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BEHAVIOUR OF MASONRY INFILLS WITH DOOR OPENINGS UNDER SEQUENTIAL IN-PLANE AND OUT-OF-PLANE LOADING

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Abstract

Reinforced concrete (RC) frame structures with masonry infills are common in seismic-prone regions. Masonry infills are activated in in-plane and out-of-plane directions under seismic loading and often damaged during earthquakes. Several recent investigations have shown that the combined effects of in-plane and out-of-plane loads are particularly dangerous for masonry infills. However, most of these studies focused on solid infills, and there is little information about the influence of openings on the seismic performance of infills, even though openings may alter the seismic performance of infilled frames significantly. This paper presents results of two experimental tests carried out on masonry infills with full-height door openings. One was tested under pure out-of-plane load, and the second one with sequential in-plane and out-of-plane loads. Thereafter, results of these two tests are compared with experimental findings obtained from two experimental tests with similar loading protocol conducted on solid masonry infills. Results of the study demonstrate the deteriorating effect of door openings, especially under combined in-plane and out-of-plane loads. The results also highlight a need for practical solutions for damage prevention in both infills with and without openings.

Keywords: *Seismic loading, In-plane load, Out-of-plane load, Interaction, Door opening*

1. Introduction

Masonry infills are non-load bearing masonry walls that are frequently installed as outer walls or inner partitions in RC frame buildings. As they are erected after the casting of the bounding frame (columns and upper and lower beams or slabs), they do not take part in the transfer of vertical loads. However, in the case of an earthquake event masonry infills are subjected to in-plane, out-of-plane and combined in-plane and out-of-plane seismic actions. Due to the rather complex seismic performance of infilled frames, most of the seismic codes consider masonry infills as non-structural elements, which is an unrealistic and non-conservative assumption.

Seismic performance of infilled frames has been investigated for more than seventy years. Results of some of the first experimental findings revealed that masonry infills significantly increase the in-plane stiffness and load capacity of RC frames [1,2]. This was followed by numerous experimental studies that focused on the in-plane performance of infilled frames [3-6]. Among various parameters investigated, openings were recognized to affect the in-plane behaviour of infilled RC frames most significantly because they can alter the stress field induced in the infill and thus change the infill failure mode [5,7]. In addition to this, in several experimental campaigns [8-10] the detrimental crack patterns on infills due to openings were observed, showing that openings had an adverse effect on the seismic safety.

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In the pioneering studies on the out-of-plane behaviour of unreinforced masonry walls, McDowell et al. (1956a,b) [11,12] investigated experimentally the formation of the arching action within the wall, which has proven to be the load-resisting mechanism against out-of-plane seismic forces in masonry infills too. The findings on the out-of-plane behaviour of masonry infills were extended in [3,13,14]. Boundary conditions and slenderness ratio are recognized as the most influential parameters, while the effect of openings is still not clear, due to contradictory results from a limited number of studies [13,15,16].

However, particularly important for out-of-plane response of masonry infills are effects that can cause the reduction of out-of-plane capacity or even totally hinder the formation of arching action. Firstly, inappropriate execution of frame-infill mortar connections, especially the top connection, which is not the rare case in the practice, can be the reason for the worse out-of-plane behaviour of masonry infills, as reported in [15,17]. Furthermore, masonry infills at the lower and middle storeys can experience significant reduction of out-of-plane load capacity or even the complete out-of-plane failure due to the combined effects of in-plane and out-of-plane actions. This could be observed in recent earthquakes in L’Aquila, Italy (2009) and Albania (2019), where masonry infills obtained the life-threatening out-of-plane failures due to the in-plane and out-of-plane load interaction, as reported in [18-20].

