NUMERICAL INVESTIGATION ON THE DYNAMIC RESPONSE OF MASONRY BRIDGES UNDER EARTHQUAKE LOADING

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Abstract: *Masonry arch bridges represent vital infrastructure in many seismic regions worldwide. Most of these structures were built over one hundred years ago without being explicitly designed against earthquakes. Moreover, over the last decades, increasing traffic loadings and weathering effects exacerbated by climate change have accelerated masonry degradation. As a result, masonry bridges are potentially exposed to high seismic risk even in regions characterised by moderate seismicity. Therefore, accurate assessment is crucial to identify structures susceptible to severe damage and even collapse. This paper investigates the effects of some key geometric parameters on the dynamic response under increased seismic loading of the representative multi-span bridge. Incremental nonlinear time-history analyses are performed on 2D bridge models employing an efficient anisotropic continuum macroscale description for the masonry part of the bridge. The proposed methodology can be used for accurate seismic assessment of existing masonry bridges and viaducts.*

1 Introduction

Masonry arch bridges represent key transportation infrastructure components for many countries in seismic areas. Accurate assessment under seismic loading is vital to identifying vulnerable structures and addressing the design of effective retrofitting solutions. However, realistic structural assessment represents a complex task, since masonry bridges show a complex response affected by the nonlinear interaction between the different structural (arches, piers, spandrel walls) and non-structural (backfill) parts. Moreover, local failure mechanisms including spandrel wall failure (Forgács et al.; 2020; Panto' et al., 2022a) and shear cracking in the arch barrel (Melbourne et al., 2004; Panto' et al., 2022b) induced by the cyclic nature of the loading may adversely affect the seismic performance of the bridge structure.

Modelling strategies for rapid assessment of masonry bridges are mainly formulated following limit analysis principles (Gilbert et al., 2020; Zampieri et al., 2021). These computational approaches, however, do not enable accurate predictions under earthquakes, as they do not consider the dynamic nature of the loading and the effects due to the progressive masonry stiffness and strength degradation under seismic actions. Conversely, detailed nonlinear finite element (FE) mesoscale models allowing for an explicit representation of masonry bonds, where mortar joints and masonry units are modelled separately, can be used for realistic assessment of masonry bridges under general loading conditions, including seismic actions (Tubaldi et al., 2020; El Ashriet al., 2023). However, this detailed masonry mesoscale modelling requires superior computational resources and specialist users, thus it is not suitable for practical assessment. A refined macroscale modelling strategy for brick/block masonry has been recently developed (Panto' et al., 2022c). It considers an accurate representation of the anisotropic mesostructure of masonry, including the cohesive and frictional characteristics of the masonry joints and the degradation of strength and stiffness under cyclic loading. This model generally leads to realistic predictions of complex cracking patterns while guaranteeing computational efficiency. In addition, a practical and robust calibration procedure can be used to determine the material model parameters based on the mesoscale mechanical properties of bricks and masonry joints

(Panto' et al., 2022c), which can be easily obtained by non-destructive or low-invasive in-situ tests suitable for historical constructions and cultural heritage assets.

Previous research studied the effects of the main geometrical features of masonry bridges on the ultimate load capacity under static loading (Oliveira et al., 2010; De Arteaga et al., 2012). This paper investigates the effects of the bridge geometry on the seismic response using the macroscale model proposed by (Panto’ et al., 2022a,b) and implemented in the nonlinear FE program ADAPTIC (Izziddin, 1991). Nonlinear dynamic simulations have been carried out on different bridge structures varying three main geometrical ratios, namely the arch thickness-to-span, rise-to-span and pier height-to-width ratios, by considering different natural earthquake ground acceleration time-histories. The results indicate that all of the considered geometric ratios exhibit strong influence on the complex dynamic behaviour under realistic earthquake loading.

