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INVESTIGATION OF SEISMIC BEHAVIOUR OF EXISTING MASONRY INFILLS THROUGH COMBINED CYCLIC IN-PLANE AND DYNAMIC OUT-OF-PLANE TESTS

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Abstract

The seismic behaviour of an existing masonry infill typology has been investigated through a comprehensive experimental campaign involving five full-scale specimens subjected to in-plane pseudo-static cyclic tests and out-of-plane dynamic shake table tests. The infill specimens were built within a composite steel-concrete frame, representing a single bay of a reinforced concrete frame structure constructed prior to the use of seismic codes in structural design. The masonry typology is comprised of horizontally perforated 8-12 cm thick clay units and mortar head and bed joints, which was commonly used in the Mediterranean countries between 1960s and 1980s. In this study, the pure in-plane and out-of-plane behaviours of infills fully connected to the frame were characterized first. Then, the effect of previous in-plane damage on the out-of-plane capacity was assessed by applying in-plane drift and subsequently out-of-plane dynamic loading up to failure. Furthermore, an infill connected to only the top and bottom beams of the frame was tested purely out-of-plane to explore the seismic behaviour of a one-way spanning infill. The experimental campaign, including tests of characterisation of materials and masonry, has enabled to provide insight to in-plane drift capacity, out-of-plane load-displacement capacity and failure mechanisms, and the in-plane/out-of-plane interaction of the existing infill typology subjected to seismic actions.

Keywords: Masonry infills, Existing infills, In-plane and out-of-plane interaction, Shake table tests, Seismic behaviour

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1 INTRODUCTION

The vulnerability of masonry infills to seismic actions has been substantiated repeatedly during past earthquakes [1,2,3], and the need for accurate evaluation of infill panels for seismic safety is of utmost importance to reduce risk of major economic loss and threat to life safety. The seismic behaviour of masonry infills is influenced by many factors such as the infill typology, infill material and masonry properties, panel geometry, the nature of the connection with the surrounding frame, presence of openings, frame properties, interaction of in-plane and out-of-plane response, local interaction between the panel and the frame, and global structural response. Therefore, generalizing the behaviour of infills could lead to inaccurate assessments and inadequate designs. In fact, infills are non-engineered elements, and recognized as non-structural elements in current seismic codes [4,5,6,7]. The guidelines provided for damage limitation, resistance verification and seismic demand evaluation of masonry infills are rather general, not specific to the infill typology, and do not account for boundary conditions or the structural configuration especially for the out-of-plane assessment. Therefore, over the last decades, a number of studies have been dedicated to exploring the seismic behaviour of different masonry infill typologies in various configurations considering the in-plane behaviour [8,9,10,11] and the out-of-plane behaviour with and without in-plane damage [12,13,14,15,16]. The experimental campaign presented in this paper will be the first of its kind involving in-plane pseudo static tests and out-of-plane shaking table tests to investigate the seismic behaviour of an existing masonry infill typology, exploring the influence of boundary conditions, in-plane/out-of-plane interaction, and presence of openings. The experiment campaign is currently ongoing at the Eucentre Foundation of Pavia and is conducted in three phases; the results of the first phase involving tests on five specimens will be presented herein along with the description of specimens, material characterisation, test setup and adopted protocols.

The existing masonry infill typology investigated in this study comprised of horizontally perforated hollow clay units of 12 cm thickness, which is commonly present in Italy as enclosures and partitions in reinforced concrete frame structures built before seismic codes were implemented in structural design. Due to its high percentage of perforation and slenderness introduced from the small thickness, such an infill typology is typically classified as “weak” masonry infills. The enclosures of this type of infills are commonly found in two layers with a cavity in between. In the current study, the first phase consisted of five single leaf infill panels plastered on one side, constructed within steel concrete composite frames representing one panel of a double leaf infill in a single storey single bay of an existing reinforced concrete frame structure. Out of the five specimens, four specimens were fully connected to the frame in all edges with a mortar layer, and one specimen was built with two vertical gaps between the wall boundaries and the columns, connected only at the top and bottom beams. The fully connected specimens were tested purely in-plane, purely out-of-plane and sequentially in-plane and out-of-plane. The specimen with vertical gaps was tested only in the out-of-plane to observe the single bending/arching behaviour in a vertically spanning wall. The in-plane tests were displacement-controlled pseudo-static cyclic tests at increasing target drifts, and the out-of-plane tests were shake table dynamic tests with incremental peak floor accelerations. The results are presented in terms of damage observed, in-plane force-displacement response, in-plane drift capacity, out-of-plane accelerations and displacements, and collapse mechanisms. The influence of the in-plane damage on the out-of-plane capacity is discussed, and the effect of the boundary conditions is elaborated through comparison of out-of-plane tests on specimens fully connected to the frame and connected only at the top and bottom.

