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Advanced nonlinear simulations of a masonry viaduct using a macroscale anisotropic model

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Abstract

This paper presents the results of advanced numerical simulations on the 5-span Quebradas viaduct, located in the Douro valley, built at the beginning of the 20th century. The bridge structure has been analysed by nonlinear dynamic analysis to represent the response up to collapse under earthquake loading. The analyses are performed by adopting a novel macromodelling approach based on a recently developed macroscale anisotropic masonry model with embedded discontinuities.

Keywords: Finite Elements, macroscale models, multiscale approaches, nonlinear analyses, earthquake loading, time-history analyses, extreme environmental actions.

1 Introduction

Masonry arch bridges play a crucial role within existing railway and roadway networks and represent important architectural heritage assets in many countries around the world. Accurate simulations of their complex 3D response under different loading conditions require sophisticated models, allowing for the nonlinear masonry behaviour and the interaction among the different bridge components, including arches, backfill, spandrel walls and piers. Under dynamic loads, such as those inducted by earthquakes, the response becomes even more complex due to mechanical degradation with the reduction of stiffness and strength induced by the opening and closure of tensile cracks and shear sliding along the mortar joints and by the energy dissipation associated with the hysteretic behaviour of the backfill material.

This paper presents the results of a numerical study on the Quebradas viaduct, which is located in the Douro valley, a low-to-medium seismic hazard area in Northern Portugal. The 5-span viaduct, which is made of regular granitic blocks, was built at the beginning of the 20th century. The bridge structure has been analysed by nonlinear dynamic analysis to represent the response up to collapse under earthquake loading. Numerical simulations have been performed adopting a macromodelling approach with a recently developed macroscale anisotropic masonry model with embedded discontinuities [1]. The model allows for the actual masonry bond requiring simple material calibration and enables the representation of tensile cracking, crushing and shear damage in the brick/blockwork. A two-scale representation is utilised, where 3D continuum elements at the structural scale are linked to embedded nonlinear interfaces representing mortar joints at the mesoscale. The adopted masonry material model has been validated against physical experiments in previous research within the RAMBEA project [2], considering the response of masonry arch and bridge specimens under cyclic loading, including dynamic actions induced by earthquakes [3].

2 Methods

This paper employs a novel continuum macromodelling strategy for brick/block masonry, enabling an accurate description of the anisotropic response under cyclic loading. The model has been recently formulated and validated based on the in-plane and out-of-plane behaviour of masonry panels [1] and curved structures such as masonry arches and vaults. [3]. The adopted material description utilises embedded internal layers describing masonry bond at the local level, while taking into account the characteristics of the units and the mortar joints. The model adopts a continuum Cauchy description at the macroscale level, reducing the number of degrees of freedom compared to detailed mesoscale models, therefore leading to improved efficiency. The modelling strategy enables the consideration of different masonry bond in the radial and transversal directions, which is typical of multi-ring arches of masonry bridges (Figure 1a,c,d). The orientation of the internal layers, coinciding with the directions of the masonry joints, is defined by the local reference system (*oxyz*) of each continuum solid element within the FE mesh for a generic masonry component (Figure 1b). A multi-linear cohesive-frictional yield surface governs the nonlinear response of the internal layers (Figure 1e), allowing for the tensile cracking (mode I), sliding (model II), and compressive (model III) failure modes of masonry joints [4]. Different damage variables in tension, shear and compression rule material strength and stiffness degradation.

A robust yet straightforward multiscale approach is adopted to transfer information from the macroscale to the local level and vice versa at each Gauss integration point of the domain [1]. This modelling strategy enables a practical model calibration by directly using mesoscale mechanical parameters, which can be evaluated through simple in-situ tests [5]. The ability of the model to predict the cyclic and dynamic response of masonry arches and bridges has been shown in [3] considering 2D and 3D arch specimens, also interacting with backfill.

