Numerical modelling of reinforced concrete frames with masonry infills and rubber joints

Prateek Kumar Dhir\textsuperscript{a, *}, Enrico Tubaldi\textsuperscript{b}, Hamid Ahmadi\textsuperscript{c}, Julia Gough\textsuperscript{d}

\textsuperscript{a} Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, UK
\textsuperscript{b} Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, UK
\textsuperscript{c} Tun Abdul Razak Research Centre (TARRC), Brickendonbury, Hertford, UK
\textsuperscript{d} Formerly Tun Abdul Razak Research Centre (TARRC), Brickendonbury, Hertford, UK

ARTICLE INFO

Keywords:
Masonry infill
Rubber-joints
Non-structural component
Finite element analysis
Soft layers

ABSTRACT

Masonry infill walls are critical components of reinforced concrete (RC) frames, which may be damaged even under earthquake events of moderate intensity, thus resulting in significant losses. Recent experimental and numerical studies have investigated innovative solutions for protecting these walls by reducing their interaction with the RC frame. Among these, specially shaped rubber joints were developed that can be inserted between the brick units, and between the masonry wall and the frame.

In the present study, a novel computational modelling strategy is developed using ABAQUS to investigate the in-plane behaviour of RC frames with infill walls and rubber joints. The proposed approach employs three-dimensional solid finite elements to simulate the concrete components, 3D beam elements (for the reinforcing bars, and a meso-scale approach for the infill wall with rubber joint. The numerical strategy is validated against two past experimental studies whose results can be found in the literature, one on RC frames with traditional infill walls, the other on RC frames with traditional walls and walls with rubber joints. The results shed light on the effectiveness of the rubber in minimising the in-plane seismic damage to the bricks, by localizing the deformation mostly in the rubber joints, and reducing the overall stiffness of the infilled system. Further analyses are carried out to investigate the effect of the rubber joints’ layout and stiffness on the behaviour and capacity of the system and its components.

1. Introduction

Seismic events throughout the world have demonstrated the high vulnerability of masonry infills in reinforced concrete (RC) 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, they 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 losses can be considerable, with many studies\textsuperscript{[1–4]} showing that the repair cost of infills may significantly exceed that of structural components.

Recent experimental and numerical studies 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 is available for this purpose (see e.g. Elgawady and Lestuzzi\textsuperscript{[5]} for a state of the art review of strengthening techniques of unreinforced masonry walls and Koutas et al.\textsuperscript{[6]} for recently proposed solutions). However, these techniques also require the strengthening of the frame members adjacent to the infills, due to the increased forces transmitted to them. Thus, they may not be cost-effective. In the recent years, alternative design solutions have been proposed for engineered infill walls with enhanced behaviour, exhibiting minimal interaction with the building structural components. 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\textsuperscript{[7–12]}. 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 one of the most promising, because of the wide range of stiffness and dissipation capacity achievable by the choice of suitable compound and geometry. The Tun Abdul Razak Research Centre...
(TARRC) has recently developed an innovative rubber layer (Fig. 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 tests carried out within the European research project INSYSME [13] (INnovative SYStems for earthquake-resistant Masonry Enclosures in RC buildings) on seismic protection of infill walls (Fig. 2).

In the last decades, significant research effort has been directed towards the implementation of finite element (FE) models for simulating the complex interaction between infill walls and RC frames [14–25]. Different modelling approaches have been investigated, including macro modelling [15,17,20,24,26–30], micro modelling [24], discrete-element modelling [31] and meso-scale modelling [23,32–37]. Some finite element studies have been carried out to evaluate the behaviour of RC frames with masonry infill walls and soft or sliding joints [7,9,12,38,39], but the case of rubber joints has not been fully investigated yet. Thus, a modelling strategy is needed to further study the complex interaction of infilled frames with rubber joints and shed light on the potential benefits stemming from the use of rubber joints and on the optimal layout and stiffness properties.

The aim of this study is to develop an advanced three-dimensional modelling strategy for describing the dynamic behaviour of RC frames with traditional masonry infill walls and for evaluating the effectiveness of rubber joints for their protection. The proposed strategy, developed in Abaqus [40], is based on the use of three-dimensional solid elements for describing the RC frame, and a meso-scale approach for describing the masonry infill, where zero-thickness interfaces simulate the behaviour of the mortar joints and the rubber layers. The proposed strategy, never used before for studying the problem at hand, provides an accurate description of the development of cracks in the bricks and at the mortar interfaces and compared to macro-modelling approaches it allows for a better evaluation of the effects of the introduction of the rubber joints on the in-plane behaviour of the infill and frame.

