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RC FRAMES WITH MASONRY INFILLS WITH AND WITHOUT OPENINGS: EXPERIMENTAL AND NUMERICAL RESULTS

Aleksa Milijaš[1*], Bogdan Šakić[1], Marko Marinković[2], Christoph Butenweg[3], Matija Gams[4], Sven Klinkel[1]

[1] Chair of Structural Analysis and Dynamics
RWTH Aachen University
Mies-van-der-Rohe-Straße 1, 52074 Aachen, Germany
milijas@lbb.rwth-aachen.de, sakic@lbb.rwth-aachen.de, klinkel@lbb.rwth-aachen.de

[2] Chair of Engineering Mechanics and Theory of Structures, Faculty of Civil Engineering
University of Belgrade
Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia
mmarinkovic@grf.bgd.ac.rs

[3] Center for Wind and Earthquake Engineering
RWTH Aachen University
Mies-van-der-Rohe-Straße 1, 52074 Aachen, Germany
butenweg@lbb.rwth-aachen.de

[4] Department of Structural and Earthquake Engineering, Faculty of Civil and Geodetic Engineering
University of Ljubljana
Jamova cesta 2, 1000 Ljubljana, Slovenia
matija.gams@fgg.uni-lj.si

Abstract

RC frames with masonry infills are a widespread construction form in seismically active regions. Under seismic loading, masonry infills are activated in in-plane direction due to the frame deformation. This leads to the complex frame-infill interaction which can cause the failure of masonry infills or whole RC frame structures. Therefore, the in-plane behaviour of infilled RC frames was a subject of many research projects that aim to predict the seismic performance of infilled frame structures or prevent the damage in masonry infills. Among many parameters that affect seismic response of infilled frames, openings are recognized to play the most significant role as they can affect the stress fields and thus alter the failure mechanism of masonry infills. This paper presents results of the investigation of in-plane behaviour of masonry infilled RC frames with and without openings. In the study, experimental results are firstly presented, and they are afterwards used for validation of numerical model. Further, influence of different opening arrangements on in-plane response of infilled frames is studied in numerical simulations. Results of the study show that openings cause the extensive damage on masonry infills and thus lead to deterioration in in-plane behaviour of infilled RC frames.

Additionally, the study reveals that even large openings affect the seismic response of infilled RC frames and that they cannot be easily neglected in design process, which makes the reliable prediction of the seismic response of infilled RC frames complicated. The study points at the urgency of development of innovative solutions that will be able to prevent the damage in masonry infills and simplify their seismic design.

Keywords: Seismic loading, In-plane load, Openings, Numerical modelling, Masonry infill design

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1 INTRODUCTION

Reinforced concrete frame structures are widely favoured in today's modern construction practice for their numerous advantages. Firstly, construction process of these buildings is quite simple and economical and it does not necessitate highly skilled labour. In addition, RC frame structures properly designed in accordance with the current aseismic design principles show an excellent performance under seismic loading. Furthermore, RC frame structures are usually built in combination with masonry infills, which are installed as exterior walls or inner partitions. On one side, the utilization of masonry infills as enclosure systems confers many advantages, such as enhanced fire resistance, acoustic and thermal insulation, as well as improved energy efficiency. On the other side, masonry infills have a predominantly adverse impact on the seismic performance of RC frame structures. Namely, under seismic loading, frame-infill interaction takes part, as masonry infills are activated in the in-plane direction due to the deformation of RC frames, while in out-of-plane direction, they are subjected to forces induced by seismic acceleration and wall mass. Due to this, masonry infills experience detrimental in-plane, out-of-plane and mixed failure mechanisms, as it was observed in recent earthquake events in Wenchuan 2008 [1], Central Italy 2016 [2] and Albania 2019 [3]. Furthermore, effects of frame-infill interaction may cause a severe damage or a complete failure of frame members and beam-column joints [3-5]. Moreover, irregular distribution of infills in elevation and plan can lead to the collapse of the whole structures due to the development of soft-storey mechanisms or dangerous effects of torsional irregularities [3-5].

Despite the widespread damage to infilled RC frame structures in the latest earthquake events, masonry infills are still generally regarded as non-structural elements, and as such, they are neglected in the design process of frame structures. The reason for this is the absence of simple analytical design models that could be used for verification of masonry infills [6]. However, it is not surprising that simple directions for design of RC frame structures accounting for masonry infills are still missing, as frame-infill interaction is a complex problem, which has been investigated for more than sixty years.

Experimental and numerical investigations focus mostly on in-plane behaviour of infilled frames [7-10]. Crisafulli (1997) [11] defined the major failure mechanisms of masonry infills and surrounding RC frames under in-plane loads. Various parameters have been recognized to affect the in-plane behaviour of infilled RC frames, such as strength of infill and RC frame [7,12], aspect ratio [7,13,14] and level of vertical loads acting on the frame [7,13,15]. However, according to FEMA 306 (1998) [16] seismic performance of infilled RC frames is most critically influenced by the presence of openings, such as doors and windows. In several experimental studies [17-19] the alteration of failure mechanisms of masonry infills due to modified stress field caused by presence of openings was observed. Furthermore, authors [17-19] reported that cracking occurred earlier in infills with openings, which lead to reduction of infilled

RC frame ductility. Ahani et al. (2019) [20] investigated the effects of opening size and location on in-plane behaviour of infilled frames. Based on the results of the parametric study, Asteris (2003) [21] and Asteris et al. (2012) [22] provided the directions for calculation of initial in-plane stiffness of infilled frames with openings. However, further investigations are required in order to better understand the in-plane behaviour of infilled frames with various opening configurations.

In this paper, results of experimental tests carried out on infilled RC frames with and without openings are presented. Afterwards, numerical model developed by Marinković and Butenweg (2022) [23] is validated against experimental results. Finally, influence of different opening arrangements is studied by means of numerical simulations.

