FLEXIBLE JOINTS FOR SEISMIC-RESILIENT MASONRY-INFILLED RC FRAMES: PRELIMINARY ANALYSES FOR SHAKING TABLE TESTING

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Abstract: *Masonry infills are among the most vulnerable components of building frames, often undergoing severe damage even under minor or moderate seismic shaking. In recent years, flexible joints have emerged as a promising technique for protecting the infills from damage. To fully demonstrate the effectiveness of this technique, it is necessary to carry out full-scale tests on a structural prototype under realistic loading conditions, which can be simulated with shaking table testing. There is also a need to assess whether the joints can provide enough energy dissipation capabilities to enable a resilient-based design of infilled frames. The ERIES-FLEJOI project aims to address these gaps by investigating the performance of two promising systems based on flexible joints, one aimed at increasing the compliance of the infills, the other aimed at decoupling them from the frame. These systems, installed in two identical reinforced concrete (RC) frame prototypes, will be tested at the Dynamic Testing Laboratory of IZIIS (Skopje, N. Macedonia). This paper illustrates the two systems, the preliminary investigations, and the numerical analyses carried out to design the joint systems in order to meet the performance objectives and constraints posed by the shaking table capacity. The analyses involve two recently developed alternative modelling strategies, one based on a meso-scale description of the infill walls and the other on an equivalent discrete macro-element.*

1. Introduction

Among the various structural and non-structural components of building frames, masonry infills are one of the most vulnerable to earthquakes. They often undergo severe damage even under minor or moderate shaking, leading to injury and even death of occupants and hampering rescue operations and recovery. The economic losses can be considerable, and several studies (*e.g.,* Del Vecchio *et al.* 2018, De Risi *et al.* 2019 and Freddi *et al.* 2021) demonstrated that the repair cost of infills might significantly exceed that of structural components. Many research efforts have focused on the development of technological solutions for protecting infill walls. One way to do this is to increase their resistance, and a significant number of techniques are available for this purpose (*e.g.,* Elgawady *et al.* 2004, Koutas *et al.* 2015). However, these techniques also require strengthening the frame members adjacent to the infills and, hence, may not be cost-effective. In recent years, alternative solutions have been proposed for engineered infill walls with enhanced behaviour, exhibiting minimal interaction with the building's structural components. The idea behind most of these techniques is to increase the flexibility of the infill panel and/or isolate it from the surrounding frame through flexible or sliding joints. Several systems of flexible/sliding joints have been proposed (*e.g.,* see Marinković 2018 for a review), and rubber joints have emerged as the most capable ones, thanks to the wide range of stiffness and dissipation capacities achievable by choosing suitable compounds and geometries. TARRC and the University of Padova developed flexible rubber layers with different stiffness along the three orthogonal directions (Ahmadi *et al.* 2017) to achieve an optimal behaviour in both in-plane and out-of-plane directions. Rubber joints are placed horizontally within the infill panel and used together with vertical rubber joints placed at the interface with the columns to achieve a 'complaint system' (Figure 1a). In this way, the rubber absorbs most of the displacement demand of the panel in the in-plane direction by also minimising the interaction (*i.e.,* contact stresses) between the panel and the frame (Dhir *et al.* 2021). INODIS (Marinković 2018; Marinković *et al.* 2019) is another joint system that has recently emerged. It is a decoupling system consisting of strips made of recycled rubber, placed between the four sides of the panel and the frame to minimise their interaction (Figure 1b). Rubber strips with low compressive stiffness, placed at the column-panel interface provide decoupling under in-plane direction, whereas stiffer and thinner strips placed at the top and bottom of the panel provide a strong support, enabling the arching effect. The out-of-plane movement of the wall at its edges is prevented using three rubber strips. Two outer strips are connected to the wall and the inner strip to the frame, thus making a shear key.

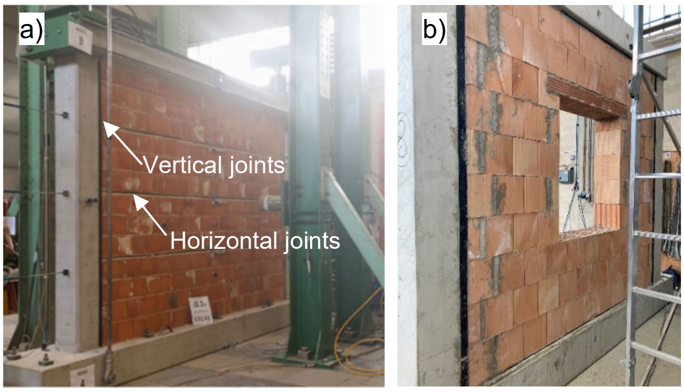


Figure 1. (a) Compliant system with horizontal and vertical rubber joints tested at University of Padova, (b) Decoupling system (INODIS) with rubber joints between frame and infill tested at University of Ljubljana.