2 The continuum macroscale model used for the masonry

This study adopts a continuum anisotropic macroscale model for masonry. It has been formulated by Panto' et al. (2022c) to simulate the in-plane and out-of-plane response of masonry panels and subsequently extended to model masonry arches, vaults and masonry arch bridges (Panto' et al., 2022b). The model is based on a two-scale nonlinear description for the masonry material. A continuum strain field discretised by a standard FEM mesh is considered at the macroscale level, whilst a distribution of internal layers allows for the local anisotropic nature of brick/block masonry. A damage-plasticity constitutive model is employed to mechanically characterise the coupled response in tension and shear of each internal layer (Figure 1) considering three different yield surfaces (F_c, F_t, F_s) associated with masonry failure in compression, tension and shear along masonry joints (Figure 1). The main material parameters of the three yield functions comprise strengths in compression (f_c) and tension (f_t), the corresponding fracture energies (G_c,G_t), cohesion (c), friction (ϕ) and dilatancy (ϕ_g) angles. According to the calibration procedure described in (Panto' et al., 2022a,b), different material properties are used in each principal direction. Figure 2 shows the cyclic tension, shear and bending responses of a basic brick-masonry sample, as predicted by the macroscale model compared with a refined mesoscale representation (Panto' et al., 2022a). The accuracy and the efficiency of the adopted macroscale model in simulating the cyclic in-plane and out-of-plane responses of masonry panel and curved elements, like arches and vaults, were evaluated by Panto' et al. (2022 b,c) by comparing the response predicted by the macroscale model against experimental results from the literature.

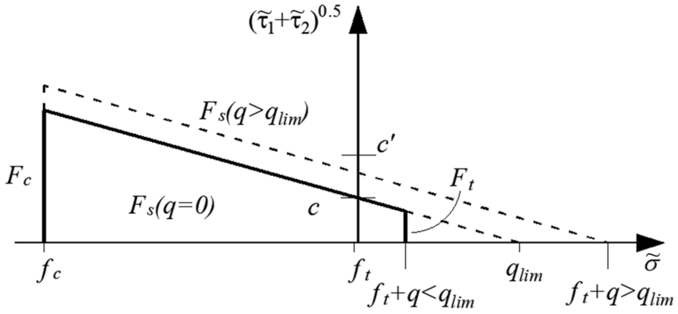
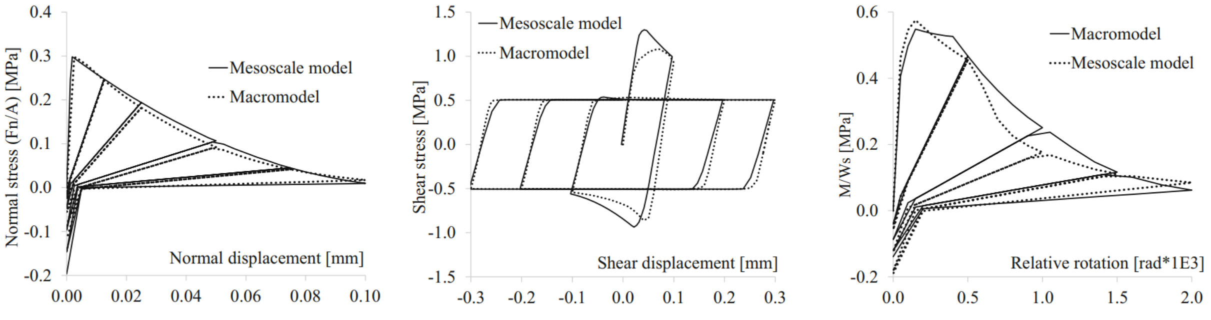


Figure 1. Nonlinear constitutive law adopted for the mechanical characterisation of the internal layers.



(a) (b) (c)

Figure 2. Mesoscale and macroscale cyclic responses of a basic brick-masonry sample under (a) tensile, (b) shear and (c) bending actions (Panto’ et al., 2022c).

3 Analysed structure

The case study considered in this paper corresponds to the three-span arch bridge specimen *Bridge-2* tested by Melbourne et al. (1997) and numerically investigated in Panto' et al. (2022b), where spandrel walls are detached from the arches to represent a damaged bridge. The bridge specimen is 2880 mm wide and characterised by the longitudinal geometry shown in Figure 3. The masonry of the specimen consists of class A engineering clay bricks with 154 MPa compression strength and 1:2:9 (cement:lime:sand) mortar with 2.4 MPa compression strength. The mechanical parameters of the brickwork and backfill obtained in material tests are described in Panto' et al. (2022b) and summarised in Table 1.