After introducing the modelling approach, a validation study is carried out by considering the experimental quasi-static tests carried out by Mehrabi et al. [41] on a RC frame with traditional masonry infills made of solid bricks under in-plane loading. The rubber layers are added to the model, and a parametric analysis is performed to evaluate the influence of their layout (horizontal layers only, or horizontal and vertical layers) and stiffness on the in-plane behaviour. In the second part of the study, the modelling approach is validated against the experimental results described in INSYSME project [13] on a RC frame with traditional hollow bricks and horizontal rubber joints subjected to in-plane load and further numerical analyses are performed by changing the layout and stiffness of the rubber layers.

It is noteworthy that although the present study focuses on the behaviour under in-plane quasi-static loading only, the developed three-dimensional models can also be used to simulate the out-of-plane behaviour of infills and the contribution of the rubber joints to the damping capacity of the system. Several studies have investigated numerically the out-of-plane behaviour of traditional infills using different modelling approaches (see e.g. [42–45]), but few [8] have analysed the case of infills with sliding/flexible, using oversimplified models. No numerical study has analysed yet the problem of the contribution of the joints to energy dissipation capabilities of the system, which can be sig-
Fig. 4. (a) Masonry portion describing meso-scale model for masonry components (b) element model for brick units.

Fig. 5. Schematic diagrams for a rubber-mortar joint (all dimensions are in mm units).

Fig. 6. Geometric details of the selected infilled frame (Mehrabi et al. [41]) with RC section details and brick dimensions (dimensions in mm).
Table 1
Mechanical properties of the frame components and brick units.

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Concrete (MPa)</th>
<th>Brick units (MPa)</th>
<th>Steel reinforcement (MPa)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus, $E$</td>
<td>21,930</td>
<td>9520</td>
<td>210,000</td>
<td>[14, 41]</td>
</tr>
<tr>
<td>Poisson’s ratio, $\nu$</td>
<td>0.18</td>
<td>0.15</td>
<td>0.30</td>
<td>[14, 41]</td>
</tr>
<tr>
<td>Compressive strength, $\sigma_c$</td>
<td>30.90</td>
<td>15.59</td>
<td>–</td>
<td>[14, 41]</td>
</tr>
<tr>
<td>Strain at peak compressive stress</td>
<td>0.002</td>
<td>0.002</td>
<td>–</td>
<td>[55]</td>
</tr>
<tr>
<td>Ultimate strain (zero residual stress)</td>
<td>0.0035</td>
<td>0.0035</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>–</td>
<td>–</td>
<td>400</td>
<td>[14, 41]</td>
</tr>
<tr>
<td>Peak tensile strength, $\sigma_t$ (MPa)</td>
<td>3.29</td>
<td>1.57</td>
<td>–</td>
<td>[41]</td>
</tr>
<tr>
<td>Fracture energy in tension, $G_f$ (MPa-mm)</td>
<td>0.09</td>
<td>0.07</td>
<td>–</td>
<td>[14]*</td>
</tr>
<tr>
<td>Post-elastic to elastic stiffness ratio</td>
<td>–</td>
<td>–</td>
<td>0.002</td>
<td>[14]*</td>
</tr>
</tbody>
</table>

* Not directly measured but assumed based on literature and/or calibrated to provide best fit to results.

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

<table>
<thead>
<tr>
<th>Mortar Interaction Properties</th>
<th>Bed joints</th>
<th>Head joints</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_s$ (N/mm²)</td>
<td>500</td>
<td>500</td>
<td>[32]*</td>
</tr>
<tr>
<td>$k_s$ $k_p$ (N/mm²)</td>
<td>250</td>
<td>250</td>
<td>[32]*</td>
</tr>
<tr>
<td>Cohesion, $c$ (MPa)</td>
<td>0.015</td>
<td>0.005</td>
<td>[14]*</td>
</tr>
<tr>
<td>Coefficient of friction, $\mu$ (-)</td>
<td>0.90</td>
<td>0.70</td>
<td>[14]</td>
</tr>
<tr>
<td>Normal fracture energy per unit area, $G_f$ (MPa-mm)</td>
<td>0.015</td>
<td>0.005</td>
<td>[14]*</td>
</tr>
<tr>
<td>Shear fracture energy per unit area, $G_f$ (MPa-mm)</td>
<td>0.09</td>
<td>0.07</td>
<td>[14]*</td>
</tr>
</tbody>
</table>

* Not directly measured but assumed based on literature and/or calibrated to provide best fit to results.

Table 1
Mechanical properties of the frame components and brick units.