The effectiveness of these two joint systems was proved by quasi-static experimental tests carried out within the European research project INSYSME (INnovative SYStems for earthquake resistant Masonry Enclosures in reinforced concrete buildings) (Verlato 2017) and other campaigns (Marinković 2018; Marinković *et al.* 2019). However, further tests are required to achieve a complete validation of these systems by considering larger-scale prototypes and realistic loading conditions (*i.e.,* dynamic effects). Moreover, there is a need to assess whether the joints can provide enough energy dissipation capabilities to enable the structural system to withstand moderate to severe earthquake shaking without experiencing any damage.

The recently started EU-funded project ERIES-FLEJOI (Flexible joints for seismic-resilient design of masonry-infilled RC frames) aims to address the above gaps by performing shaking table tests of realistic three-dimensional structural prototypes equipped with the two joint systems. The tests carried out in the FLEJOI project will unlock the potential of flexible joints for seismic-resilient based design (Freddi *et al.* 2021) of infilled RC frames. They will provide key data for modelling strategies validation and inform the development of design methods and recommendations for the new generation of seismic codes. This will ultimately have a transformative impact on how RC buildings are designed and constructed.

This paper illustrates the investigated specimens and the preliminary analyses carried out on structures with the compliant rubber joint system. Two alternative numerical modelling strategies are presented and applied, one using a three-dimensional meso-scale modelling approach (Dhir *et al.* 2021, Marinković and Butenweg 2022) and the other using a more computationally-efficient discrete macro-element model (DMEM) modelling approach (Dhir *et al.* 2022).

2. Specimens design and test programme

The two prototypes consist of a three-dimensional one-storey full-scale RC frame with masonry infills and differ in the type of joint system, as illustrated in Figure 2.

