IN-PLANE AND OUT-OF-PLANE TESTS ON STEEL FRAME WITH SIM INFILL

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ABSTRACT

Masonry walls are often used in multi-storey framed structures as infill panels. A new masonry system has been developed to improve the seismic behaviour of framed structures with masonry infill panels. It is called semi interlocking masonry (SIM). In this system dry-stack infill panels are built with masonry units capable of relative sliding in-plane of a panel. SIM panels have reduced in-plane stiffness and increased frictional energy dissipation capacity compared with traditional masonry infill panels. Under seismic loads these panels do not detrimentally interfere with the natural frame vibration but rather positively contribute to earthquake resistance mainly by increasing damping. A universal steel testing frame was built to test this new masonry system. A cyclic displacement test was performed to evaluate the in-plane behaviour of topologically interlocking SIM panel. An air bag test was performed to evaluate out-of-plane structural integrity on this masonry panel. This paper presents force-displacement graphs, energy dissipation analysis, and comparison to the previously performed similar test with RC frame. Results indicate that SIM has considerable out-of plane strength and stability and can improve the seismic behaviour of framed structures with masonry infill panels.

KEYWORDS: dry stack, masonry, interlocking, in-plane, out-of-plane, energy dissipation

INTRODUCTION

Masonry is one of the most popular and oldest construction materials. However, the use of masonry has been limited in seismic areas because traditional un-reinforced masonry is too rigid and at the same time too brittle. To achieve better seismic performance, masonry is usually combined with other more ductile materials to form a dual load bearing system. For example, one of the most common dual systems combines a ductile RC frame with masonry panels. Although framed masonry panels are often considered non-structural elements, they are very rigid compared to RC columns and hence may attract high seismic forces that could be damaging for panels and frames. This is a common cause of structural damage found after earthquakes. A very recent example that exposed the disadvantages of traditional RC framed masonry panels is the 2010 Maule Earthquake in Chile [1].

Most research in this area is concerned with the seismic behaviour of confined and in-filled traditional masonry panels. The results show that panels improve the energy dissipation of the frame. However, most of the energy dissipation in traditional structures is accompanied by damage to both the frame and masonry panels (crushing of bricks or cracks in concrete elements and mortar joints) with the reduction in the stiffness and resulting dangerous loss of the out-of-plane structural integrity of panels.

There is limited research on the behaviour of dry-stack masonry. Lourenço [2-4], Uzoegbo [5,6] and Bansal [7] have done some experimental studies. Lourenço focused on the behaviour of dry-stack stone wall. He carried out a series of tests on the friction behaviour of single brick [2] and set of cyclic tests and shaking table tests both on both dry-stack stone and mortared stone wall [3,4]. According to his research, the failure criteria of dry-stack stone can be considered as Mohr-Coulomb failure. The type of wall and the recompression level are confirmed as two important factors for the failure mode. A considerable nonlinear deformation had been attained (storey drift = 2.5%). However, because of the rocking failure mechanism, the dry-stack walls seemed unable to dissipate energy [4].

Uzoegbo researched both in-plane and out-of-plane seismic behaviour of masonry walls [5,6]. According to his research, the strength of dry-stack units makes no significant difference in the resistance to lateral loads. Interlocking and friction between units govern the lateral load bearing capacity. A shake table test had been performed on the dry-stack system, which demonstrated that the masonry structure can resist acceleration up to 0.3g.

Bansal reported on the use of interlocking dry-stack masonry and compliance of this innovative method to the Indian Standard. His research was focused on various economic advantages of this system.

A conceptually new system for framed masonry panel is being developed by Totoev [8-10]. According to this concept, masonry in-fill panels are no longer considered non-structural elements. Instead, they are considered as “non-gravity-load-bearing” structural elements fully participating in resisting horizontal loads. To achieve a positive contribution from masonry panels to horizontal load resistance, panels should (i) be less rigid in-plane of a wall and (ii) contribute mostly to the energy dissipation. Panels are built with dry-stack masonry units capable of relative sliding only in-plane of a wall. These panels have reduced in-plane stiffness but increased frictional energy dissipation capacity. The frame is bearing all gravity loads, resists horizontal loads together with the in-fill, and confines the masonry panel to avoid the rocking and out-of-plane instability.