One of the first studies on the effects of the prior in-plane damage on the out-of-plane behaviour of masonry infills were carried out by Angel et al. (1994) [3] and Flanagan and Bennett (1999) [21]. However, this topic has gained more attention recently and the number of experimental studies dealing with this topic increased. In experimental studies [22-26] mostly thin masonry infills used in the existing buildings in the Southern Europe were investigated. Reduction of out-of-plane capacity due to the prior in-plane damage was reported. Among these studies, interesting findings on the effect of the slenderness ratio [24] or aspect ratio [27] can be found. On the other side, less studies on the effect of the prior in-plane damage on the out-of-plane behaviour of modern strong masonry infill with larger thickness are available in the literature. Among them, Morandi et al. (2017) [28], Butenweg et al. (2019) [29] and da Porto et al. (2020) [30] observed the reduction of out-of-plane capacity due to the prior in-plane drifts too. Based on the available experimental database, some authors also proposed the reduction factors that could account for prior in-plane damage when estimating the out-of-plane capacity of masonry infills. Proposals for these reduction factors can be found in [23,31,32], for instance, but their correctness needs to be checked on the larger experimental database.

In addition to this, there is a clear gap in the experimental findings on the effect of the prior in-plane damage on out-of-plane behaviour of masonry infills with openings. This is somehow unjustified, as openings significantly affect the seismic performance of infilled RC frames. So far, da Porto et al. (2020) [30] carried out experimental tests on modern and thick masonry infills and Furtado et al. (2021) [16] investigated thin infills. Further experimental results on the topic are of the utmost importance for: a) the better understanding of the influence of the load interaction on masonry infills with different opening arrangements, b) validation of numerical results that can be used for extensive parametric studies and c) development of simple and practical approaches that could consider effects of the load interaction in seismic codes in the future.

In this paper the effects of prior in-plane damage on out-of-plane behaviour of masonry infills with full-height door opening are experimentally investigated. Out-of-plane behaviour of masonry infill with full-height door opening is first investigated in the pure out-of-plane test (T7). Afterwards, the behaviour of the same infill configuration is analysed in a sequential loading test (T8), in which masonry infill is first subjected to in-plane cyclic loads, which is followed by the out-of-plane load phase and the last in-plane load phase. Finally, in order to determine the effect of door opening, the experimental results obtained from these two tests are compared with experimental results of pure out-of-plane test (T1) and sequential loading test (T2) carried out on fully infilled RC frames [33]. The results of this study show that door openings further deteriorate the behaviour of infilled RC frames under interacting in-plane and out-of-plane loads.

2. Experimental campaign

2.1 Test specimens

The dimensions of the frame and masonry infill used in experimental tests are indicated in Fig. 1. The full-height door opening takes around 38 % of the wall surface. Masonry infill is built in line with the usual building practice. Thick hollow clay bricks with percentage of narrow vertical voids of around 56 % are used. Bed joints are filled with thin layer mortar, while head joints are executed as dry tongue and groove connections. The levelling layer and connections of masonry infill to the RC columns are made of mortar, while the gap between masonry infill and the top beam is filled with a thin layer mortar, which was inserted by a special hand pump. Due to this precise, but time-consuming execution, frame-infill connections at the top were exceptionally strong.