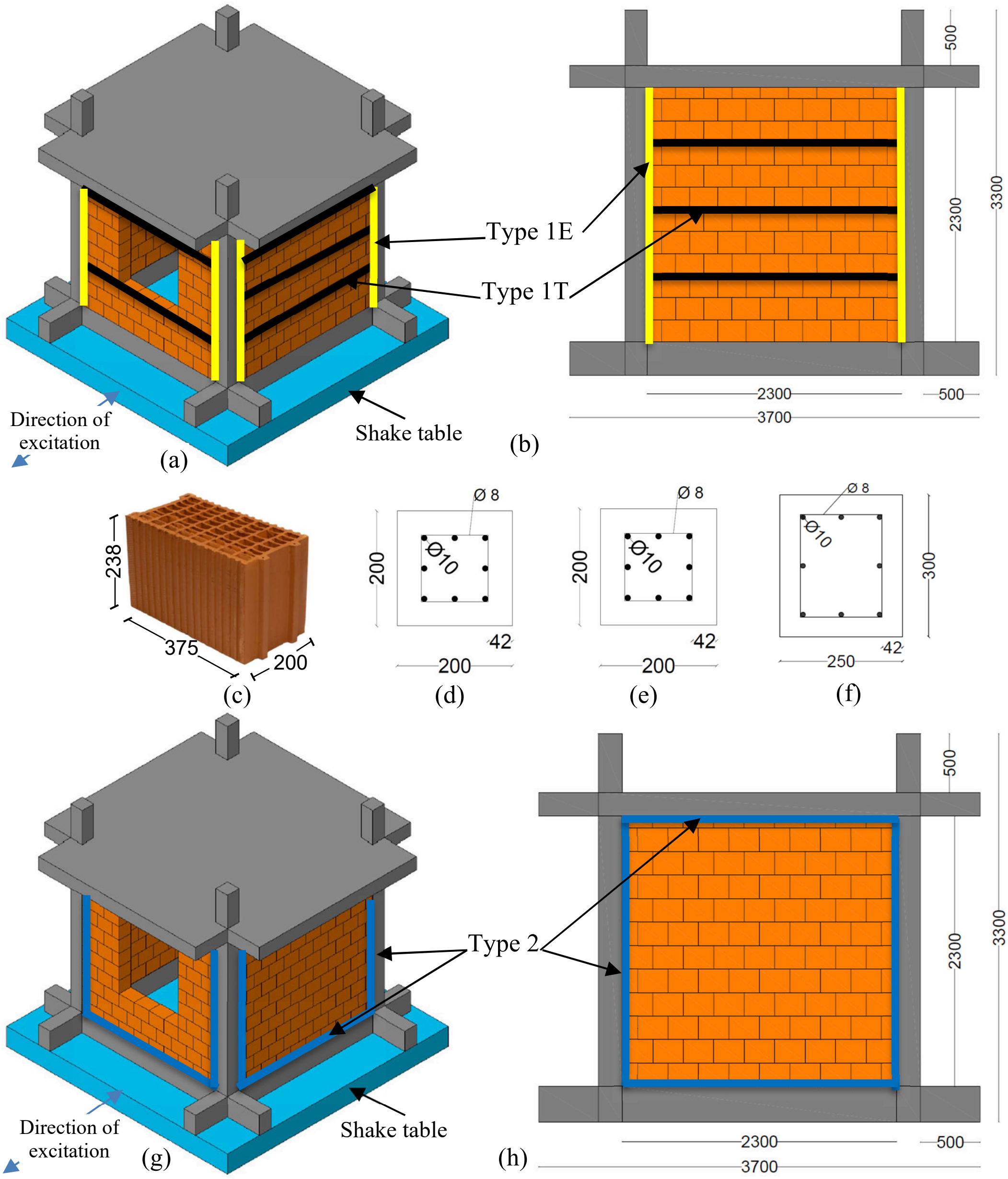


Figure 2. (a, b) 3D view and geometric details with Type 1 joints, (c) masonry unit, (d) column, (e) top beam, (f) top beam, and (g, h) 3D view and geometric details with Type 2 joints. [Dimensions in mm].

The RC frame is the same as the one of the EU-funded SERA project INMASPOL (Rousakis *et al.* 2020), which focused on deformable polyurethane joints and fibre grids for reinforced concrete frames with orthoblock brick infills. It is designed according to EC2 and EC8 (including capacity-design principles). It has plan dimensions of 3.7 m × 3.7 m and a total height of 3.3 m. The class of concrete is C30/37. The columns have a square section of 20 cm × 20 cm and are 2.7 m high. They are reinforced with B450 steel rebars. The beams are embedded within the top slab, which is 30 cm thick and is reinforced with welded meshes at the top and at the bottom. Differently from INMASPOL project, the slab has no hole at the centre since access to inside the frame is possible via the openings in the infills. The frames are constructed on a special foundation, with holes to attach them to the shake table and hooks for lifting it. The infill walls are made with Porotherm hollow blocks (Figure 2c), typically employed in construction practice for traditional infills. The interior side of the walls is covered in plaster to check the damage incurred by this.

The Type 1 joint system (Figure 3a) consists of horizontal joints developed by TARRC (Type 1T in Figure 2a, b) and elastomeric joints at the interface between the panel and the frame's columns (Type 1E in Figure 2a, b). This system is a 'compliant system' that aims to increase the flexibility of the panel as well as control the interaction between the panel and the frame. The Type 1T joints (Figure 3a) have a thickness t_r of 15 mm, and are made from a natural rubber compound with low stiffness and high damping capacity (*i.e.,* shear modulus G_r of the order of 0.25 MPa at a shear deformation of 50%, and equivalent damping ratio higher than 15%). Added ribs enhance the strength of the bond between the rubber and the thick mortar layers connecting the joints to the blocks. Type 1E rubber layers (Figure 3b), made with recycled rubber, have low compressive stiffness and high deformation capacity to avoid stress concentration along the column-infill interface.

The Type 2 joints system (Figure 3c, d) is a 'decoupling system' consisting of rubber strips provided by Regupol that isolate the infill from the frame. Decoupling of the in-plane direction is achieved because rubber strips have low compressive stiffness and are highly deformable. The out-of-plane connection is provided with the arrangement of the rubber strips, having them divided into three parts, where two outer parts are connected to the infill wall and inner strips are glued to the frame (columns and top/bottom beam). Rubber strips are connected to the frame/wall using thin-layer mortar usually applied in practice.

