Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 45-55

ECCOMAS
Proceedia

COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

NUMERICAL MODELLING OF MASONRY-INFILLED RC FRAMES WITH RUBBER JOINTS

Prateek K. Dhir[1], Enrico Tubaldi[2], Hamid Ahmadi[3], and Bartolomeo Panto[4]

[1*] Department of Structures for Engineering and Architecture, University of Naples Federico II, Italy.
e-mail: prateek.dhir@strath.ac.uk

[2] Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, UK.
e-mail: enrico.tubaldi@strath.ac.uk

[3] Tun Abdul Razak Research Centre (TARRC), Brickendonbury, Hertford, UK.
e-mail: hahmadi@tarrc.co.uk

[4] Department of Engineering, Durham University, UK.
e-mail: bartolomeo.panto@durham.ac.uk

Abstract

Numerous models have been developed in the last decades for enhancing the seismic performance of masonry infills. In the present study, two alternative approaches are adopted to evaluate and compare the performance of masonry-infilled frames with and without rubber joints under in-plane loading. The first approach is based on a simplified two-dimensional macro-element model for defining the in-plane behavior of infills. The proposed macro modeling approach is embedded within Open-Sees. The second approach is based on a mesoscale description of the masonry infill, developed using ABAQUS. The proposed modeling strategies are calibrated and validated against quasi-static tests carried out in the past on the traditional infilled reinforced concrete (RC) frames and modified infills with mortar-rubber-mortar joints. The study results demonstrate the effectiveness of the rubber joints in enhancing the in-plane behavior of masonry-infilled frames and provide useful insight into the capability and accuracy of the two modeling approaches.

Keywords: Masonry infill, rubber-joints, non-structural component, finite element analysis, sliding joints.

doi: 10.7712/120123.10385.20714

1 INTRODUCTION

Masonry infills have always demonstrated their vulnerability in RC-framed structures, as repeatedly evidenced by seismic events throughout the world. This is because differently from beams and columns, the masonry is often excluded from the seismic resistant design calculations. This causes severe damage to infill even in the event of minor earthquakes causing severe economic as well as health losses and hindering rescue operations. Sometimes, the repair cost for the infills can be considerably higher than those for structural components [1].

Several technological solutions for protecting infill walls, with a significant number of techniques aimed to increasing their resistance [2], [3] have been developed. However, these techniques may not be cost-effective since the strengthening of the infill also increases the forces transmitted to the adjacent frames from the infill leading to a necessity of strengthening of the frame.

Recently few alternative design solutions are introduced to help in reducing the interaction between the infill panels and the building's structural components. These techniques introducees flexible/sliding layers [4-6] aiming at increasing the masonry flexibility and isolating the masonry from its surrounding frame. The Tun Abdul Razak Research Centre (TARRC) introduced an advanced rubber joint (Figure 1a, b), with different stiffnesses along the three orthogonal directions, which is an essential requisite to achieve an optimal response in the in-plane and out-of-plane directions. The effectiveness of the rubber joints was proved during tests carried out within the European research project, INSYSME [7] (INnovative SYS-tems for earthquake-resistant Masonry Enclosures in reinforced concrete buildings) on seismic protection of infill walls. In the modified infilled frame selected and tested at INSYSME project, the horizontal rubber joints divide the infill into four sub-panels. The vertical rubber joints are places at the masonry- column interactions (Figure 1c).