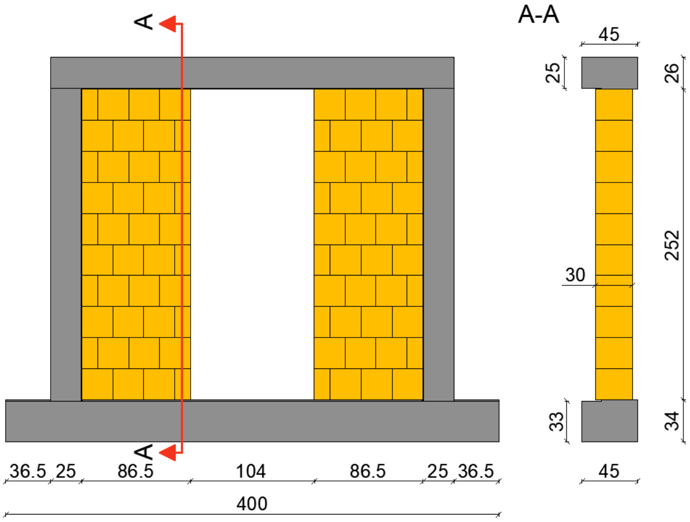


Figure 1. Test specimen

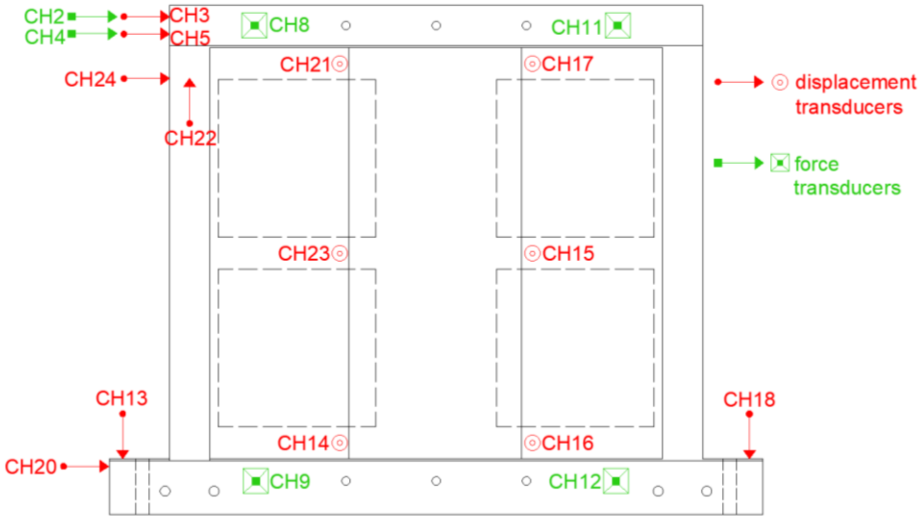


Figure 2. Position of measurement points and air bags on infilled frame with door opening

2.2 Test setup

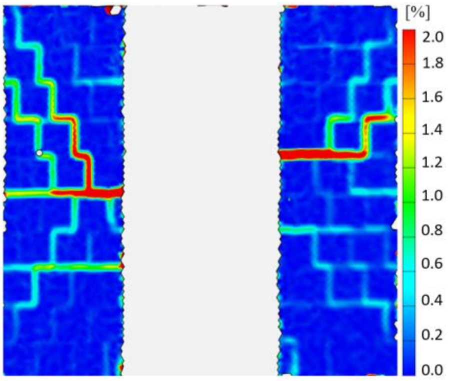
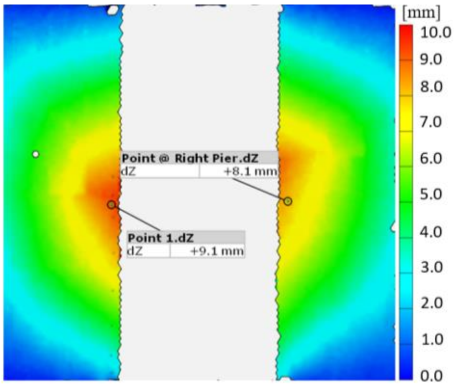
Fig. 2 shows the specimen with position of force and displacement transducers. At the beginning of each test, vertical force of 200 kN per column is applied by one-way hydraulic actuators and it is kept constant throughout the test. In-plane loads are applied to the frame in a displacement-controlled manner by two servo-controlled hydraulic actuators, which are connected to a strong reaction wall on one side and to the top beam of the RC frame on the other side. Connection to the top beam is provided by a special harness with four steel tie rods that run along the top beam and that are connected to steel plate on the other side of the beam. These steel tie rods allow application of cyclic in-plane displacements (positive-push and negative-pull direction). Positions of two in-plane load actuators on the RC frame correspond to force transducers CH2 and CH4 on Fig. 2. Out-of-plane load is applied by inflating four air bags that are installed between the back side of the infill and the timber reaction wall. In Fig. 2 positions of air bags are presented with four dashed squares. Test setup is designed and constructed to allow the fast and simple application of in-plane and out-of-plane loads within the one test.