2 EXPERIMENTAL CAMPAIGN

2.1 Specimens

The infills were constructed with 12 cm thick horizontally perforated units (Figure 1a.) laid in running bond with mortar head and bed joints with a thickness around 10 mm. The panels were plastered on one side with a 10 mm thickness, so that the final thickness of the infill was 13 cm. The frame was fabricated with steel C sections filled with reinforced concrete (Figure 1b.) and has been designed to behave as an existing frame structure remaining undamaged during tests. The infills are connected to the frame elements with a mortar layer in between the panel edge and the concrete surface of the frame, continuous through the thickness. Four specimens (named T1-T4) were fully adhered to the frame in all edges, and the remaining specimen (named T5) was connected at the top and bottom edges while having two vertical gaps of approximately 25 mm each, such that the vertical boundaries of the panel were free (Figure 1c.). The specimens were in full scale with height and length of 2.75 m and 3.5 m respectively. The completed specimen is shown in Figure 1d.

(a) (b) (c) (d)

Figure 1 (1) Horizontally perforated clay units (b) Steel-concrete composite bare frame (c) Vertical gap in specimen T5 (d) Completed fully connected specimen

2.2 Material properties

A comprehensive series of tests was carried out to determine the mechanical properties of units, mortar and the masonry. From monotonic compression tests on 10 units in each direction of horizontal and vertical, i.e., parallel to holes and perpendicular to holes [17], 40 mortar specimens following 20 flexure tests on 160 x 40 x 40 mm specimens [18], and 12 three course high wallets (770 x 770 mm) in each horizontal and vertical direction with plaster on one side and without plaster [19], the compressive strength of each entity, the elastic moduli of masonry and blocks, and flexural strength of mortar have been obtained. Moreover, triplet tests were performed under three pre-compression levels applied perpendicular to bed joints [20] to determine Mohr-Coulomb parameters of bed joints. Diagonal compression tests were carried out on three specimens of 1.29 m x 1.29 m to determine the diagonal tensile strength of the masonry [21]. The specimens of both triplet and diagonal compression tests were plastered on one side. The flexural strength of the masonry was determined by conducting four-point-bending tests in the vertical and horizontal directions, and in the orientations that the plaster is in tension and compression [22]. The results from the characterisation tests are summarized in Table 1.

Test	Property	Mean	STDV	COV (%)
Compressive test on units	Vertical compressive strength (MPa)	2.67	0.53	20.0
	Horizontal compressive strength (MPa)	6.16	0.37	6.0
Tests on mortar	Compressive strength (MPa)	4.18	1.01	24.3
	Flexural tensile strength (MPa)	1.21	0.43	35.8
Compressive tests on wallets (plastered)	Vertical compressive strength (MPa)	2.26	0.09	4.1
	Horizontal compressive strength (MPa)	3.55	0.71	20.0
	Vertical elastic modulus (MPa)	4387	461	10.5
	Horizontal elastic modulus (MPa)*	3168	26	0.8
Triplet test	Cohesion (MPa)	0.15	-	-
	Friction coefficient	0.98	-	-
Diagonal compression test	Diagonal tensile strength (MPa)	0.21	0.02	11.7
	Shear modulus (MPa)	922	159	17.2
Vertical flexure test	Flexural strength plaster in compression (MPa)	0.27	0.02	5.6
	Flexural strength plaster in tension (MPa)	0.66	0.13	20.1
Horizontal flexure test	Flexural strength plaster in compression (MPa)	0.87	0.11	13.0
	Flexural strength plaster in tension (MPa)	1.12	0.04	3.7

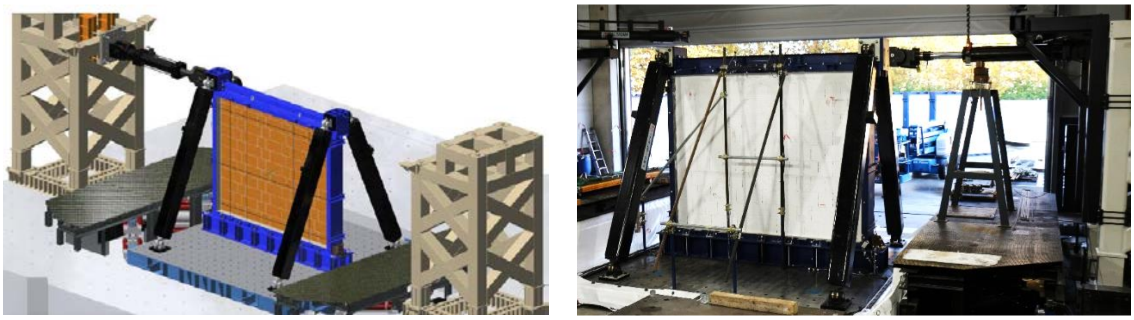
*Only two specimens were considered due to problematic readings obtained from potentiometers

Table 1: Summary of the tests of characterisation

2.3 Test setup

The infilled frames were fixed to the shake table rigidly through a steel beam foundation, and the out-of-plane movements of the frame nodes were restricted using four inclined steel braces, two on each side. To avoid transportation of the specimens during the tests, the shake table has been used as a strong floor for the in-plane tests, which was kept stationary during the static tests with an active control. For in-plane tests, the pseudo static drift cycles were applied in displacement control through a servo-hydraulic actuator supported by a strong steel frame.

