

## MODELLING OF MASONRY INFILL WALLS WITH RUBBER JOINTS

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**Abstract:** *Many seismic events in Europe and the rest of the world have highlighted the high vulnerability of buildings' non-structural components such as building contents, infill and cladding walls, and services and utilities. The losses due to damage of these non-structural elements can exceed those from the structural damage. Recent numerical and experimental investigations have shown that specially shaped rubber joints, inserted between the masonry units and at the interface with the frame, provide a cost-effective means for minimizing the seismic damage to partition and infill walls in reinforced concrete structures. This paper describes a computational modelling strategy for describing the nonlinear response of masonry infill walls with rubber joints. The reinforced concrete frame is modelled with nonlinear solid elements with embedded longitudinal and transverse reinforcement. A macro-scale modelling approach is investigated for the rubber joints and the masonry components. The proposed numerical models are calibrated and validated against experimental tests carried out on masonry-infilled walls with and without rubber joints. The results demonstrate the effectiveness of the rubber joints not only in minimizing the earthquake damage of masonry infill walls, but also in enhancing the overall damping capacity of the infilled system. They also show that the proposed modelling strategy can be employed in investigating the optimal combination of strength, deformability and dissipation capacity in three orthogonal directions of the rubber devices.*

**Keywords:** Masonry infills, rubber-joints, non-structural component, finite element analysis.

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## Introduction

Seismic events throughout the world have demonstrated the high vulnerability of masonry infills in reinforced concrete frame structures. While structural members such as columns and beams are designed to be earthquake-resistant, masonry infills are often disregarded in design calculations, since they are treated as non-structural components. For this reason, masonry infills often undergo severe damage even under minor earthquakes, which may lead to injury and death of occupants as well as hampering the rescue operations. The economic loss can be considerable; studies (Villaverde 1997, Filiatrault and Sullivan 2014, Del Vecchio et al. 2018) have shown that the repair cost of infills may significantly exceed that of structural components.

In the last decades, significant research efforts have been directed towards the implementation of finite element (FE) models for simulating the complex interaction between infill walls and reinforced concrete frames (Mehrabi et al. 1997, Caliò et al. 2012, Mohyeddin et al. 2013, Caliò and Pantò 2014, Xavier et al. 2014, Zhai et al. 2016, El-Dakhakhni et al. 2016, Kubalski et al. 2016, Okail et al. 2016, Nasiri and Liu 2017, Panto et al. 2017, Breveglieri et al. 2018, Peng et al. 2018, Redmond et al. 2018). Different modelling approaches have been investigated, including macro modelling (Pietruszczak and Niu 1991, Caliò et al. 2012, Caliò and Pantò 2014, El-Dakhakhni et al. 2016, Panto et al. 2017), micro modelling (Panto et al. 2017) and meso-scale modelling (Lourenço and Rots 1997, Dolatshahi and Aref 2011, Macorini and Izzuddin 2011; 2013; 2014, Nasiri and Liu 2017).

More recent experimental and numerical studies have focused on the development of technological improvements for infill wall protection (Flanagan and Bennett 2001, Haach et al 2010, Minaie et al 2010, Akhoundi et al. 2014, Mojsilovic et al. 2015, Ahmadi et al. 2017, Redmond et al. 2018, Tsantilis and Triantafyllou 2018). The idea behind most of the proposed techniques is to increase the flexibility of the infill panel, and to isolate it from the surrounding frame through the introduction of soft layers. These can be horizontal layers inserted between the bricks or horizontal and vertical layers placed between the infill and the frame. Among the different materials that can be employed for the soft layers, rubber is the most promising, because of the wide range of behaviour in terms of stiffness and dissipation capacity it exhibits depending on the type of compound employed. In this regards, TARRC has recently patented an innovative rubber layer (Figure 1), with different stiffnesses along the three orthogonal directions. This is an essential requisite in order to achieve an optimal behaviour in the in-plane and out-of-plane directions. The effectiveness of the rubber joints was proved during the tests carried out within the EU project INSYSME (2016) on seismic protection of infill walls (Figure 2).



Figure 1. Horizontal rubber joints used by TARRC (Ahmadi et al. 2017).