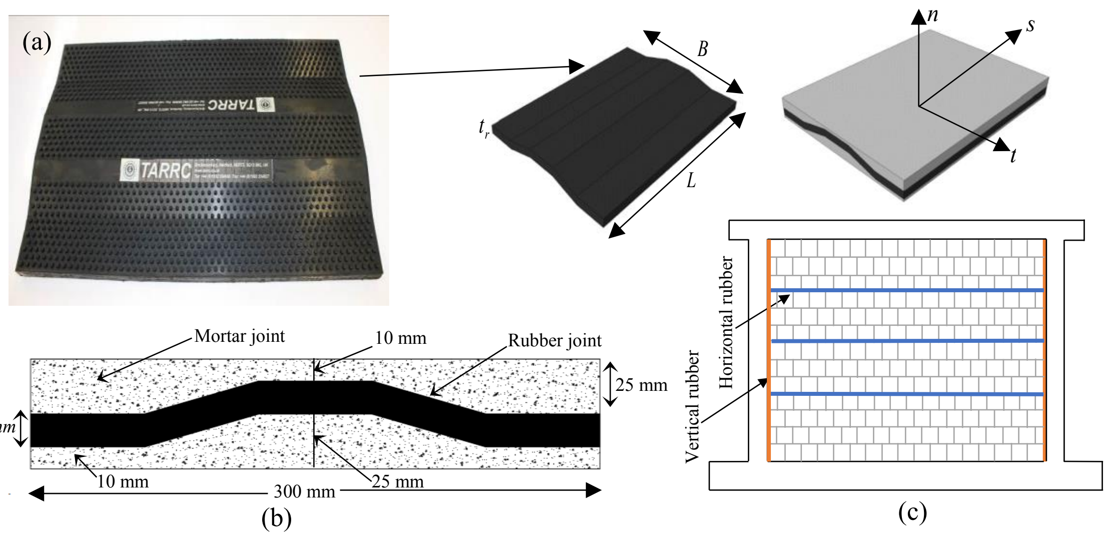


Figure 1: (a) Horizontal rubber joints developed by TARRC [10] (b) cross section of mortar-rubber-mortar joint (c) schematic diagram of modified infill with rubber joints.

The numerical simulation of the seismic performance of RC infilled frame buildings is a computationally challenging task due to the nonlinearity of the materials involved, the complex interaction between the infills and the main frame structure, and the various possible failure modes that could occur. Different modelling approaches have been proposed over the years, including macro modelling and micro/meso-scale modelling [8-10] (see e.g. [11] for a review of the state of the art). Micro and meso-scale strategies can be quite effective in studying the infill behavior of masonry infilled frame. However, analysing a large scale structure can turn out to be a difficult task due to its high computational cost. Whereas, simplified macro-models can be quite efficient having lower degrees of freedom and necessary parameters to define them. A 2D discrete macro-element model (DMEM) for masonry infilled frames was proposed by Calio and Panto [8] to eliminate the major limitations of the equivalent strut approach [12-14]. However, the response of in-plane behaviour of masonry-infilled RC frames with sliding or flexible joints using a 2D macro-elements is rarely studied.

This study presents two alternative modeling strategies for the system at hand, one using a three-dimensional meso-scale modelling approach, and the other using a DMEM modeling approach. The first strategy, developed in Abaqus [15], and the second strategy uses 2D macro modelling approach, which is based on the model proposed by Calio' and Panto' [8], subsequently implemented in Opensees [16]. Section 2 describes briefly the two modeling approaches, and Section 3 illustrates their calibration and validation considering the results of the experimental tests (INSYSME [7]) and advanced numerical analyses carried out by Verlato [17] on RC frames infilled with flexible joints.

2 PROPOSED MODELLING STRATEGIES

2.1 Mesoscale model

This modelling strategy uses Abaqus [15] which is a commercially available finite element (FE) software . Columns and beams are modeled using 20-node quadratic elements with reduced integration (C3D20R) and 2-node linear beam elements (B31) that are assigned to the rebars. Concrete Damage Plasticity (CDP) model [18] is used to consider the material nonlinearity of concrete and brick units. The rebars are embedded within the concrete with the "embedded element technique" [15].

Surface-to-surface contact interfaces representing the mortar joints as well as rubber-mortar interaction surfaces. The interaction surfaces are controlled normal stiffness, k_n, and other shear stiffness in two orthogonal directions, k_s and k_t. These stiffness parametrs depents on the elastic properties of the masonry constituents as well as geometry of the the joints [10]. From a mechanical point of view, the mortar-rubber-mortar joints work as a system of elements connected in series. Thus, the overall in-plane stiffness (normal) and out-of-plane stiffness (shear) are estimated as:

$$\frac{1}{k_i^{mr}} = \frac{1}{k_i^{r}} + \frac{2}{k_i^{m}} \qquad i = n, s, t \tag{1}$$

where m and r denotes the mortar and rubber respectively.