The accuracy of the response predictions of the Quebradas viaduct, Portugal, by the proposed macroscale model has been assessed by comparisons against detailed but computationally expensive 3D mesoscale simulations, where masonry units and mortar joints are modelled separately as in [6], using elastic solid elements and nonlinear interfaces with the yield function shown in Figure 1e, as described in [4]. This strategy has been widely employed and validated against experimental tests on masonry arches and bridges [7].

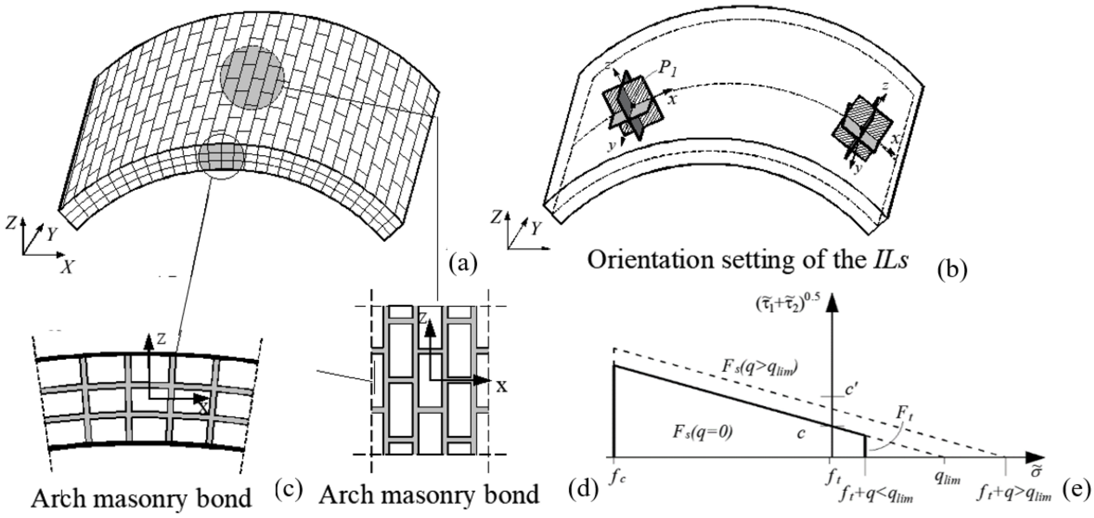


Figure 1: (a) Typical brick-masonry vault and (b) its macroscale description; examples of (c) stretch bond and (d) running bond characterising the arch and vault, respectively; (e) multi-linear yield surface of the internal layers.

3 Results

A 3D model of the bridge, including the masonry parts and the backfill, has been developed in ADAPTIC [8] according to [[9]]. Masonry components, namely piers, arches and spandrel walls, have been discretised by the continuum macroscale modelling approach described above (Figure 2a) and connected to each other and to the backfill domain by cohesive-frictional interfaces (Figure 2b). The masonry is characterised by mesoscale parameters used in previous research [9,10], including a Young's modulus of 15000 MPa and a Poisson's ratio of 0.15 for the masonry blocks, and the mechanical parameters reported in Table 1 for the mortar joints. Comparisons against in-situ monitoring results will be performed in the next stages of the study.

According to [1], mesoscale parameters are used to calibrate the macromodel. In particular, (*i*) the elastic normal and shear moduli are evaluated by combining the stiffness of the blocks and the mortar joints acting in series; (*ii*) the nonlinear model parameters in the direction orthogonal to the bed joints are assumed coincident with the nonlinear parameters of the mortar joints (Table 1); (*iii*) the tensile strength and fracture energy in the direction parallel to the bed joints are evaluated combining the tensile strength of the head joints and the sliding strength of the bed joints, resulting in 0.6MPa and 0.3N/mm, respectively. Based on historical information [[11]], the backfill material is modelled by an elastoplastic Drucker-Prager criterion (Table 2). Finally, a tensile strength equal to 0.002 MPa, a cohesion of 0.0029 MPa, 0.6 friction coefficient and zero dilatancy are assumed for the masonry-backfill interfaces [[7]].