2 EXPERIMENTAL TESTS

2.1 Test specimens and material characteristics

Figure 1 shows the RC frame with solid masonry infill used in the experimental campaign. Masonry infill is a representative of a modern infill typology. It is built of thick hollow clay bricks with narrow vertical voids. Bed joints are filled with thin layer mortar, while head joints are executed as dry tongue and groove connections, which is usual in today's practice. Mortar is used for levelling layer and for connections of the masonry infill to the columns of the RC frame. Furthermore, infills in this experimental campaign are characterized by unusually strong connections at the top, which are achieved by careful filling of the remaining gap at the top by thin layer mortar, which was applied by a special hand pump. However, such a laborious execution cannot be guaranteed on construction sites.

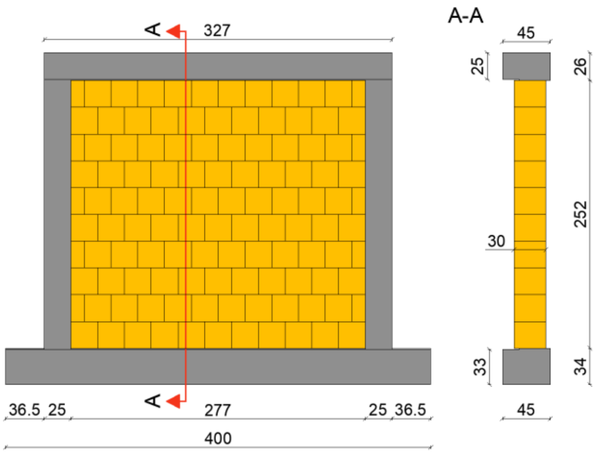


Figure 1. RC frame with solid masonry infill

In infills with openings, window and door are centrally positioned. Window opening covers around 18 % of the infill panel, while full-height door opening takes around 38 % of the panel surface. Further information on the exact position and dimensions of the openings, as well as on the detailed frame dimensions and reinforcement distribution can be found in [24].
Furthermore, mechanical characteristics of mortar, bricks and masonry that are used in the experimental campaign have been determined in standardized tests according to DIN EN 1015 (2007) [25], DIN EN 772 (2016) [26] and DIN EN 1052 (1998) [27], respectively. Table 1 summarizes the test results, while more detailed information is provided in [24].

<table>
<tr><td rowspan="3">Mortar MAXIT</td><td>Mortar type</td><td colspan="3">Compressive strength
f_m [MPa]</td><td colspan="4">Flexural tensile strength
$f_{m,flex}$ [MPa]</td></tr>
<tr><td>Thin layer mortar</td><td colspan="3">12.8</td><td colspan="4">2.4</td></tr>
<tr><td>General purpose mortar</td><td colspan="3">16</td><td colspan="4">2.4</td></tr>
<tr><td rowspan="3">Brick Thermo plan SX10</td><td>Dimensions L/T/H [mm]</td><td colspan="3">Normalised compressive strength
f_b [MPa]</td><td colspan="2">Voids [%]</td><td colspan="2">Gross dry density [kg/m^3]</td></tr>
<tr><td>247/300/249</td><td>Vertical</td><td colspan="2">Longitudinal</td><td colspan="2" rowspan="2">52.8</td><td colspan="2" rowspan="2">628</td></tr>
<tr><td></td><td>11.01</td><td colspan="2">1.92</td></tr>
<tr><td rowspan="3">Masonry</td><td colspan="3">Compressive strength
f_k [MPa]</td><td colspan="2">Modulus of elasticity
E_m [GPa]</td><td colspan="3">Flexural strengths
f_{xk1}, f_{xk2} [MPa]</td></tr>
<tr><td colspan="3" rowspan="2">2.4</td><td colspan="2" rowspan="2">4.7</td><td colspan="2">Parallel to the bed joints: f_{xk1}</td><td>Perpendicular to the bed joints: f_{xk2}</td></tr>
<tr><td colspan="2">0.26</td><td>0.12</td></tr>
</table>

Table 1. Material properties and strengths

2.2 Test setup

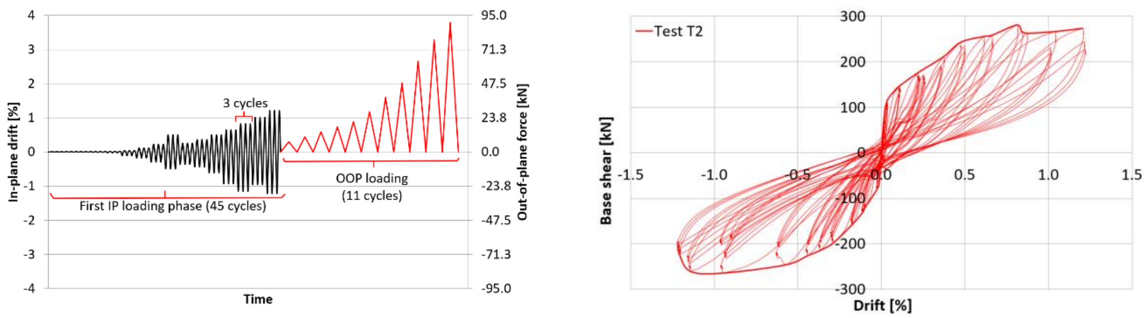
In the scope of the AiF project "Development of an innovative approach for decoupling infills and non-load-bearing masonry walls from the main structure" [28] an extensive experimental campaign has been carried out, which encompasses pure out-of-plane tests, tests with sequential in-plane and out-of-plane loading and tests with simultaneously applied in-plane and out-of-plane loading. In addition to this, at the beginning of each test, vertical force of 200 kN is applied to each column and kept constant during the whole test, in order to simulate the vertical loads from the upper floors of the building. Therefore, test setup which enables application of axial loads to the columns together with separate or combined in-plane and out-of-plane loads has been designed. One-way hydraulic actuators are used for application of the axial loads to the columns. In-plane loads are applied as displacement-controlled by two servo-controlled hydraulic actuators. On one side they are connected to the top beam of the RC frame and on the other side to the strong reaction wall. Furthermore, design of the test setup allows application of cyclic in-plane displacements. Out-of-plane loads are applied by inflating four air bags. Further details on the test setup can be found in [24].