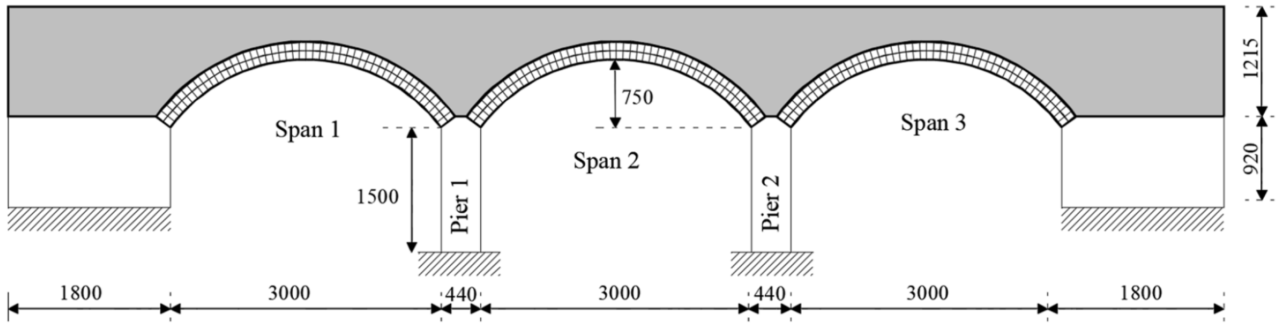


Figure 3. Geometrical layout of the experimental bridge model.

Table 1. Masonry mesoscale mechanical parameters.

Bricks		Mortar joints							
E [MPa]	ν [-]	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]	G_c [N/mm]
18500	0.15	400	167	0.20	16.00	0.29	0.05	0.05	1.00

Table 2. Masonry piers macroscopic mechanical parameters.

Piers and spandrel walls								
Direction	E_n [MPa]	E_t [MPa]	f_t [MPa]	f_c [MPa]	c [MPa]	G_c [N/mm]	G_t [N/mm]	G_s [N/mm]
Horizontal	10860	9240	0.05	26.8	0.29	5.0	0.05	0.125
Vertical	16160		0.65		Elastic		0.60	Elastic
Arches								
Direction	E_n [MPa]	E_t [MPa]	f_t [MPa]	f_c [MPa]	c [MPa]	G_c [N/mm]	G_t [N/mm]	G_s [N/mm]
Circumferential y	10860	9240	0.05	26.8	0.29	5.0	0.05	0.125
Transversal z	16160		0.65	26.8	0.58		0.60	0.250
Radial x	13353		Elastic					