The aim of this study is to develop an advanced three-dimensional modelling strategy for describing the dynamic behaviour of reinforced frames with traditional masonry infill walls and for evaluating the effectiveness of rubber joints for their protection. The proposed strategy, developed in Abaqus (Dassault Systemes 2017), is based on a meso-scale description of the masonry infills, and the use of zero-thickness interfaces for describing the behaviour of the mortar joints and the rubber layers. In the first part of the paper, the modelling approach is validated against experimental results carried out by Mehrabi et al. (1996) on a reinforced concrete frame with traditional masonry infills made of solid bricks under in-plane loading. In the second part of the study, the rubber layers are added to the model, and a parametric analysis is carried out to study the influence of their layout (horizontal layers only, horizontal and vertical layers) and stiffness on the in-plane behaviour. The results shed light on the effectiveness of the rubber layers in increasing the flexibility of the system and avoiding major damage in the masonry and the frame under drift demand levels typical of minor or moderate earthquakes.



Figure 2. Masonry wall with horizontal and vertical rubber joints tested within INSYSME project.

### Modelling strategy

The proposed modelling strategy employs material models and elements already available in a commercial FE software such as Abaqus (Dassault Systemes 2017). The reinforced concrete members of the frame are described with a continuum approach. In particular, 3D solid FEs are used to simulate the concrete material, and 3D beam elements for the reinforcing bars. The Concrete Damage Plasticity (CDP) model (Lee and Fenves 1998) is used to simulate the concrete constitutive behaviour. This model assumes cracking of the concrete in tension and crushing of concrete in compression as the two main failure mechanisms. The longitudinal and transverse reinforcement are rigidly embedded with the concrete bed through the “embedded element technique” (Dassault Systemes 2017). Bond-slip effects are disregarded, assuming perfect adherence at the bar-concrete interface. This may lead to the overestimation of the stiffness. The constitutive behaviour of the reinforcing bars is assumed to be elasto-plastic with kinematic hardening and the Von-Mises criterion defining the yielding condition.

The masonry infills are described employing a meso-scale approach. In this simplified approach, expanded units (masonry unit + half mortar joint thickness) are modelled as a series of continuum elements and the interaction between the expanded units along the bed and head joints is modelled through surface-to-surface cohesive behaviour. The initial response of the cohesive interfaces is linear elastic, followed by a cracking behaviour that describes the most critical failure modes of masonry joints, namely, tensile cracking and shear sliding. This description models the actual arrangement of masonry in the infill walls and the development of cracks in the mortar joints. The inelastic behaviour of the masonry units is also taken into account in a simplified way by employing the CDP model. Each brick units is modelled with 16 8-noded elements.

The rubber-mortar joints interface properties are described in a simplified way using surface-to-surface cohesive interfaces. These interfaces are characterized by different stiffness values along the three orthogonal directions. This accounts for the particular shape of the rubber layers, resulting in orthotropic behaviour (Figure 1). The shear stiffness of the rubber joints along the in-plane direction is low enough to accommodate the in-plane motion of the frame and the wall, whereas the transverse stiffness is higher to ensure the formation of an arching mechanism under out-of-plane conditions (Ahmadi et al. 2017). Figure 2 shows the infill wall with rubber joints tested within the INSYSME project (2016).

### Case study description

This section describes a case study to evaluate the capabilities of the proposed modelling strategy for simulating the behaviour of reinforced concrete frames with masonry infill walls. Reference is made to the experimental tests of Mehrabi et al. (1996), and to the ensuing numerical study (Mehrabi et al., 1997). Specimen 1 (bare frame) and specimen 3 (infilled frame) of the experimental campaign are considered. The height/length ( $h/L$ ) ratio of the frames is  $2/3$ . The infill panels are made with solid concrete masonry blocks arranged in a running bond pattern (Figure 3). The bed joints are fully filled with mortar, whereas the head joints are only partially filled with mortar. The bed and head joints are 9.5 mm thick. Some details regarding the frame, including

the concrete member sizes, rebar diameter and detailing scheme and masonry block dimensions, are given in Figure 3. Further details are available in Mehrabi et al. (1996). Experimental tests were carried out by Mehrabi et al. (1996) on the bare frame as well as on the infilled frame. The tests consisted of the application of vertical loads (146.8 kN at the top of each column, simulating the effect of permanent loads acting on the frame, followed by in-plane horizontal loads (monotonically increasing) applied at the beam extreme, as shown in Figure 3.