2.3 Experimental tests on infilled RC frames

This paper focuses on the investigation of the in-plane behaviour of traditionally infilled RC frames. Therefore, experimental results of in-plane loading phases of sequential loading tests will be presented herein only.

2.3.1 Fully infilled RC frame - Test T2

Figure 1a shows loading protocol of test T2. RC frame with solid traditional infill is subjected to cyclic in-plane displacements up to the in-plane drift of 1.2 %. Afterwards, the in-plane load is stopped and infill is loaded in eleven cycles up to out-of-plane force of 90 kN. Figure 1b shows hysteresis curve and its envelope, which are obtained from in-plane loading cycles of test T2. It can be seen that the first significant stiffness decrease takes part at a drift of around 0.035 % (110 kN) in positive and 0.027 % (75 kN) in negative loading direction, due to the stepwise cracking through head and bed joints. At around 0.5 % of in-plane drift stepwise cracks are distributed throughout the entire infill, and first cracks emerge in bricks, which corresponds to the damage limitation limit state (DLS), defined in [29]. Furthermore, the maximum horizontal force of 280 kN is reached at 0.8 % of in-plane drift in positive loading direction and at 0.95 % of in-plane drift (263 kN) in negative loading direction. Until 1.0 % of in-plane drift cracking is spreading and at this stage more significant cracking takes part in bricks, in addition to strong cracking of mortar joints. According to [29], damage propagation at this drift level can be classified as significant damage limit state condition. Test is stopped at 1.2 % of in-plane drift due to the further propagation of damage to masonry infill, concentrated mostly in the middle row of bricks, where spalling of outer shells of bricks take part (Figure 7a). The damage limit state at the end of the test T2 corresponds to the near collapse limit state (NCLS) described in [30].



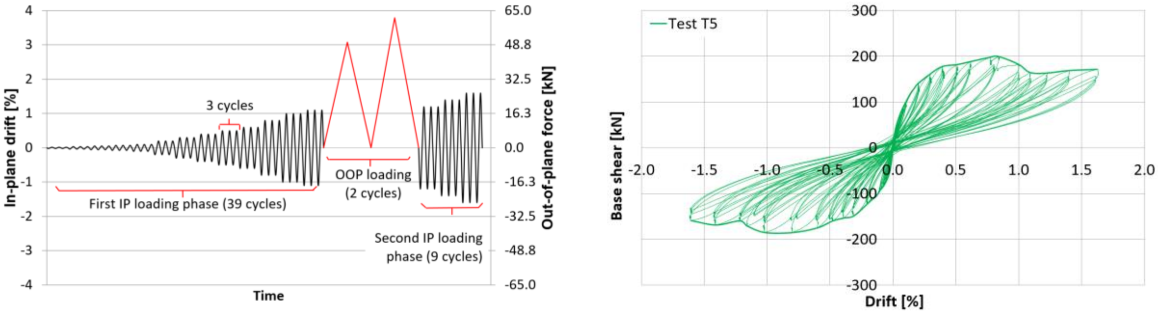
a) (b)

Figure 2. Loading protocol (a) and load-displacement curve (b) of test T2

2.3.2 Infilled RC frame with window opening - Test T5

In test T5 traditionally infilled RC frame with centric window opening is subjected to cyclic in-plane displacements up to 1.1 % of in-plane drift. After termination of the first in-plane load phase, out-of-plane load is applied in two cycles up to the total out-of-plane force of 61.6 kN. Thereafter, specimen T5 is loaded with cyclic in-plane displacements up to 1.6 % of in-plane drift.

Figure 3b shows hysteresis curve and its envelope, which are obtained from in-plane loading cycles of test T5. First stepwise cracks appear in the infill parts below and above window opening at in-plane drift of around 0.044 % (50 kN) in positive and 0.056 % (57 kN) in negative loading direction. This leads to the first decrease of stiffness. At 0.2 % of in-plane drift, first stepwise cracks occur in infill piers. At 0.5 % of in-plane drift stepwise cracking propagates further, while the first cracks emerge in bricks too. This damage level can be classified as damage limitation limit state (DLS) described in [29]. Furthermore, the maximum horizontal forces of 200 kN and 185 kN are measured at 0.8 % of in-plane drift in positive and negative loading direction, respectively. At around 0.8 % of in-plane drift, in addition to cracking and crushing of several bricks, detachment of triangular-like parts of masonry next to window opening starts. Damage observed at this drift level corresponds to the significant damage limit state conditions, defined in [29]. As the damage propagates further, the horizontal force remains almost constant from 1.1 % of in-plane drift up to 1.6 % of in-plane drift, when the test is stopped due to the complete detachment and falling out of masonry parts next to window opening.



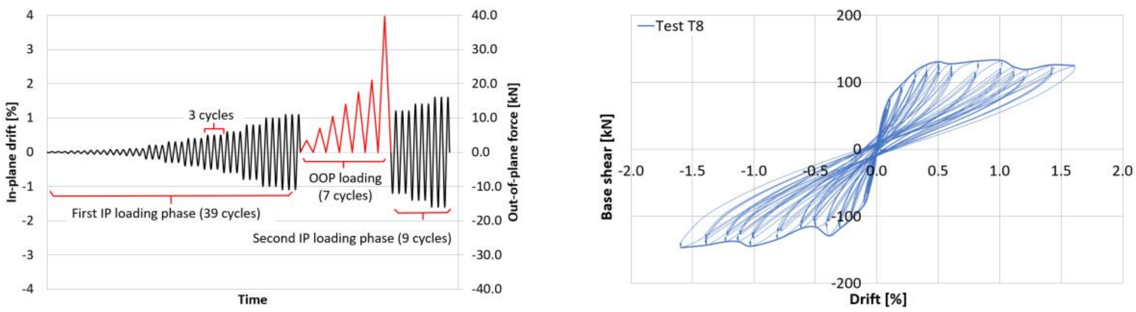
a) b)

Figure 3. Loading protocol (a) and load-displacement curve (b) of test T5

2.3.3 Infilled RC frame with door opening - Test T8

RC frame with traditional infill with door opening is investigated in a sequential test T8. Cyclic in-plane displacements are first applied to the specimen up to the in-plane drift of 1.1 %. After suspension of in-plane loads, out-of-plane load is imposed to the infill in seven cycles up to the total out-of-plane force of 39.7 kN. In the last load phase, the specimen is loaded up to 1.6 % of in-plane drift.