The out-of-plane excitations were applied to the specimen through the shake table, during which the actuator used for the in-plane tests was disconnected and the out-of-plane restraints remained attached. The schematic diagram and a picture of the full test setup is shown in Figure 2a. and b.



(a) (b)

Figure 2 (a) Schematic diagram of the test setup (b) actual configuration

2.4 Instrumentation

The layouts of the instrumentation adapted for in-plane tests and out-of-plane tests are shown in Figure 3 and 4, respectively. Linear transducers were used to measure the applied displacements during in-plane tests. During dynamic tests, the out-of-plane accelerations were recorded through accelerometers placed on the infill panel and the frame (Figure 4a.), and out-of-plane displacements were monitored through an optical acquisition system with markers and high-resolution infrared cameras. The markers positions are shown in Figure 4b. In both in-plane and out-of-plane tests, strain gauges were utilized to monitor the strains in the steel of the frame to check for yielding.

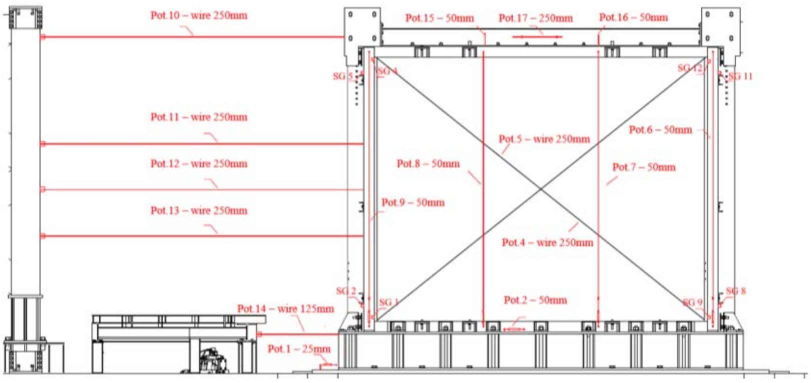
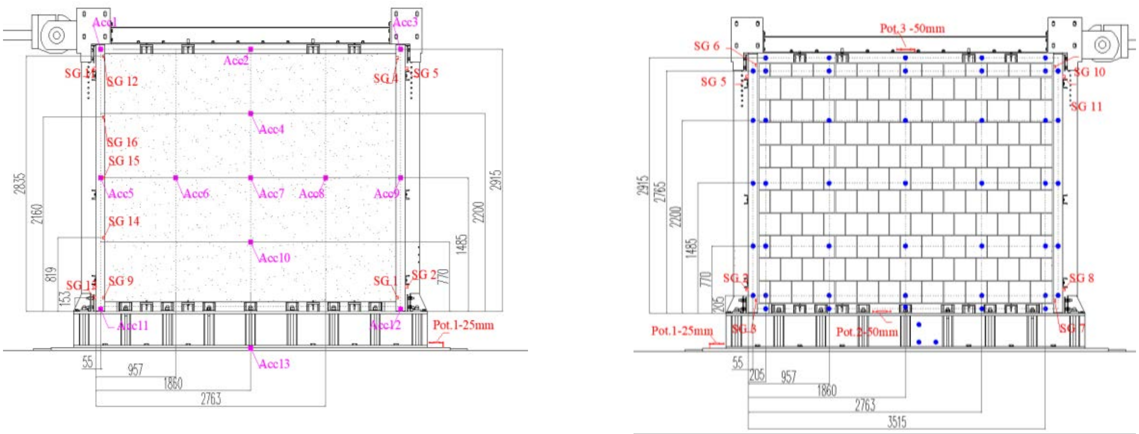


Figure 3. Instrumentation for the in-plane tests



(a) (b)

Figure 4. The layout of (a) accelerometers (b) optical markers for the out-of-plane tests

2.5 Loading protocol

The loading protocols were designed with the aim of exploring the full in-plane behaviour and the out-of-plane behaviour of infills with and without previous in-plane damage. The cyclic pseudo static loading was applied with incremental target drifts in displacement control with three cycles repeating for each drift level. Before the infills were constructed, all bare frames were subjected to a 1.5% drift in order to ensure a similar performance among them during the tests on infills, and also to obtain the in-plane force-displacement response of the bare frame. Specimens T1, T2 and T3 were subjected to 1.0%, 0.3% and 0.65% nominal drifts respectively, achieving different levels of damage in the infills. Then, specimens T2 and T3 were subsequently tested in the out-of-plane until failure. Specimens T4 and T5 were tested only in the out-of-plane without any previous in-plane damage. The in-plane loading cycles applied to specimen T1 is shown in Figure 5a.