The stiffness rubber joints is calculated as $k_s^r = G_r / t_r$, where G_r =0.50 Mpa and t_r =15mm for the joints of Figure 1a. Under a series system approximation, it coincides with the lowest among the corresponding values of bond strength of its constituents. i.e., the bond failure either in the mortar-rubber or mortar-brick interface. It is important to note that, the presence of studs on the rubber joints enhance the cohesion of rubber joints with mortar (Figure 1a) facilitating improved resistance.

2.2 Simplified 2D-macro element

This modeling approach uses 2D macro-elements that are developed by Calio and Panto [8], sub-sequently implemented in OpenSees [16] by Panto and Rossi [19]. Horizontal rubber joints divides the masonry infilled frames to a series of sub-panels as shown in Figure 2a.

The macro-element mechanical scheme of the model comprising of one articulated quadrilateral, one 1D diagonal link, and 8 numbers of 2D zero-length links as presented in Figure 2b. The 2D links connects macro-elements to the frame components [19]. The infill-frame external face has rigid offsets for geometrically consistent simulations. Each macro element can be described by twenty degrees of freedoms (DoFs). Out of which, sixteen are associated with the normal and shear displacement of perimetral 2D links and remaining four are associated with the internal panels for describing in-plane shear.

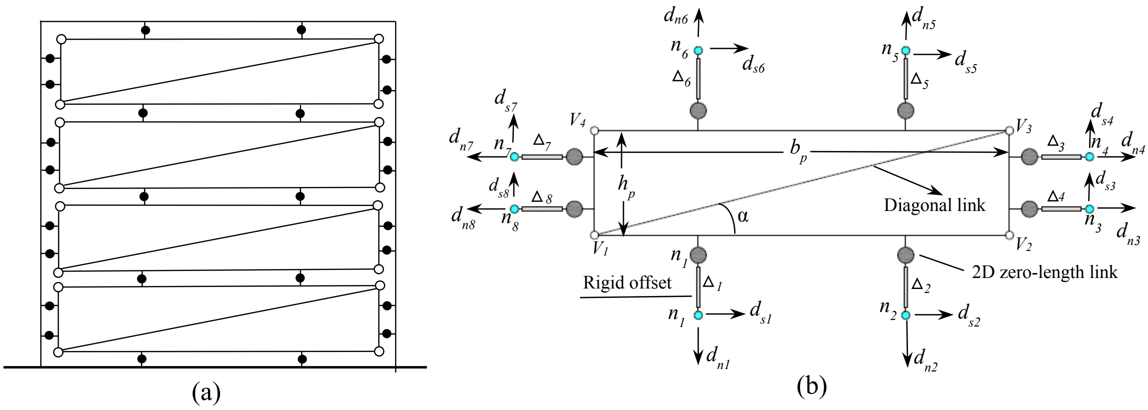


Figure 2. (a) Infilled frame with macro-elements and (b) macro-element mechanical scheme [20]

To describe the sub-panel separated by the rubber joints, the same macro-element [19] is used where the compressive/tensile response of the masonry sub-panels as well as flexible joints are simulated by using the normal behavior of the 2D contact links. The 2D contact links are also capable of simulating the shear sliding whereas the 2D diagonal links simulate the diagonal shear behavior of the masonry subpanels. It is important to note that, the representation of the shear behavior of the 2D links is identical to the approach of the mesoscale model.