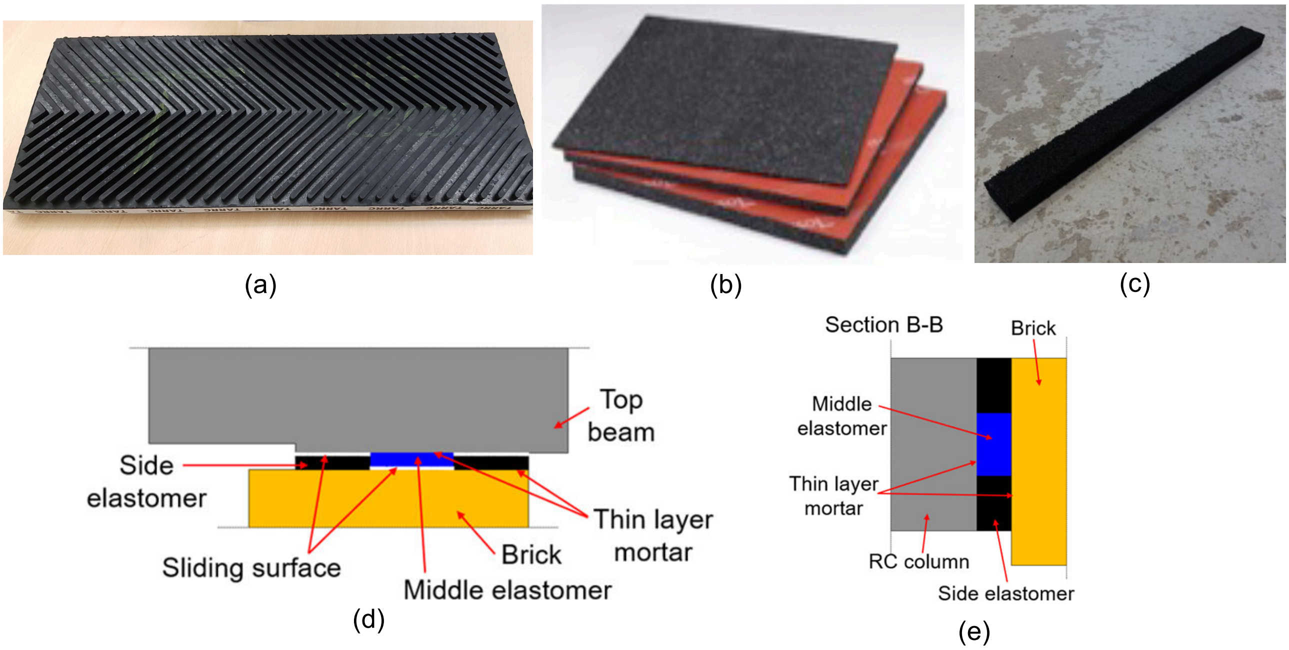

(a) (b) (c)

Figure 3. (a) Type 1T joints, (b) Type 1E joints, (c) Type 2 rubber strips, (d) and (e) Type 2 joint system.

Both prototypes have two sides fully infilled and the other two with openings (see Figure 2a, g). The first prototype uses Type 1T horizontal joints and Type 1E vertical joints between the infill and the columns. Conversely, the second prototype uses Type 2 joints around all four sides of the infill wall, between the infill and frame. An almost symmetric arrangement of the walls' openings has been considered to avoid torsional effects. This choice allows the use of simplified modelling strategies based on 2D models for the preliminary analyses to design the tests and will facilitate the interpretation of the test results.

The testing campaign involves a wide range of tests to characterise the various materials and the prototypes' dynamic behaviour and seismic response. It is noteworthy that dynamic tests are required to study the effect of strain-, rate- and history-dependent behaviour of rubber on the systems' response.

3. Numerical modeling

The numerical assessment 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 for simulating the behaviour of masonry infills. Micro and meso-scale strategies (Lourenço 1997 and Wu *et al.* 2022) provide a very accurate description of the behaviour of infills. However, they are not suitable for analysing large-scale infilled structures due to the high computational cost involved. Simplified macro-models such as the discrete macro-element model (DMEM) proposed by Calio and Panto (2014) are preferable for such analyses due to their reduced number of degrees of freedom and parameters required to define them. Previous works by some of the authors of this paper (Dhir *et al.* 2021, Dhir *et al.* 2022, Marinković and Butenweg 2022) have developed and validated meso-scale and macro-scale modelling strategies for analysing infilled frames with rubber joints subjected to in-plane loading. These strategies, briefly described below, have been used for designing the properties of the Type 1 and Type 2 joint system by taking into account the target performance requirements and the capacity of the shaking table test.

3.1 Mesoscale model

This three-dimensional modelling strategy (Figure 4) is detailed in Dhir *et al.* (2021) and Marinković and Butenweg (2022). It has been developed in Abaqus, using 20-node quadratic elements with reduced integration (C3D20R) for the RC columns and beams and 2-node linear beam elements (B31) for the rebars, which are embedded within the RC elements with the 'embedded element technique'. The Concrete Damage Plasticity (CDP) model (Lee and Fenves, 1998) is used to describe the material nonlinearity of concrete and brick units.

Surface-to-surface contact interfaces are used to describe the mortar joints, horizontal rubber-mortar joints, and vertical rubber joints. The linear elastic behaviour of these interfaces is characterised by an uncoupled response along the various directions. The values of the stiffness parameters depend on the mechanical and geometrical properties of the masonry and the joints (Lourenço 1997). They can be obtained by considering that, from a mechanical point of view, the horizontal mortar-rubber-mortar joints work as a system of elements connected in series. A damage model is used to describe the crack formation and separation in correspondence of the interfaces, with cracks that can form under tensile stresses, shear stresses, or a combination of the two. The maximum allowable stress is controlled by the strength of the bond between the mortar-rubber joints. It is important to note that the ribs on the rubber joints (Figure 3a) are included to enhance the adhesion with the mortar.