The out-of-plane loading has been applied in the form of accelerograms with incrementing peak floor accelerations (PFA) through the shake table. The accelerograms were obtained by defining target response spectra according to the AC156 guidelines [23] for testing of non-structural elements, with some modifications of the frequency range of the maximum acceleration plateau according to the methods proposed in [24] considering floor response spectra from a series of nonlinear dynamic analyses performed on infilled frames with different heights [25]. Also, due to the period elongation of the infills with accumulating damage, the plateau of the target spectrum was adjusted accordingly to include such variations during the tests. The reference target spectra adopted for specimen T2 is presented in Figure 5b., where such an adjustment of the plateau of the spectrum has been made during the test. A summary of the in-plane and out-of-plane loading protocols are presented in Table 2 and 3.

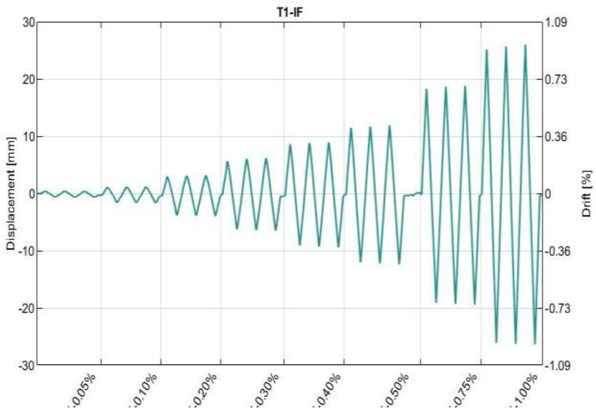
Drift(%)	0.1	0.2	0.3	0.4	0.5	0.65	0.75	1.0
T1	x	x	x	x	x	-	x	x
T2	x	x	x	-	-	-	-	-
T3	x	x	x	x	x	x	-	-

Table 2. Summary of the in-plane tests

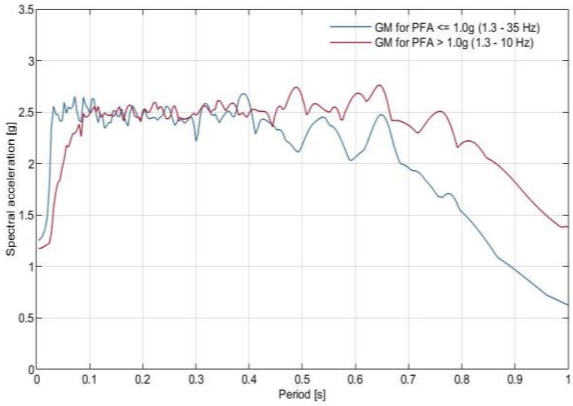
PFA (g)	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.75	0.80	1.00	1.25	1.50	1.80	2.00	2.25	2.50
T2	x	x	x	x	x	-	-	x	-	x	x	x	x	x	x	x
T3	x	x	x	x	x	-	-	x	-	x	x	x*	-	-	-	-
T4	x	x	x	-	x	-	-	x	-	x	x	x	x	-	-	-
T5	x	x	x	x	x	x	x	-	x	x	-	-	-	-	-	-

*Test repeated 3 times

Table 3. Summary of the out-of-plane tests



(a)



(b)

Figure 5. (a) In-plane loading protocol for specimen T1 (b) Reference target spectra adopted for specimen T2

3 RESULTS

The primary results for the in-plane, out-of-plane and the combined in-plane and out-of-plane tests will be discussed with a focus on the performance of the infills during the tests, damage propagation, capacities reached, and recorded displacements and accelerations.