3 CASE STUDY: INSYSME PROJECT

The experimental test carried out on a traditional infilled frame and a modified infilled frame with mortar-rubber-mortar joints tested within INSYSME project [7]. Hollow clay blocks of type-D (Figure 3) are used in the infill panel. 10 mm thick bed mortars are used while head mortar joint is absent. However, the transfer of stresses from bricks to bricks are perfomed by interlocking mechanism. Figure 3 also provides the details of frame geometry, rebar details and the dimentions of the masonry unit. Further details can be found in Verlato [17]. All test frames (bare, traditional infilled and modified infilled) tested under INSYSME project [7] considers 200 kN acting veritcally on the top of each column, followed by monotonic in-plane loads applied at the top of the beam (Figure 3). A calibration study is carried out in this section using the two above discussed modelling strategies (macro-element model and mesoscale model).

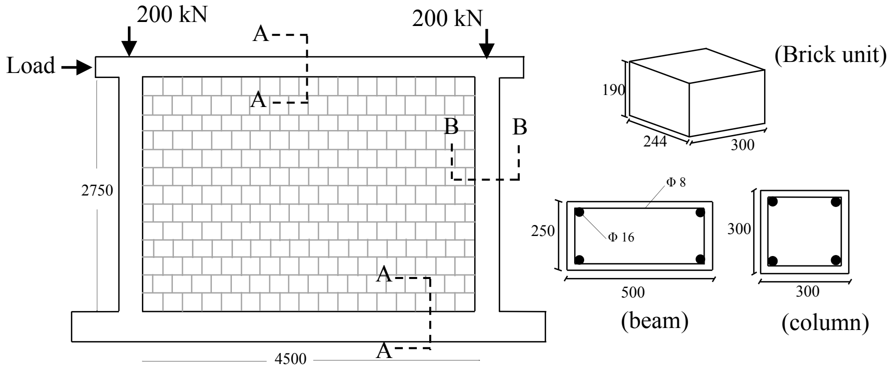


Figure 3 Traditional infilled frame geometric details (dimensions in mm)

The important mechanical strength properties of concrete, rebar, brick units and the masonry infill are reported in Table 1. Similarly, the mortar joints representing the masonry-masonry, and masonry-frame interaction properties are presented in Table 2. Table 1 and Table 2 are based on the experimental test results carried out at INSYSME [7] and numerical models of Verlato [17].

Mechanical properties	Concrete	Steel reinforcement	Brick units		Masonry infill	
			Parallel to holes	Perpendicular to holes	Vertical	Horizontal
Elasticity modulus E (MPa)	22000	180000	7147	3693	6158	1904
Poisson Ratio ν (-)	0.15	0.3	-	-	0.4	0.4
Compressive strength, f_c (MPa)	40	-	12900	4250	7.63	1.40
Yielding stress (MPa)	-	535	-	-	-	-
Tensile strength, f_t (MPa)	3.91	-	0.33	0.22	0.52	0.1

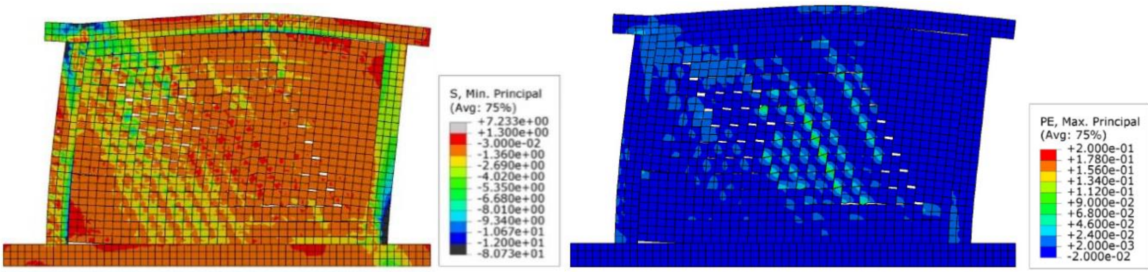
Table 1. Mechanical properties of RC frame, brick, and masonry infill [17].

Mortar Interaction Properties	Bed mortar	Head mortar
k_n^m per unit area (N/mm^3)	200	200
k_s^m , k_t^m per unit area (N/mm^3)	100	-
Tensile strength f_t (MPa)	0.346	-
Cohesion c (MPa)	0.485	-
Friction coefficient, μ (-)	1.13	0.8
Fracture energy in tension, G_f^I (MPa.mm)	0.005	-
Fracture energy in shear, G_f^{II} (MPa.mm)	0.05	-

Table 2. Properties of the contact interfaces describing the mortar joints in the mesoscale model [17].