Figure 4b shows hysteresis curve and its envelope, which are obtained from in-plane loading cycles of test T8. The first reduction of stiffness is visible at around 0.1 % of in-plane drift, due to the light stepwise cracks in the bottom parts of the both piers. With increase of in-plane drifts, these stepwise cracks become more pronounced (at a drift of around 0.2 %) and diagonal cracking starts first in the middle of infill piers (at a drift of around 0.4 %) and afterwards in the upper parts of the piers. Propagation of damage to infill, with diagonal cracks running through bed and head joints and bricks at 0.4 % of in-plane drift goes in line with the damage limitation limit state conditions proposed in [29]. Furthermore, edge bricks in the lowermost row of both piers experience crushing already at 0.5 % of in-plane drift. With increase of in-plane drift further propagation of damage to infill is observed. The damage level at 0.8 % of in-plane drift corresponds to the significant damage limit state conditions defined in [29]. The maximum horizontal loads are reached at 1.0 % of in-plane drift (132.4 kN) in positive and at 1.6 % of in-plane drift (146.5 kN) in negative direction. As it can be seen on load – drift curves in Figure 4b, after around 1.1 % of in-plane drift, horizontal force is mostly constant due to the propagation of the damage to infill. Triangular like parts next to door opening, which are formed due to diagonal cracking in both piers tend to detach from the rest of the infill. Due to the complete detachment of such a masonry portion test is stopped at 1.6 % of in-plane drift.



a) b)

Figure 4. Loading protocol (a) and load-displacement curve (b) of test T8

2.3.4 Comparison of the experimental results

Figure 5 shows the comparison of envelopes obtained from in-plane loading phases of sequential loading tests T2, T5 and T8. The envelope of the hysteresis curve obtained from the test on bare frame specimen (test A) is shown in Figure 5 too, in order to compare the in-plane response of RC frames with different infill configurations with the in-plane response of a bare frame. Test A was carried out in the frame of the INSYSME project (2016) [31]. The test is described in [32]. Since the same geometric and mechanical characteristics are used for a bare frame and traditionally infilled RC frame, the direct comparison of experimental results is possible.

Comparison of envelopes presented in Figure 5 points at a significantly different response of traditionally infilled RC frames and bare frame. Firstly, the initial in-plane stiffnesses of infilled RC frames are much higher in comparison to the initial in-plane stiffness of the bare RC frame. For the case of fully infilled RC frame, initial in-plane stiffness is around 10 times higher, while for cases of infilled RC frame with window and door opening initial in-plane stiffness is around 6 and 4 times higher than initial in-plane stiffness of the bare frame, respectively. These results show that masonry infills significantly contribute to the initial stiffness of the frame structure and thus alter dynamic characteristics of frame structures, even if they contain large full-height openings, as in test T8. Furthermore, due to the higher initial stiffnesses, masonry infills are activated at low in-plane drifts and maximum horizontal loads of infilled frames are already reached at in-plane drifts of around 0.8 and 1.0 %. On the other side, maximum horizontal load of bare frame in test A is reached at around 2.0 % of in-plane drift. Moreover, bare frame is characterized by a ductile behaviour which allows reaching high in-plane drifts (3.5 %), while traditionally infilled RC frames fail at in-plane drifts lower than 1.6 % due to the severe damage or complete failure of infills.

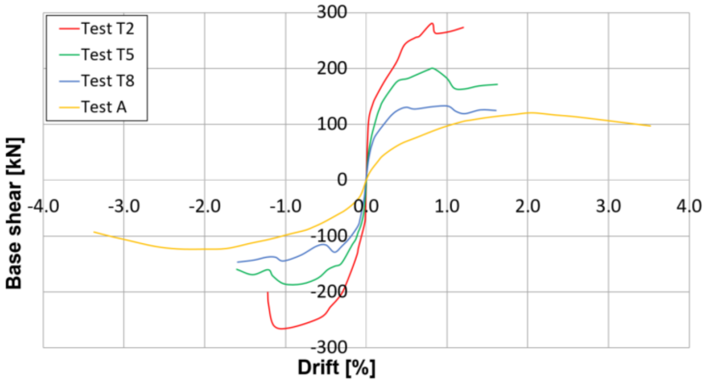


Figure 5. Comparison of envelopes obtained from tests T2, T5, T8 and test A

Figure 5 shows that the maximum in-plane load capacity is reached by fully infilled RC frame in test T2. Due to the window opening of around 18 %, in-plane load capacity of infilled RC frame with window opening in test T5 is reduced for around 30 % in comparison to in-plane load capacity of fully infilled RC frame. Furthermore, due to the full-height door opening in test T8, in-plane load capacity of specimen T8 is around two times smaller than in-plane load capacity of specimen T2. As it can be seen in Figure 5, in-plane load capacity of the infilled RC frame with door opening (test T8) is not much higher than the in-plane load capacity of the bare frame.

Results of experimental tests clearly show that masonry infills have an adverse effect on in-plane response of frame structures. As described in Chapters 2.3.2 and 2.3.3, openings increase damage level on infills in test T5 and T8. Fragile crack patterns are formed next to openings and significant damage occurs on infills at lower in-plane drifts in comparison to solid infills.

