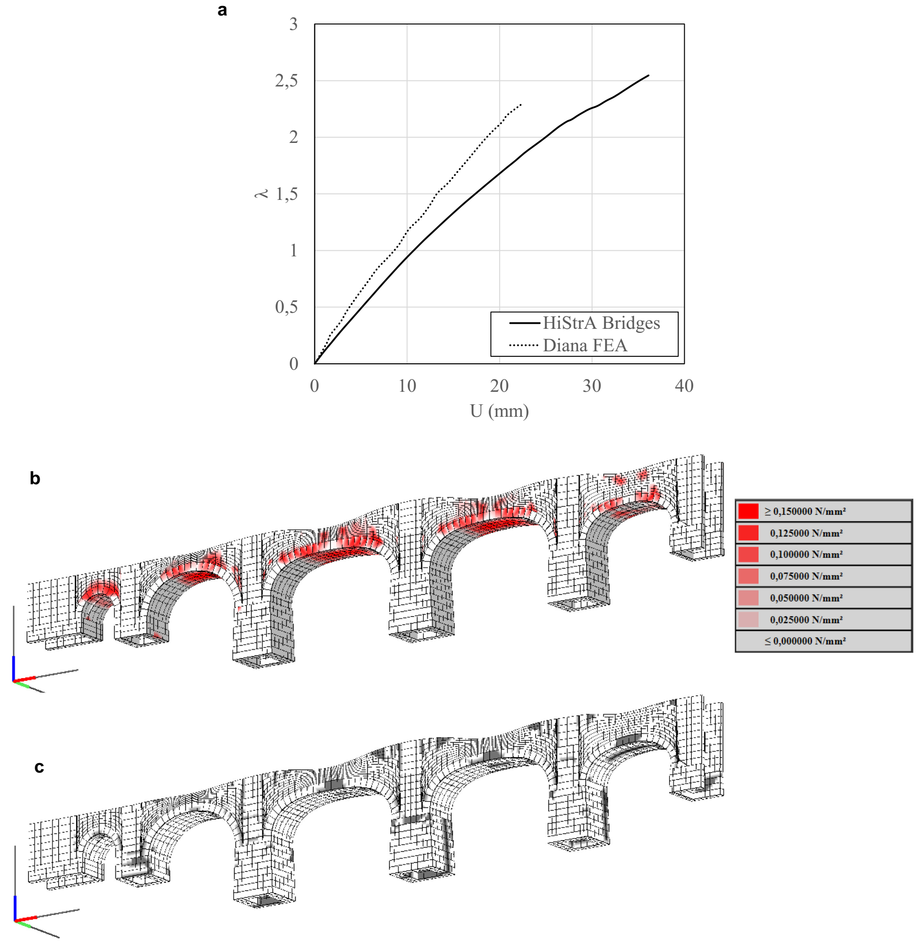

Fig. 5. Capacity of the bridge against gravity loading: (a) pushdown capacity curves (load factor λ versus vertical displacement U) obtained with HiStrA Bridges and Diana FEA; (b) vertical tensile stresses; (c) damage indicators associated with plastic strains.

3.3 Pushover Analysis

In order to evaluate the structural response of the bridge under seismic loadings, a pushover analysis has been performed. A mass proportional load pattern has been considered, applied in the transversal direction, which is the critical one for this type of bridges compared to the longitudinal direction. From the comparison shown in the plot load factor λ versus transversal displacement (see Fig. 6), there is a good agreement between the results obtained with HiStrA and the Diana software, despite the differences between the two models already mentioned above.

Furthermore, the contours of the principal stresses at the pushover capacity reported in Fig. 6 show that the failure mechanism of the structure obtained with HiStrA is similar to that found in Diana [13]. It starts by forming hinges at crowns of the mid large

