



AN INNOVATIVE LOW DAMAGE SEISMIC SOLUTION FOR UNREINFORCED CLAY BRICK INFILL WALLS

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ABSTRACT

In the past design codes, infill panels/walls within frame buildings were considered as non-structural elements and thus have been typically neglected in the analysis stage of the design process. The observations made after major earthquakes in recent years (e.g. Duzce 1999, L'Aquila 2009, Darfield 2010) have shown that although infill walls are neglected elements, they interact with the structural system during seismic actions and modify the behavior of the structure. More recent code design provisions (CEN, 2004; FEMA, 1997; NZS4230, 2004) do now recognize the complexity of such interactions and require either a) consider these effects of frame-infill interaction during the design and modeling phase or b) assure no or low-interaction of the two systems with proper detailing and arrangements in the construction phase. To consider the interaction in the design stage can be impractical and in most cases does not solve the actual problem related to their brittle behavior. This paper reports the development of an innovative low damage solution/technology for non-structural unreinforced clay brick infill walls by which the interaction with the structural frame is minimized. The seismic performances of an existing (as built) unreinforced clay brick infill wall system (Fully infilled unreinforced clay brick infill wall FIF3-UCBI) and the developed low damage solution (MIF5-UCBI) are reported as a result of the experimental testing program.

INTRODUCTION

The non-structural walls in a building can be constructed of different materials depending on the local preferences. Drywalls, walls made of light gauge steel or timber inner framings covered with gypsum plaster boards, are very common in Canada, US, Europe, Australia and New Zealand. Compared to clay bricks or concrete blocks, this is a comparably light-weight alternative. On the other hand, unreinforced clay brick infill walls are still one of the most common non-structural wall type in Europe and south America. These walls are usually assumed as non-structural and are not taken into account in the analysis phase of structural design, which is partly due to their unsuitability as an engineering material. Nonetheless, these walls are stiff and strong enough to affect the structural response by interacting with the structural system during an earthquake. The result of this interaction is either significant damage to the infill wall itself or to the surrounding structural system (Figure 1).

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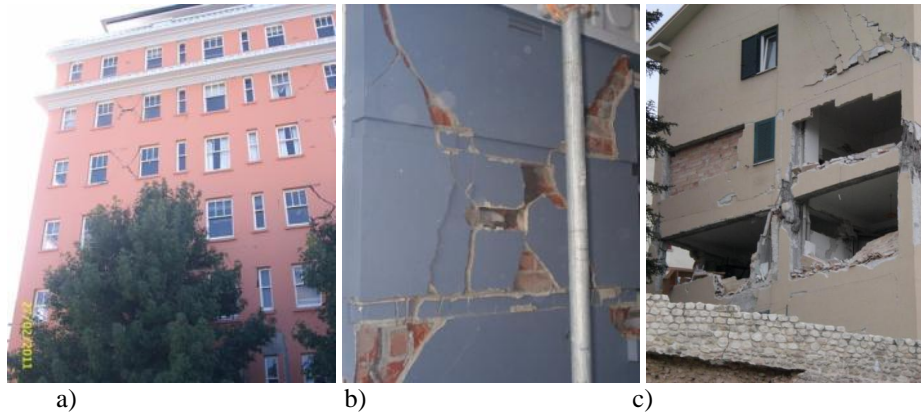


Figure 1 Infill wall damage photos: a-b) 22 February 2011 Christchurch earthquake in New Zealand; c) L'Aquila earthquake in Italy in 2009 (Courtesy of Anna Brignola)

Because of the brittle nature of the clay bricks and the mortar joints, the interaction is inevitably brittle, which may change the ductile response of a reinforced concrete frame and results in brittle global response. In some cases, this brittle interaction may cause soft storey mechanisms due to the sudden drop in stiffness and strength (Magenes and Pampanin, 2004). The uncertainty regarding the positive or negative effects of unreinforced clay brick infill walls on the structural response is not questioned or answered in the reported work. This is simply due to the unsuitability of the as-built unreinforced clay brick infill walls within a ductile seismic design philosophy where the structures are expected to resist increasing levels of deformation by maintaining their capacities, i.e. ductility (Park and Paulay, 1975). The reported work experimentally investigated the behaviour of an as-built unreinforced clay brick infill wall and the behaviour of the proposed low damage unreinforced clay brick infill wall solution.

EXPERIMENTAL PROGRAMME

The tests were carried out using reverse cyclic quasi-static testing protocol prepared in accordance with ACI 374 (ACI374.1-05, 2005), shown in Figure 2a. The utilized structural frame was a moment resisting PRESSS frame (Pampanin et al., 2010), a low damage seismic rocking structural system that has the capability for repeatable use. The structural system was constructed by connecting two reinforced concrete (RC) beams and two RC columns by two D40 unbonded post-tensioning bars with 80 kN post-tensioning (Macalloy, 2007), connection detail of which is shown in Figure 2b. The utilized pin supported structural frame simulates the inner-storey of a multi-storey building where the damage to the infill wall is induced by increasing amplitudes of inter-storey drifts.