3.1 In-plane tests

The in-plane behaviour of the masonry infill fully connected to the frame in all edges could be explicated through specimen T1 which was subjected to in-plane incremental drifts up to failure. Specimens T2 and T3 were tested until the infills reached states of slight and moderate damage respectively, prior to the out-of-plane tests. The damage observed at the last drift level in each infill is illustrated in Figure 6. The damage during the in-plane cycles was mainly characterised by steep diagonal cracks and a horizontal strip of damage (see Figures for T1 and T3). The damage initiated at the boundaries first, developing cracks along the mortar layer binding the infill to the frame. Then, diagonal step cracks appeared along with a main horizontal crack to which the diagonal cracks connected at the ends. As the drift increased, more diagonal and horizontal cracks along mortar joints developed, also damaging the surrounding plaster and unit shells. The level of damage was similar in the specimens at the drifts which they were subjected to. However, while specimen T2 and T3 followed an in-plane damage pattern typically observed in specimens fully bound to the frame where diagonal cracks spread almost symmetrically from the corners to the middle to meet a main horizontal crack in the mid courses, in specimen T1, the horizontal damage zone was shifted to the lower courses, probably due to localized effects. Considering the progression of damage observed in the infill specimens during the in-plane cycles, it was possible to deduce in-plane drift values for operational, damage and life safety limit states as 0.16, 0.29, and 0.81%, respectively.

The force-displacement response obtained for cycles up to 1.0% drift for specimen T1 is reported in Figure 7a. The force-displacement envelope of the bare frame has been subtracted from that of the fully infilled frame to obtain the contribution of the infill panel alone, and it is worth to note that the bare frame remained elastic for the range of drifts that the infill was tested. The backbone curves derived for the infill panels (alone) for specimens T1, T2 and T3 are compared in Figure 7b along with the damage limit states specified above. The specimen T1 reached a higher peak force than specimens T3, while specimen T2 did not enter the post-peak branch.

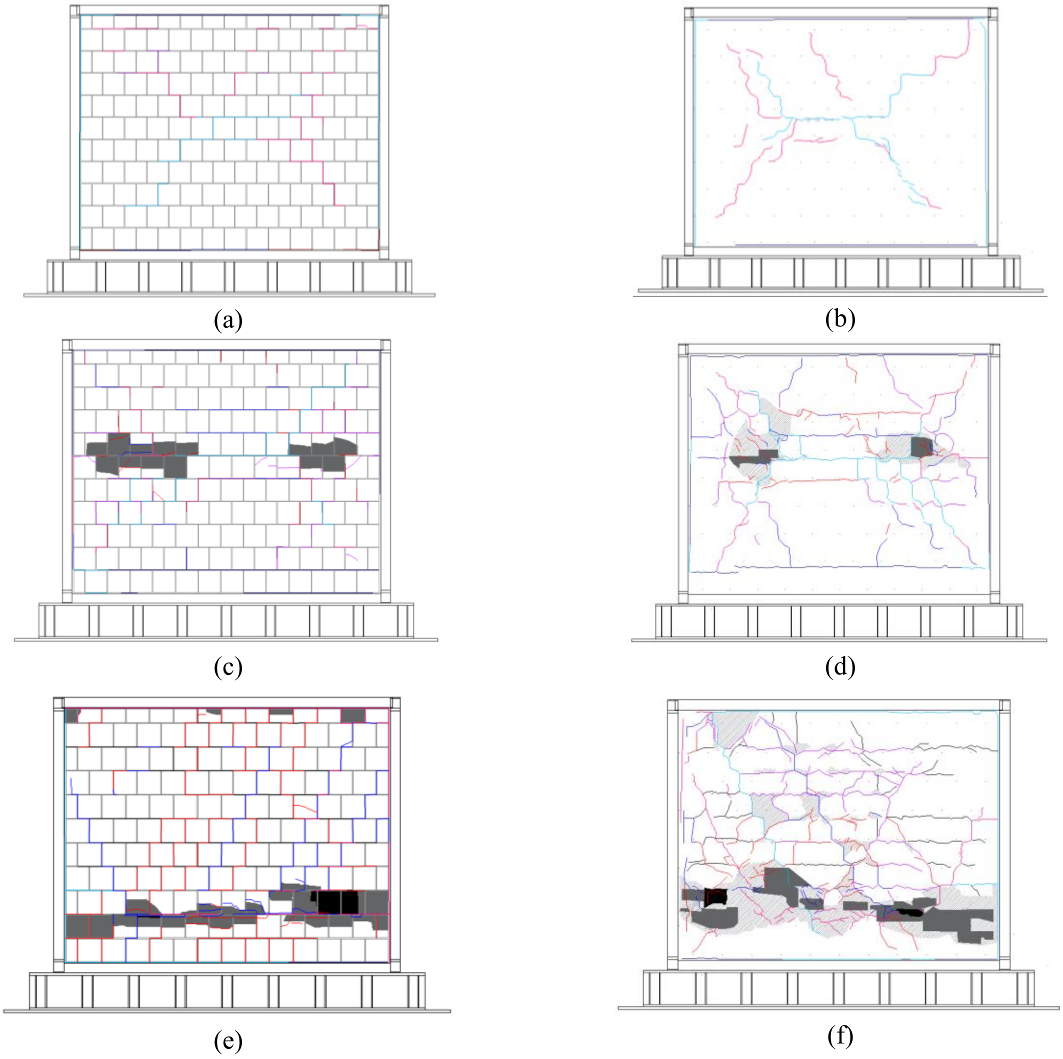
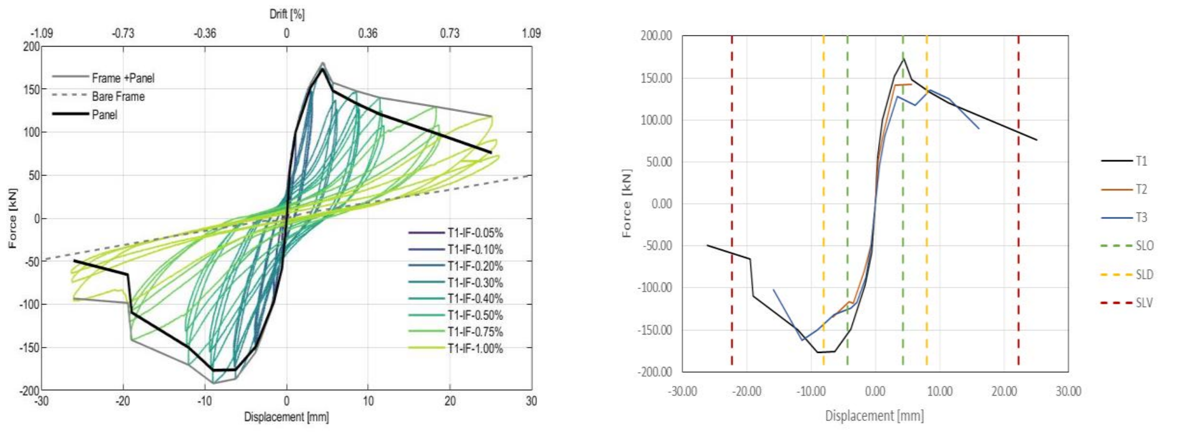