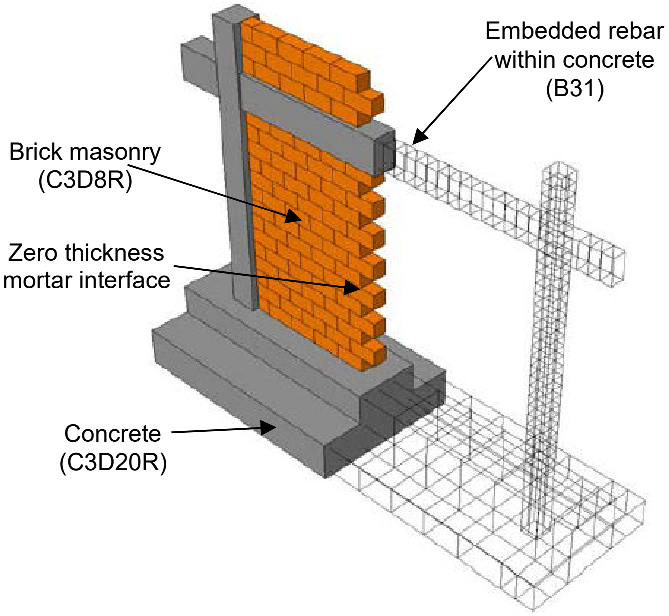


Figure 4. Schematic diagram of the present meso-modelling strategy.

3.2 Discrete macro-element model

This simplified yet accurate modelling approach is illustrated in detail in Dhir *et al.* (2022). It uses the 2D macro-elements developed by Calio and Panto (2014) and subsequently implemented in OpenSees (Mazzoni *et al.* 2006) by Panto and Rossi (2019) to describe the behaviour of the masonry sub-panels, the interaction between adjacent sub-panels through the mortar-rubber joints, and the interaction between the sub-panels and the adjacent frame members through the horizontal mortar joints and vertical mortar-rubber joints.

The macro-element mechanical scheme, illustrated in Figure 5a, consists of one articulated quadrilateral, one 1D diagonal link, and eight 2D zero-length links. The 2D links connect the macro-elements representing the sub-panels to each other and to the frame components. The infill-frame external face has rigid offsets for geometrically consistent simulations. Each macro element can be described by twenty degrees of freedom (DoFs). Sixteen of these are associated with the normal and shear displacement of perimeter 2D links, whereas the remaining four are associated with the in-plane shear deformation of the internal panels. Figure 5b illustrates a possible discretisation of a masonry infill with rubber joints. Forced-based non-linear beam elements with two Legendre integration points are used to describe both beams and columns, with the cross-sections discretised into fibres. The discretisation of the frame elements depends on that of the infill. The compressive/tensile response of the masonry sub-panels and their interaction through the flexible joints are simulated by the normal behaviour of the 2D contact links. The 2D contact links are also used to simulate the shear deformations of the rubber joints and the frictional sliding following the bond failure. It is important to note that the representation of the shear behaviour of the 2D contact links is identical to the one used for the mesoscale model. The 2D diagonal links simulate the shear behaviour of the masonry subpanels.

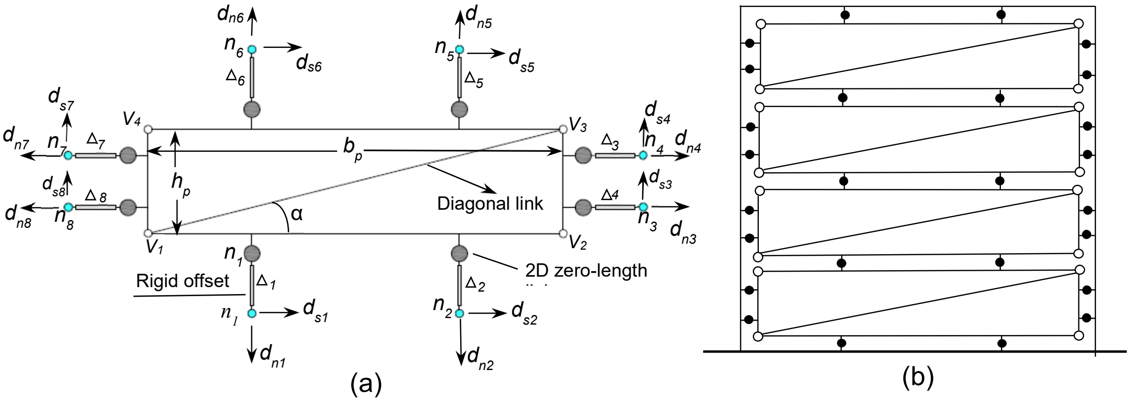


Figure 5. (a) Macro-element mechanical scheme, (b) Infilled frame with macro-elements.