For instance, significant damage limit state conditions defined in [29] are reached at 1.0 % of in-plane drift for solid infill (test T2), and at 0.8 % of in-plane drift for infill with window (test T5) and door opening (test T8). In addition to this, particularly adverse effect of large opening in test T8 is recognized, as masonry infill significantly contributes to the initial in-plane stiffness of the frame, but exhibits a rather small in-plane load capacity. Negligence of such infill in the design process could lead to a large error in determination of the dynamic characteristics of the frame structure.

3 NUMERICAL ANALYSIS

In order to extend experimental results on in-plane behaviour of masonry infilled RC frames with and without openings, numerical study was carried out. For this purpose, a three dimensional finite element numerical model developed by Marinković and Butenweg (2022) [23] is employed in the Finite Element package Abaqus [33]. Numerical model is first validated against experimental results. Afterwards, it is used for investigation of other opening arrangements on the in-plane response of infilled frames.

3.1 Numerical model

Explicit dynamic analysis is used in numerical simulations. Therefore, according to recommendation [34], concrete frames and masonry bricks are modelled with three dimensional 8-node hexahedral continuum finite elements, with reduced integration (C3D8R). Furthermore, truss elements (T3D2) are used to model reinforcement and they are embedded in the solid concrete elements. RC frame is modelled with its actual geometry, with exception of the bottom beam, which is modelled as a discrete rigid plate due to its high stiffness and strength. In addition, exact distribution and size of reinforcement bars and stirrups is taken into account in the model.

To model masonry infill, simplified micro-modelling technique is used, which means that bricks are modelled as parts, while actual geometry of mortar joints is not modelled, as corresponding interaction depicts their behaviour. Namely, general contact with the specified interaction properties is used to define interactions in the model. Interaction property with “hard” contact and penalty based friction formulation is assigned to interactions between all parts in the model. However, for definition of mortar connections (bed joints and frame-infill connections) cohesive behaviour with a specified damage evolution is included too.

Since concrete and masonry are both quasi-brittle materials the constitutive model for definition of these two materials is the concrete damage plasticity (CDP) model available in Abaqus [33]. This material model allows separate definition of stress-strain and stress-displacements relationships for the case of compressive and tensile stresses, respectively.

For the case of compression, behaviour of concrete is linear in the elastic range, up to $0.4f_{cm}$, as suggested by Eurocode 2 [35]. For the values higher than $0.4f_{cm}$ the plastic behaviour of concrete starts. Stress-strain curve in plastic region is divided into two sections. Up to the nominal ultimate strain expression proposed in Eurocode 2 [35] is used, while for strains higher than the nominal ultimate strain the formula according to Pavlović (2013) [36] is applied.

For the case of tension loads, linear behaviour is expected until reaching the mean tensile strength f_{ctm}. In the plastic region, stress-displacement curve is defined instead of a stress-strain curve. Stress-displacement curve is generated according to equation proposed by Hordijk (1992) [37].

Furthermore, CDP model allows definition of different damage characteristics in tension and compression. Damage parameters are defined according to exponential function proposed by

Lee and Fenves (1998) [38], which determine the degradation of the elastic stiffness due to cracking.

Regarding the material model for masonry, it should be pointed out that the bricks are modelled as solid parts without any holes, although they actually contain vertical voids. Due to this, material characteristics of masonry assembly are assigned to bricks to take into account the effect of holes. The applied modeling approach was first proposed by Stavridis and Shing (2010) [39], who suggested assignment of the material characteristics of masonry prisms to the masonry units, instead of material characteristics of individual masonry units.

Behaviour of masonry in the elastic range is defined by the modulus of elasticity and Poisson's ratio. For compression loads, stress-strain curve is divided into two sections. Parabolic part of the curve is defined by Stavridis and Shing (2010) [39], while for definition of descending branch another expression is used, which can be found in Marinković and Butenweg (2022) [23].

Under tension loads, the approach proposed by Stavridis and Shing (2010) [39] is used to define the behaviour of masonry in the plastic region.

Similar to the case of concrete, damage parameters are separately defined for compression and tension loads.

Experimental data are used to define the stress-strain curve of reinforcement bars.

More detailed description of numerical model and material constitutive laws can be found in [23]. In [23] material models for concrete and masonry were calibrated and numerical model was validated against experimental tests on fully infilled RC frame. In this study, different brick and mortar type are used, as shown in Table 1. Therefore, mechanical characteristics of masonry and mortar interactions are modified accordingly. Numerical model is validated against experimental tests carried out on fully infilled RC frame (T2) and RC frames with window (T5) and door opening (T8), as it will be shown in the following.

3.2 Simulations of experimental tests on infilled RC frames

In the model, three steps are defined to account for the loading conditions of the experimental test on the infilled frame: gravity, vertical load and horizontal displacements. In numerical simulations horizontal displacements are applied monotonically, in only one direction, from left to right (positive direction). Therefore, load-drift curves obtained from numerical simulations are compared with envelopes of load-drift curves obtained from experimental tests. More information on the boundary conditions and load application can be found in [23].

3.2.1 Fully infilled RC frame - Test T2

The developed numerical model is used for the simulation of in-plane loading phase of test T2. Figure 6 shows comparison of load-drift curves obtained from the experimental test T2 and numerical simulation. The curve from the simulation shows a quite good matching with the experimental result in terms of both initial stiffness and maximum load. Furthermore, Figure 7a shows the major strain propagation at maximum in-plane drift of 1.2 %, while Figure 7b shows the tensile damage propagation in numerical model. It is clear that the model is able to depict the distribution of damage to infill quite well.