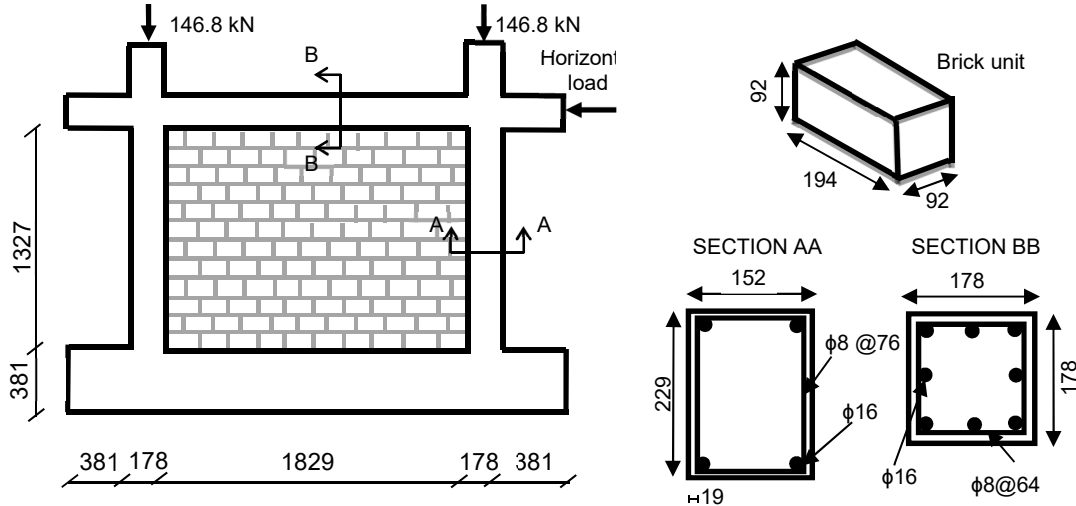


Figure 3. Geometric details of the infilled frame (dimensions in mm).

**Numerical model and validation study**

The FE models of the bare frame and infilled frame have been developed by following the approach outlined in the previous section. The main mechanical properties of the concrete material employed for the frame components and brick units are reported in Table 1. The steel used for the reinforcements has a Young’s modulus of 210000 MPa, a Poisson ratio of 0.3, a yield strength of 400 MPa, and a post-elastic to elastic stiffness of 0.002. The properties of the zero-thickness interface elements describing the mortar joints are reported in Table 2. Most of the values reported in Table 1 and Table 2 are based on the results of the experimental tests carried out by Mehrabi et al. (1997), e.g. on the concrete and mortar samples, and masonry units and prisms. Where not available, the values for the parameters have been taken from the literature (e.g. Lourenço 1997). The head joints have been given different properties to account for the fact that they were only partially infilled with mortar. The wall to frame mortar interfaces have been assigned the same properties as the head joints.

Mechanical properties	Frame	Brick units
Young’s modulus (MPa)	21930	9520
Compressive strength (MPa)	30.9	15.59
Peak tensile strength (MPa)	3.29	1.57
Fracture energy in tension (MPa·mm)	0.09	0.07
Poisson’s ratio (-)	0.18	0.15

Table 1. Mechanical properties of concrete for frame components and brick units.

Mortar Interaction Properties	Bed joints	Head joints
Friction coefficient (-)	0.9	0.7
Contact stiffness (N/mm <sup>3</sup> )	500	500
Normal stiffness (N/mm <sup>3</sup> )	500	500
Shear stiffness (N/mm <sup>3</sup> )	250	250
Normal fracture energy (MPa·mm)	0.015	0.005
Shear fracture energy (MPa·mm)	0.09	0.07

Table 2. Properties of the contact interfaces describing the mortar joints

After applying the vertical static loads at the top of the columns, an in-plane horizontal displacement was applied incrementally to the end of the beam (see Figure 3). The beam-end was free to deflect in the vertical and out-of-plane horizontal directions. Figure 4a shows the

deformed shape of the bare frame (specimen 1) for a horizontal displacement of 50mm, and Figure 4b compares the experimental and numerical force-deformation curves. The overall agreement is good, but it can be observed that the proposed model overestimates the initial stiffness of the system. This is thought to be because the compliance due to the slip behaviour between the steel reinforcement and concrete, has been neglected. In the same figure, the numerical curve according to model developed by Mehrabi et al. (1997) is plotted for the sake of comparison.