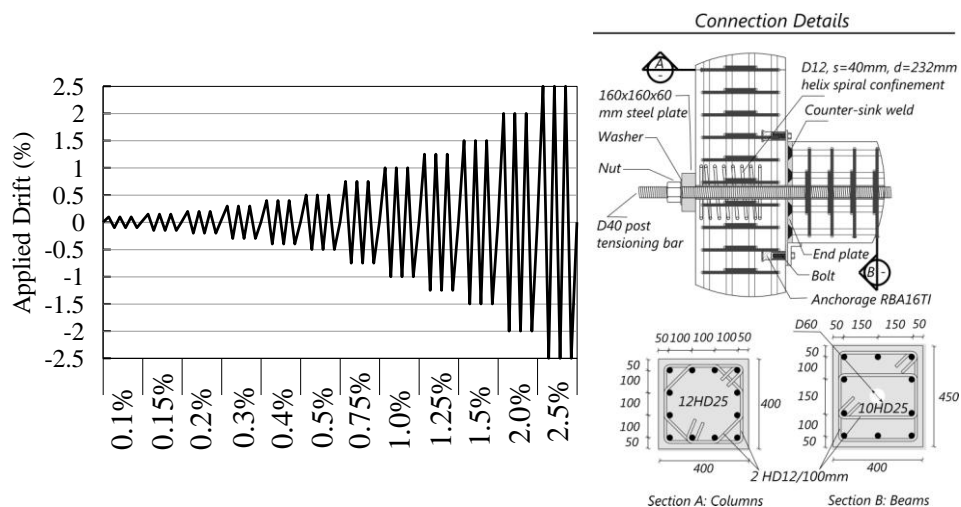


Figure 2 a) Displacement protocol; b) Beam-to-column connection and reinforcement details

In the test setup, the lower beam-column connections had pivot points at mid-height of the beam in order to eliminate the effects of different rates of beam elongation occurring at the upper and lower beams. The deformations were applied by a 1000 kN hydraulic jack at the top level of the left RC column. The displacement control was carried out by a ± 150 mm rotary pot at the top level of the right RC column (the same height as the hydraulic jack). The structural frame was constrained in-plane by four rollers located at the top RC beam level. The details of the test setup are summarized in Figure 3.

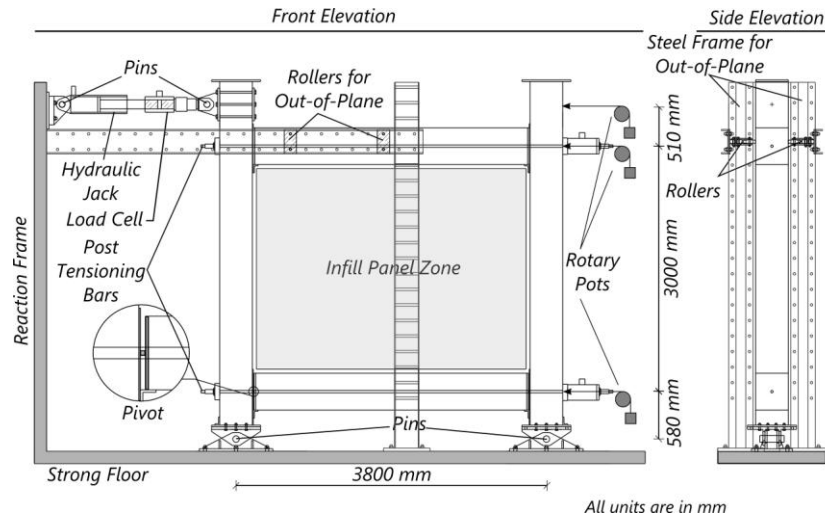


Figure 3 Test setup

Three tests were carried out. In the first test, the reverse cyclic behaviour of the bare frame (BF) was quantified, which was linear elastic. The second test specimen was the as-built unreinforced clay brick infill wall (FIF3-UCBI) and the last one was low damage unreinforced clay brick infill wall (MIF5-UCBI), as summarized in Table 1.

Table 1 Test specimens

| Specimen | Description | Connection Type |
|----------------------------|--|---|
| Test 1 BF | Bare frame | - |
| Test 2 FIF3-UCBI | As-built unreinforced clay brick infill wall | As-built monolithic connections: Fully connected to the structural frame |
| Test 3 MIF5-UCBI | Low damage unreinforced clay brick infill wall | Infill panel zone divided into individual cantilever infill panels by a light gauge steel sub-framing |

CONCEPTUAL DEVELOPMENT OF THE LOW DAMAGE UNREINFORCED CLAY BRICK INFILL WALL

As it will be shown in the test results of FIF3-UCBI, an as-built unreinforced clay brick infill wall does not have much deformation capacity and is rather brittle. Considering this fact, one of the possible low damage solutions can be achieved by adding sliding capability to the infill wall (Figure 4b), which was already investigated by Mohammadi and Akrami (Mohammadi and Akrami, 2010; Mohammadi et al., 2011). However, this system may have significant out-of-plane issues, which may not easily be addressed in practical applications. Moreover, at high drift levels, the system may induce shear failure in the columns. Based on the study of the performances of different infill wall systems and the infill panel zone behaviour, carried out by the authors, a low damage infill wall consisting of individual cantilever panels built within a light gauge steel sub-frame seemed more appropriate (Figure 4c). Therefore, the solution developed in this research was typically and fundamentally inspired from the old construction practice of armature cross walls (Langenbach, 2008) and recent rocking structural systems (Pampanin et al., 2010; Priestley et al., 1999).

The objective of the developed low damage solution was the reduction of interaction between the infill wall and the structural system. This was achieved by delaying the formation of the strut action by introducing gaps among the individual cantilever infill wall panels, which can be designed to close at a selected inter-storey drift level. Moreover, when the gaps do close and the strut action is activated, the resulting behaviour is rather ductile due to the flexure dominated individual cantilever infill wall panels. On the other hand, the behaviour of the as-built option was typically a shear dominated squad wall resulting in brittle failure mechanisms.