This paper reports a part of the on-going experimental program on frames with dry-stack masonry panel using cyclic and air bag tests. Its main objective is to extend the previous experimental study by including steel frames. A series of in-plane cyclic tests have been performed to evaluate the behaviour of different masonry panels. The main testing program included four in-plane tests: (i) the bare steel frame test; (ii) the test on the frame in-filled with the topologically interlocking SIM panel with the narrow gap between the frame and the top of the panel; (iii) the test on the frame in-filled with SIM panel without the gap between the frame and the top of the panel; and (iv) the repeated test on the bare frame to check its strength deterioration during the second test. The out-of-plane air bag test was performed on the SIM panel already damaged in the fourth in-plane test. Supplementary tests included free vibration tests on the bare steel frame and compressive tests on SIM wallets [11].

IN-PLANE TEST SETUP

The purpose built steel testing frame with SIM infill panel is shown in Figure 1. The frame was designed for multiple tests. It can be used for testing panels from 2470×2470 mm to 1570×1570 mm. The frame has elastic horizontal load capacity of 250 kN and the vertical load capacity of 200 kN. The frame was attached to the strong floor. The vertical load was applied by the hydraulic jack through the mid point of the spreader beam of the testing frame. The separate orange frame seen in Figure 1 was also attached to the strong floor and formed an enclosed reaction system. The horizontal load was applied by the INSTRON hydraulic actuator through the top corner of the frame. The actuator was attached to the strong wall.

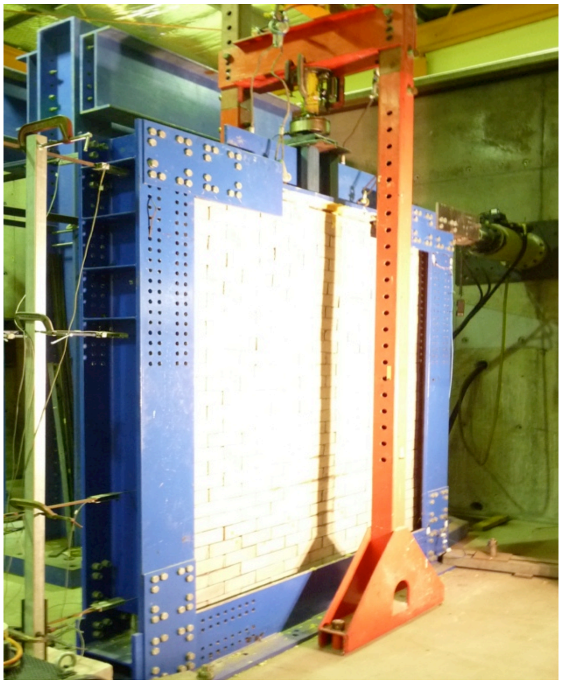


Figure 1: In-Plane Test Set Up

SIM PANEL DESCRIPTION

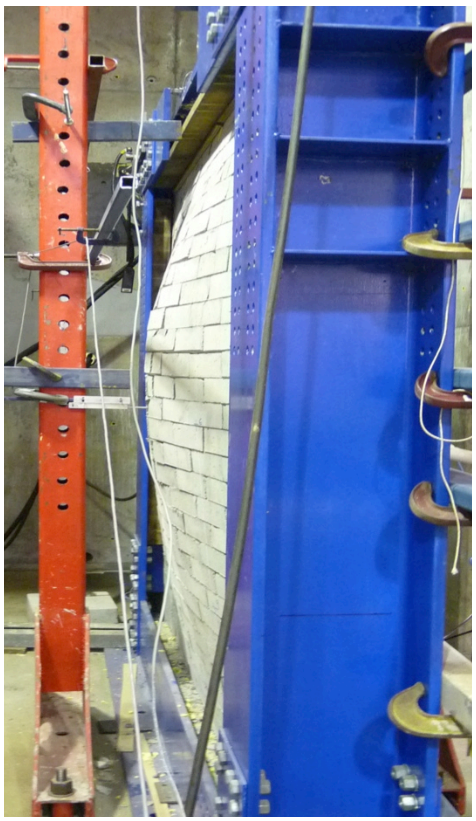
a) Topologically Interlocking SIM Bricks **b) Frame-Panel Connection**