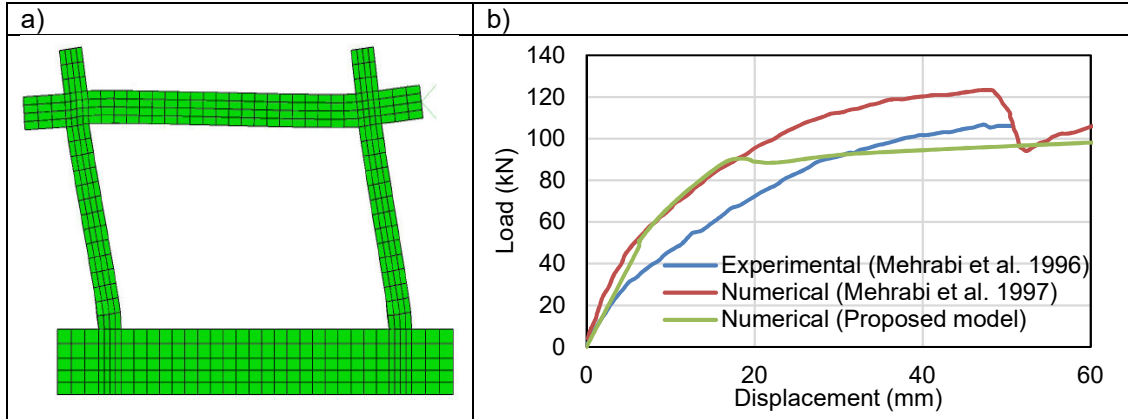


Figure 4. a) Plastic deformations in the bare frame b) Comparison between load-displacement curves for bare frame.

Figure 5a shows the deformed shape and cracking pattern of the masonry infilled wall for a horizontal displacement of 13 mm, corresponding to a drift of about 1%. It can be observed that the horizontal load induces the formation of several diagonal cracks in the wall. Figure 5b illustrates and compares the experimental and numerical force-displacement curves obtained for the infilled frame. Again, the proposed model describes the initial as well as the post-peak behaviour of the wall with good accuracy.

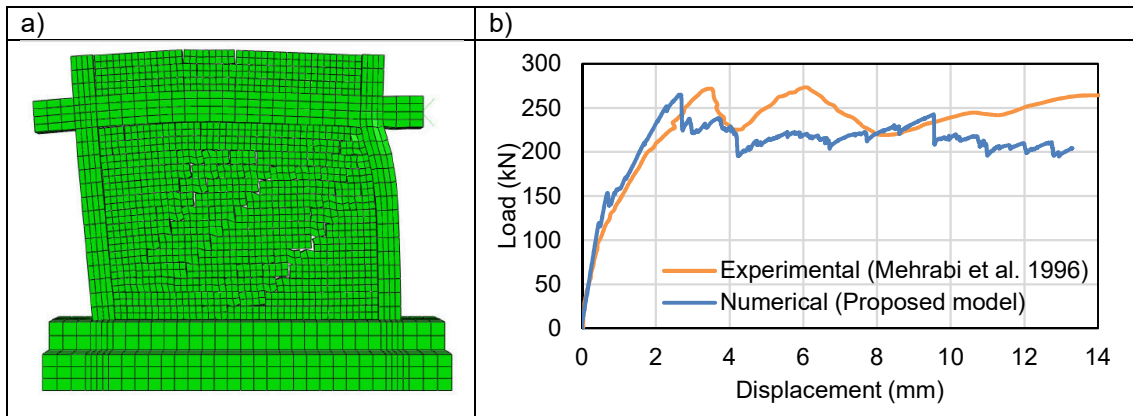


Figure 5. a) Simulated cracking pattern of the masonry infill wall, b) Comparison between numerical and experimental load-displacement curves.

Figure 6 shows a contour plot of the maximum principal compressive stress in the masonry and concrete components for a horizontal displacement of 10 mm (0.7% drift). The maximum value of principal compressive stress in the masonry units is of the order of 11 MPa, which is only slightly less than the compressive resistance of the bricks. The plot of the plastic deformations, not shown due to space constraint, indicates that the frame and many bricks are significantly damaged.

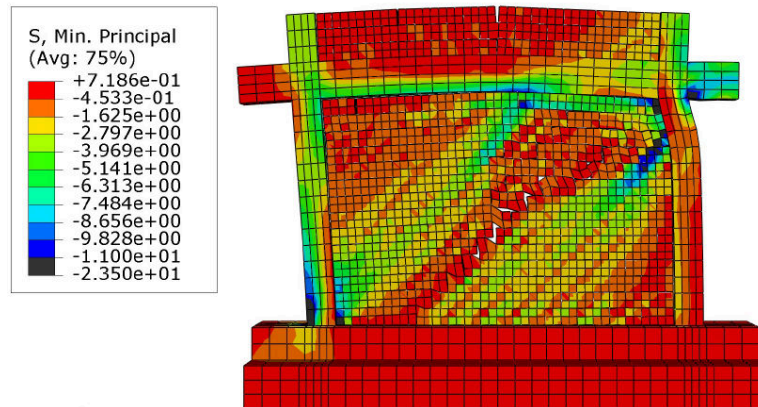


Figure 6. Maximum principal compressive stress distribution for a horizontal displacement of 10 mm (0.7% drift).