- Young’s modulus, $E$: 21,930 MPa
- Poisson’s ratio, $\nu$: 0.18
- Compressive strength, $\sigma_c$: 30.90 MPa
- Strain at peak compressive stress: 0.002
- Yield strength: –
- Peak tensile strength, $\sigma_t$: 3.29 MPa
- Fracture energy in tension, $G_f$: 0.09 (MPa-mm)
- Post-elastic to elastic stiffness ratio: –

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

- $k_s$: 500 N/mm²
- $k_p$: 250 N/mm²
- Cohesion, $c$: 0.015 MPa
- Coefficient of friction, $\mu$: 0.90
- Normal fracture energy per unit area, $G_f$: 0.015 (MPa-mm)
- Shear fracture energy per unit area, $G_f$: 0.09 (MPa-mm)

2. Modelling strategy

The proposed modelling strategy employs material models and elements already available in the commercial FE software Abaqus [40] as shown in Fig. 3. The RC members of the frame are described with a continuum approach and discretised using 3D 20-noded solid elements (C3D20R), whereas 3D linear beam elements (B31) are used for the reinforcing bars. The concrete behaviour is initially linear elastic, and then it follows the Concrete Damage Plasticity (CDP) model [47,48] once cracking of the concrete in tension or crushing in compression occurs. A damage model with linear loss of strength after cracking and a plasticity model are considered respectively for tension and compression. The constitutive behaviour of the steel reinforcing bars is assumed to be elasto-plastic with kinematic hardening (with constant post-yield stiffness) and the Von-Mises criterion defines the yielding condition. The longitudinal and transverse reinforcement are rigidly embedded within the concrete through the “embedded element technique” [40]. Bond-slip effects are disregarded, assuming perfect adherence at the rebar-concrete interface. It is noteworthy that this approach may lead to a slight overestimation of the stiffness of the RC frame, but this can be acceptable since the overall behaviour in terms of strength and stiffness of the system is significantly influenced by the infills.

The masonry infill walls are described employing a meso-scale approach [32,33]. Expanded units, representing the brick units plus half mortar joint thickness per side (Fig. 4a), 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 contact 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 approach 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 considered in a simplified way by employing the CDP model. Each brick unit is modelled with 16 8-noded elements (C3D8R) as shown in Fig. 4b.

The mortar joints and rubber-mortar interfaces can be assigned different behaviour along the three orthogonal directions, which is useful to account for the particular shape of the rubber layers (Fig. 1), resulting in orthotropic behaviour. The surface-to-surface contact is described by a linear elastic traction separation relationship for the condition prior to damage. Assuming uncoupled behaviour, this is controlled by the stiffness along the direction normal to the joint, $k_n$, and along two orthogonal shear directions in the plane of the joint, $k_s$ and $k_t$. The values of the joint stiffnesses depend on the elastic properties of the components and on the geometry of the joints [32].

A damage model is used to describe the crack formation and separation, with cracks that can form under tensile stresses, shear stresses, or a combination of the two. The damage criterion under uniaxial tensile stress is defined by the tensile strength $\sigma_t$. The critical shear stress at onset of damage is defined by a Mohr-Coulomb criterion [32]:

$$\tau_{sq}^{\text{max}} = c + \mu \sigma_t$$

![Fig. 7](image-url) (a) Plastic strain distribution at a deformation of 28.4 mm (2.0% drift) (b) load–displacement curves for the bare frame.
where $c$ is the cohesion between the masonry joints interfaces, $\mu$ is the coefficient of friction between the masonry joints interfaces, and $p$ is the normal contact pressure.

A quadratic stress criterion is used to define the damage initiation under combined stresses.

$$
\left(\frac{\sigma_x}{\sigma_y}\right)^2 + \left(\frac{\sigma_z}{\sigma_{max}}\right)^2 + \left(\frac{\tau_{xy}}{\tau_{max}}\right)^2 = 1
$$

**Table 3** Interaction properties of the mortar-rubber joints.

<table>
<thead>
<tr>
<th>Interaction properties</th>
<th>Horizontal joint</th>
<th>Vertical joint</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{ij}^H$ per unit area (N/mm$^2$)</td>
<td>10.0</td>
<td>300</td>
<td>0.87</td>
</tr>
<tr>
<td>$k_{ij}^V$ per unit area (N/mm$^2$)</td>
<td>0.067</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$\sigma_c$ (MPa)</td>
<td>0.15</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>$c$ (MPa)</td>
<td>0.05</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\mu$ (-)</td>
<td>0.36</td>
<td>0.4</td>
<td>0.31</td>
</tr>
<tr>
<td>$G_l'$ (MPa·mm)</td>
<td>0.005</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$G_f'$ (MPa·mm)</td>
<td>0.05</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

$^*$ Not directly measured but assumed based on literature and/or calibrated to provide best fit to results.

where $\sigma_x = \sigma_* \text{ if } \sigma_x > 0 \text{ (positive), and } \sigma_x = \sigma_* = 0 \text{ if } \sigma_x < 0 \text{ (negative)}$ [49,50]. $\tau_{xy} = \text{ shear stresses along the first and second shear direction, respectively.}$

The post-elastic behaviour is controlled by the Mode I and Mode II fracture energies, namely $G_l'$ and $G_f'$ [32]. It is noteworthy that the interfaces cannot fail under compressive loads, but failure in compression of masonry can be taken indirectly into account through the CDP model employed for the bricks. Further details about the interface model can be found in Abdulla et al. [49].