3.1 Traditional infilled frame

Figure 4a shows the contour plot of peak compressive stress developed in the RC infilled frame recorded at a displacement of 28 mm, obtained using the 3D mesoscale modeling approach. The highest stress concentrations of compressive strength are seen at the top-left corner and at the bottom-right corner due to the attainment of peak compressive strength of the masonry units (Table 1). Similarly, the plastic strain distribution representing the cracking of brick units are shown in Figure 4b for a 1% drift level (i.e., 28mm). The masonry cracks are found to be localised in the form of diagonal bands with an angle of 60^0 with horizontal as seen in Figure 4b.



(a) (b)

Figure 4 (a) Peak compressive stress (b) Plastic strain distribution at 28 mm [21].

Figure 5 illustrates the comparisons of the load-displacement curves obtained experimentally and the numerical mesoscale model of the traditional RC infilled frame. Though the mesoscale model analysis aborted after reaching a displacement of 28 mm due to convergence issues and could not describe the softening stage, still, elastic behaviour is well validated with the experimental response. In the meantime, macro-model could be able to describe both initial and the post-peak behaviour with considerable accuracy. Plotted in the same figure is the curve obtained using the DMEM approach, using four macro-elements for describing the subpanels and forced-based non-linear finite elements with cross-sections discretised into fibres for describing the RC components. The properties of the macro-model are consistent with mechanical characterisation test results and with those employed for the 3D model.

To give an idea of the computational cost savings achieved with the second modelling approach, the numerical simulation was carried out using a computer with 16 GB RAM, intel i5-8500 processor and windows OS (64-bit). It was observed that, the 3D mesoscale model developed for the traditional infilled frame, with a total number of 12812 nodes, took approximately 24 hours to reach 28 mm displacement, whereas the DMEM with 12 nodes took only 6.8 seconds to reach the same level of displacement. It can also be noted that both experimental and macro-model results depicted a softening branch beyond 25 mm of lateral displacement due to cracking/crushing of bricks with a peak force between 450 kN and 510 kN.

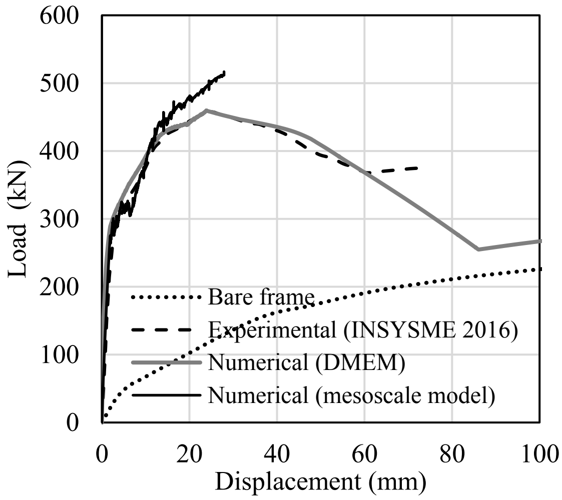


Figure 5 Experimental and numerical load-displacement of traditional and modified infilled frame [21].

3.2 Infilled frame with rubber joints

The interaction parameters in the 3D mesoscale model of infilled frame with rubber joints describing the horizontal and vertical mortar-rubber interface are presented in Table 3. It is to be noted that, the mechanical properties of mortar-rubber-mortar joint are controlled only by the rubber joint compliance and doesn't get affected by the thickness of the mortar layers.

Interaction properties	Hor. joint	Ver. joint
k_n^{mr} per unit area (N/mm^3)	11.7	1
k_s^{mr} , k_t^{mr} per unit area (N/mm^3)	0.033	0
f_t (MPa)	0.15	0
c (MPa)	0.05	0
μ (-)	0.36	0.31
G_f^I (MPa·mm)	0.005	-
G_f^{II} (MPa·mm)	0.04	-

Table 3. Mortar-rubber joint interaction properties used in the mesoscale model [17].