Figure 2: SIM Panel Details

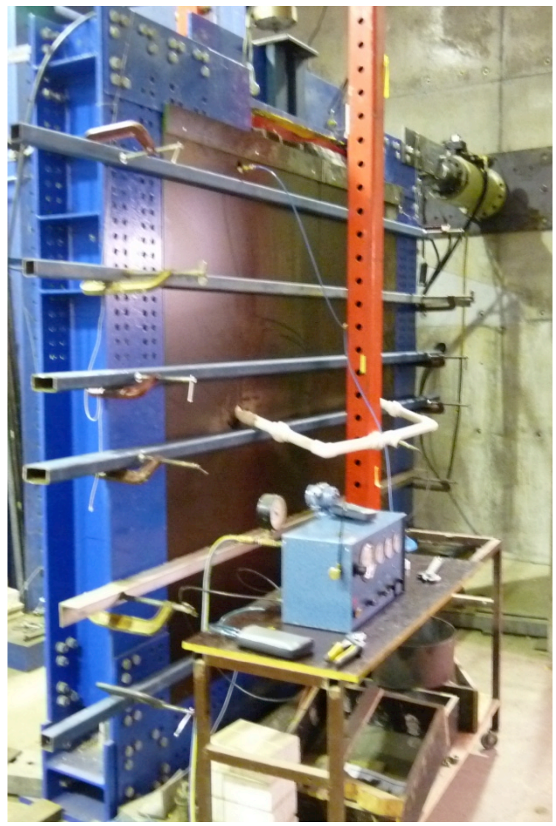
SIM infill panel was built of topologically interlocking bricks as shown in Figure 2a. The bricks used for the frame were 230×110×76 mm. The bricks compressive strength of 38.01 MPa was determined in supplementary compression tests. Units were arranged in the panel in dry stack running bond. The first and the last unit in each raw were flat cut and placed hard against steel columns for tight connection (see Figure 2b). The edges of the panel were completely restrained against out-of-plane displacement by timber packers between the panel and the frame on both sides.

OUT-OF-PLANE TEST SETUP

For out-of-plane tests the air bag was placed between the SIM panel and the rigid reaction plate attached to the frame (see Figure 3). The load was applied by increasing the air pressure in the air bag. The displacements were measured by potentiometers on the other side of the panel. There were no in-plane loads applied during this test.



a) Potentiometers Side



b) Air Bag Side

Figure 3: Out-of-Plane Test Set Up

TESTING PROCEDURE

Tests in this program were carried out in following sequence:

1) The in-plane cyclic displacement test on the bare steel frame (first bare frame test, for short);

2) The in-plane cyclic displacement test on the steel frame with SIM infill having the gap between the frame and the top edge of the panel (SIM infill with gap test);
3) The in-plane cyclic displacement test on the steel frame with SIM infill without the gap between the frame and the top edge of the panel (SIM infill without gap test);
4) The out-of-plane test on the steel frame with SIM infill (out-of-plane test);
5) The repeat in-plane cyclic displacement test on the bare steel frame (second bare frame test).

All in-plane tests were displacement controlled. Firstly, the vertical load of 80kN was applied through the spreader beam, which is integrated into the testing frame, in all in-plane tests except the SIM infill without gap test. In that test, a thin wood plate and dental plaster was placed between the panel and the top of the frame and the vertical load was increased to 100kN to completely close the gap. Then in all in-plane tests the frame was loaded according to the displacement history presented in Figure 4 and Table 1.

The out-of-plane test was pressure controlled.