Fig. 5 illustrates schematically a rubber-mortar joint. The properties of the interfaces describing these joints are derived hereinafter.

For the normal direction, the rubber joint stiffness (force per unit area per unit displacement) $k_{ij}^H$ can be evaluated as [51]:

$$
$$
Fig. 11. (a) Deformed shape of infilled RC frame with horizontal rubber joints (RJ_H) (b) numerical responses of the bare frame, infilled frame with traditional infills and infilled frame with horizontal rubber joints (RJ_H).

Fig. 12. Minimum compressive principal stress (in MPa unit) distribution under a horizontal displacement of 14.2 mm (1.0% drift).

where \( G_r \) is the shear modulus of the rubber, \( t_r \) is the thickness of the layer, and \( S \) is the shape factor. Its expression for rectangular layers is:

\[
S = \frac{BL}{2t_r(B + L)} \tag{4}
\]

where \( B \) is the width of the rubber layer, which coincides with the thickness of the wall.

In the case of plane strain, this expression reduces to:

\[
S = \frac{B}{2t_r} \tag{5}
\]

For the shear direction along the plane of the wall (s), the rubber stiffness can be evaluated as:

\[
k_s' = \frac{G_r}{t_r} \tag{6}
\]

In the out-of-plane shear direction (t), Eq. (6) provides only an approximation of the rubber stiffness in the case of specially shaped rubber joints such as those of Fig. 1. In fact, the shape of these joint results in a higher value of the transverse stiffness, allowing the formation of an arching mechanism under out-of-plane conditions [8]. In the case of simple rectangular rubber joints \( k_s' = k_t' \).

The mortar-rubber-mortar joints work, from a mechanical point of view, as a series system. Thus, if \( k_{nm} \), \( k_{nt} \), and \( k_{tt} \) are the stiffness of each mortar joint in the normal and shear directions respectively, then
The composite stiffness of the mortar-rubber-mortar joint in the normal and shear directions can be approximated as follows:

$$ k^*_{ij} = \frac{1}{\frac{1}{k^*_{ij}} + \frac{1}{k_{ij}}} \quad i = n, s, t $$  \hspace{1cm} (7)

The values of $k^*_{ij}$ are controlled by the compliance of the rubber, which is much higher than that of the mortar in order to accommodate large displacements of the in-plane motion of the frame and the wall. It is also noteworthy that these stiffness values should be adjusted to account for the fact that the joint has zero thickness and each brick unit in contact with the joint has to be expanded by the half joint thickness [32].

Fig. 13. Minimum principal compressive stress (in MPa unit) distribution under a horizontal displacement of 28.4 mm (2.0% drift).

Fig. 14. Plastic strain distribution under a horizontal displacement of 14.2 mm (1.0% drift).
With regards to the maximum allowable stresses in the mortar-rubber joints, under the series system approximation they can be assumed to coincide with the lowest among the values of the strengths of the constitutive components and the values of the bond resistance. In fact, failure could also occur in the bonds between the mortar and the rubber or in the bonds between the mortar and the bricks. It is noteworthy that the joint of Fig. 1 is equipped with studs that increase the bond between the rubber and the mortar, thus providing an increased bond resistance in shear with respect to the case of smooth rubber joints [46].

Although the proposed model is valid for all types of structural configurations of RC infilled frames, it suffers from some limitations, among which the most important ones are the simplification of the stress field of the mortar and mortar/rubber joints, the use of an isotropic behaviour for the bricks, and the high computational cost. While the first two limitations could be eliminated by using a micro-modelling strategy with an orthotropic constitutive model for the bricks, at the cost of an increased computational burden, the latter limitation could be overcome by resorting to macromodels for describing the infills (e.g. Panto and Rossi [52]). This would allow to investigate the seismic performance of a full building with infills and rubber joints. Nevertheless, the proposed strategy can still be useful for simulating and interpreting experimental results, and for calibrating/validating simplified modelling approaches when experimental tests are not possible.

3. Validation study

Two case studies are considered to evaluate the capabilities of the proposed modelling strategy for simulating the behaviour of RC frames with traditional and innovative masonry infill walls. The first one is RC frame with traditional infill walls made with solid blocks, experimentally tested by Mehrabi et al. [41]. This case study has been selected because it is widely employed by other authors [2,17,45,53,54], including also Mehrabi et al. [14] to validate their modelling strategy for RC frames with masonry infills. Moreover, together with the results of the tests of the infilled frame, various data from material and component tests were made available. These latter data have been used to calibrate the model parameters, whereas the experimental test results on the structural systems (i.e. bare frame and infilled frames) have been used for model validation. After validating the proposed approach, the infilled frame is studied numerically by performing pushover analyses for different layouts and stiffnesses of the rubber joints. The second case study is a RC frame that has been experimentally studied in three configurations: with no infills, with traditional infills made of hollow masonry blocks, and with these infills and rubber joints. The results of the tests, available in INSYSME project [13], are very detailed and useful for validating the proposed modelling strategy for RC frames with masonry infills and rubber joints.
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 Fig. 6.