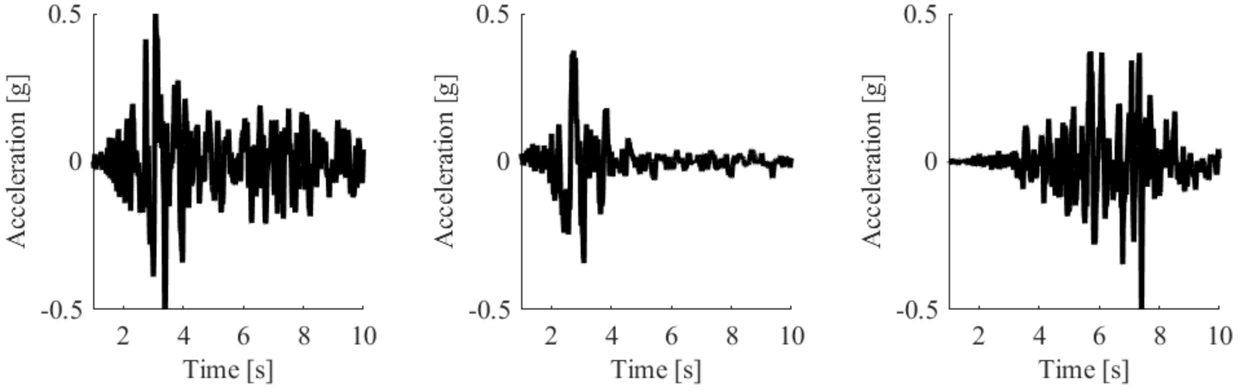
A strip model has been developed using the macroscale modelling approach described in Section 2, considering fixed supports at the base of the piers and preventing the horizontal displacements in the longitudinal direction on the two vertical end faces at the bridge abutments. More realistic boundary conditions at the two bridge ends could be obtained by including a more significant volume of soil domain interacting with the bridge or adopting advanced elements to simulate free-field boundary conditions (Zienkiewicz et al., 1988; Nielsen, 2006; Kontoe et al., 2007). The mechanical parameters of the anisotropic macromodel for the masonry arches and piers (as reported in Table 2) have been obtained by a simplified homogenization procedure (Panto' et al. 2022b), which transfers the mesoscale masonry characteristics to the model internal layers. The backfill is modelled using an elastoplastic Drucker-Prager model fitted to the inner edges of the Mohr-Coulomb yielding surface, with a Young's modulus of 50 MPa, Poisson's ratio of 0.20, cohesion of 0.003 MPa and friction and dilatancy coefficients of 0.95 and 0.45, respectively. The backfill-masonry physical interface is modelled by nonlinear interfaces with negligible cohesion (0.001 MPa) and a friction coefficient of 0.6 (Tubaldi et al., 2020b). Finally, specific weights of 22.4 kN/m^3 and 22.2 kN/m^3 are assumed for the masonry and backfill, respectively.

4 Parametric Analyses

This section reports the results of an extensive parametric study conducted assuming the bridge specimen described in Section 3 as the baseline model and varying the main geometrical parameters expressed by the three geometric ratios as reported in Table 3, where v_0 indicates the baseline values for the bridge specimen tested experimentally; v_{min} and v_{max} represent two additional values obtained by reducing and amplifying the initial values v_0. The geometrical ratios are changed one at a time, keeping the other two constant and equal to the values v_o. Each geometrical combination is analysed by performing time history analyses adopting three natural earthquakes: L'Aquila-Italy, 2009; Amatrice-Italy, 2016; Flagbjarnarholt-Island, 2000 (Figure 5), with amplification factors of 1.0 and 2.0 (Figure 4). Figure 5, Figure 6, and Figure 7 show the displacement time-histories at key sections on the central arch, considering each earthquake ground motion for the two amplification factors. Each figure includes three plots showing the influence of a single geometrical ratio. It is possible to observe that the arch rise-to-span and the pier height-to-width ratios are the most influential parameters that significantly affect the ultimate response under seismic loading. Finally, Figure 8 shows the failure mechanisms obtained considering the L'Aquila 2009 earthquake with 2.0 amplification factor. It can be observed that the different geometrical layouts lead to totally different failure modes. Moving from high to low arch rise-to-span ratios, the failure mechanism changes from flexural (with the activation of plastic hinges along with the arch span) to a shear failure at the arch supports.