3. Experimental tests

3.1. Test T7 - Pure out-of-plane test

In test T7 out-of-plane load was imposed to the masonry infill with full-height door opening in six cycles. In Fig. 9a the load-displacement curve measured on the left infill pier is shown. Specimen responded linearly up to the out-of-plane force of around 60 kN in the second cycle, when the first light stepwise cracks appeared on the left pier. With the increase of out-of-plane load, more cracks through bed and head joints emerged leading to the further decrease of stiffness. In the last load cycle maximum out-of-plane force of 145.3 kN (33.6 kPa) was reached. The major strain propagation obtained by optical measurement system and measured out-of-plane displacements on both piers are shown in Table 1. They both depict the typical out-of-plane behaviour of masonry infill with strong connections to the frame along three sides. The load-resisting mechanism is strong vertical arching. In the last load cycle, due to the pronounced cracking and crushing of the bricks in the arc supports (Table 1, right), out-of-plane displacements increased significantly for the same level of out-of-plane force applied and the test was stopped due to the safety reasons. However, the reached out-of-plane force represents the high out-of-plane capacity for this masonry infill, which is explained by the low slenderness ratio of infill and its strong connections to the surrounding frame.

Table 1. Selected experimental results at the maximum out-of-plane force of test T7

		
Major strain at $F_{MAX,OOP}$	OOP displacements at $F_{MAX,OOP}$	Cracks in the bricks at $F_{MAX,OOP}$

3.2. Test T8 – Sequential in-plane and out-of-plane test

In test T8 masonry infilled RC frame with door opening was tested in three loading phases. In the first phase, cyclic in-plane displacements were applied to the specimen. Three load cycles were carried out for each level of in-plane displacement applied. After reaching 1.1 % of in-plane drift masonry infill experienced significant level of damage. Therefore, the specimen was unloaded and then loaded with seven cycles of out-of-plane loading in the second loading phase, in order to investigate the influence of the prior in-plane damage on the out-of-plane behaviour. This phase was terminated after reaching maximum out-of-plane force of 39.7 kN (9.2 kPa). In the third loading phase, cyclic in-plane displacements were applied again, up to the complete collapse of the infill at the 1.6 % of in-plane drift.

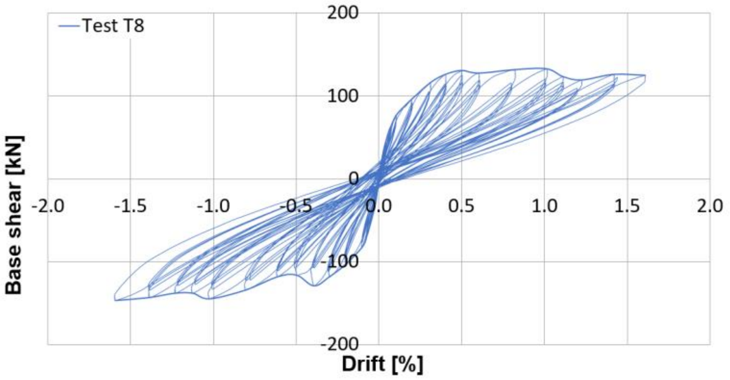


Figure 3. Hysteretic force-drift curve obtained from in-plane loading phases of test T8

The hysteretic curve obtained from in-plane loading phases is shown in Fig. 3. At the lower levels of in-plane drifts (Δ < 0.2 %), the stepwise cracks already appeared in the bottom parts of both piers. At a drift of 0.5 % diagonal cracking through the middle parts of piers emerged and stepwise cracks through head and bed joints propagated in the upper part of piers too. In addition to this, the cracks due to the crushing of the corner bricks in the lowermost rows of bricks could be observed (Fig. 4). The maximum horizontal force in positive (push) direction was reached at 1.0 % of in-plane drift. With the increase of in-plane drifts, diagonal cracks widened (Fig. 5). In Fig. 6 triangular-like pieces of masonry defined by diagonal cracks that occurred due to the cyclically imposed in-plane displacements can be more clearly seen. These triangular-like pieces of the infill started to lose connection to the rest of the infill. Due to the significant damage at 1.1 % of in-plane drift, in-plane load was suspended.