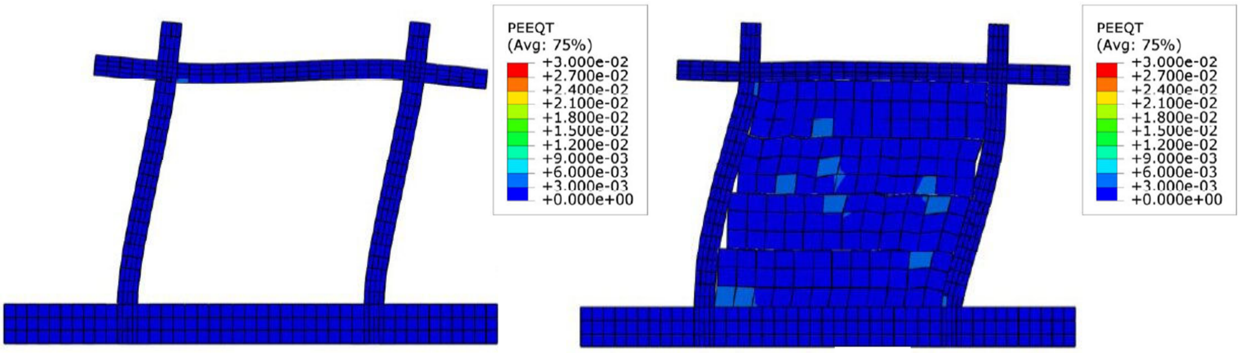
4. Results

This Section illustrates the numerical results from the application of the two alternative modelling strategies presented in Section 3 to investigate the seismic response of the prototype equipped with Type 1 rubber joint system. The results also include some comparisons between the performance of the bare frame, the frame with traditional infills, and the frame with infills with rubber joints.

The parameters of the developed models for the Type 1 joints have been derived based on the geometrical and mechanical properties of the various components. The concrete is characterised by a Young modulus of 28000 MPa, a Poisson ratio of 0.18, and compressive and tensile resistance, respectively, equal to 22.58 MPa and 1.75 MPa. Steel rebars are characterised by a Young modulus of 200 GPa and yield stress of 560 MPa, whereas the brick units are characterised by a Young modulus of 4500 MPa, a Poisson ratio of 0.18, and compressive and tensile resistance, respectively, equal to 6.2 MPa and 0.4 MPa. The horizontal rubber joints, with a thickness of 15 mm, have been assigned a shear modulus of 0.25 MPa. The cohesion and friction angle characterising the bond between the horizontal rubber and the mortar are assumed respectively equal to 0.05 MPa and 0.36. Vertical rubber joints have a 30 mm thickness and a compression modulus of 0.34 MPa. The coefficient of friction between these joints and the masonry panels is assumed to be equal to 0.6.

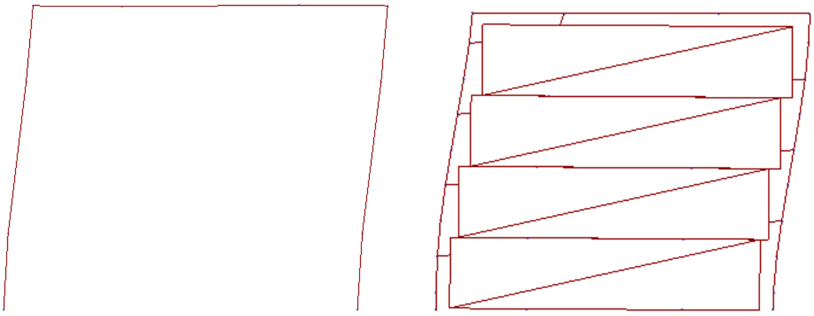
Numerical model for investigating Type 2 joints is made in software package Abaqus, where Young modulus for concrete is taken as 32558 MPa, a Poisson ratio of 0.2, and mean compressive and tensile strength, respectively, equal to 38 MPa and 2.9 MPa. Steel rebars are characterised by a Young modulus of 200 GPa and yield stress of 540 MPa, whereas the brick units are characterised by a Young modulus of 4870 MPa, a Poisson ratio of 0.2, and compressive and tensile resistance, respectively, equal to 3.1 MPa and 0.31 MPa. Rubber strips for Type 2 joints are modelled with hyper-foam material model available in Abaqus with the characteristic defined as in Marinković and Butenweg (2022).Figure 6 shows the contour plots of the tensile equivalent plastic strains (PEEQT) observed in the bare frame and the infilled frame with Type 1 rubber joints with a quasi-statically imposed drift of 1.5%. It can be noted that most of the lateral deformations are localised in correspondence of the horizontal rubber joints.

Similarly, Figure 7 illustrates the deformed shape of the bare frame and the infilled frame with Type 1 rubber joints obtained using the DMEM approach. The contact normal links that are active in compression, thus helping to visualize the location where the infill subpanels are in contact with the frame (see Figure 7b).The results show that, similarly to the meso-scale one, this modelling strategy is capable of simulating the localisation of deformations in correspondence with the rubber joints. Figure 7b shows the perimeter 2D links acting in compression, highlighting the formation of diagonal struts within each sub-panel.



(a) (b)

Figure 6. Tensile equivalent plastic strains (PEEQT) in the (a) bare frame and (b) infilled frame with Type 1 rubber joints at 1.5% drift.