### Infill frames with rubber joints

In this section, the effectiveness of rubber joints for the seismic protection of masonry infills is investigated by considering different cases, corresponding to the use of horizontal joints only (IFR\_H) or horizontal and vertical joints (IFR\_HV). The horizontal layers of rubber joints are introduced between three or four courses of units and the vertical layers are introduced between the masonry infill and the frame, as shown Figure 7. These rubber joints are characterised by high compression stiffness in the vertical direction and low shear stiffness and high deflection capacity in the in-plane direction in order to reduce the displacement demand in the infill. Similarly, the vertical rubber joints, which may be manufactured from a different rubber material, are characterised by a low compression stiffness to accommodate the relative displacements between the infill blocks and the frame, and thus minimize the stresses between the frame columns and the masonry infill itself. In order to investigate the effect of the stiffness of the vertical rubber layer, two further sub-cases are considered, where the rubber stiffness is increased by 10 times (IFR\_HV\_High) and decreased by 10 times (IFR\_HV\_Low) with respect to the IFR\_HV case. The properties of the cohesive interfaces representing the rubber joints, reported in Table 3, have been evaluated by following the indications of Ahmadi et al. (2017) and considering a shear modulus of 0.5MPa and a thickness of 7.5 mm.

Interaction properties	Horizontal layer	Vertical layer		
		IFR_HV	IFR_HV_High	IFR_HV_Low
Friction coefficient (-)	0.5	0.3	0.3	0.3
Contact stiffness (N/mm <sup>3</sup> )	10	10	100	1
Normal stiffness (N/mm <sup>3</sup> )	10	10	100	1
Shear stiffness (N/mm <sup>3</sup> )	0.067	-	-	-
Normal fracture energy (MPa·mm)	0.005	-	-	-
Shear fracture energy (MPa·mm)	0.05	-	-	-

Table 3. Interaction properties of the rubber joints.

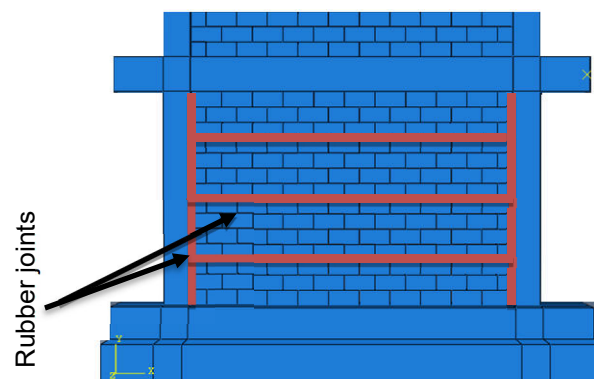


Figure 7. Masonry infilled walls with horizontal and vertical rubber joints.

Figure 8a shows the deformed shape of the infilled frame with horizontal, but no vertical, rubber joints. In this case no mortar joints have been modelled between the columns and the wall; the corresponding interfaces have only frictional behaviour, with very high stiffness to avoid penetration along the normal direction. The addition of the rubber joints is found to enhance the compliance of the infill wall, and it can be observed that most of the deformations/sliding is located at these joints. Figure 8b shows the load-deflection curve of the system with horizontal rubber joints, compared to the curves obtained for the bare frame and the frame with traditional infills. From the plots, it is possible to appreciate the remarkable flexibility of the system with rubber joints, which is quite close to the one of the bare frame. This reduction of stiffness also limits the absolute accelerations in the system under seismic excitation, which in turn improves the behaviour of acceleration-sensitive components.