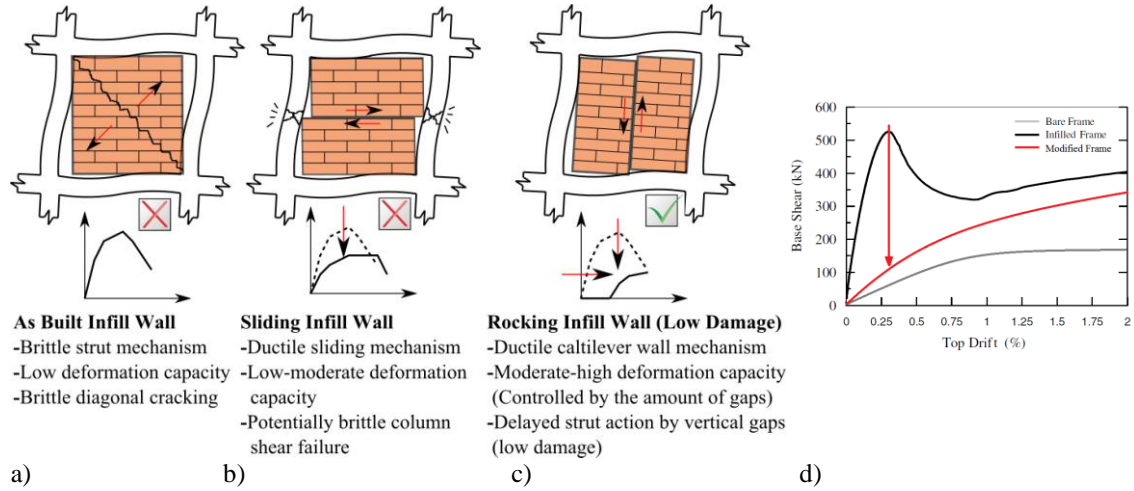


Figure 4 Conceptual development of the low damage solution for unreinforced clay brick infill walls: a) As-built unreinforced clay brick infill wall; b) Infill wall with sliding capability at mid-height (Mohammadi and Akrami, 2010; Mohammadi et al., 2011); c) Low damage rocking infill wall (Developed solution); d) The objective of the low damage solution (Original graph is from Magenes and Pampanin, 2004)

TEST 1: BARE FRAME (BF)

The bare frame specimen (Figure 5a) was post-tensioned with a post-tensioning force of 80kN, which was roughly 10% of the yield strength of the post-tensioning bars. The drift history, which was previously given in Figure 2a, was applied on the specimen. During the test, the bare frame behaved as expected, linear elastically with very minor flexural cracking at the cover concrete. The hysteresis behaviour of the bare frame is shown in Figure 5b and the prevented beam elongation in the lower beam can be seen in the post-tensioning force curve shown in Figure 5c.

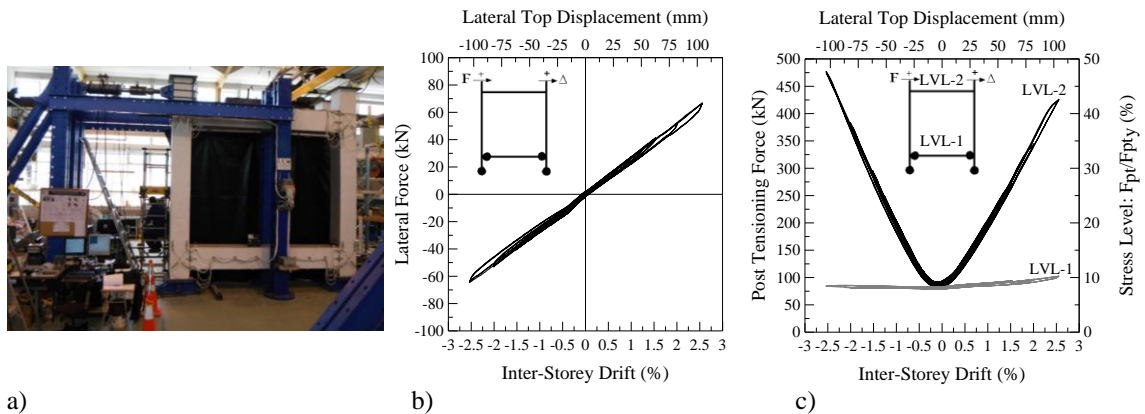


Figure 5 a) Bare frame; b) Reverse cyclic hysteresis behaviour; c) Post tensioning force vs. inter-storey drift

TEST 2: AS-BUILT UNREINFORCED CLAY BRICK INFILL WALL (FIF3-UCBI)

Unreinforced clay brick infill walls have been obsolete in New Zealand for a long time. Nevertheless, it is still a very common practice around the world (i.e. Mediterranean countries, South America, India etc.). Most of the buildings with unreinforced clay brick infill walls in New Zealand are of pre 60s. St. Elmo Courts was the oldest RC building in Christchurch (1930s), but was demolished due to the extensive damage suffered after 22 February 2011 earthquake in Christchurch. The unreinforced clay brick infill wall type used in this building was cavity wall, which is a double skinned wall type. The same wall type was also found in other structures around the Christchurch Central Business District (CBD) during the building assessments. As a result of lack of current practice, these old examples were used for the construction of the test specimen. For the construction of the specimen, the specifications contained in the unreinforced masonry wall construction standard “Masonry Construction in Materials and Workmanship” was followed and complied (NZS4210, 2001).

In the construction of the infill wall, standard clay bricks of 70 mm width, 75 mm height and 220 mm length were used. This was the same clay brick type used in St. Elmo Courts as well as for the construction of the masonry veneers in most of the residential houses in New Zealand. The binding mortar was composed of portland cement and fine sand mixed 1 to 4 weight ratios accordingly (Figure 6). The water content was arranged according to the workability of the mix by the contractor. In the construction of the infill wall, no specification was given to the contractor with the intent to respect the real life construction practice for brick work as much as possible.



Figure 6 Used clay brick type (70×75×220 mm), Portland cement and fine sand

The bricks were laid four courses at a time from the lower corners of the infill panel zone to meet at the mid-span of the RC beam. Steel ties were placed between the two skins of the wall at every fourth course of clay bricks laid in vertical. The steel ties were placed 600 mm apart from each other horizontally. The average thickness of the mortar layers was about 10 mm. Including the 10 mm cavity in between the two skins, the total thickness of the infill wall was 150 mm (Figure 7). The wall was finished just by the application of a thin coat of white paint to allow for crack visibility.