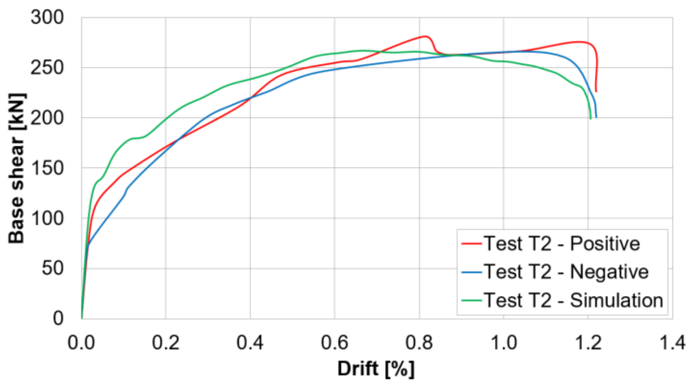
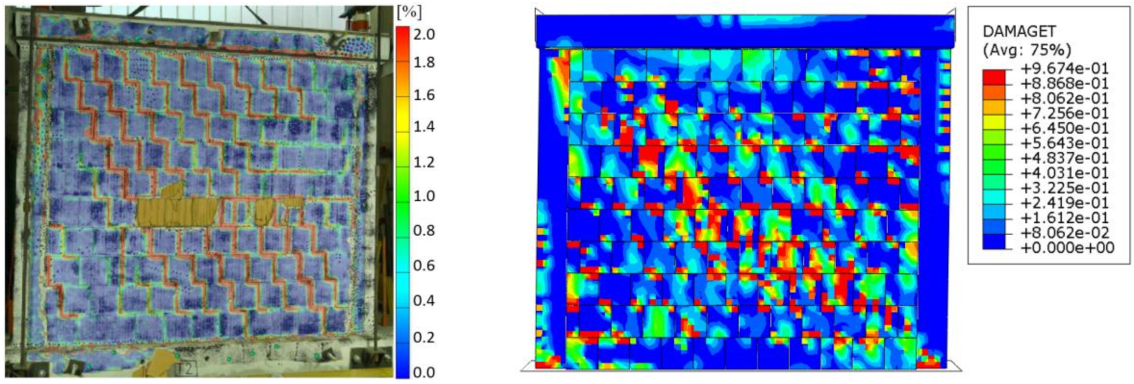


Figure 6. Comparison of load-drift curves obtained from experimental test T2 and numerical simulation



a) b)

Figure 7. Major strain propagation in infill in test T2 (a) and damage in tension in numerical model of test T2 (b) at the end of test T2 (Δ = 1.2 %)

3.2.2 Infilled RC frame with window opening - Test T5

Simulation of in-plane loading phases of experimental test T5 are also carried out in Abaqus [33]. In Figure 8 load-drift curve obtained from numerical simulation of test T5 is compared with a positive and negative branch of the load-drift envelope of test T5. As it can be seen in Figure 8, numerical model can quite precisely capture the initial stiffness and maximum load obtained in experimental test. In addition to this, damage propagation obtained in numerical simulation corresponds to the damage observed in test T5. For instance, major strain propagation in test T5 and damage in tension in numerical simulation at in-plane drift of 1.1 % are shown in Figures 9a and 9b, respectively. As in experimental test, masonry infill is already experiences most of the damage in piers next to window opening in numerical simulation.

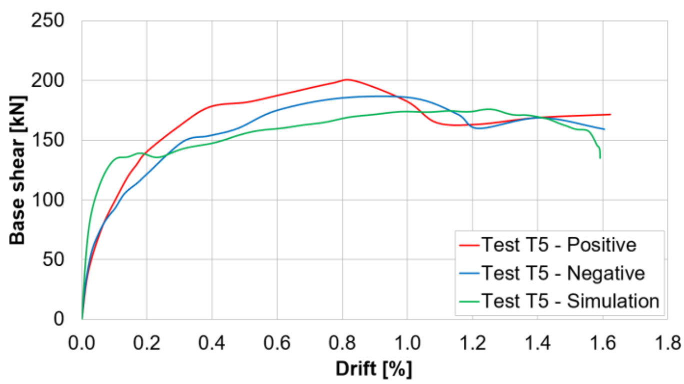
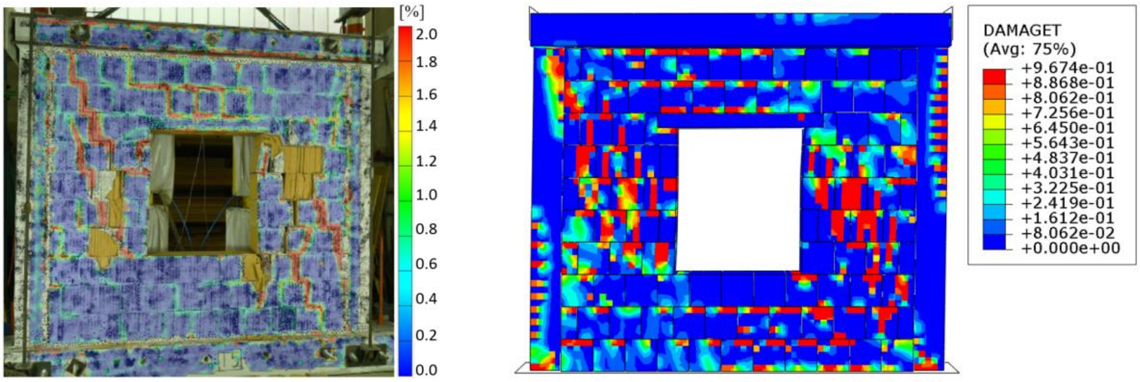


Figure 8. Comparison of load-drift curves obtained from experimental test T5 and numerical simulation



(a) (b)

Figure 9. Major strain propagation in infill in test T5 (a) and damage in tension in numerical model of test T5 (b) at 1.1 % of in-plane drift

3.2.3 Infilled RC frame with door opening - Test T8

In-plane behaviour of traditionally infilled RC frame with door opening tested in test T8 is also further investigated by means of numerical simulations. Force-drift curve obtained from numerical simulation of test T8 is presented in Figure 10 together with positive and negative branch of envelope of hysteresis curve of test T8. Comparison of curves clearly shows that numerical model can quite well capture the in-plane response of infilled RC frame with door opening too. In Figure 11a major strain propagation on infill measured at infill failure at 1.0 % of in-plane drift is shown, while damage in tension in numerical model for the same drift level is presented in Figure 11b. Damage propagation in numerical model corresponds to the experimental result, as diagonal cracking is dominant failure mode, combined with toe crushing in the right edge of the left infill pier.