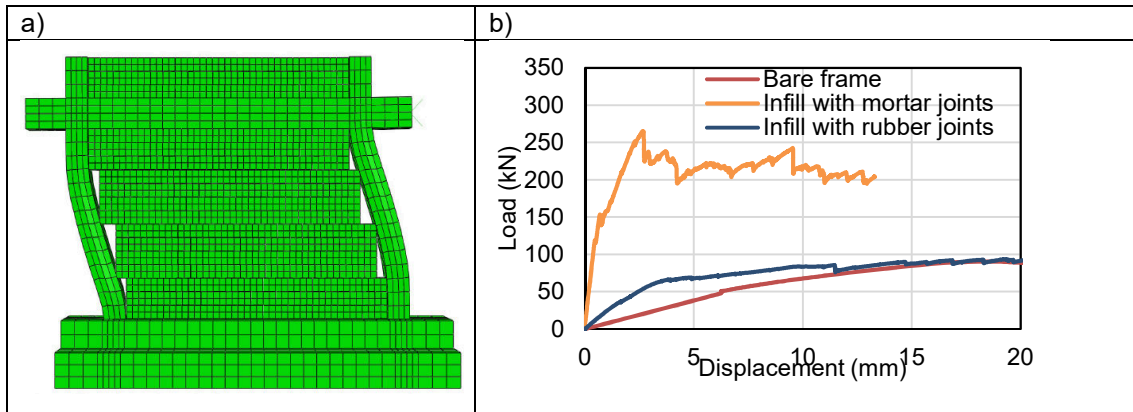


Figure 8. a) Deformed shape of infill walls with rubber joints, b) Force vs. displacement curve for with and without consideration of horizontal rubber joints.

Figure 9a shows the maximum principal compressive stress distribution in the concrete and masonry components for a horizontal deflection of 10 mm (0.7% drift). These stresses are significantly lower compared to the case of the frame with traditional infill (see Figure 6). The plot of the plastic deformations, not shown here due to space constraints, also confirms that the effectiveness of the rubber joints in minimizing the damage to the masonry components, with only few bricks at the infill corners experiencing localized damage.

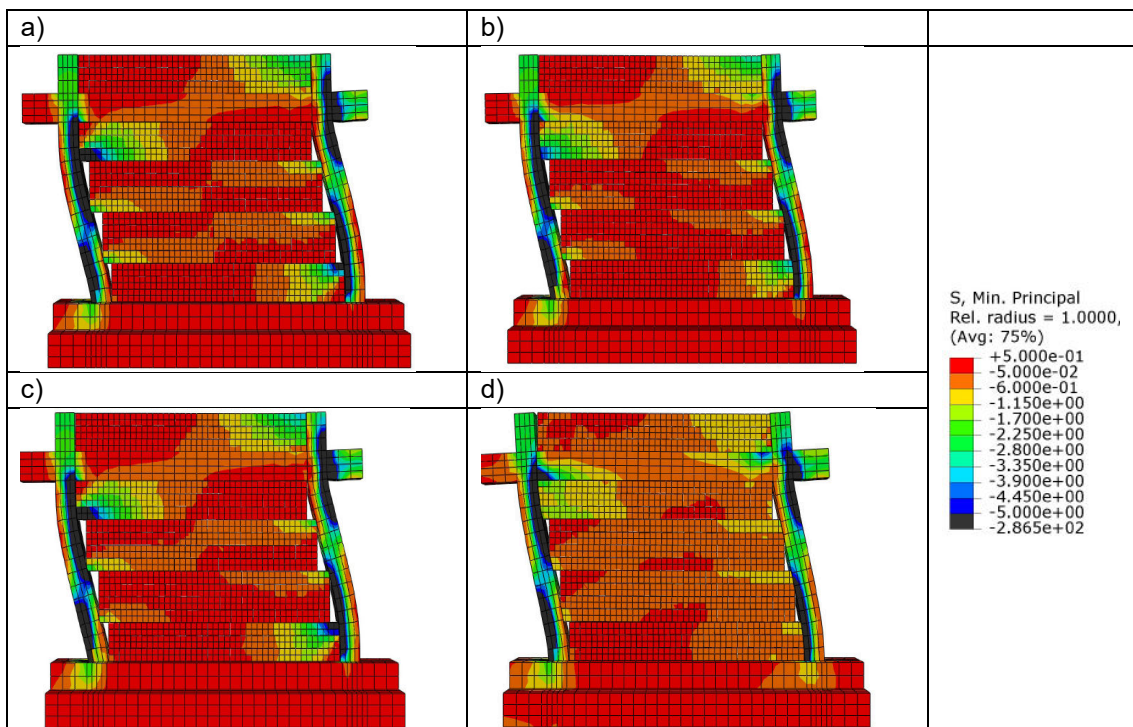


Figure 9. Maximum principal compressive stress distribution for a) IFR\_H b) IFR\_HV c) IFR\_HV\_High d) IFR\_HV\_Low for a horizontal displacement of 10 mm (0.7% drift).

In order to evaluate the effect of the vertical rubber joints on the system behaviour, Figure 10 shows the plot of the horizontal force-deflection curve for the different cases considered. It can be observed that adding the vertical rubber joints does not change significantly the global behaviour of the system compared to the case with only horizontal rubber joints. Thus, the only effect of adding the vertical rubber joints is to reduce the compressive stress in the bricks adjacent to the frame, without affecting significantly the global force-displacement response. This can be observed in Figure 9. Decreasing the stiffness of the vertical rubber joints has a beneficial effect in reducing the peak compressive stress.