Figure 6a shows the contour plot of peak compressive stress recorded at 55 mm (i.e., 2% inter-story drift). The introduction of low-stiffness vertical rubber joints can significantly reduce the overall stiffness of the infilled frame causing better performance as compared to the traditional infill (see Figure 4 for traditional infill). Reduction in the stresses in the masonry units (bricks) are also observed. Overall, most of the lateral deformations are localised at the rubber joints in terms of rubber shear flexibility. The present numerical model successfully simulated the cracks that are also observed experimentally [17]. The plastic strain contours showing the cracking failure of the bricks are presented in Figure 6b for the same horizontal displacement (2% drift limit). The rubber joint solutions are found to be significantly enhancing the performance of infilled frame as compared to the traditional infill by lowering the cracking of the infill at higher drift limits and opening a gap at the subpanel-frame interface. Figure 6c presents the deformed shape of the modified infill with rubber joints using DMEM approach, featuring the sliding between the subpanels with respect to horizontal sliding joints, and formation of diagonal struts in each subpanel. In Figure 6c only the perimeter 2D links in compression are shown.

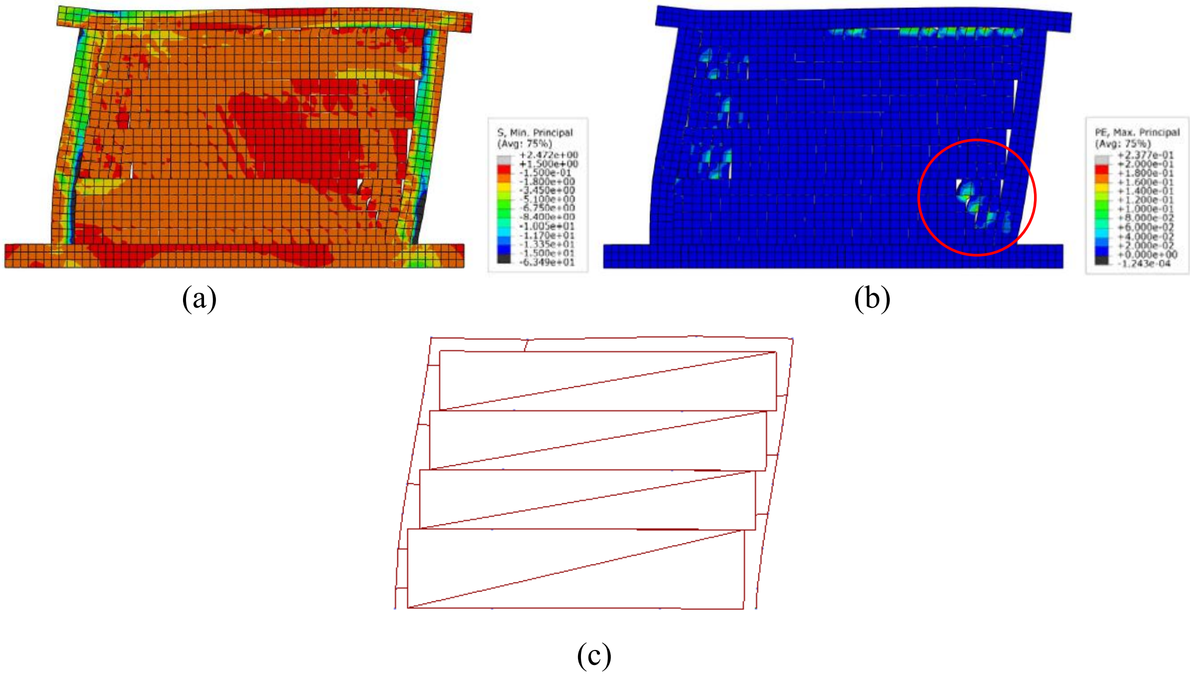


Figure 6 (a) Peak compressive stress contour (b) Plastic strain distribution of modified infill (c) OpenSees model deformation (at 55mm) [21]