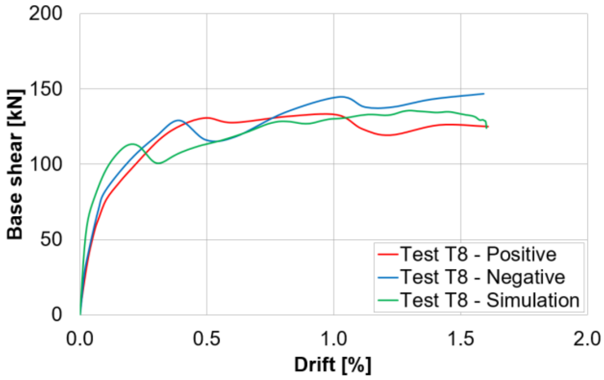
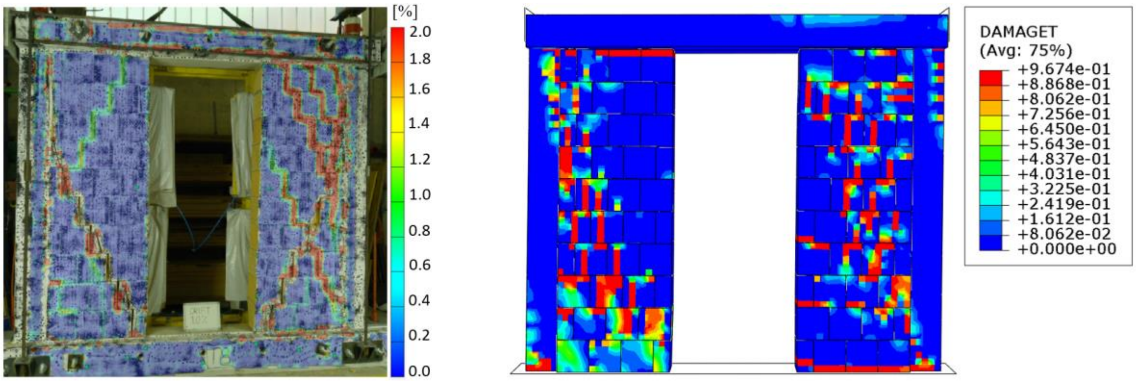


Figure 10. Comparison of load-drift curves obtained from experimental test T8 and numerical simulation



(a) (b)

Figure 11. Major strain propagation in infill in test T8 (a) and damage in tension in numerical model of test T8 (b) at 1.0 % of in-plane drift

3.3 Infilled RC frames with different opening configurations

Numerical model is used for a further investigation of in-plane behaviour of infilled RC frames with openings. RC frames with six infills are considered. Simulation of test T2 refers to the case with solid masonry infill, while simulation of test T5 refer to infill with centric window opening that takes around 18 % of panel surface. In simulation of test T8 full-height door opening covers around 38 % of panel surface. In addition to this, infills with window and door opening that take around 50 % of infill surface are considered, as well as the infill with reduced height, which fills 50 % of frame height.

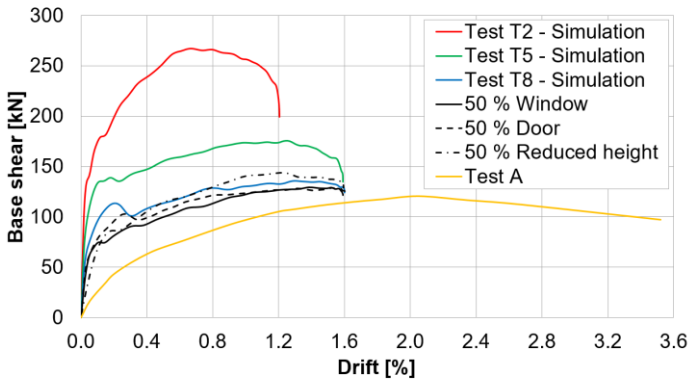


Figure 12. Comparison of force-drift curves obtained from infills with different opening configurations and bare frame (test A)

Figure 12 shows force-drift curves obtained from additional three numerical simulations together with force-drift curves obtained from numerical simulations of tests T2, T5 and T8 and positive branch of envelope of test A (bare frame). It can be clearly seen that despite the increase of opening percentages in infills, initial in-plane stiffness of infilled frames with openings is still much higher than initial in-plane stiffness of the bare frame, which means that even infills with such large openings (50 % of panel surface) can significantly affect the stiffness of the bare frame and thus global response of the frame structure. Furthermore, the damage propagation on infills is observed in all six models. In simulation of test T2, the damage limitation limit state conditions (DLS) described in [29] occur at around 0.5 % of in-plane drift, while significant damage limit state conditions defined in [29] are observed at 1.0 % of in-plane drift. In simulation of tests T5 and T8, damage at in-plane drifts of around 0.4 % and 0.8 % correspond to damage limitation limit state conditions and significant damage limit states, respectively.

These results confirm that numerical model is capable of accurately representing the extent of damage on masonry infills. The similar trend is observed for three infills with larger opening percentages (A_o/A_{infill} = 0.5), with damage limitation limit state conditions (DLS) reached at low in-plane drifts (around 0.4 %) and significant damage limit state conditions reached at around 0.8 % of in-plane drifts. Figures 13a-c show the tension damage distribution in three additional models at the limit of significant damage state (0.8 % of in-plane drift). It can be seen that diagonal cracking takes part in narrow piers of infills with 50 % of centric window and door opening (Figures 13a,b). In addition to this, infill that fills only 50 % of the frame height is strongly activated under imposed in-plane drifts too, with significant cracking through bricks at 0.8 % of in-plane drift.