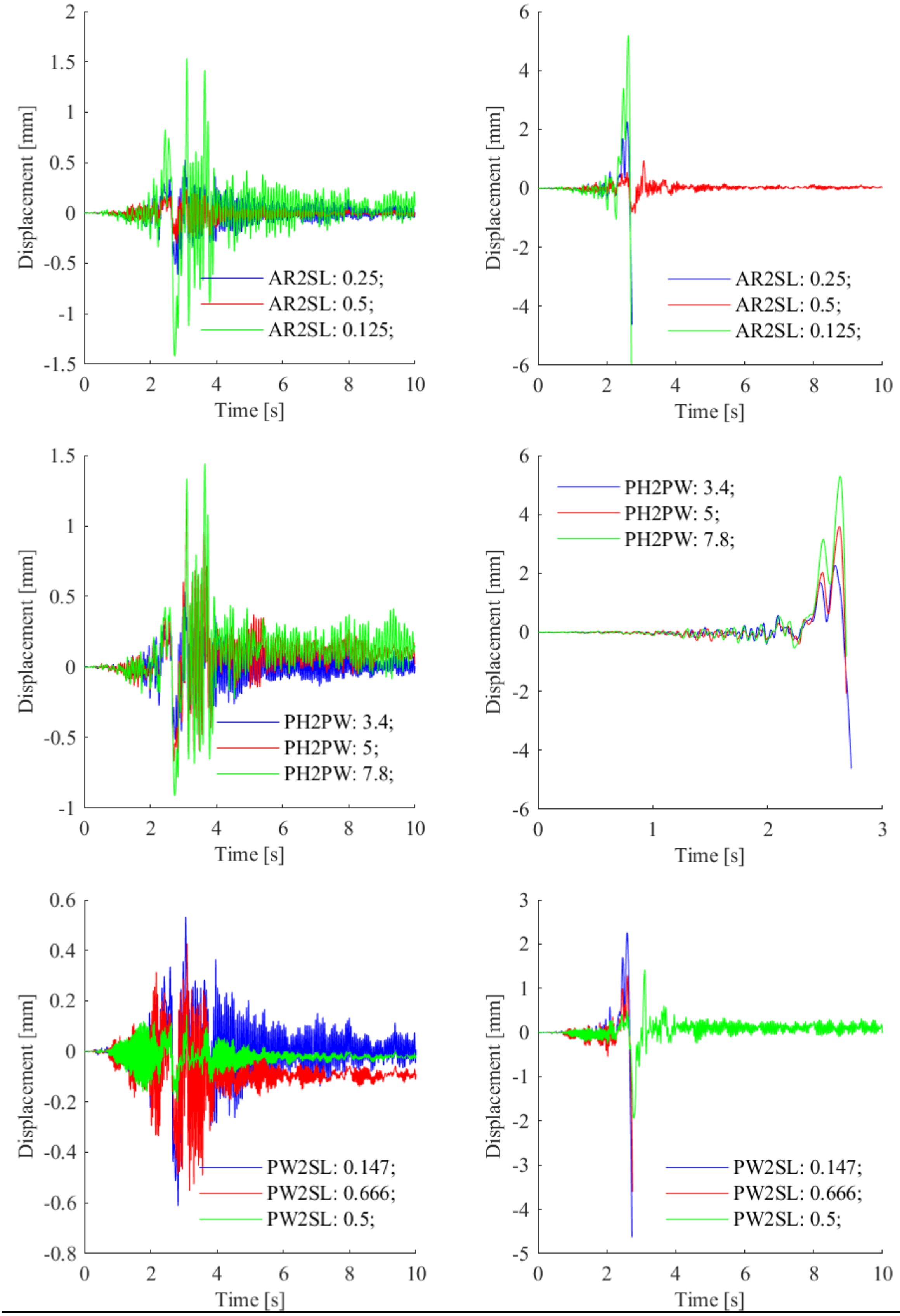
Table 3. Masonry piers macroscopic mechanical parameters.

Parameters	v_0	v_{min}	v_{max}
ρ_a = Arch rise / Arch span (AR2SL)	**0.25**	0.125	0.50
ρ_h = Pier height / Pier width (PH2PW)	**0.34**	5.00	7.80
ρ_w = Pier width / Arch span (PW2SL)	**0.15**	0.50	0.67