Figure 7 shows the force-displacement curve of the infilled frame system with rubber joints. The introduction rubber joints improve the performance of the infill system, as observed in Figure 4. Both numerical approaches adopted in the present study (3-D mesoscale model and the 2-D macro-model) are efficient in predicting accurate global force-deflection responses identical to experimental observations. Apart from the mesoscale model providing some local drops of force between 12 to 20 mm, the global response is monotonically increasing up to maximum displacement. The simplified DMEM approach with few seconds of analysis predicts the same load-displacement response as compared to the computationally expensive 3-D meso-model. In fact, the 3D model with a total of 12812 nodes took 85 hours to reach 55 mm displacement and the same displacement is achieved in 24 seconds with the DMEM (with 30 nodes).

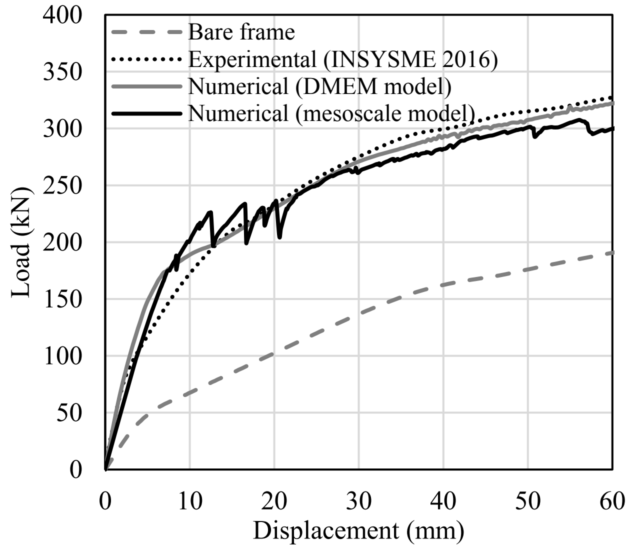


Figure 7. Force-displacement behaviour of the bare frame, traditional infill, and modified infill [21].

4 CONCLUSIONS

This study illustrates the development of two alternative modeling strategies for simulating the traditional infilled RC frame as well as the modified infilled frame subjected to in-plane loading. The first approach is based on a 3-D mesoscale modeling approach which is quite computationally expensive but is extremely useful in providing an insight into the local behavior of the components of the system, like the joints and the brick units. The second approach is a more computationally efficient 2-D model, which is characterized by very few degrees of freedom thanks to the use of macro-models for describing the infill panels with rubber joints.

The two-modeling strategy are applied to a case study consisting of an RC frame with traditional infill wall and with an infill wall with rubber joints. Based on the study presented in this paper, the following conclusions can be drawn:

- The compliance of the RC infilled frame system can be significantly improved by introducing horizontal and vertical rubber joints resulting reduced damage to the infill and the frame.
- Both the modeling strategies provide an accurate assessment of the global force-displacement response of the system.
- The macro-modeling approach (DMEM) is computationally more efficient, as this can be up to 12,000 times faster than 3-D meso-scale approach depending on the targeted drift limits to achieve.

The present study can contribute to investigate the optimal design combinations by considering the strength, dissipation energy and deformability of the joints. This has potential in enhancing the seismic performance of various types of infilled frames. This research can be further extended to study the combined in-pane and out-of-plane behaviour of infilled frame.

REFERENCES

[1] M. T. De Risi, M. Di Domenico, P. Ricci, G. M. Verderame, G. Manfredi. Experimental investigation on the influence of the aspect ratio on the in-plane/out-of-plane interaction for masonry infills in RC frames. *Engineering Structures*, **189**, 523-540, 2019.

[2] M. ElGawady, P. Lestuzzi, M. Badoux. A review of conventional seismic retrofitting techniques for URM. *13th international brick and block masonry conference* (pp. 1-10), 2004.