In preliminary simulations, the viaduct has been subjected to a vertical patch load at the middle of the second span. The load-deflection curve predicted by the macromodel is shown in Figure 3, where it is compared to the numerical curve obtained by the mesoscale model. A good agreement can be observed between the two models, both in terms of stiffness and ultimate load capacity. Figure 4 compares the deformed shapes with von Mises stress distribution at failure predicted by the efficient macroscale and detailed mesoscale model.

Subsequently, the viaduct has been subjected to ground acceleration time histories applied at the bases of the piers and at the two end-abutments adopting the signal used in [3]. Figure 5 shows the displacement time histories at six locations at the top of the spandrel walls and the failure mechanism predicted by the anisotropic model for a PGA=0.15g.

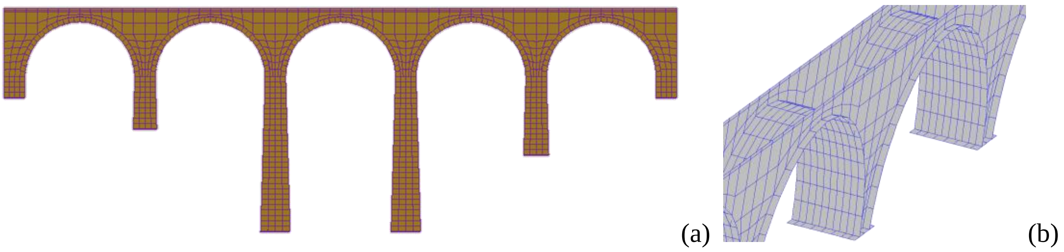


Figure 2: (a) Numerical bridge model in ADAPTIC; (b) masonry-backfill interfaces.

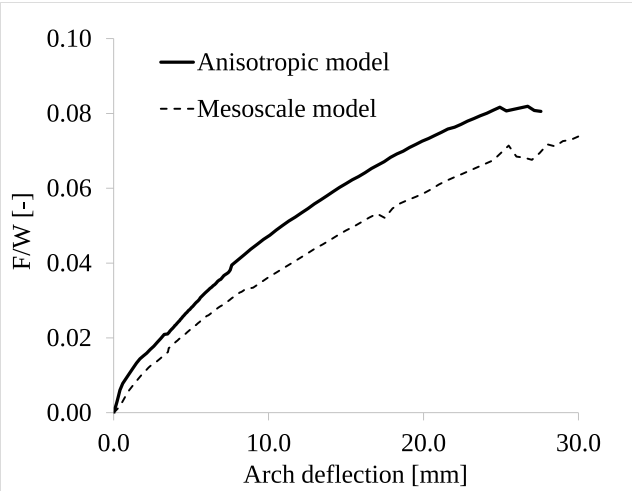


Figure 3: Numerical load-displacement macroscale and mesoscale curves of the Quebradas viaduct under patch loading.

k_n [N/mm^3]	k_t [N/mm^3]	f_t [MPa]	f_c [MPa]	c [MPa]	G_t [N/mm]	G_s [N/mm]	$tan\phi$ [-]	$tan\phi_g$ [-]
10^4	10^4	0.10	16.0	0.15	0.05	0.125	0.50	0.00

Table 1: Mechanical parameters of masonry interfaces.

Young's modulus [MPa]	cohesion [MPa]	friction coefficient [-]
500	0.1	0.57

Table 2: Mechanical parameters of backfill.