The FE models of the bare frame and infilled frame have been developed by following the approach outlined in Section 2. The main mechanical properties of the concrete material employed for the frame components, brick units, and steel reinforcement are reported in Table 1. 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. [41], 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 [32]. The head joints have been given different properties to account for the fact that they were only partially filled with mortar. The wall to frame mortar interfaces have been assigned the same properties as the head joints.

### 3.1. Case study 1

In the first case, reference is made to the experimental tests of Mehrabi et al. [41], and to the ensuing numerical study [14]. Specimen 1 (bare frame) and specimen 3 (frame infilled with solid concrete masonry blocks) of the experimental campaign are considered. The concrete member sizes, rebar diameter and detailing scheme and masonry block dimensions (dimensions in mm) are given in Fig. 6. The beam-end was free to deflect in the vertical and out-of-plane horizontal directions. Fig. 7(a) shows the plastic strain distribution of the bare frame (specimen 1 in Mehrabi et al. [41]) for a horizontal displacement of 28.4 mm (corresponding to an inter-storey drift of 2.0%) and Fig. 7(b) compares the experimental and numerical force–deformation curves. The overall agreement is reasonable, although 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 is neglected. In the same figure, the numerical curve according to the model developed by Mehrabi et al. [41] is plotted for comparison.

#### 3.1.1. Frame with traditional infill

Fig. 8(a) shows the model’s predictions of the deformed shape and cracking pattern of the masonry infilled RC frame for a horizontal displacement of 14.2 mm, corresponding to a drift of about 1.0%. It can be observed that the horizontal load induces the formation of several diagonal cracks in the infill wall. The cracks affect both the bead and the head mortar joints. Fig. 8(b) 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.

Fig. 9(a) shows a contour plot of the minimum principal compressive stresses in the masonry and concrete components for a horizontal displacement of 14.2 mm (1.0% drift). The distribution of these stresses is significantly affected by the cracks forming along the main diagonal of the wall, with the highest absolute values observed in the corner regions. The plot of the plastic deformations (Fig. 9b), indicates that the frame and many bricks are significantly damaged.

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**Table 4**

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Concrete</th>
<th>Brick units</th>
<th>Steel reinforcement</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ (MPa)</td>
<td>22,000</td>
<td>3693</td>
<td>180,000</td>
<td>[46]</td>
</tr>
<tr>
<td>$v$ (-)</td>
<td>0.15</td>
<td>0.40</td>
<td>0.30</td>
<td>[46]</td>
</tr>
<tr>
<td>Strain at peak compressive stress</td>
<td>0.002</td>
<td>0.002</td>
<td>–</td>
<td>[55]</td>
</tr>
<tr>
<td>Ultimate strain (zero residual stress)</td>
<td>0.0035</td>
<td>0.0035</td>
<td>–</td>
<td>[55]</td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>3.90</td>
<td>0.22</td>
<td>–</td>
<td>[46]</td>
</tr>
<tr>
<td>$G''_f$ (MPa·mm)</td>
<td>0.075</td>
<td>0.04</td>
<td>0.002</td>
<td>[46]*</td>
</tr>
</tbody>
</table>

* Not directly measured but assumed based on literature and/or calibrated to provide best fit to results.

**Table 5**

<table>
<thead>
<tr>
<th>Mortar Interaction Properties</th>
<th>Bed joints</th>
<th>Head joints</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k$ (per unit area) (N/mm²)</td>
<td>200</td>
<td>200</td>
<td>[46]*</td>
</tr>
<tr>
<td>$k'$ (per unit area) (N/mm²)</td>
<td>200</td>
<td>200</td>
<td>[46]*</td>
</tr>
<tr>
<td>$c$ (MPa)</td>
<td>0.346</td>
<td>–</td>
<td>[46]</td>
</tr>
<tr>
<td>$c'$ (MPa)</td>
<td>0.485</td>
<td>–</td>
<td>[46]*</td>
</tr>
<tr>
<td>$\mu$ (-)</td>
<td>1.13</td>
<td>0.80</td>
<td>[46]</td>
</tr>
<tr>
<td>$G''_f$ (MPa·mm)</td>
<td>0.005</td>
<td>–</td>
<td>[46]*</td>
</tr>
<tr>
<td>$G''_f'$ (MPa·mm)</td>
<td>0.05</td>
<td>–</td>
<td>[46]*</td>
</tr>
</tbody>
</table>

* Not directly measured but assumed based on literature and/or calibrated to provide best fit to results.