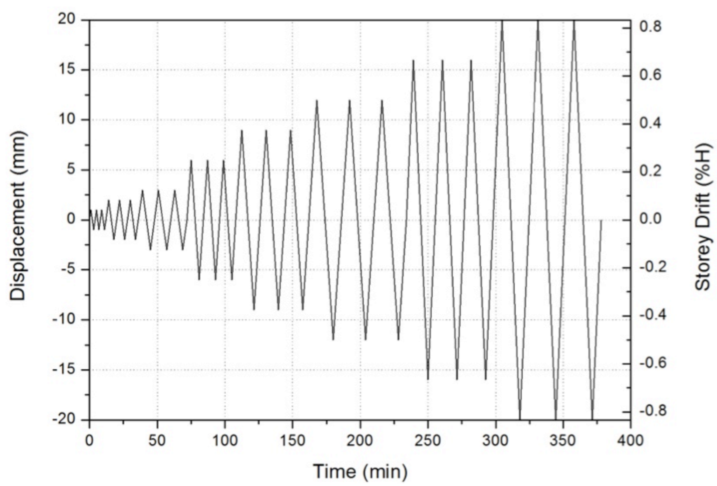


Figure 4. Applied Displacement History

Table 1: Displacement Parameters

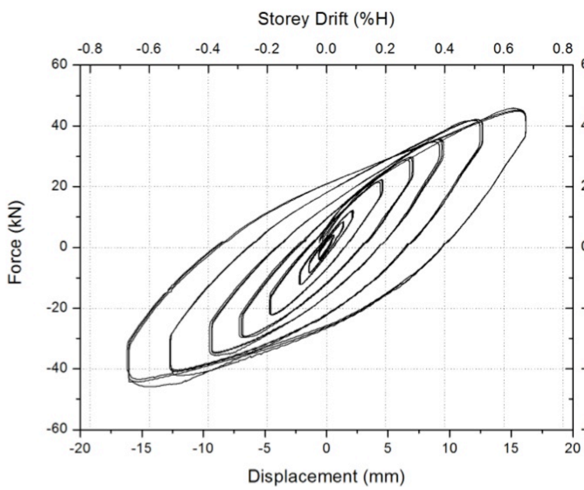
Travel Displacement (mm)	1	2	3	6	9	12	16	20
Travel Speed (mm/min)	1	1	1	2	2	2	3	3
Period (min)	4	8	12	12	18	24	21.3	26.7
Frequency (Hz)	0.0042	0.0021	0.0014	0.0014	0.0009	0.0007	0.0008	0.0006

The linear variable displacement transducers (LVDTs) were used to record the displacements of the frame. The testing frame was instrumented with several strain gauges to monitor the frame response and make sure that the frame remains elastic during testing.

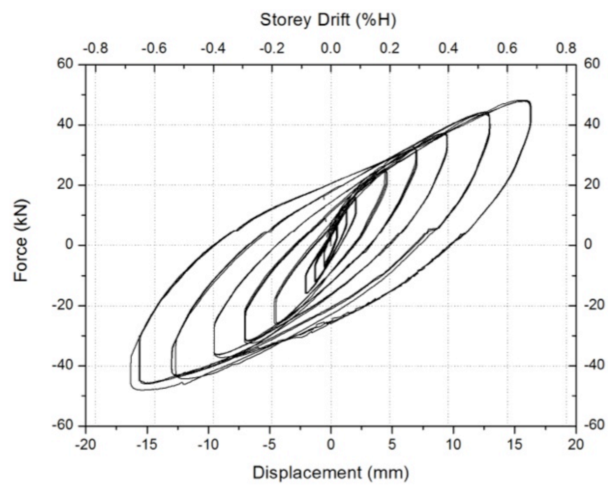
RESULTS AND DISCUSSION

The hysteretic force-displacement curves for all the in-plane tests are shown in Figure 5 and the comparison of the envelope curves is presented in Figure 6. The envelope curves from previous in-plane cyclic tests on RC frame with prototype SIM infill panel [8] are also shown in Figure 6 for comparison.

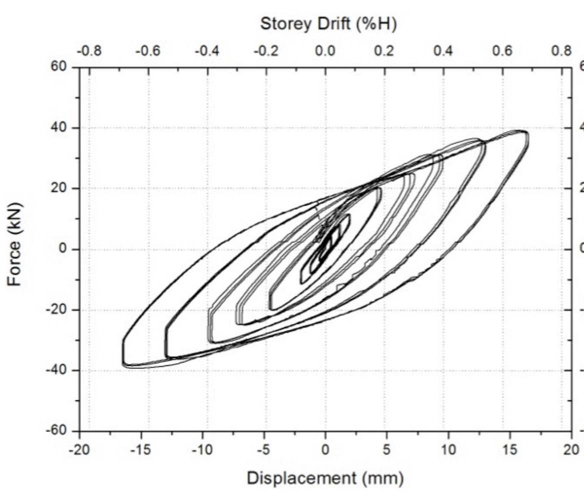
In the first bare frame test, the hysteretic curves (Figure 5a) were smooth. There was no noticeable difference in the stiffness degradation between the three cycles at all levels of displacement. This indicates that the testing frame does not suffer any damage during the cycling at these amplitudes.