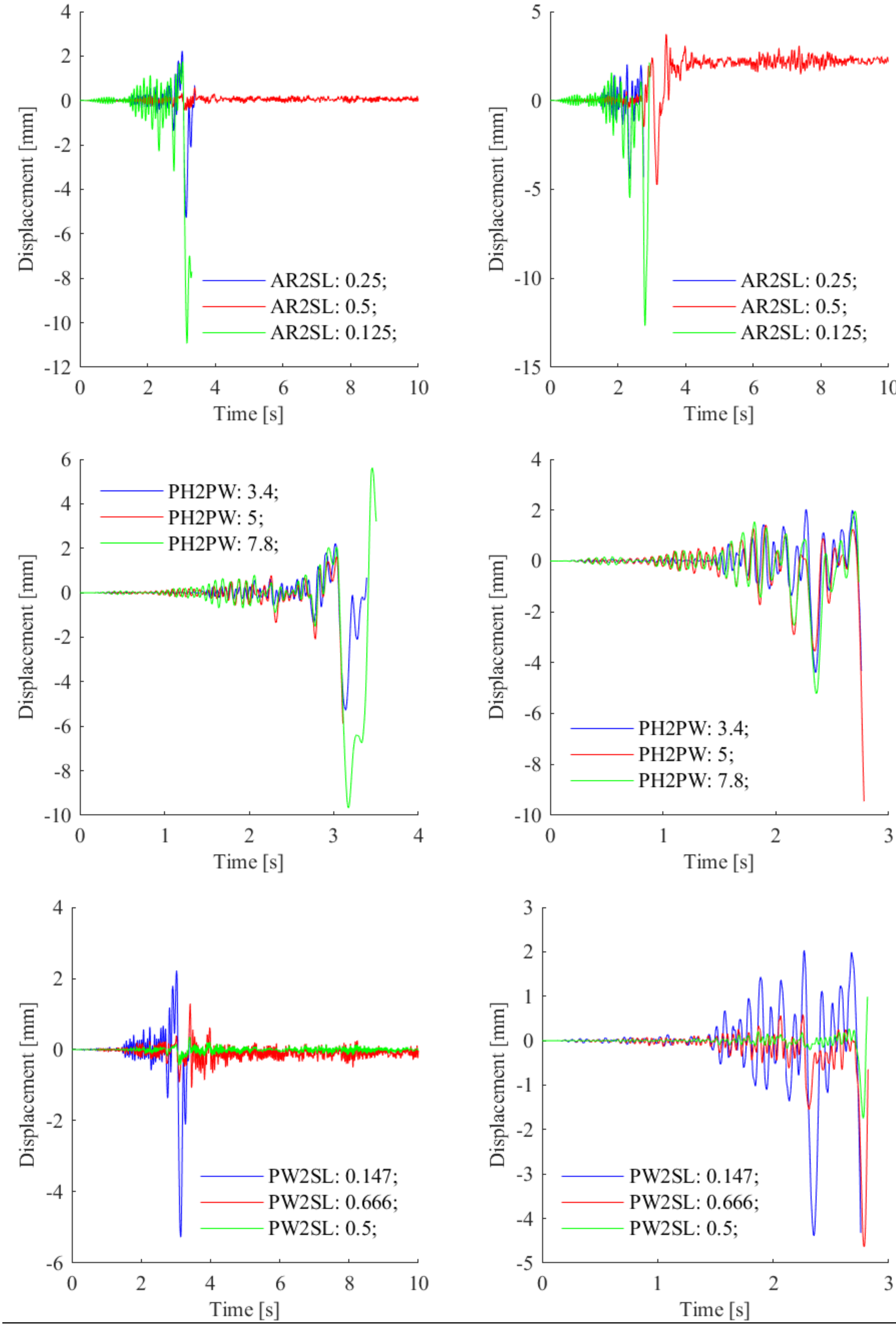
L'Aquila - 2009 Amatrice - 2016 Flagbjarnarholt - 2000

Figure 4. Seismic signals adopted in the analyses (amplification factor = 1.0).