(a) (b)

Figure 7. Deformed shape obtained with the DMEM for the (a) bare frame and (b) Infilled frame with Type 1 rubber joints at 1.5% drift.

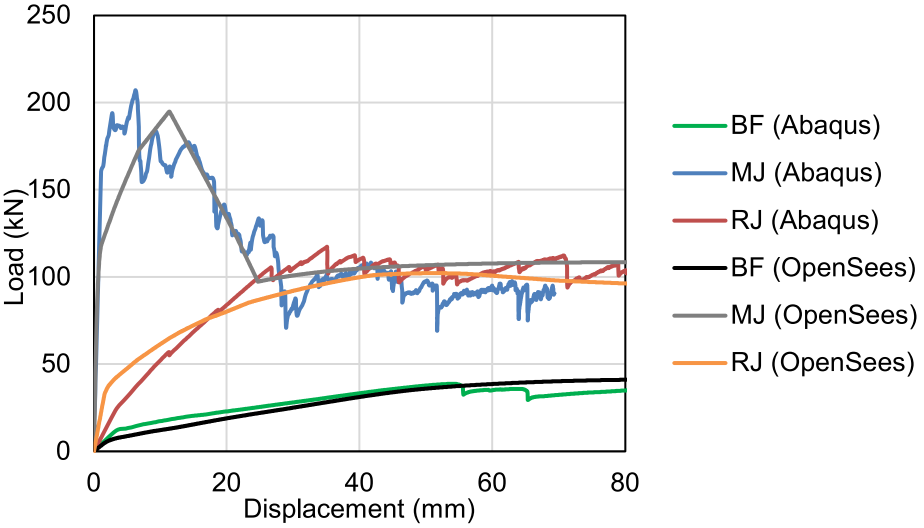


Figure 8. Force-displacement behaviour of the bare frame, traditional infill, and infill with rubber joints (half model considered due to symmetry).

Bare frame (BF), tradition infilled frame with mortar joints (MJ), and modified infilled frame with rubber joints (RJ) models are developed in both Abaqus and OpenSees platforms and Figure 8. compares the horizontal force-displacement responses obtained using the two alternative modelling strategies for Type 1 joints. The results show that the DMEM-based approach provides response estimates very close to the ones obtained with the meso-scale approach with a significantly lower computational cost (*e.g.,* the 3D model with a total of 9446 nodes requires approximately 78 hours to reach 40 mm displacement and the same displacement is achieved in 30 seconds with the DMEM - with 30 nodes). The same figure also shows the response of the equivalent frames with traditional infill walls with mortar joints. This response is characterised by a significantly higher stiffness and strength compared to the infilled frame with rubber joints. This response is also characterised by a softening behaviour following the formation of cracks oriented along the diagonal of the infill and horizontal cracks at the interface between the infill and the base RC beam.

For the model with Type 2 joints, in order to investigate what would happen if in experiment test specimen would be loaded up to higher in-plane drifts, a quasi-static analysis has been performed by imposing an in-plane displacement. It can be observed in Figure 9 that the contact between the frame and the infill is soft due to Type 2 rubber strips placed around the infill. This allows reaching high in-plane drifts without damaging the wall, with very minor cracking initiating in the infill at around 2.8% of in-plane drift.

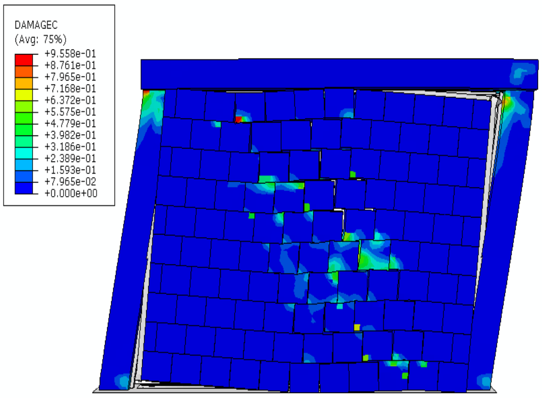
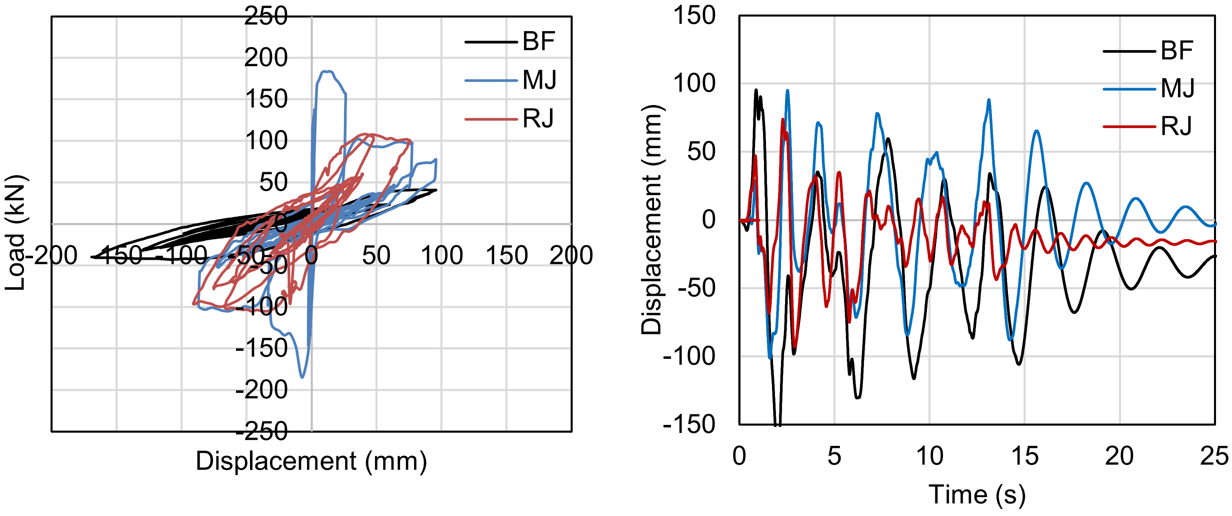