Figure 7 The construction of the as-built double skinned unreinforced clay brick infill wall (FIF3-UCBI)

In the first drift level of 0.1%, boundary cracks formed between the infill wall and the RC frame. In the negative cycle of 0.2% drift (pull cycle), a diagonal crack formed stretching from the lower left corner to the upper right corner of the infill wall. The width of the diagonal crack at this level of drift was 0.35-0.8 mm near the lower left corner and 1.5-2.5 mm at the middle of the infill panel zone. In the positive 0.3% drift level (push cycle), another diagonal crack formed stretching from lower right corner to upper left corner of the infill wall panel, which also corresponded to a

sudden loss of strength and stiffness (Figure 10a-b). The width of this crack was 0.4-0.5 mm near the corners of the specimen and 1.5 mm at the middle of the infill panel zone. Then, in the negative cycle of 0.3% drift, additional diagonal cracks formed in parallel to the previous one, stretching from lower left to upper right corner of the infill wall. It was mainly from 0.3% drift level onwards that sliding cracks started to form at different levels of the infill wall. In some cases, these sliding cracks were forming in combination with additional diagonal cracks. However, the formation of the sliding cracks only continued till 1.25% drift level. At 2.0% and 2.5% drift levels, the corner crushing at the lower and upper corners occurred accordingly. At 2.5% drift level, the test was finalized. The progress of the cracks forming during the test is summarized in Figure 8. The test gave an insight into the behaviour of fully infilled unreinforced clay brick infill walls, which was used as a benchmark for the development of the low damage solution.

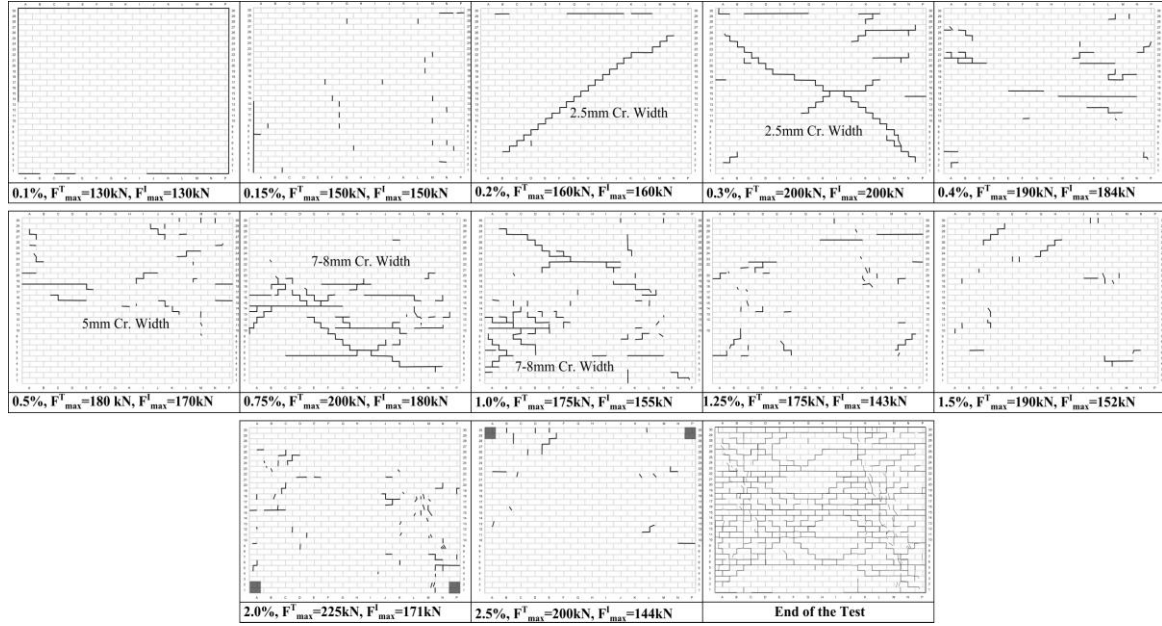


Figure 8 Progress of cracks during the test of the as-built unreinforced clay brick infill wall specimen FIF3-UCBI (F^T : Total lateral force, F^I : Lateral force exerted by the infill wall only)

An important observation was that as-built unreinforced clay brick infill wall showed a number of failure modes triggered by the increasing displacement demands. For example, a structure that experiences only 0.3% drift may only exhibit diagonal cracking. However, another structure that experiences 1.0% drift level, the cracking mode may seem like sliding cracks. Similarly, a structure experiencing 2.0% drift may further develop corner crushing. In this particular case, these failures were not exactly different and exclusive failure modes, but rather incremental members of a chain of consecutive failures starting with the weakest one, i.e. diagonal cracking. The summary of these progressive crackings and their inter-storey drift intervals are shown in Figure 10c. The damage at the end of the test is photographically reported in Figure 9.

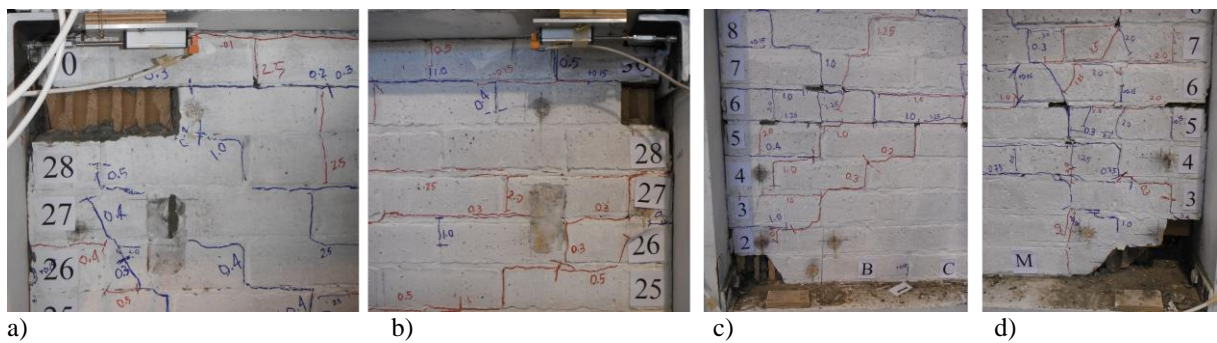


Figure 9 Damage photos of the as-built unreinforced clay brick infill wall specimen FIF3-UCBI at the end of the test: a) Top left corner; b) Top right corner; c) Bottom left corner; d) Bottom right corner