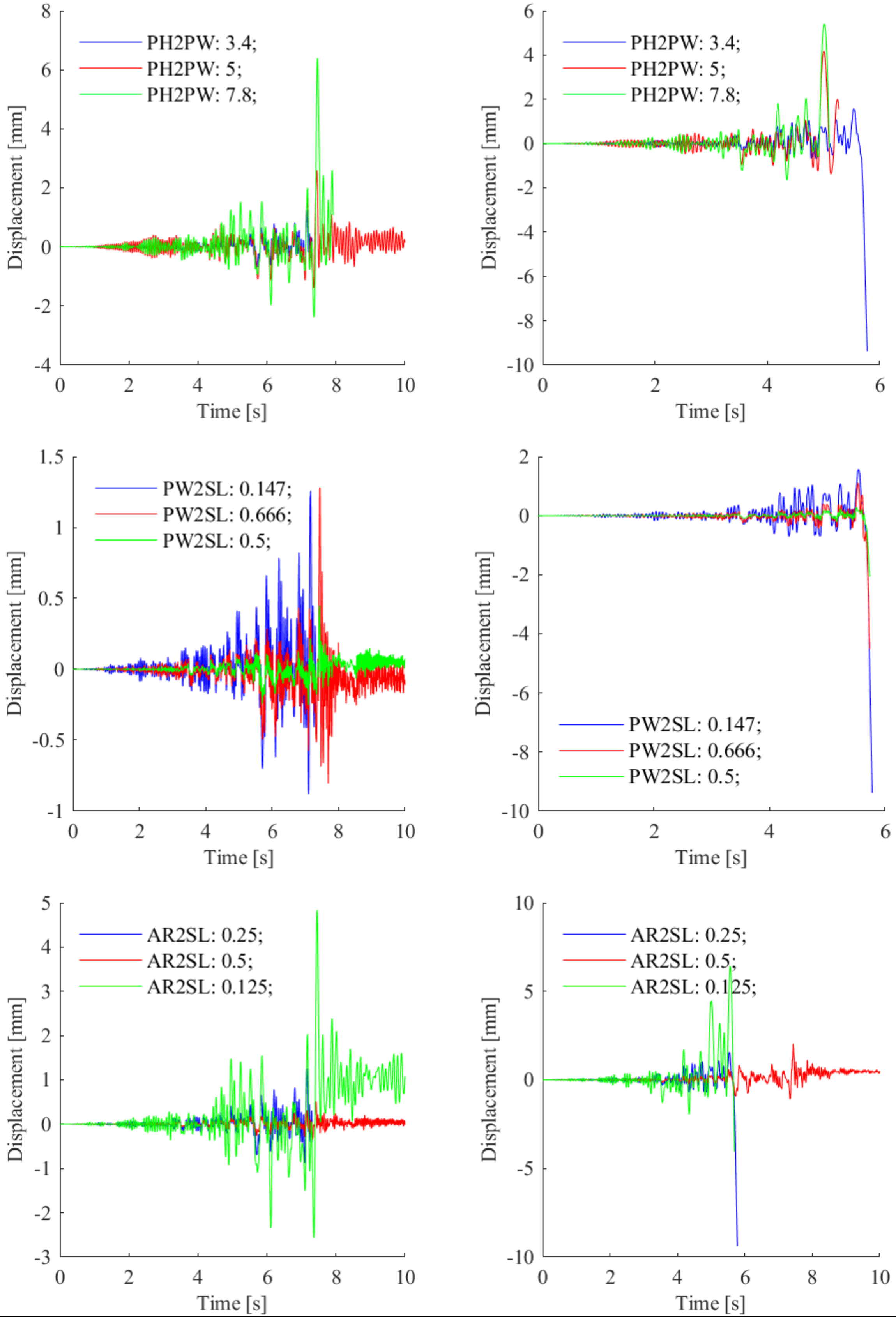
Amplification factor 1.0 Amplification factor 2.0

Figure 5. Displacement time-histories for the L'Aquila (2009) earthquake.



Amplification factor 1.0 Amplification factor 2.0

Figure 6. Displacement time-histories for the Amatrice (2016) earthquake.



Amplification factor 1.0 Amplification factor 2.0

Figure 7. Displacement time-histories for the Flagbjarnarholt (2000) earthquake.