[3] L. Koutas, S. N. Bousias, T. C. Triantafillou. Seismic strengthening of masonry-infilled RC frames with TRM: Experimental study. *Journal of Composites for Construction*, **19**(2), 04014048, 2015.

[4] M. Petrović, N. Mojsilović, B. Stojadinović. Masonry walls with a multi-layer bed joint subjected to in-plane cyclic loading: An experimental investigation. *Engineering Structures*, **143**, 189-203, 2017.

[5] A. Calabria, G. Guidi, F. da Porto, C. Modena. Innovative systems for masonry infill walls based on the use of rubber joints: Finite element modelling and comparison with in-plane tests, *Brick Block Mason. Trends, Innov. Challenges - Proc. 16th Int. Brick Block Mason*, 2016.

[6] H. Ahmadi, A. Dusi, J. Gough. A Rubber-Based System for Damage Reduction in Infill Masonry Walls. In *16th World Conference on Earthquake Engineering, 16WCEE*, pp. 9-13, 2017.

[7] INSYSME, Innovative systems for earthquake resistant masonry enclosures in RC buildings, *SME-2013–606229, FP7-*, www.insysme.eu, 2016.

[8] I. Caliò, B. Pantò. A macro-element modelling approach of Infilled Frame Structures. *Computers & Structures*, **143**, 91-107, 2014.

[9] B. Pantò, I. Calio, P. B. Lourenço. Seismic safety evaluation of reinforced concrete masonry infilled frames using macro modelling approach. *Bulletin of Earthquake Engineering*, **15**(9), 3871-3895, 2017.

[10] P. J. B. B. Lourenço. Computational strategies for masonry structures. *Delft University of Technology*, Holland,1997.

[11] P. G. Asteris, S. T. Antoniou, D. S. Sophianopoulos, C. Z. Chrysostomou. Mathematical macromodeling of infilled frames: state of the art. *Journal of Structural Engineering*, **137**(12), 1508-1517, 2011.

[12] B. Stafford Smith, Carter, C. A method of analysis for infilled frames. *Proceedings of the institution of civil engineers*, **44**(1), 31-48, 1969.

[13] W. W. El-Dakhakhni, M. Elgaaly, A. A. Hamid. Three-strut model for concrete masonry-infilled steel frames. *Journal of Structural Engineering*, **129**(2), 177-185, 2003.

[14] F. Di Trapani, P. B. Shing, L. Cavaleri. Macroelement model for in-plane and out-of-plane responses of masonry infills in frame structures. *Journal of Structural Engineering*, **144**(2), 04017198, 2018.

[15] Dassault Systemes, http://www.3ds.com/products-services/simulia/products/abaqus/, 2017.

[16] S. Mazzoni, F. McKenna, M. Scott, G. Fenves. Open system for earthquake engineering simulation (OpenSees). User command language manual, Pacific Earthquake Engineering Research Center. *University of California, Berkeley*, *465*, 2006.

[17] N. Verlato. Development of a Clay Masonry Enclosure System with Deformable Joints: Experimental Analysis and Numerical, *Università Degli Studi Di Brescia*, Italy, PhD dissertation, 2017.

[18] J. Lee, G. L. Fenves. A plastic-damage concrete model for earthquake analysis of dams. *Earthquake engineering & structural dynamics*, **27**(9), 937-956, 1998.

[19] B. Pantò, P. P. Rossi. A new macromodel for the assessment of the seismic response of infilled RC frames. *Earthquake Engineering & Structural Dynamics*, **48**(7), 792-817, 2019.

[20] P. K. Dhir, E. Tubaldi, B. Pantò, I. Caliò, A macro - model for describing the in - plane seismic response of masonry - infilled frames with sliding/flexible joints. *Earthquake Engineering & Structural Dynamics*, **51**(12), 3022-3044, 2022.

[21] P. K. Dhir, E. Tubaldi, H. Ahmadi, J. Gough, Numerical modelling of reinforced concrete frames with masonry infills and rubber joints. *Engineering Structures*, **246**, 112833, 2021.