Figure 9. Deformed shape with compression damage distribution at cracking initiation-2.8 % of in-plane drift (5 times scaled deformation), infill with Type 2 rubber joints.

Thanks to its computational efficiency, the DMEM modelling strategy allows easily simulating the seismic responses of the three systems (see Figure 10a). Figure 10b shows the dynamic responses obtained under a seismic record (El Centro Earthquake) in terms of force-displacement curves and displacement time-histories. The hysteretic behaviour of the mortar-rubber joints has been described using an elastic perfectly-plastic model, with initial stiffness controlled by the shear modulus of the rubber (assumed constant) and yield stress equal to 0.24 MPa. A more accurate model capable of better describing the complex, rate- and amplitude-dependent behaviour of the mortar-rubber joints (Dhir *et al.* 2022b) is currently under development. It can be observed that the infilled frame with Type 1 rubber joints experiences a lower displacement demand compared to the bare frame and the infilled frame with mortar joints, thanks to the additional energy dissipation capabilities provided by the joints. Moreover, no damage is experienced in the sub-panels, whereas significant cracking is observed in the frame with mortar joints.

It is noteworthy that the tests to be carried at IZIIS will not explore the response of the system beyond inter-storey drift levels of about 1%, in order to comply with the overturning moment capacity of the shaking table. Nevertheless, the prototype is not expected to experience such high levels of drift even under very strong earthquakes, thanks to the added stiffness and energy dissipation capabilities of the system of infill and rubber joints.



(a) (b)

Figure 10. Comparisons between seismic responses of bare frame, infilled frame with mortar joints, and infilled frame with Type 1 mortar-rubber joints, in terms of (a) force-displacement curves and (b) displacement time history.

5. Conclusions

This paper briefly presents the preliminary analyses conducted to design the shaking table tests that will be performed as part of the ERIES-FLEJOI. This is a recently started EU-funded project aimed at further proving the effectiveness of rubber joints for reducing the vulnerability of masonry infills and improving the seismic performance of masonry-infilled RC frames. Within this project, two RC frame prototypes will be tested in the shaking table facility at IZIIS: one frame will be equipped with a ‘compliant system’ of horizontal and vertical rubber joints, and one with a ‘decoupling system’ consisting of rubber joints placed only at the interface between the infill and the frame.

The paper illustrates the application of two alternative modelling strategies for simulating the in-plane behaviour of the frame with the compliant rubber joint system. The first approach is based on a 3-D mesoscale modelling approach, which is quite computationally expensive but extremely useful in providing insights into the local behaviour of the components of the system, like the joints and the brick units. The second approach is a more computationally efficient 2D model, which is characterised by very few degrees of freedom thanks to the use of discrete macro-elements for describing the infill panels with rubber joints.

Based on the results of the numerical analyses, the following main conclusions can be drawn:

- The complaint rubber joint systems allow the localisation of the deformation demand in correspondence with the horizontal rubber joints, by avoiding the formation of cracks within the masonry infill and controlling the contact stresses between the infill and the frame.

- The macro-modelling approach (DMEM) provides similar global response estimates of the meso-scale modelling approach but with a significantly lower computational cost.
- The high energy dissipation capabilities of the rubber joints allow controlling the seismic performance and minimising the displacement demand in the system, thus avoiding damage to the frame even under high-intensity earthquake inputs.

It is expected that the shaking table tests to be carried out at IZIIS will demonstrate the effectiveness of the rubber joint technology for the seismic resilient design of RC frames that experience minimal damage even under severe earthquake inputs. They will also provide a large amount of data that will be used to inform the development and validation of modelling strategies, accounting also for the out-of-plane behaviour of the infill panels with joints.

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