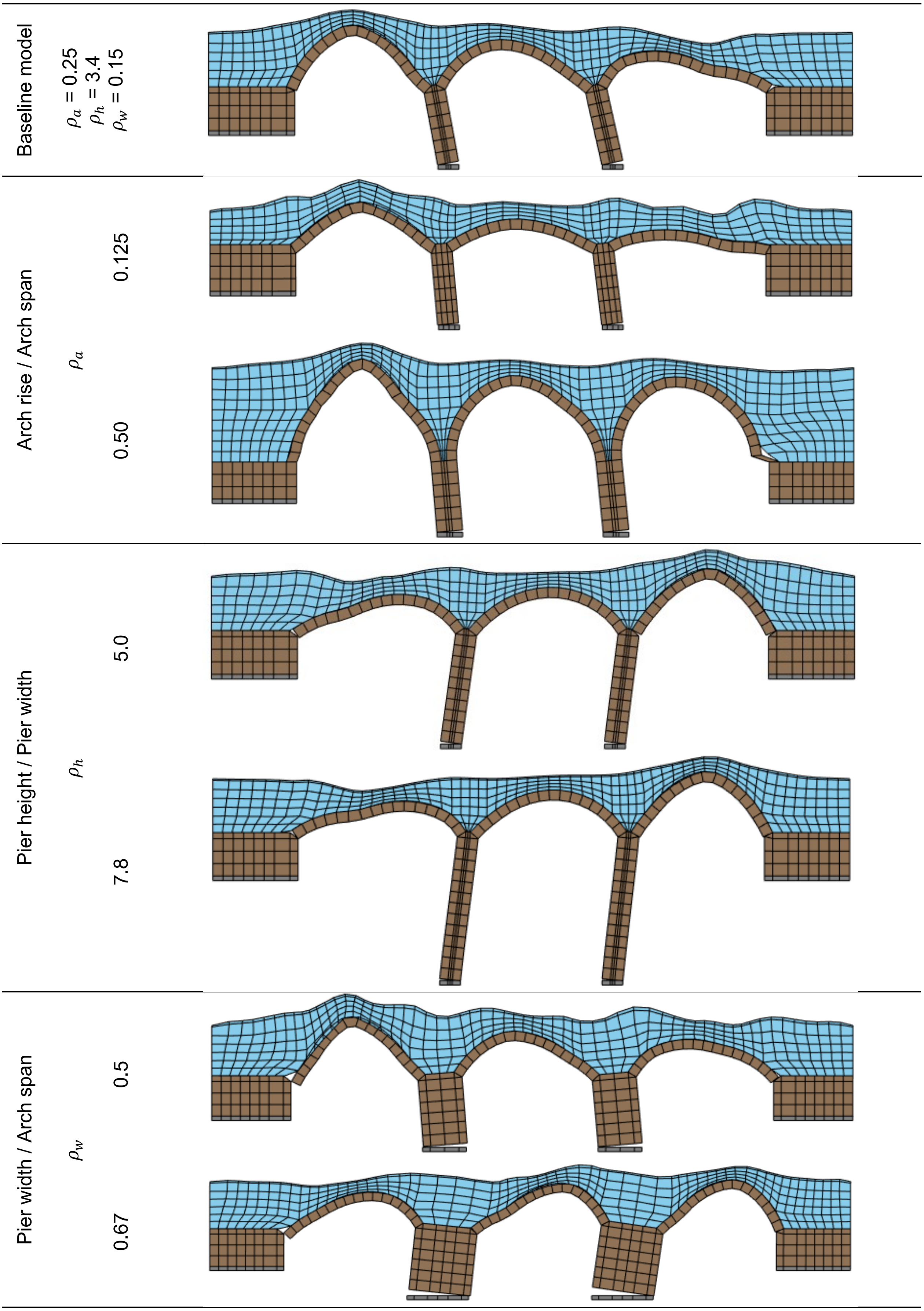


Figure 8. Failure mechanisms obtained considering L'Aquila earthquake (200%) for the different layouts.

5 Conclusions

In this paper, the effects of some key geometrical characteristics of multi-span masonry bridges on the behaviour under earthquake loading have been investigated. Nonlinear dynamic analyses have been conducted considering a 3-span masonry bridge sample previously studied both experimentally and numerically under vertical static loading. The bridge has been represented using a 2D model (assuming perfect confinement provided by detached spandrel walls). In the simulations, acceleration time-histories associated with the horizontal ground motion have been applied at the base of the piers and at the two vertical bridge ends and scaled by different amplification factors to simulate different earthquake intensities. The results obtained in terms of displacement time-histories and failure mechanisms allowed for the evaluation of the effects of each of the investigated geometrical parameters. Further analyses are planned to extend the present study including a broader range of earthquakes and more general boundary conditions for the analysed bridge structures.

6 References

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