---

**Fig. 17.** Geometric details of the selected infilled frame (INSYSME project [13]) with RC section details and block dimensions (dimensions in mm).
3.1.1.2. Frame with infill and 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 mortar-rubber joints only, and no vertical rubber joints present between the columns and the wall (RJ_H) or horizontal and vertical joints (RJ_HV). The horizontal layers of rubber joints are introduced between three or four courses of bricks and the vertical layers are introduced between the masonry infill and the frame, as shown in Fig. 10. The rubber joints are assumed to be flat.

The horizontal rubber joints are characterised by a relatively high compression stiffness in the vertical direction, and low shear stiffness of masonry sub-panels in the in-plane direction, in order to reduce the displacement demand on the infill. The shear modulus of the rubber is equal to \( G_r = 0.5 \text{ MPa} \) and the thickness of the horizontal joints is assumed equal to 7.5 mm. This value has been chosen such that each joint can undergo up to a shear deformation of approximately 125% (i.e., 9.5 mm), under a peak inter-storey drift of 2.0% (i.e., 28.4 mm relative displacement between top and bottom beams), assuming that the blocks of masonry between the joints behave rigidly under the horizontal forces. Table 3 reports the properties of the cohesive interfaces representing the mortar-rubber joints. The stiffness values evaluated are based on Eqs.3 to 7, assuming mortar layers with thickness \( t_m = 10 \text{ mm} \).

The vertical rubber joints 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
Table 6
Interaction properties of the mortar-rubber joints.

<table>
<thead>
<tr>
<th>Interaction properties</th>
<th>Horizontal joint</th>
<th>Vertical joint</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{ij}$ per unit area (N/mm$^3$)</td>
<td>11.7</td>
<td>200</td>
<td>1.0</td>
</tr>
<tr>
<td>$\sigma$, $\sigma^*$ per unit area (N/mm$^3$)</td>
<td>0.033</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>$\sigma_{ij}$ (MPa)</td>
<td>0.15</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>$\rho$ (–)</td>
<td>0.05</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\sigma^*$ (MPa/mm)</td>
<td>0.36</td>
<td>0.4</td>
<td>0.31</td>
</tr>
<tr>
<td>$\sigma_{ij}^*$ (MPa/mm)</td>
<td>0.005</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

* Not directly measured but assumed based on literature and/or calibrated to provide best fit to results.

columns and the masonry infill itself. This reduced stiffness in compression can be achieved by using joints of the same rubber as the horizontal joints, with a higher thickness of 30 mm, or by using a softer rubber compound. These joints, placed between the wall and the frame, are not bonded with vertical mortar joints. Thus, the interfaces used to represent these joints are characterized by zero cohesion and zero tensile resistance, and a friction coefficient of 0.31. The values of fracture energies are taken from Verlato [46] which are also consistent with the range of values reported in Lourenco [32].

In order to investigate the effect of the stiffness of the vertical rubber layers on the system behaviour, two further sub-cases are considered, where the rubber stiffness is increased by 10 times (RJ_HVH) and decreased by 10 times (RJ_HVL) with respect to the RJ_H case.

Fig. 11(a) shows the deformed shape of the infilled frame for RJ_H where, no mortar joints have been considered between the columns and the wall; the corresponding interfaces have only frictional behaviour, with very high stiffness (300 N/mm$^3$) to avoid penetration along the normal direction. Fig. 11(b) shows the load–deflection curve of the system with horizontal rubber joints, compared to the curves obtained in the bare frame and the frame with traditional infills. The addition of the rubber joints is found to increase the compliance of the infill wall, and it can be observed that most of the deformation/sliding is located at these joints, whereas the masonry blocks between the rubber joints behave rigidly. From the plots, it is possible to appreciate the remarkable flexibility of the system with rubber joints, which is similar to a bare frame. It is noteworthy that the reduction of stiffness can also help to reduce the demand of absolute accelerations in the infilled frame under seismic excitation, due to increase in natural period. This in turn helps to protect acceleration-sensitive components.

Fig. 12 and Fig. 13 show the principal stress distribution in the concrete and masonry components for a horizontal deflection of 14.2 mm (1.0% drift) and 28.4 mm (2.0% drift) respectively. These stresses are significantly lower compared to the case of the frame with traditional infill (see Fig. 9a), with the exception of two small regions at the interface of the bottom subpanel and the right column, and the top subpanel with the left column. The plot of the plastic deformations (Fig. 14 and Fig. 15), also confirms the effectiveness of the rubber joints in minimizing the damage to the masonry components, with bricks experiencing almost no damage even under a 2.0% drift.