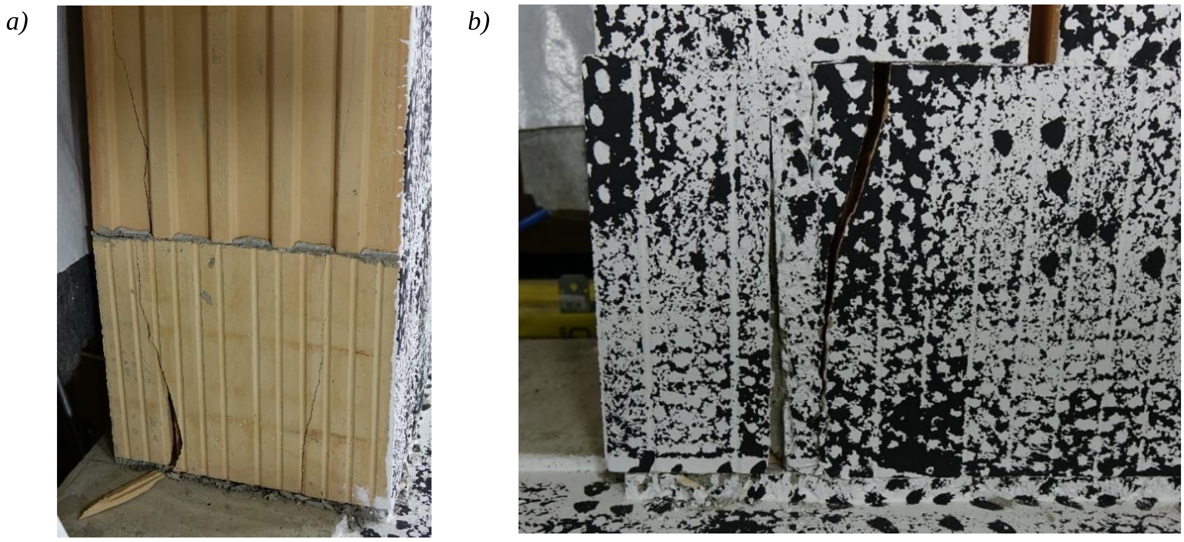


Figure 4. Cracks in the lowermost row of bricks (Δ = 0.5 %): side view (a) and front view (b)

After the first in-plane loading phase, seven cycles of out-of-plane loading were applied. The out-of-plane load – displacement curve is shown in Fig. 9a. The maximum out-of-plane force of 39.7 kN was reached in the last cycle, which is only 27 % of the out-of-plane capacity of the masonry infill tested in test T7, which had no prior in-plane damage. In addition to this, the significant decrease of the out-of-plane stiffness can be noticed due to the prior in-plane damage. However, frame-infill connections remained in a quite good condition after the in-plane loading phase. Therefore, the boundary conditions for the vertical arching were provided. Table 2 shows selected experimental results at the maximum out-of-plane force of test T8. Due to the three-sided support and developed vertical arching in both piers, out-of-plane displacements were rather small with the largest values near the pier middle, at the pier edges. Larger out-of-plane displacements can be measured locally too, due to the detachment and initiation of the falling off of the brick outer shells, which already started under in-plane loads. Major strain propagation indicates that most of the cracks originate from the prior in-plane loading phase. Due to increasing residual out-of-plane displacements and for safety reasons, out-of-plane loading phase was terminated.