Figure 6. The damage state of infills (a) T2 bare face at 0.3% (b) T2 plastered face at 0.3% (c) T3 bare face at 0.65% (d) T3 plaster face at 0.65% (e) T1 bare face at 1.0% (f) T1 plaster face at 1.0% drifts

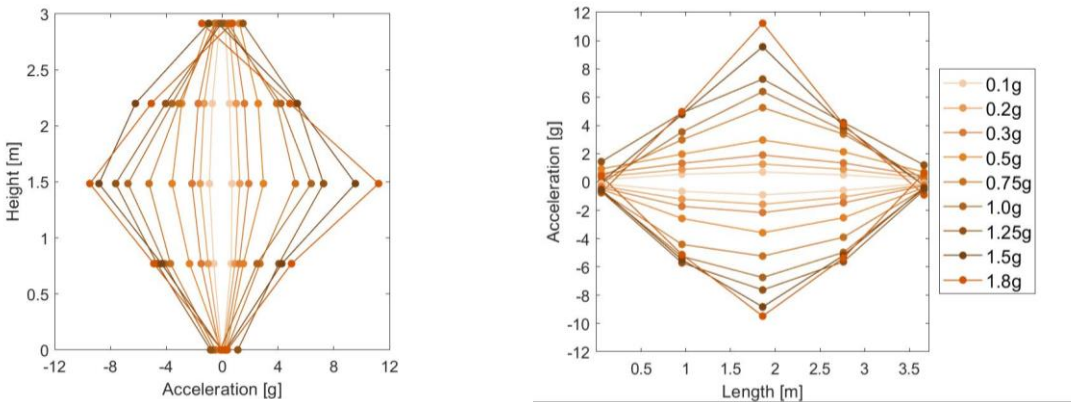


(a) (b)

Figure 7. (a) The force-displacement cycles of specimen T1 (b) Force-displacement backbone curves derived for infill panels with damage limit states