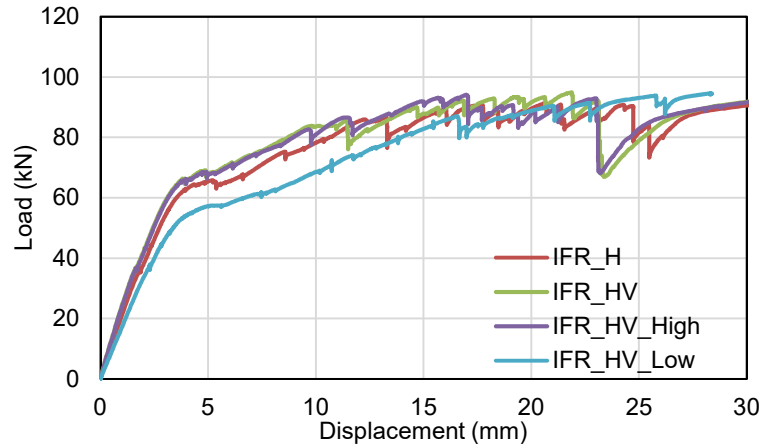


Figure 10. Comparison of rubber joints with various layouts and stiffness.

## Summary and Conclusions

In this study, an advanced meso-scale approach is developed for simulating the response of masonry infill walls with rubber joints under horizontal loads such as those induced by earthquakes. In the first part of the paper, the proposed model is validated by simulating experimental results carried out on a reinforced concrete frame with traditional infills. In the second part of the paper, the case of infill with horizontal and vertical rubber joints is considered. The results show that adding the rubber joints significantly increases the compliance of the system, and protects the infills and the frame from damage. Moreover, using vertical rubber joints with low stiffness in addition to the horizontal ones allows to further improve the behaviour in terms of reduction of stresses in the masonry units, while providing global response similar to the case with only horizontal joints.

The proposed modelling strategy will be employed in future studies to investigate the combined in-plane and out-of-plane behaviour and the optimal combination of strength, deformability and dissipation capacity in three orthogonal directions of the rubber devices for enhancing the seismic performance for a wide variety of infilled frames.

## References

- Ahmadi H, Dusi A and Gough J (2017), A Rubber-Based System for Damage Reduction in Infill Masonry Walls. In *16th World Conference on Earthquake Engineering, 16WCEE* (pp. 9-13).
- Akhoundi F, Lourenço PB and Vasconcelos G (2014), Numerical modelling of masonry-infilled reinforced concrete frames: model calibration and parametric study. In *9th International Masonry Conference (9IMC2014)* (pp. 1-13). Universidade do Minho.
- Breveglieri M, Camata G and Spacone E (2018), Strengthened infilled RC frames: Continuum and macro modeling in nonlinear finite element analysis. *Composites Part B: Engineering*, 151:78-91.
- Caliò I and Pantò B (2014), A macro-element modelling approach of Infilled Frame Structures. *Computers & Structures*, 143: 91-107.
- Caliò I, Marletta M and Pantò B (2012). A new discrete element model for the evaluation of the seismic behaviour of unreinforced masonry buildings. *Engineering Structures*, 40: 327-338.
- Dassault Systemes (2017). Abaqus. Retrieve from <http://www.3ds.com/products-services/simulia/products/abaqus/>, (Accessed on April 2019).