Figure 5. Damage to masonry infill at 1.1 % of in-plane drift

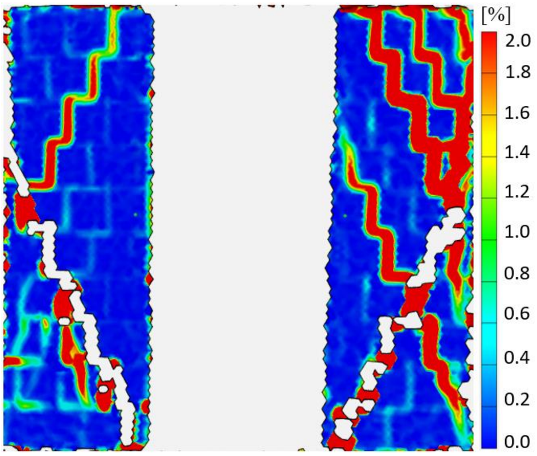
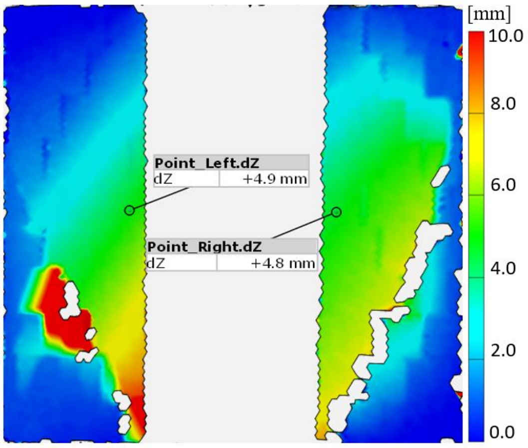
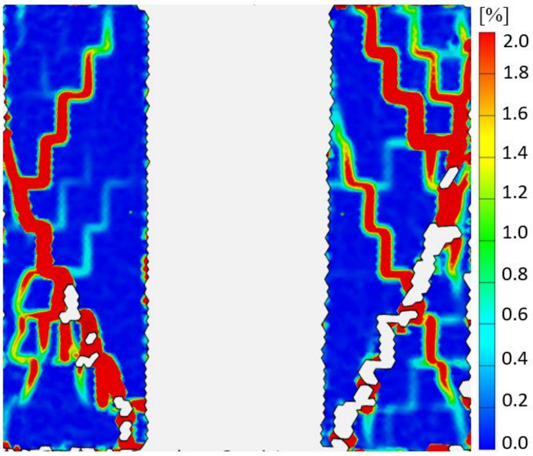


Figure 6. Major strain propagation at 1.1 % of in-plane drift

After the out-of-plane loading phase, one more in-plane loading phase was carried out to investigate the in-plane behaviour of the infilled frame with door opening. Already at 1.2 % of in-plane drift, diagonal cracks widened and more cracking through bricks could be observed. Furthermore, some brick outer shells fell off and the corner brick on the left infill pier was crushed (Fig. 7). The diagonal cracking propagated further with the increase of the applied in-plane displacements. Triangular-like masonry parts gradually lost their connection to the remaining parts of the infill, which resulted in a complete detachment and failure of the infill at 1.6 % of in-plane drift (Fig. 8). In addition to this, hysteresis curve obtained from in-plane loading phase shows that the in-plane force capacity remained almost constant in the second in-plane loading phase (Δ > 1.1 %), due to the significant damage to masonry infill.

Table 2. Selected experimental results at the maximum out-of-plane force of test T8