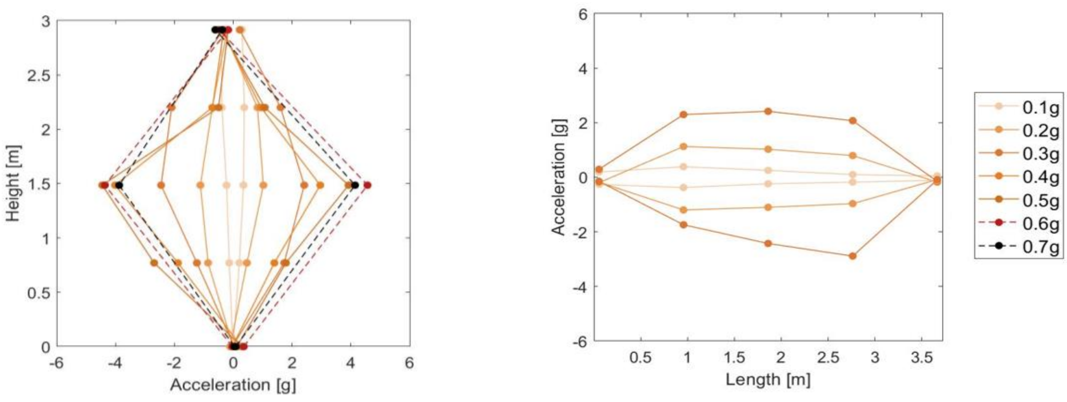
3.2 Out-of-plane tests

The out-of-plane tests on infills which were not subjected to previous in-plane loading were conducted on two specimens with different boundary conditions. Specimen T4 which was fully connected to the frame did not show any significant damage except for a few horizontal cracks and very thin stepped cracks as the nominal PFA was increased up to 1.8g. While the boundaries cracked for both T4 and T5 in the beginning when lower PFAs were applied, the specimen T4 was more robust and stiffer with presumably double bending/arching conditions. Specimen T5 exhibited single bending/arching mechanism in the vertical direction characterised by horizontal cracks along the bed joints spanning the whole length of the infill around the mid-height. The double and single bending behaviours are also evident in the acceleration profiles obtained at the maximum response for each test run, recorded along the height and length at the centre of the panels (Figures 8 and 9). When comparing the profiles along the length at mid-height for the two specimens, in infill T5 which had free vertical edges, an almost uniform acceleration profile is observed (the two corners are the acceleration of the frame at the same height). Thus, it is apparent that when the panel is connected in the opposite edges the acceleration profile will be closer to a triangular shape than a uniform profile. Both specimens did not reach collapse, and the maximum accelerations attained at the panel centre were 11.2g at 1.8g nominal PFA (amplification of 5.75) for T4 and 4.57g at 0.6g nominal PFA (amplification of 6.65) for T5.



(a) (b)

Figure 8. The acceleration profiles recorded for specimen T4 (a) along height at centre (b) along length at mid-height



(a) (b)

Figure 9. The acceleration profiles recorded for specimen T5 (a) along height at centre (b) along length at mid-height

3.3 Combined in-plane and out-of-plane tests

When specimens T2 and T3 were subjected to out-of-plane loading, having previous in-plane damage of 0.3 and 0.65% drift, considerable damage propagation was observed when compared to T4, and the infills finally reached collapse in a catastrophic nature at nominal PFAs of 2.5g and 1.5g, respectively. The maximum acceleration recorded at the panel centre was 10.76g with an amplification of 4 for specimen T2, and 6.25g with an amplification of 3.65 for specimen T3. The recorded acceleration profiles along the height at time of the maximum response at each PFA for T2 and T3 are shown in Figure 10 a. and b. It is interesting to recall the damage patterns of the in-plane tests (Figure 6) which most likely weakened the upper half of the infills, and draw a connection to the observed accelerations in Figure 10 which at lower PFAs seem to be higher in the upper half of the infill than in the lower half. However, in T2 as the motion intensity was increased, the profiles shifted to a triangular shape with the maximum acceleration at the centre. In T3 at higher PFAs the accelerometers were removed except for the one at the centre of the panel and the ones attached to the frame to avoid damage to the accelerometers. Therefore, a complete acceleration profile could not be determined for PFAs after 0.75g, hence they are shown in dashed lines.