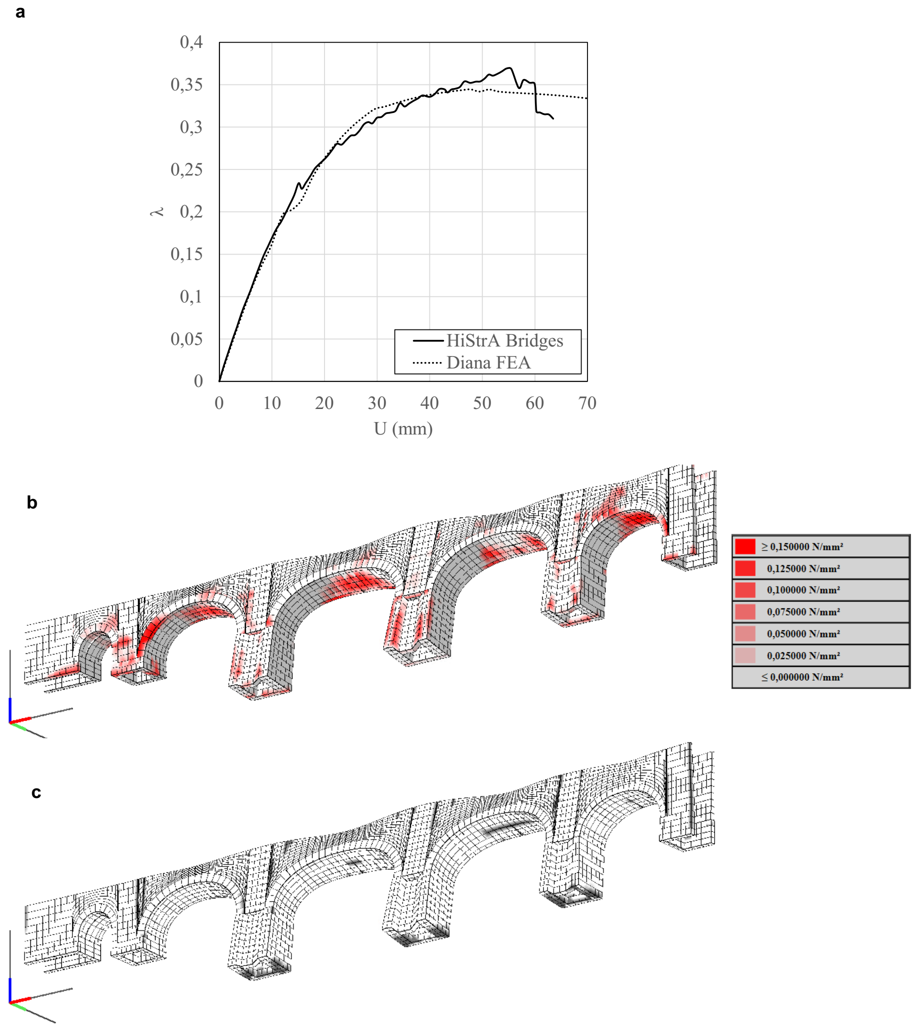

Fig. 6. Capacity of the bridge against seismic loading: (a) pushover capacity curves (load factor λ versus transversal displacement U) obtained with HiStrA Bridges and Diana FEA; (b) vertical tensile stresses; (c) damage indicators associated with plastic strains at pushover capacity.

arches and also springs of the arches. The oscillations of the HiStrA curve are due to the partialization of the sections in correspondence with the interfaces, caused by the mechanical nonlinearity of the constitutive law of the links not resistant to traction, and by the achievement of the failure conditions in the diagonal shear and sliding links.

4 Conclusions

In this study, a comparison between two different numerical approaches, termed as the FEM and DMEM, was made to assess the structural performance of a Medieval stone masonry arch bridge. A simplified geometry has been adopted for the DMEM model, performing its validation in the linear field and nonlinear pushover and pushdown analysis. Despite the differences between the two approaches, such as the geometric simplifications adopted in modeling with the DMEM and the different computational cost, the results obtained are in good agreement. Slight differences in terms of deformability and ultimate load factor were found in the pushdown analysis, but these are due to the different approaches of the two models. On the other hand, the comparison between the two methods for the modal and pushover analysis has demonstrated the validity of the DMEM approach for the study of masonry arch bridges, of which Barcelos Bridge is an exemplary case.

Further studies should be done with the DMEM approach, not only related to the case study here discussed but also extended to others. In particular, the study of foundation settlements applied to the bridge piers is of considerable interest, as well as that of the possible hydrodynamic thrusts due to the river flow. As a matter of fact, recent events have shown that the collapse of this type of structures may occur due to events such as those mentioned above.

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