In order to highlight the effect of the vertical rubber joints on the system behaviour, Fig. 16 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. The initial stiffness is lower for the case of horizontal and vertical rubber joints compared to the case of only horizontal joints, and it reduces by reducing the vertical joint stiffness. The maximum forces achieved by the various systems are quite similar. The peak force obtained for the system RJ HV is slightly higher than the one obtained for the system RJ H, and it is attained for a higher displacement. With the systems RJ_HVH and RJ_HVL slightly lower peak forces are attained compared to the system denoted to as RJ_HV. However, in Fig. 12 and Fig. 13, it can be seen that adding the vertical rubber joints reduces the compressive stresses in the bricks adjacent to the frame. This reduction is more significant for the case of flexible vertical joints (RJ_HVL) compared to the case of ordinary or stiff vertical joints.
Fig. 23. Load-deflection curve of the system with horizontal and vertical rubber joints.

Moreover, comparing the various contour plots of the plastic deformations in Fig. 14 and Fig. 15, it can be noted that the solution with vertical joints with low stiffness reduces significantly the damage of the frame, compared to the other solutions.

3.2. Case study II

The second case study considers a set of prototypes experimentally tested by University of Padova within INSYSME project [13] and described in Verlato [46]. Experimental results for bare frame, infilled frame with mortar joints (4th frame specimen, FC. MJ enclosure) and infilled frame with rubber joints (DRES-V2) are considered for the validation of the numerical modelling strategy. Fig. 17 illustrates the infilled frame prototype, whose aspect ratio is of 2/3. The infill panels are made with hollow clay masonry blocks (D-type in Verlato [46]) arranged in a running bond pattern (Fig. 17). D-type blocks are characterised by a lower percentage of holes, equal to 50%, and “tongue and groove” lateral surfaces that do not require the application of vertical mortar joints [46]. The transfer of shear stress under in-plane shear loading relies on friction. For modelling and computational simplicity, the hollow block behaviour is assumed to be isotropic, with properties based on the results of the compression test carried out along the direction parallel to the holes. The bed joints are fully filled with mortar and they are 10 mm thick, whereas there are no mortar head joints and the transfer of stresses from a brick to the adjacent ones relies on the brick interlocking. Some details regarding the frame, including the concrete member sizes, rebar diameter and detailing scheme and masonry block dimensions, are given in Fig. 17. Further details are available in Verlato [46]. The experimental quasi-static tests conducted on the bare frame and the frame infilled with traditional mortar joints and TARRC’s innovative mortar-rubber joints, shown in Fig. 3, consisted of the application of vertical loads (200 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 Fig. 17.

Table 4 reports the main mechanical properties of the concrete material employed for the frame components, the brick units, and the steel reinforcement. Table 5 reports the properties of the zero-thickness interfaces describing the mortar joints. The values reported in Table 4 and Table 5 are based on the results of the experimental tests carried out by INSYSME project [13] and numerical models developed by Verlato et al. [56] to simulate these tests. The head joints have been given different properties to account for the fact that they were not filled with mortar. The wall to frame mortar interfaces have been assigned the same properties as the head joints.

3.2.1. Bare frame

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 Fig. 18a). Fig. 18(a) shows the plastic strain distribution of the numerical model of the bare frame for a horizontal displacement of 55 mm (2.0% drift) and Fig. 18(b) compares the experimental and numerical force–deformation curves. The overall agreement is good although the proposed model slightly overestimates the initial stiffness of the system.

3.2.1.1. Frame with traditional infill. The analysis was run with a computer architecture of 16gb RAM, intel i5-8500 processor (3 GHz clock speed) and 64-bit operating system. With the 3D model with traditional infill (12812 nodes), 24.07 h of analysis are required to reach a displacement of 27.5 mm (equivalent to 1.0% of inter-storey
drift). Fig. 19(a) shows the deformed shape and cracking pattern of the masonry infilled wall for a horizontal displacement of 27.5 mm. It can be observed that the horizontal load induces the formation of several diagonal cracks in the wall. Fig. 19(b) 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.

Fig. 20(a) shows a contour plot of the minimum principal compressive stresses in the masonry and concrete components for a horizontal displacement of 27.5 mm (1.0% drift). The highest values of the compressive stresses are observed at the top right corner and at the bottom left corner, where they attain the compressive resistance of the bricks (Table 4). The principal stresses at the other two corners are tensile ones, as expected. Fig. 20(b) shows the plastic strain distribution indicating the cracking of the bricks for the same horizontal displacement. The cracks are localized in correspondence of diagonal bands. Also, the plastic deformations, shown in Fig. 20, are localized along diagonal bands with an inclination angle of about 60 degrees with respect to the horizontal plane.

3.2.1.2. Infill frames with rubber joints. The horizontal layers of rubber joints are placed between four courses of the bricks and the vertical layers are introduced between the masonry infill and the frame, as shown in Fig. 21. They have a thickness of 15 mm and are made with a rubber compound with shear modulus of 0.5 MPa. The mortar layers have a maximum thickness $t_{m2} = 20$ mm and a minimum thickness $t_{m1} = 5$ mm. The vertical joints are made with a different compound, which comprises recycled styrene-butadiene rubber and ethylene propylene monomer rubber granules anchored to a support of non-woven fabric [46].