	
OOP displacements at $F_{MAX,OOP}$	Major strain at $F_{MAX,OOP}$

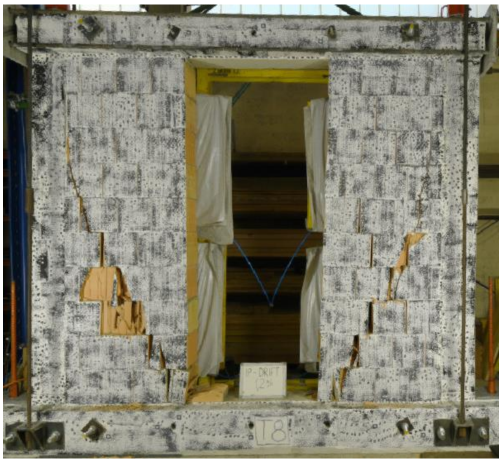


Figure 7. Damage to masonry infill at 1.2 % of in-plane drift

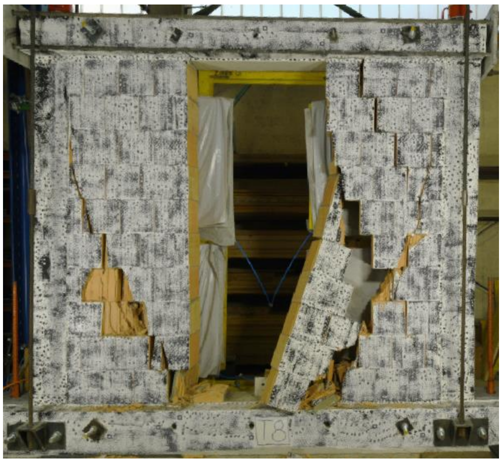


Figure 8. Collapse of masonry infill at 1.6 % of in-plane drift

4. Comparison of the test results

Fig. 9a shows load-displacement curves of out-of-plane test T7 and out-of-plane loading phase of test T8. In test T7 high out-of-plane capacity was reached due to the developed vertical arching action. Furthermore, in the first in-plane loading phase of test T8 frame-infill connections were not severely damaged and out-of-plane capacity was achieved due to the developed vertical arching too. However, due to the significant prior in-plane damage, out-of-plane capacity of masonry infill in test T8 is 3.7 times smaller than the out-of-plane capacity of masonry infill in test T7, which was tested under pure out-of-plane load only. In addition to this, effects of the prior in-plane damage can be seen in the significantly decreased out-of-plane stiffness of masonry infill in test T8.

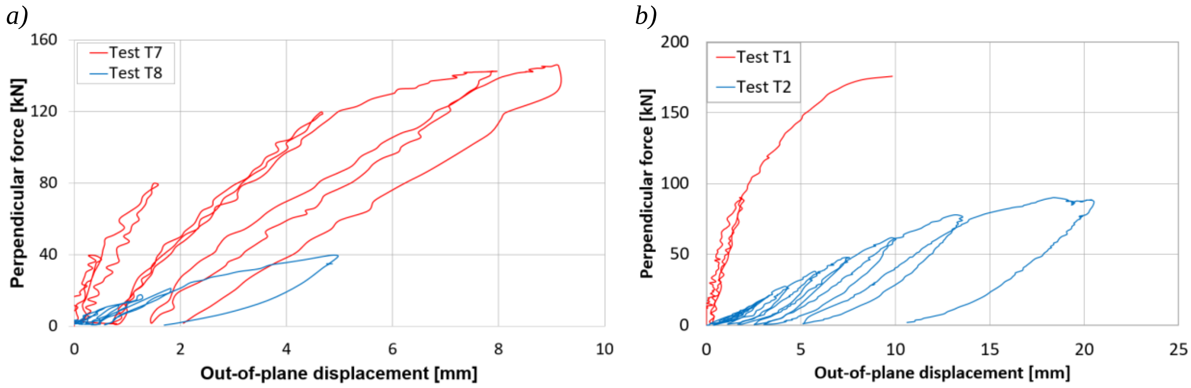


Figure 9. a) Load-displacement curves of test T7 and out-of-plane loading phase of test T8; b) Load-displacement curves of test T1 and out-of-plane loading phase of test T2 [33]

Tests with similar loading protocol were carried out on fully infilled RC frames within the same experimental campaign. Test T1 is a pure out-of-plane test, while in test T2 masonry infilled RC frame was firstly loaded in in-plane direction up to the 1.2 % of in-plane drift and then in out-of-plane direction. Further details can be found elsewhere [33]. Load-displacement curve obtained from test T1 and out-of-plane loading phase of test T2 are presented in Fig. 9b. In both tests high out-of-plane capacities were reached due to the developed two-way arching action in the wall, with dominant vertical arching. However, due to the prior in-plane damage in test T2, out-of-plane capacity was reduced around two times. Even larger reduction can be observed for the out-of-plane stiffness.