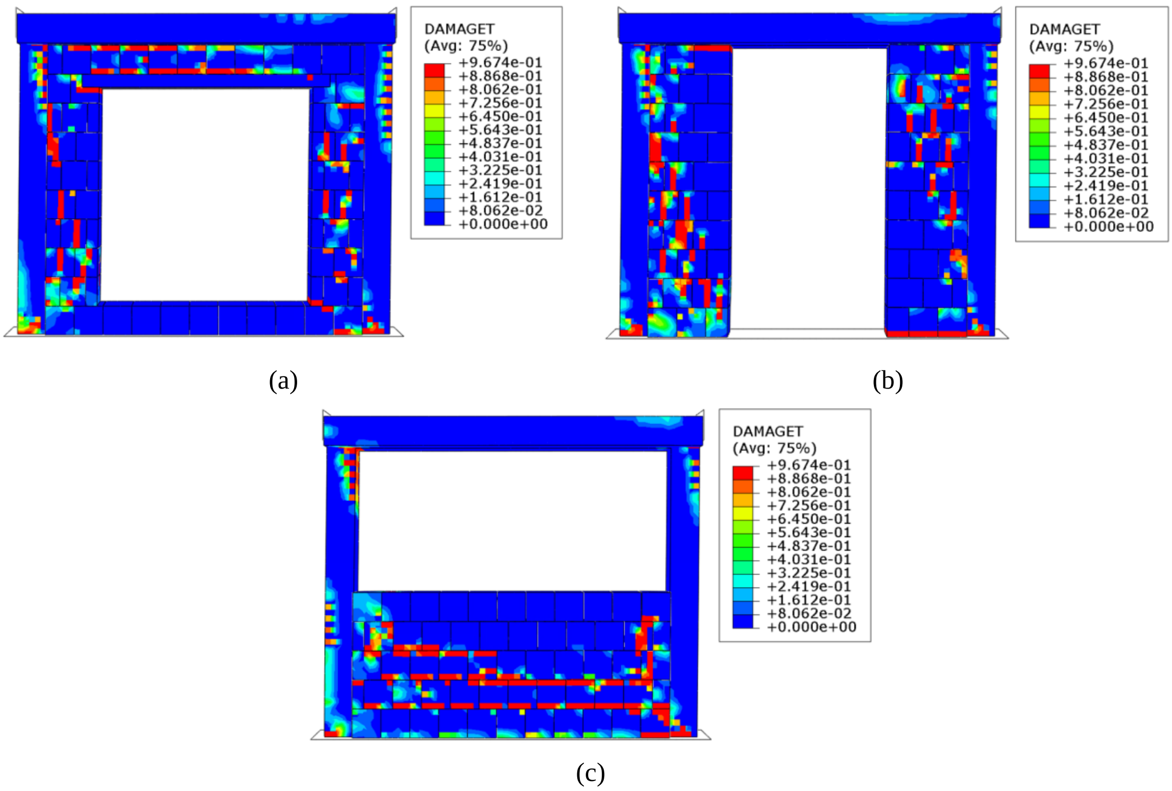


Figure 13. Damage in tension in numerical model of infill with centric window opening (A_o/A_{infill} = 0.5) (a), infill with centric door opening (A_o/A_{infill} = 0.5) (b) and partial height infill (A_o/A_{infill} = 0.5) at the significant damage limit state (0.8 % of in-plane drift)

4 CONCLUSIONS

This paper deals with investigation of in-plane behaviour of infilled RC frames with and without openings. Firstly, full scale experimental tests carried out on fully infilled RC frames are described. Experimental results point at the adverse effect of masonry infills on seismic performance of RC frame structures. Infilled RC frames are characterized by much less ductile response in comparison with a bare frame specimen. For instance, maximum horizontal loads are reached at 0.8-1-0 % of in-plane drift by infilled RC frames, and at 2.0 % of in-plane drift by a bare frame. Moreover, bare frame reaches in-plane drift of 3.5 %, while masonry infills in RC frames collapse much sooner. Furthermore, it is observed that openings further deteriorate seismic response of infilled RC frames. Due to the centric window and door opening, significant damage to masonry infills occurs at lower in-plane drifts in comparison to solid infills. In addition to this, fragile crack patterns are formed next to openings which lead to complete detachment of triangular-like parts of masonry.

Furthermore, three dimensional finite element model developed in [23] is validated against results of experimental tests. Comparison of experimental and numerical force-drift curves shows that numerical model is able to satisfactory capture the in-plane response of infilled RC frames, as it provides good agreement with experimental results in terms of initial stiffness and maximum load. In addition to this, damage pattern obtained in numerical simulations corresponds to the damage propagation in actual experiments.

Finally, numerical model is used to investigate the in-plane behaviour of RC frames with three more infill configurations: 1) infill with window opening that covers 50 % of panel, 2) infill with door opening that covers 50 % of panel and 3) infill with reduced height, which fills 50 % of the bare frame height. Results of additional simulations clearly show that even infills with such large openings are activated under in-plane loads and that they significantly contribute to initial in-plane stiffness. Due to this, infills with large openings should be also considered in the design process, which makes the development of simple directions for design of RC frames with masonry infills even more complicated. In addition, effects of various sizes and locations of openings should be investigated, which is the part of on-going work of authors.

Experimental and numerical results presented in the paper confirm the vulnerability of infilled RC frames when subjected to seismic loading. In order to prevent the detrimental damage and improve the seismic performance of infilled frames, more work should be done on the development of innovative engineering solutions. For instance, the decoupling system presented in [40] successfully improved the seismic performance of masonry infill in experimental test, as it prevented the damage due to in-plane loads and provided stable boundary conditions for out-of-plane loads at the same time. However, the decoupling system was tested only on solid infill configuration and its effectiveness needs to be validated on infills with openings too. If this is fulfilled, decoupling measures should simplify consideration of masonry infills in the design process.

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