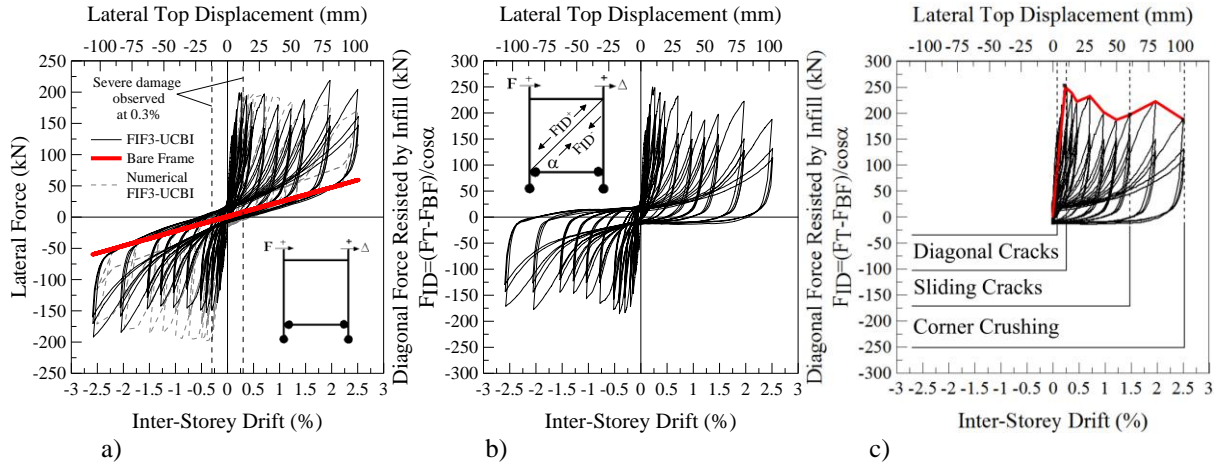


Figure 10 As-built unreinforced clay brick infill wall specimen FIF3-UCBI: a) Total lateral force vs. inter-storey drift; b) Diagonal force resisted by the infill wall vs. inter-storey drift (Used for numerical modelling purposes); c) Inter-storey drift intervals corresponding to the observed damage (0.2-0.3%: Diagonal cracks; 0.3-1.5%: Sliding cracks; 1.5-2.5%: Corner crushing)

TEST 3: LOW DAMAGE UNREINFORCED CLAY BRICK INFILL WALL (MIF5-UCBI)

In order to achieve a low damage solution, as explained in the conceptual development, the infill panel zone was divided into three individual cantilever panels. These individual panels were constructed within a light gauge steel sub-frame constructed in the infill panel zone. The sub-framing was attached to the surrounding structural frame such that the out-of-plane weight of the infill wall could be carried by the sub-framing. The number of divisions was decided according to the aspect ratio of each individual panel and the tributary out-of-plane weight that can be carried by the vertical studs. These panels were separated by vertical gaps between adjacent steel studs, which were filled with elastic polyurethane joint sealant afterwards. The sealant integrated the three panels while allowing deformation at the vertical gaps. The width of the gaps were calculated by Eq. (1). Using $D=1.5\%$ and $h_c=2550$ mm, Δ_G was calculated as 20 mm, which was the gap required on one side of the infill wall. Therefore, the total gap required per floor was $2 \times 20 = 40$ mm, which can be divided into 4 vertical joints as 10 mm gaps. The resulting overview of the specimen and the details are shown in Figure 11.

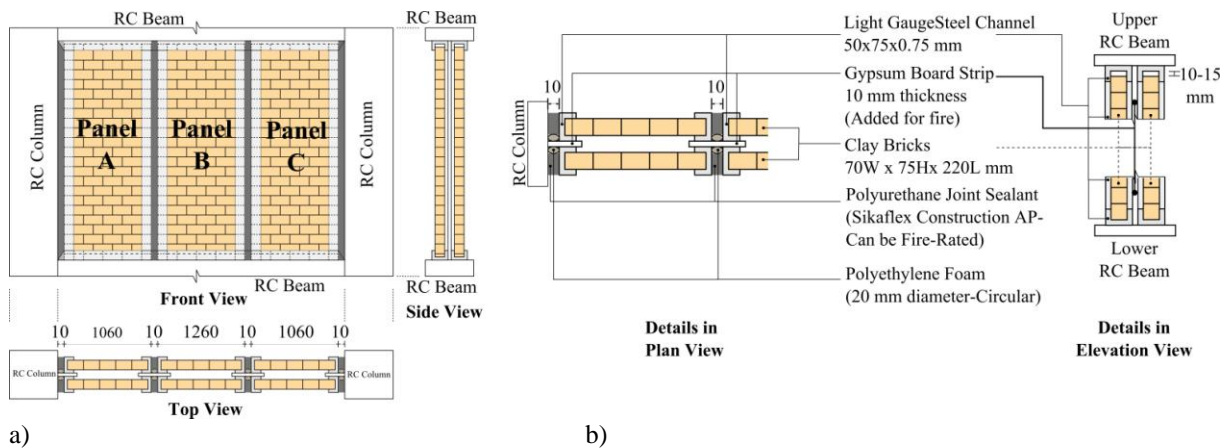


Figure 11 a) Overview of the low damage unreinforced clay brick infill wall specimen MIF5-UCBI; b) The details adopted in the low damage solution

$$\Delta_G = D \cdot \frac{h_c}{2} \cdot \frac{1}{100} \quad (1)$$

Where Δ_G : Calculated gap on one side of the infill wall
D: Design inter-storey drift limit in % after which damage is acceptable
 h_c : Infill wall clear height (2550 mm for the test specimen)