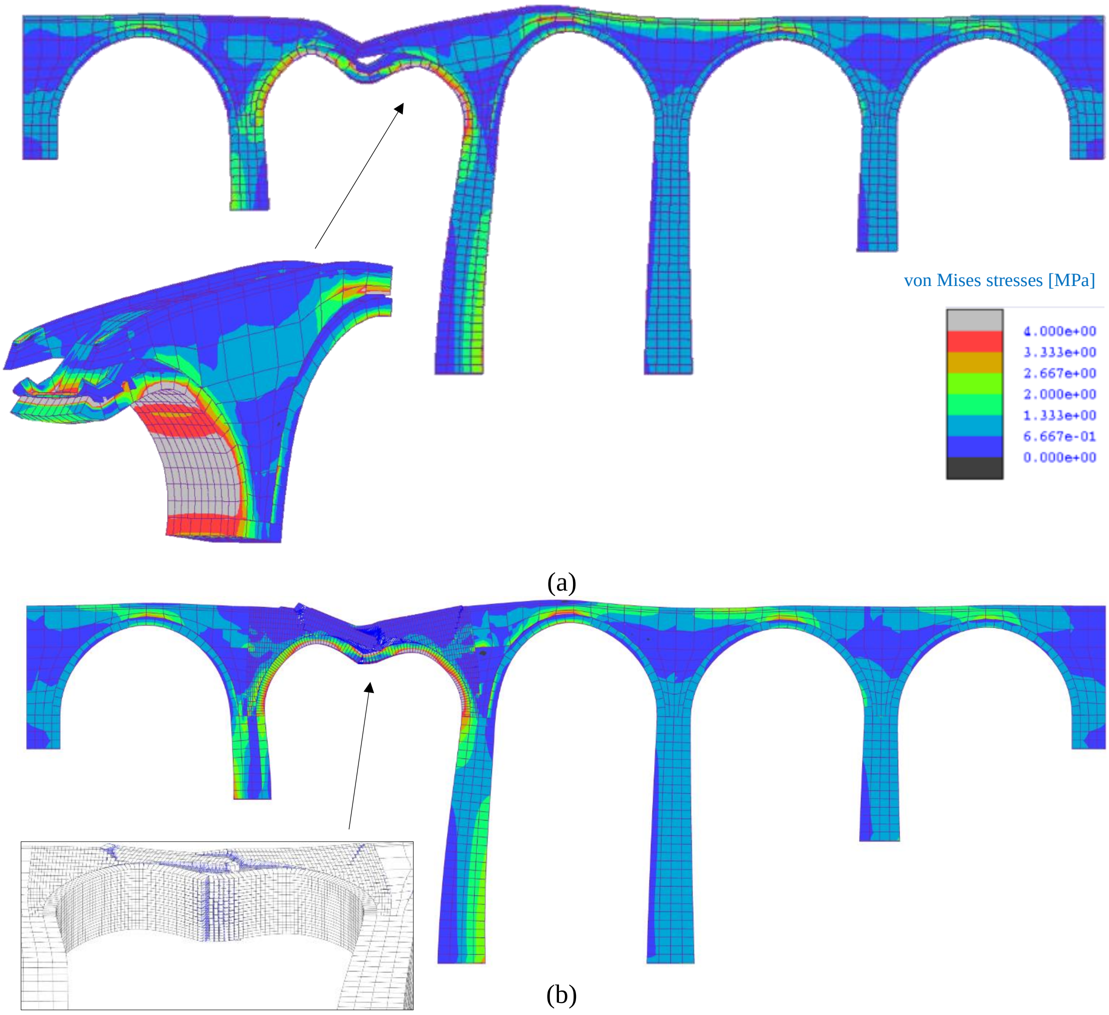
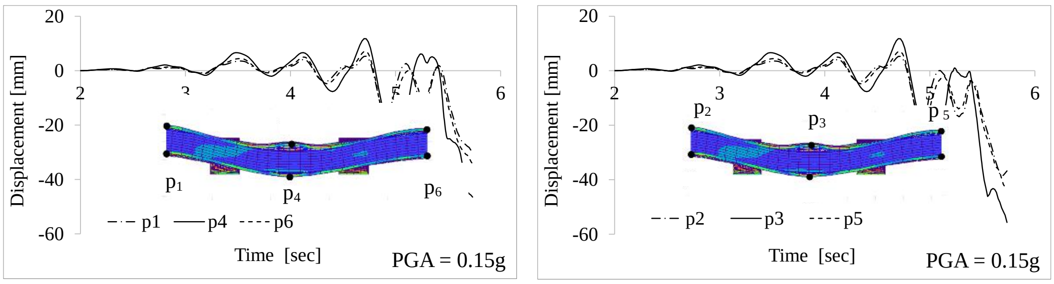


Figure 4: Failure mechanism of the bridge subjected to a vertical patch load applied at the middle of the second span predicted by the (a) macroscale and the (b) mesoscale model.