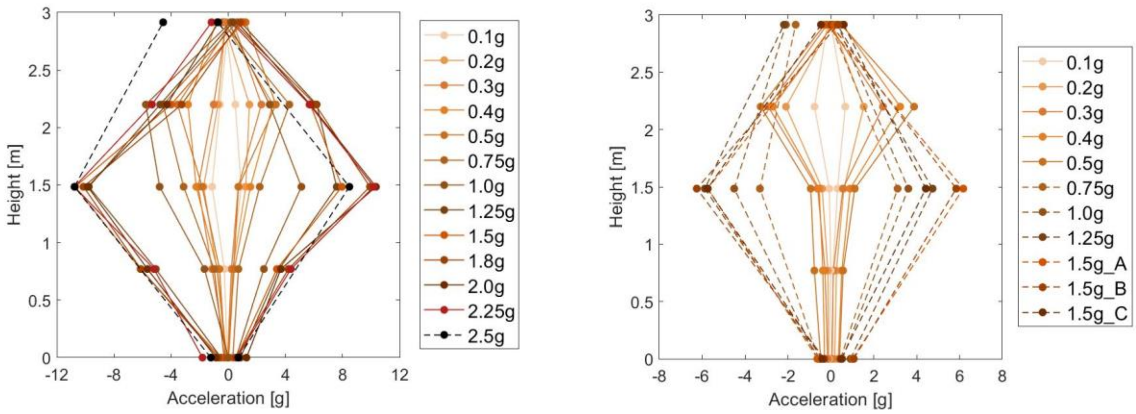
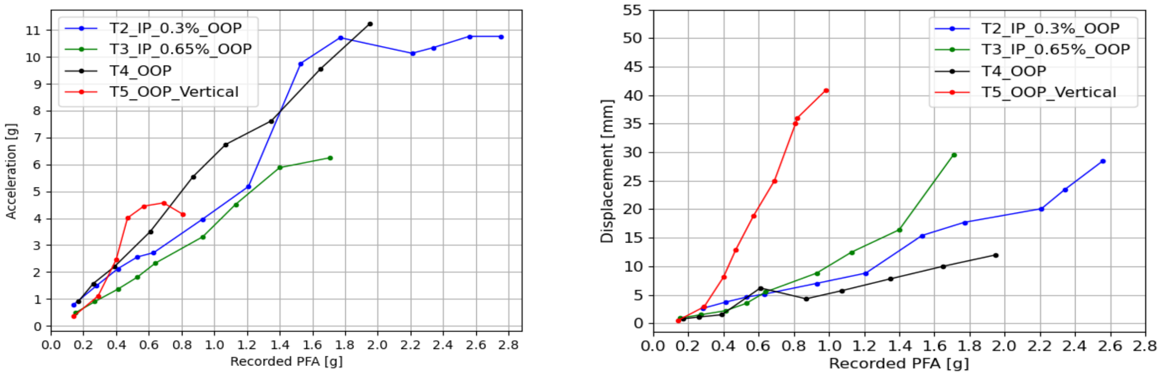


Figure 10. The acceleration profiles recorded along height at centre for specimens (a) T2 (b) T3

4 DISCUSSION

The behaviour of the infills during the out-of-plane tests could be further elucidated by comparing the maximum accelerations and displacements recorded at the centre of the panels for increasing PFA, as depicted in Figure 11. In specimen T4, which did not have any significant damage except for slight cracks, the maximum acceleration increased almost linearly, indicating an elastic behaviour still at the stage where the other two similar specimens were severely damaged or collapsed, and the potential for a significantly higher out-of-plane capacity. Comparing T2 and T3, up to a PFA of 1.2g the maximum accelerations are similar increasing almost linearly, then the two specimens enter a nonlinear range where T3 immediately reaches collapse, and T2 has a fairly constant branch of high accelerations before collapse. The drastic reduction in the out-of-plane capacity of the specimen T3 with higher in-plane damage is evident with respect to the specimen T2 with lower in-plane damage, with a 42% reduction in the maximum acceleration recorded during the test, and also reaching collapse at a lower PFA. The vertically spanning specimen T5 differed from the fully connected specimens having lower accelerations and reaching a peak acceleration at a lower PFA, where the other infills still seem to be in the elastic range.

Observing the maximum displacements recorded at the centre, for fully connected specimens the reduction in stiffness is clearly observed decreasing from the undamaged specimen to the most damaged specimen. The highest displacements were exhibited by the specimen with free vertical edges.



(a) (b)

Figure 11. The maximum (a) accelerations (b) displacements recorded at panel centre

5 CONCLUSIONS AND FUTURE WORK

The seismic behaviour of an existing masonry infill typology has been investigated through in-plane pseudo static cyclic tests and out-of-plane dynamic shaking table tests conducted on five infill specimens. While characterising the in-plane response of a fully connected infill in all edges to the frame, the influence of previous in-plane damage on out-of-plane capacity of similar specimens was explored, and then compared to the pure out-of-plane behaviour of a specimen without any previous in-plane damage. Moreover, the pure out-of-plane behaviour of a vertically spanning specimen with vertical gaps at the columns was also examined, drawing comparisons with the fully adhered specimen. The main observations from the test series are summarized as follows.

- An infill panel can be expected to possess a considerable out-of-plane capacity when there is no in-plane damage. However, in a real earthquake event infills are subjected to high in-plane demands in lower stories, which can drastically reduce the out-of-plane capacity leading to collapse of a catastrophic and life threatening nature.
- The boundary conditions of the panel significantly influence the out-of-plane response. The vertical spanning infill reached peak accelerations at lower PFAs and had a significantly lower stiffness compared to the fully supported infill exhibiting higher displacements.
- The distribution of accelerations is not uniform over the panel but close to triangular shape when the opposite edges are supported by the frame. In double bending specimens the triangular distribution of accelerations was apparent in both directions, and in the single bending specimen the distribution was observed along the height.

In the following phases of the experimental campaign, the seismic response of specimens with a thin gap at the top will be explored, as well as the influence of presence of openings on the seismic behaviour of infills. The out-of-plane capacity of the undamaged specimen is also to be determined with an improved test setup.

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