In general, the construction of the specimen consisted of only two steps. Firstly, the light gauge steel sub-frame was constructed according to the developed details. Then, the clay bricks were layed inside the sub-frame in the same way as FIF3-UCBI, with wall ties at every fourth course in vertical and 600 mm apart in horizontal. However, no mortar was used at the bottom and top borders of the infill panel zone to allow sliding between the infill wall and the steel sub-frame. Instead of a single infill panel, the wall was constructed as three separate cantilever panels as shown in Figure 12. Seven days after the infill wall was finished, the gaps were filled with polyethylene foam and polyurethane joint sealant. The finalized elevation of the specimen is shown in Figure 12d.

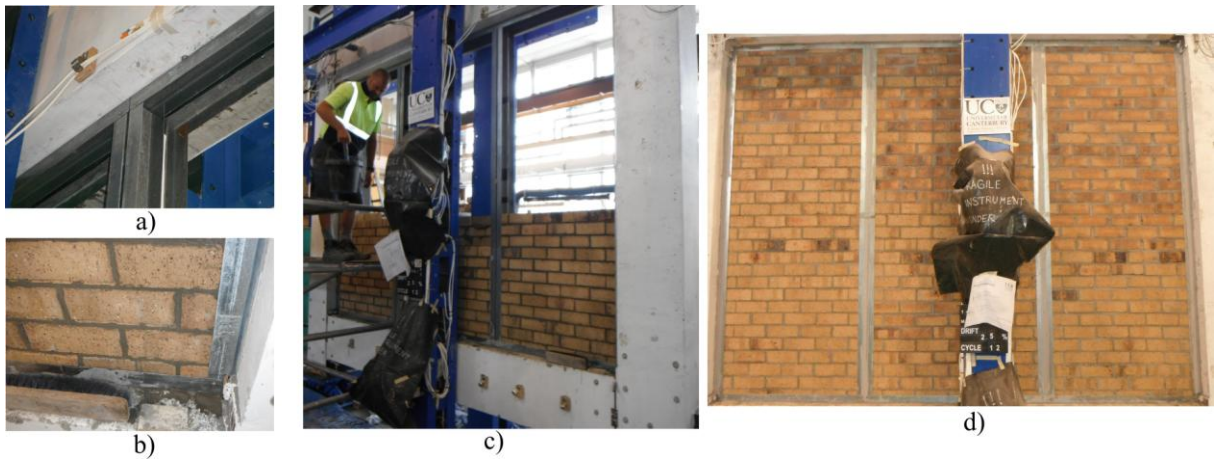


Figure 12 Construction of the low damage unreinforced clay brick infill wall specimen MIF5-UCBI: a) Light gauge steel subframing; b-c) The clay bricks layed within the steel subframe; d) The specimen after the polyurethane joint sealant application into the gaps

Under the displacement protocol, the specimen did not show any significant damage until the end of the test at 2.5% drift. At 0.75% drift, one minor horizontal mortar crack at the top right corner of the Panel C was observed. Then at 1.5% drift, two other minor mortar cracks were observed at the bottom left and top right corners of the Panel A. 1.5% drift was the drift limit until which the interaction with the structural system was minimized. After this, the individual infill wall panels engaged with the structural system. As a result, another horizontal crack and minor toe crushing occurred at the top right corner of the Panel C, which was caused by the rocking of the panels and the interaction with the structural system. Similar horizontal cracks formed at the top left corner of the Panel A at 2.5% drift level. The damage progress of the specimen is summarized in Figure 13.

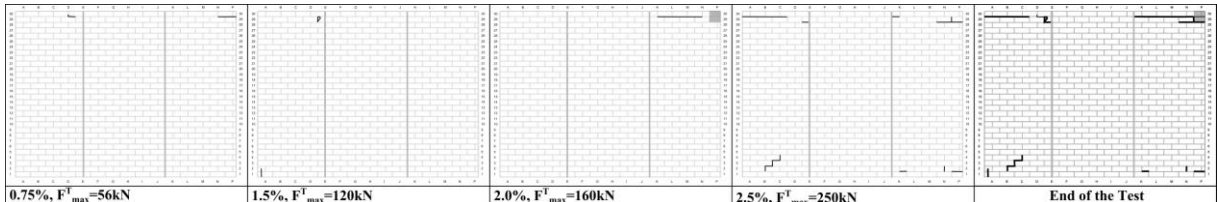


Figure 13 Damage progress of the low damage unreinforced clay brick infill wall specimen MIF5-UCBI

The adopted details worked effectively and prevented the formation of in-plane damage. As a result, the solutions preserved the out-of-plane capacity, which was dependent on the in-plane strength of the infill wall and the condition of the sub-frame. The system worked as it was intended; the infill wall panel had degree of freedom to slide, and the polyurethane joint sealant acted as a bumper for

sliding. In addition, the infill panels were able to rock as sliding action reached its limit, which started when the compressibility of the polyurethane joint sealant reached its limit. At the end of the test, very low and minor damage was observed at the specimen (Figure 14). Also, the polyurethane joint sealant proved its strong bonding capabilities within the given low damage concept (Figure 15b). At the end of the test, the joint sealant was intact and functional. The behaviour of the specimen is schematically summarized in Figure 15a.