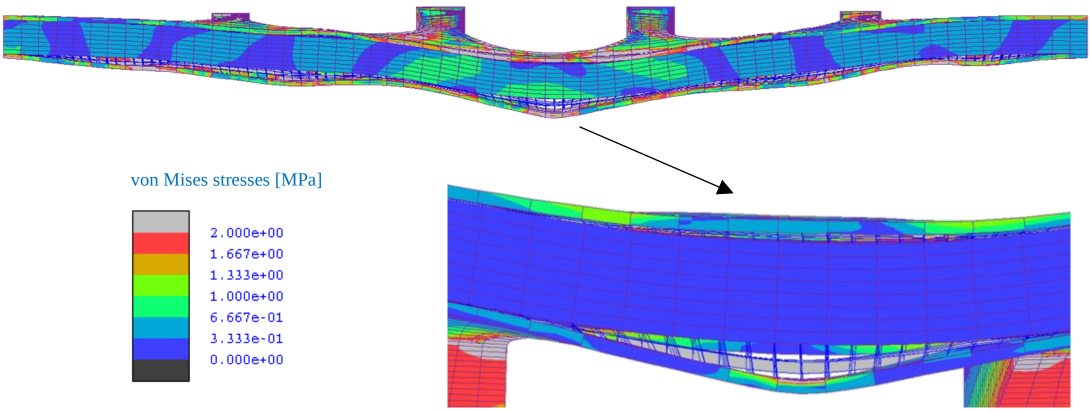
4 Conclusions and Contributions

The paper applies a novel 3D macroscale anisotropic masonry description to assess the performance of a masonry railway viaduct under different loading conditions, including earthquake ground accelerations. The accuracy of the macroscale predictions has been assessed by comparisons against detailed mesoscale simulations, considering simple loading scenarios with vertical patch loads first and then the dynamic nonlinear behaviour under earthquake loading.

The results from nonlinear static analyses under patch loading confirmed a good agreement between macroscale and the mesoscale models with close load-displacement curves and a very similar representation of the global failure mode mainly involving the loaded arch and the adjacent masonry piers. Subsequent nonlinear dynamic time-history analyses showed a complex 3D response and a failure mechanism of the viaduct characterised by the separation of the spandrel walls from the backfill and their independent out-of-plane response. This can be clearly seen by examining a set of displacement time histories at six points located at the top of the spandrel walls above the central piers and at the mid-length of the bridge (Figures 5a and 5b). Moreover, a pronounced torsional response of the piers can be observed (Figure 6). The results obtained confirm the potential of the adopted 3D modelling strategy with the novel anisotropic masonry model for the realistic assessment of masonry viaducts under different loading conditions, including earthquake actions.



(a)



(b)

Figure 5: (a) Displacement time-histories at different locations and (b) failure mechanism under earthquake loading.

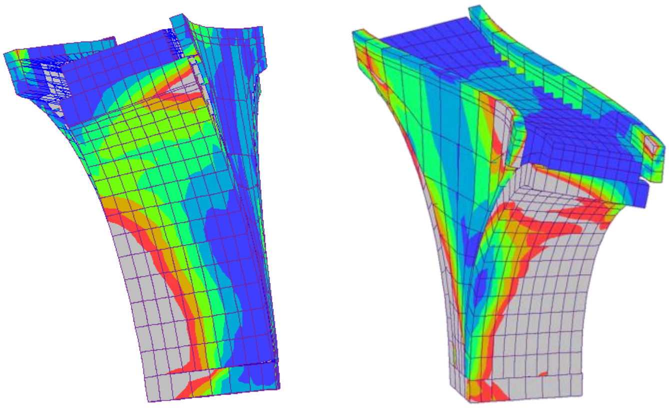


Figure 6: Torsion response of the piers under earthquake loading.

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