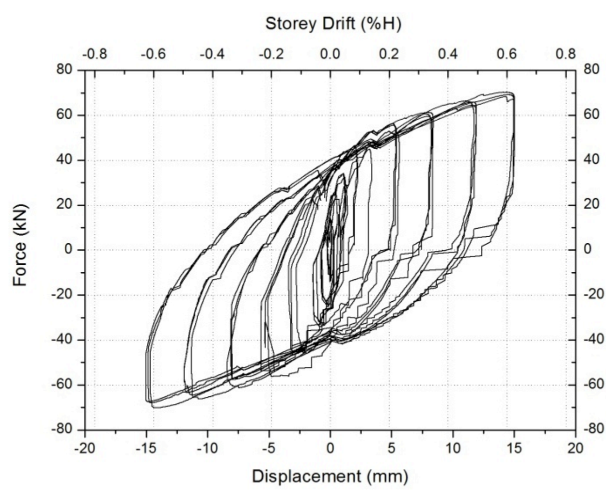
a) Fist Bare Frame Test



b) SIM Infill with the Gap Test



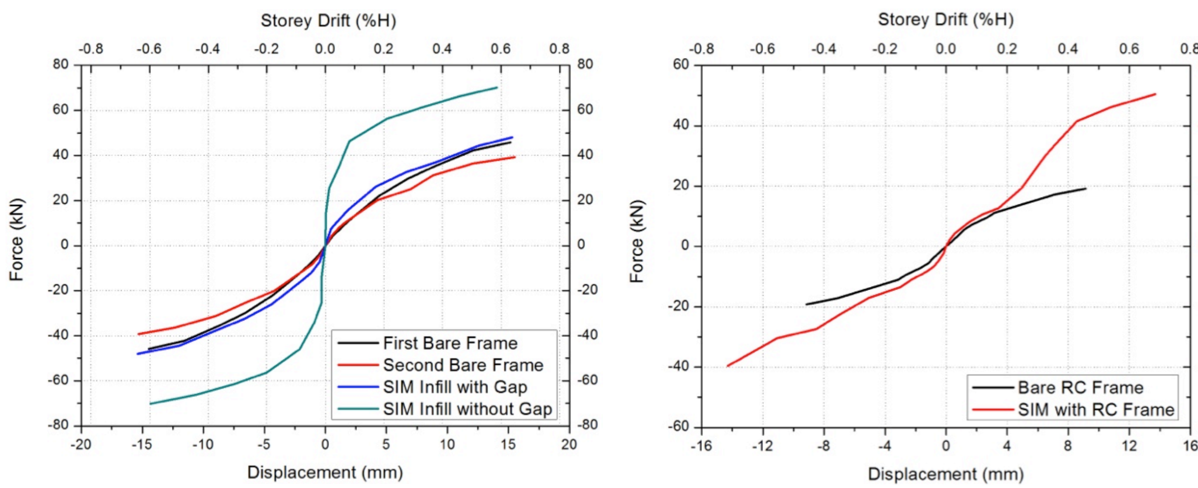
c) Second Bare Frame Test



d) SIM Infill without the Gap Test

Figure 5: Hysteretic Force-Displacement Curves

In the SIM infill test with the gap, the hysteretic curves (Figure 5b) appear to almost repeat those of the first bare frame test. This was not surprising. A similar effect was previously observed during the initial stage of tests on RC frame with SIM infill as can be seen in Figure 6b. As long as a gap exist between the frame and the SIM infill panel the compressive strut in the panel could not be formed. Interaction between the frame and the SIM infill is in the so called constant friction response stage. The frame is interacting with the SIM panel compressed by its own weight only. Frictional forces between bricks are therefore relatively small and constant. At this stage, the envelope response curve for the structure closely follows the response curve of the first bare frame test. The frame resists most of the horizontal force with the friction between bricks contributing approximately 2.23 kN to the strength of the structure. There was little difference in the stiffness degradation between the three cycles at the same level of displacement. This indicates that neither the testing frame nor the SIM panel suffer much damage during the cycling.



a) Steel Frame **b) RC Frame** [8]