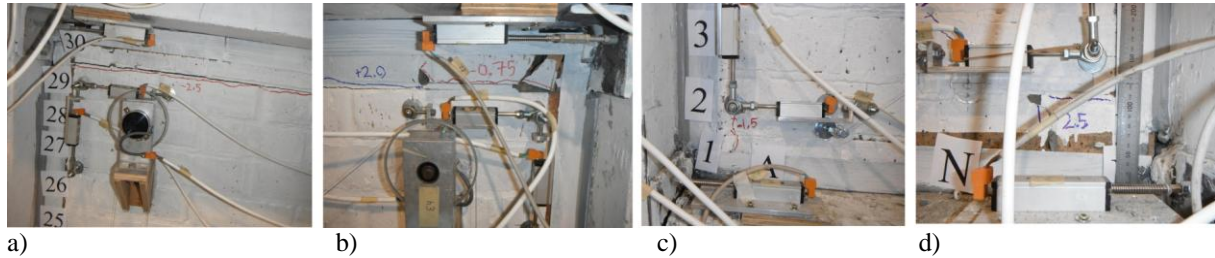


Figure 14 Damage photos of the low damage unreinforced clay brick infill wall specimen MIF5-UCBI at the end of the test: a) Top left corner; b) Top right corner; c) Bottom left corner; d) Rocking at bottom right corner at 2.5% drift (The border of the white line represents the level of the steel track at 0 displacement)

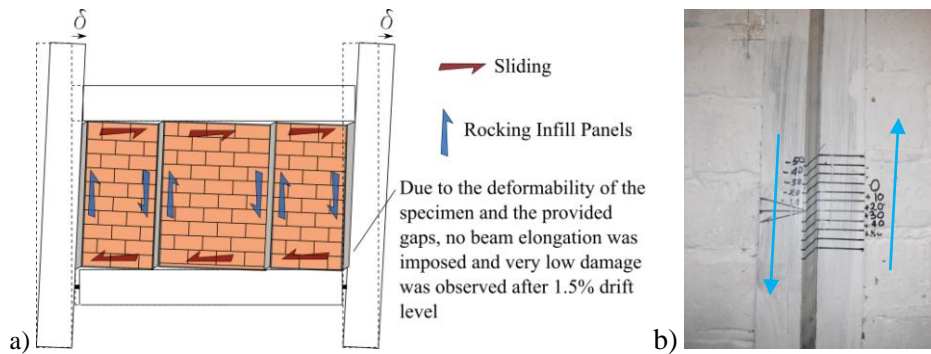


Figure 15 a) Behaviour of the low damage unreinforced clay brick infill wall specimen MIF5-UCBI, b) The deformation of polyurethane joint sealant at +2.5% drift level

Structurally, the effect of these flexible gaps was observed in the resulting global hysteresis curve, shown in Figure 16a. As design suggested, the interaction of the infill panel zone with the structural system was minimized until the theoretical design drift limit of 1.5%. After this drift, the infill panel zone started to interact with the structural system. However, even the highest drift limit of 2.5% could not cause a serious damage to the developed low damage infill solution. The infill remained intact and serviceable both structurally and architecturally. In Figure 16, the lateral force exerted by the infill panel zone and its projection into diagonal direction are shown for numerical modelling purposes.

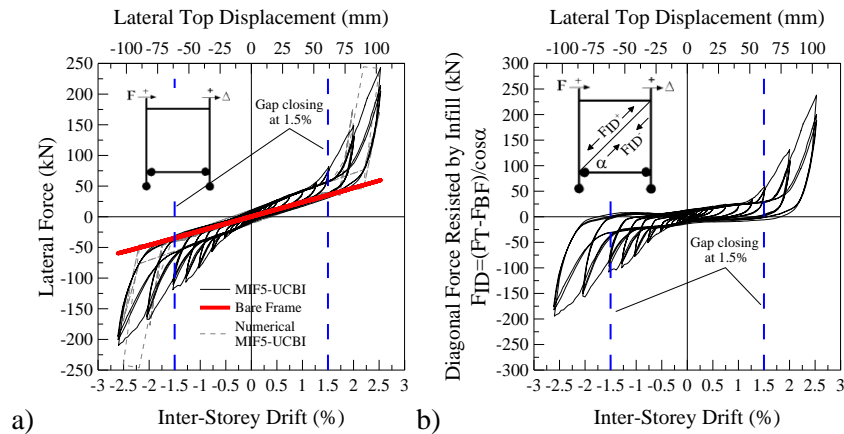


Figure 16 Low damage unreinforced clay brick infill wall specimen MIF5-UCBI: a) Total lateral force vs. inter-storey drift; b) Diagonal force resisted by the infill wall vs. inter-storey drift (Used for numerical modelling purposes)

COMPARISON OF AS-BUILT AND LOW DAMAGE SPECIMENS

The low damage solution minimizes the interaction with the structural frame, resulting in behaviour close to the bare frame until the design drift limit of 1.5% (Figure 17). After 1.5%, the infill wall interacts with the structure due to the activated strut action. After the design drift limit, the infill turns into an additional structural component in the system, a back up element. Accordingly, it can be stated that the solution can be an alternative dissipative solution to be utilized/activated when the inter-storey drift level in the structure exceeds the design drift level. Moreover, the developed solution does not apply only to unreinforced clay bricks, but to any kind of panels with enough strength and stiffness that can be utilized as structural elements (i.e. timber panels, steel plate shear walls, reinforced concrete panels, etc.). Therefore, individual cantilever infill wall panels within an infill panel zone is a concept adaptable to other suitable infill materials with a potential of becoming secondary backup structural elements that engage the structural system depending on the imposed inter-storey drift levels in a building.