- Del Vecchio C, Di Ludovico M, Pampanin S and Prota A (2018), Repair costs of existing RC buildings damaged by the L'Aquila earthquake and comparison with FEMA P-58 predictions. *Earthquake Spectra*, 34(1): 237-263.
- Dolatshahi KM and Aref AJ (2011), Two-dimensional computational framework of mesoscale rigid and line interface elements for masonry structures, *Engineering Structures*, 33:3657–67.
- El-Dakhakhni WW, Drysdale RG and Khattab MM (2006). Multilaminate macromodel for concrete masonry: Formulation and verification, *Journal of Structural Engineering*, 132(12): 1984-1996.
- Filiatrault A and Sullivan T (2014), Performance-based seismic design of nonstructural building components: The next frontier of earthquake engineering, *Earthquake Engineering and Engineering Vibration*, 13(1): 17-46.
- Flanagan RD and Bennett RM (2001). In-plane analysis of masonry infill materials. *Practice Periodical on Structural Design and Construction*, 6(4): 176-182.
- Haach VG, Vasconcelos G and Lourenço PB (2009), Experimental analysis of reinforced concrete block masonry walls subjected to in-plane cyclic loading, *Journal of structural engineering*, 136(4): 452-462.
- INSYSME: Innovative systems for earthquake resistant masonry enclosures in RC buildings, FP7-SME-2013–606229.Website: www.insysme.eu, 2016.
- Kubalski T, Marinković M and Butenweg C (2016), Numerical investigation of masonry infilled RC frames. In *16th International Brick and Block Masonry Conference, Padova, Italy* (pp. 1219-1229).
- Lee J and Fenves GL, (1998), Plastic-damage model for cyclic loading of concrete structures. *Journal of engineering mechanics*, 124(8): 892-900.
- Lourenço PB, and Rots JG (1997). Multisurface interface model for analysis of masonry structures. *Journal of engineering mechanics*, 10.1061/ (ASCE) 0733- 9399, 123(7): 660–668.
- Lourenço PJBB. (1997), Computational strategies for masonry structures, PhD Dissertation, Delft University of Technology, Holland.
- Macorini L and Izzuddin BA (2014), Nonlinear analysis of unreinforced masonry walls under blast loading using mesoscale partitioned modelling, *Journal of Structural Engineering*, 140(8): A4014002.
- Macorini L and Izzuddin BA (2011), A non-linear interface element for 3D mesoscale analysis of brick-masonry structures. *Int. J. Numer. Methods Eng.*, 85(12): 1584–1608.
- Macorini L and Izzuddin BA (2013), Nonlinear analysis of masonry structures using mesoscale partitioned modelling, *Advances in engineering software*, 60: 58-69.
- Mehrabi AB and Shing PB (1997), Finite element modelling of masonry-infilled RC frames, *Journal of structural engineering*, 123(5): 604-613.
- Mehrabi AB, Benson Shing P, Schuller MP and Noland JL (1996), Experimental evaluation of masonry-infilled RC frames, *Journal of Structural engineering*, 122(3): 228-237.
- Minaie E, Mota M, Moon FL and Hamid AA (2010), In-plane behavior of partially grouted reinforced concrete masonry shear walls. *Journal of Structural Engineering*, 136(9): 1089-1097.
- Mohyeddin A, Goldsworthy HM and Gad EF (2013), FE modelling of RC frames with masonry infill panels under in-plane and out-of-plane loading, *Engineering Structures*, 51: 73-87.
- Mojsilović N, Petrović M and Anglada XR (2015), Masonry elements with multi-layer bed joints: Behaviour under monotonic and static-cyclic shear, *Construction and Building Materials*, 100: 149-162.
- Nasiri E and Liu Y (2017), Development of a detailed 3D FE model for analysis of the in-plane behaviour of masonry infilled concrete frames, *Engineering Structures*, 143: 603-616.
- Okail H, Abdelrahman A, Abdelkhalik A and Metwaly M (2016), Experimental and analytical investigation of the lateral load response of confined masonry walls, *HBRC Journal*, 12(1): 33-46.
- Pantò B, Caliò I and Lourenço PB (2017), Evaluation of the Seismic Vulnerability of Infill Frame Structures. *Atti del XVII Convegno ANIDIS L'ingegneria Sismica in Italia*, 24-32.
- Peng Q, Zhou X and Yang C (2018), Influence of connection and constructional details on masonry-infilled RC frames under cyclic loading. *Soil Dynamics and Earthquake Engineering*, 108: 96-110.
- Pietruszczak S and Niu X (1992), A mathematical description of macroscopic behaviour of brick masonry. *International journal of Solids and Structures*, 29(5): 531-546.
- Redmond L, Stavridis A, Kahn L and DesRoches R (2017), Finite-element modeling of hybrid concrete-masonry frames subjected to in-plane loads. *Journal of Structural Engineering*, 144(1), p.04017178.
- Tsantilis AV and Triantafyllou TC (2018), Innovative seismic isolation of masonry infills using cellular materials at the interface with the surrounding RC frames. *Engineering Structures*, 155: 279-297.

- Villaverde R (1997) , Seismic design of secondary structures: state of the art. *Journal of structural engineering*, 123(8): 1011-1019.
- Xavier FB, Macorini L and Izzuddin BA (2014) , Robustness of multistory buildings with masonry infill, *Journal of Performance of Constructed Facilities*, 29(5): B4014004.
- Zhai C, Kong J, Wang X and Chen Z (2016), Experimental and finite element analytical investigation of seismic behavior of full-scale masonry infilled RC frames. *Journal of Earthquake Engineering*, 20(7):1171-1198.