Furthermore, in Fig. 10 load-displacement curves obtained from out-of-plane loading phases of test T2 and test T8 are compared. It can be seen that masonry infill with door opening (test T8) reaches smaller out-of-plane load and displacement capacity than solid masonry infill (test T2). Moreover, the higher

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reduction of out-of-plane capacity due to the in-plane damage is measured for masonry infill with door opening (test T8 - 3.7 times) than for solid masonry infill (test T2 - 2 times). The worse out-of-plane behaviour of masonry infill with door opening is attributed to the more pronounced in-plane damage in infill with door opening. Due to the centric full-height door opening, masonry infill in test T8 suffered more damage at 1.1 % of in-plane drift than solid masonry infill in test T2 at 1.2 % of in-plane drift. Furthermore, due to the door opening a specific crack pattern was formed in masonry infill, with triangular-like portions of masonry detaching from the rest of the infill. In masonry infill with door opening, diagonal cracking and crushing of edge bricks took part already at 0.5 % of in-plane drift, while solid masonry infill experienced more significant damage at around 1.0 % of in-plane drift.

In their extensive experimental campaign, da Porto et al. (2020) [30] investigated effects of the prior in-plane damage on out-of-plane behaviour of masonry infill with full-height door opening too. As in this study, the authors reported that masonry infill with full-height door opening obtained worse out-of-plane behaviour due to the more fragile crack patterns developed under prior in-plane loads. Moreover, more studies [8-10,34] showed that openings increase the seismic vulnerability of masonry infills, as unstable portions of masonry next to openings tend to fall out of wall plane in pure in-plane tests. In tests with sequential or simultaneous in-plane and out-of-plane loads, the worse performance and higher reductions of out-of-plane capacity could be expected. However, experimental campaigns on infills with openings with this loading protocol are still missing.

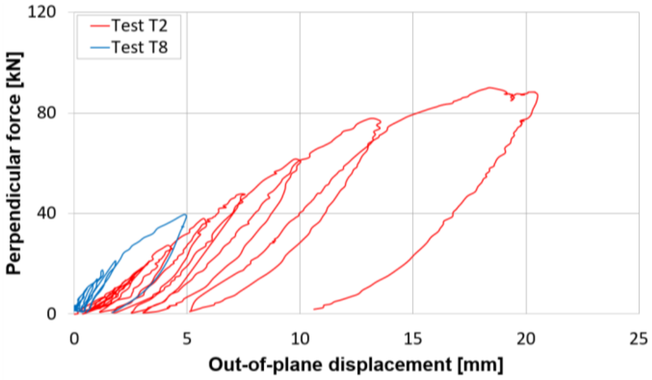

Figure 10. Load-displacement curves of out-of-plane loading phases of tests T2 and T8

5. Conclusions

Experimental tests conducted within the scope of the project named “Development of an innovative approach for decoupling infills and non-load-bearing masonry walls from the main structure” are presented in this paper. Experimental results show that full-height door opening has an adverse effect on seismic performance of infilled RC frames. Firstly, due to the presence of door opening damage to edge bricks occurs at already 0.5 % of in-plane drift, whereas solid masonry infill suffers more significant damage at 1.0 % of in-plane drift. Furthermore, with the increase of in-plane drifts, triangular-like portions of masonry formed around door opening gradually lose their connection to the rest of the infill along diagonal cracks and tend to fall out of wall plane. As a consequence of the more significant prior in-plane damage, out-of-plane capacity of masonry infill with door opening is reduced 3.7 times, while for solid infill out-of-plane capacity is reduced 2 times. However, it should be pointed out that vertical arching could be formed in all specimens in this experimental campaign. This was possible due to the strong boundary conditions provided by perfect execution of frame-infill connections, which is not common in practice. In more realistic cases even worse out-of-plane behaviour of masonry infills with and without door opening could be expected. Due to this, it seems reasonable to work on the development of the engineering solutions that could increase the seismic safety of masonry infilled RC frames. The decoupling system presented in the paper of [35] successfully prevented in-plane damage and at the same time provided a support for out-of-plane forces. However, the system was only tested on the fully infilled RC frame and it needs to be further validated on masonry infills with openings, which are definitely more prone to the seismic damage.

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