Table 6 reports the values of the mechanical parameters describing the horizontal mortar-rubber joints and the vertical rubber joints. These properties of the cohesive interfaces representing the mortar-
rubber joints, have been evaluated based on Eqs. (3)–(7), assuming an average mortar thickness of 10 mm. It is noteworthy that the value assumed for the mortar layer thickness does not affect significantly the composite joint properties, which are controlled by the rubber layer compliance. The interfaces used to represent these vertical joints are characterized by zero cohesion and zero tensile resistance, and a friction coefficient of 0.31 evaluated experimentally during tests carried out within INSYSME project [13].

Fig. 22(a) shows the deformed shape of the infilled frame with both horizontal and vertical rubber joints. Overall, 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 deformation/sliding is located at these joints. Some cracks are observed at the top left corner of the lower portion of the wall, just below the first rubber layer. Other cracks are found on the right side of the top three subpanels. It is noteworthy that all these cracks were also observed experimentally [46]. Fig. 22(b) compares the load–deflection curve of the bare frame, the frame with traditional infills, and the frame with infill walls and rubber joints. In contrast to the case analysed previously, the frame with the innovative infills is significantly stiffer than the bare frame. Nevertheless, using the rubber joints yields significant reduction of stiffness compared to the case with traditional infills. The model used for the simulation is found to be quite accurate, with a global force–deflection curve very close to the experimental one (Fig. 23).

As for the previous case study, a comparison is carried out of the performances obtained considering horizontal rubber joint only and vertical rubber joints with higher and lower stiffness values compared to the reference model. Fig. 24 and Fig. 25 show the minimum compressive principal stress distribution for all selected cases, respectively under 1% and 2% imposed drift. It is clearly visible that the frame with vertical rubber joint of lower stiffness is performing better than the other cases (and the traditional infill, see Fig. 20a) in terms of minimization of the compression stresses in the bricks.

Fig. 26 and Fig. 27 show the distribution of plastic strains at 1% and 2% drift limits respectively. The solution with least damage is that corresponding to the lower vertical rubber stiffness (RJ_HVL), which performs significantly better than the frame with traditional infill (Fig. 20b) and exhibits less cracking in the masonry at high drift levels (Fig. 27) with larger gaps opening at the interface between the masonry subpanels and the frame compared to the other solutions investigated. The plastic deformations in the frame are also slightly reduced. The force–displacement curves, presented in Fig. 28, indicate that the use of rubber joints with low stiffness (case RJ_HVL) also corresponds to a further decrease of global stiffness and strength compared to the reference case (RH_HV).

4. Summary and conclusions

In this study, a novel meso-scale approach is developed for simulating the response of RC frames equipped with masonry infill walls and rubber joints under horizontal loads such as those induced by earthquakes. The behavior of the RC frame is described using solid elements and embedded rebars, whereas the mortar-rubber joints are described by means of zero-thickness interfaces, whose behavior is calibrated to simulate the in-series arrangement of the components. This approach, employed for the first time to investigate the system at hand, illuminates the response at local level of the components of the system, such as the bricks or the joints. The proposed strategy is validated against experimental results carried out on two case studies; a RC frame with traditional infills and a RC frames with both traditional and TARRC’s innovative infills with rubber joints. A generally good agreement is ob-
served between experimental and numerical results, in terms of global force–displacement response and location of cracks in the bricks. The study results show that adding the rubber joints significantly increases the compliance of the system, helping to avoid or reduce the damage to the frame and the infills. Moreover, using vertical rubber joints with low stiffness in addition to the horizontal ones further improves the behaviour in terms of reduction of compressive stresses and cracking in the masonry at large displacements, while providing a horizontal force–deflection response similar to the case with only horizontal joints. Even the plastic deformations in the frame can be reduced by using vertical joints with low stiffness.

The proposed modelling strategy can be employed to investigate the optimal combination of strength, deformability and dissipation capacity of the rubber joints for enhancing the seismic performance for a wide variety of infilled frames. It is also useful for calibrating simplified modelling strategies, such as those based on diagonal equivalent struts. Further analyses will be carried out, using the same modelling approach developed here and simplified ones, to evaluate the combined in-plane and out-of-plane behaviour of the system. Moreover, a more complex constitutive model of the joints, describing also the energy dissipation capacities of the rubber, will be developed and calibrated based on experimental results to investigate the benefits of introducing the rubber joints in terms of enhancement of the global damping capacity of the system.

5. Data availability statement

The data used to support the findings of this study are available from the corresponding author upon request.

Supplementary materials

The data used to support the findings of this study are available from the corresponding author upon request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References