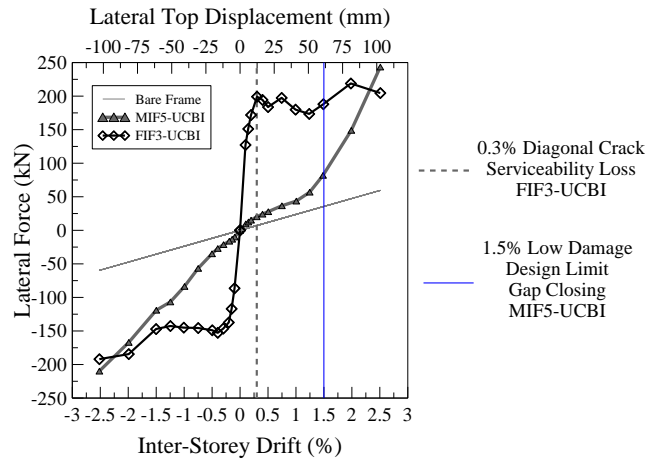


Figure 17 Envelope curves comparison of as-built and low damage unreinforced clay brick infill wall specimens (FIF3-UCBI and MIF5-UCBI)

The efficiency of the low damage solution can also be shown by using the axial strut strain (ε_w) in relation to the drift (δ) and aspect ratio (L/H) of the infill panel zone using Eq. 2 suggested by Magenes and Pampanin (Magenes and Pampanin, 2004). Low damage design drift directly adds up in the given equation so that it causes an increased drift capacity for each level of strain. This modification given by the low damage solution is shown in Eq. 3. The graphical comparison of these two equations, using a low damage design drift of 1.5%, summarizes the effect of the low damage solution compared to the as built option in Figure 18.

$$\delta = \frac{L}{H} - \sqrt{(1 - \varepsilon_w)^2 \cdot \left(1 + \left(\frac{L}{H}\right)^2\right) - 1} \quad (2)$$

$$\delta_{low} = D + \frac{L}{H} - \sqrt{(1 - \varepsilon_w)^2 \cdot \left(1 + \left(\frac{L}{H}\right)^2\right) - 1} \quad (3)$$

For the tested specimens, the aspect ratio (L/H) was 1.33, which corresponded to a diagonal strut strain of 0.002 at 0.4% drift level (Figure 18a). Incorporating the low damage solution increased this drift limit to approximately 2.0% (0.4%+1.5% design drift=1.9%) for the same strain of 0.002 (Figure 18b). These results also confirmed the experimental observations since the damage to the infill wall started only after 2.0% drift level while the interaction was minimized until 1.5% drift level.

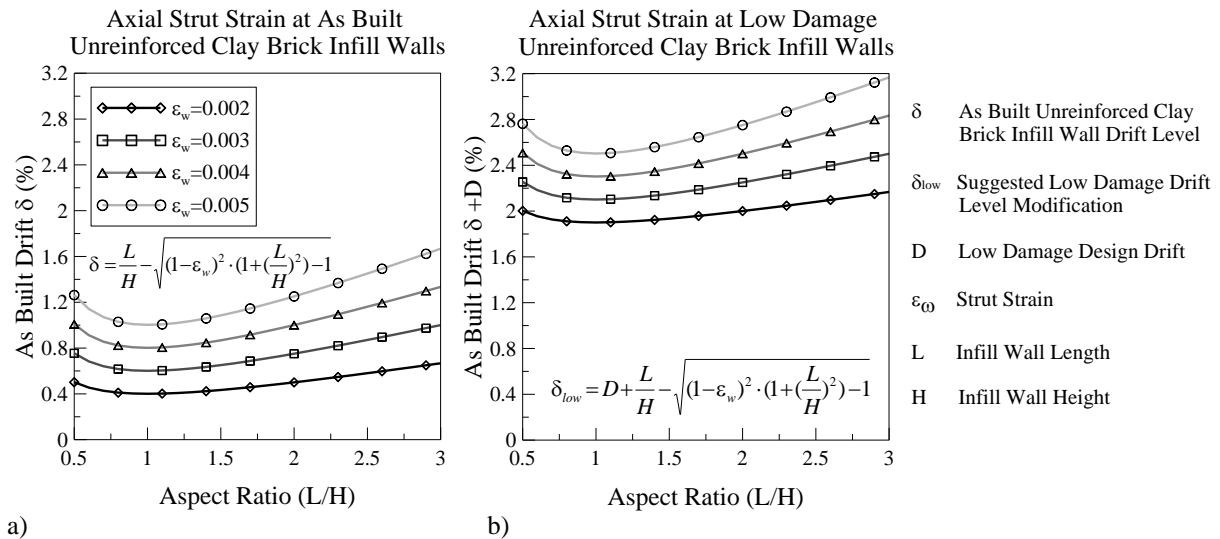


Figure 18 Axial diagonal strut strains with respect to aspect ratio of the infill panel zone and imposed drift levels given by Magenes and Pampanin (2004) and the modification to incorporate the gap system in the low damage infill wall solution ($D=1.5\%$ in the shown case above): a) As built unreinforced clay brick infill walls; b) Low damage unreinforced clay brick infill wall solution

CONCLUSIONS

The old practice of armature cross walls and the concept of rocking systems were adapted to be used in modern structures in order to obtain a low damage solution for unreinforced clay brick infill walls. The low damage solution concept was developed by dividing the infill panel zone into three using light gauge steel sub-framing. The three panels were separated by 10 mm vertical gaps from each other and from the RC columns. These gaps were filled with polyurethane joint sealant, a very elastic structural joint sealant. The achieved low damage system was, in principle, a rocking infill wall system.

The low damage system proved its effectiveness and remained serviceable even at high drift levels imposed during the test (2-2.5% drift). Until the design drift limit of 1.5%, the low damage system's behaviour was very close to the bare frame, which meant the interaction between the structural frame and the non-structural wall was minimized. After the design drift (i.e. gap closing), the low damage infill wall started to take forces by the activation of the diagonal strut. In other words, the low damage non-structural wall solution worked as a low damage system until the design drift limit and the gaps were fully closed. After the design drift level, the system behaved as a structural component. Therefore, the low damage solution is potentially a reserved backup or secondary seismic resisting structural element that activates when a structure experiences extreme drifts provided that they do not develop brittle local or global mechanisms. Other than clay bricks, this solution can also be applicable to other types of appropriate materials with adequate strength and stiffness (i.e. timber walls, steel plate shear walls, RC panels, etc.).

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