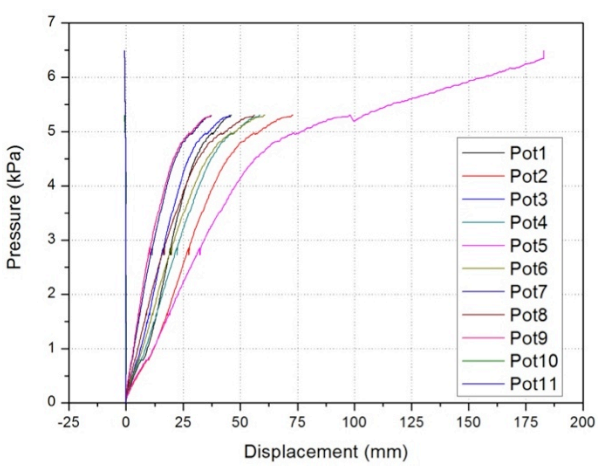
Figure 6: Envelope Response Curves

The SIM infill test without the gap has considerably different hysteretic response curves (Figure 5d) compared to the first two tests. Frame-panel interaction is very pronounced. It is typical of Mohr-Coulomb response mechanism. The frame during this test is in contact with the top of the panel. This has two significant effects: (i) the friction between bricks is increasing due to increasing compression of the panel by the frame and (ii) a type of compressive strut is formed within panel. Compared with the test without gap, the stiffness of the structure has increased considerably during cycling at small amplitudes (up to about 0.1% storey drift). Then after some damage to the SIM panel, the stiffness has reduced to about the same as in previous two tests. During cycling at larger amplitudes (above 0.1% storey drift), the SIM panel contributes about 35% to the strength of the structure. It can be seen from Table 2, that the SIM panel without the gap also contributes about 52% to the energy dissipation in this structure. Some minor cracking of bricks was observed during cycling above 0.2% storey drift.

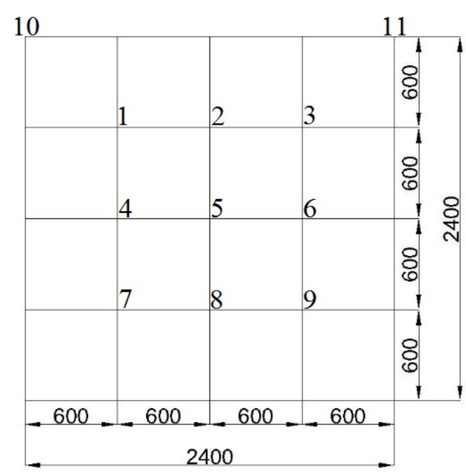
The results of the out-of-plane test on the SIM infill panel (next in testing sequence) are presented in form of the pressure-displacement curves in Figure 7. Surprisingly, the SIM panel already damaged in previous tests proved to be quite resilient for out-of-plane load. The displacement of the mid point (Pot.5) of this confined SIM 2.4x2.4 m panel reached more than 180 mm (more than 1.5 time the thickness of the wall) when test was stopped to avoid sudden collapse of the panel. However, it took considerable effort hammering panel from the "compression" side to break it after the test. The assumption of approaching the out-of-plane displacement capacity of the panel appears to be too conservative. The out-of-plane displacement response of the SIM panel in Figure 7 could be described as bi-linear. In the first linear stage (up to about 55mm or half of the wall thickness) no new damage to the panel was observed in addition to that sustained during previous in-plane tests. It is assumed that at this stage the work of external load is balanced by the work done by compressive forces in the panel induced by arching between supports. Then several new vertical cracks opened in the middle of bricks in the central part of the panel as shown in Figure 8. It appears that this damage indicated the formation of a mechanism where torsional forces do work over the relative rotation of SIM units.

Table 2: Energy Dissipation

Travel (mm)	E_D of bare frame in the first test (kN·mm)			E_D of structure in the SIM without gap test (kN·mm)			E_D contribution of SIM Only (kN·mm)		
	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3
1	2.59	2.87	2.86	8.59	7.18	5.04	6.00	4.31	2.18
2	10.74	10.38	10.40	45.73	39.11	35.27	34.99	28.73	24.87
3	23.35	22.89	22.86	89.62	96.10	90.88	66.27	73.21	68.02
6	101.08	100.50	98.95	310.94	259.68	260.06	209.86	159.18	161.11
9	228.16	234.39	232.45	635.77	610.38	608.15	407.61	375.99	375.70
12	418.39	430.49	427.27	1089.41	1013.78	986.18	671.02	583.29	558.91
16	749.98	783.70	773.99	1569.71	1549.90	1486.57	819.73	766.2	712.58
20	1134.35	1174.11	1152.83	2052.87	2026.05	1997.79	918.52	851.94	844.96
Total	8149.58			16874.76			8725.18		

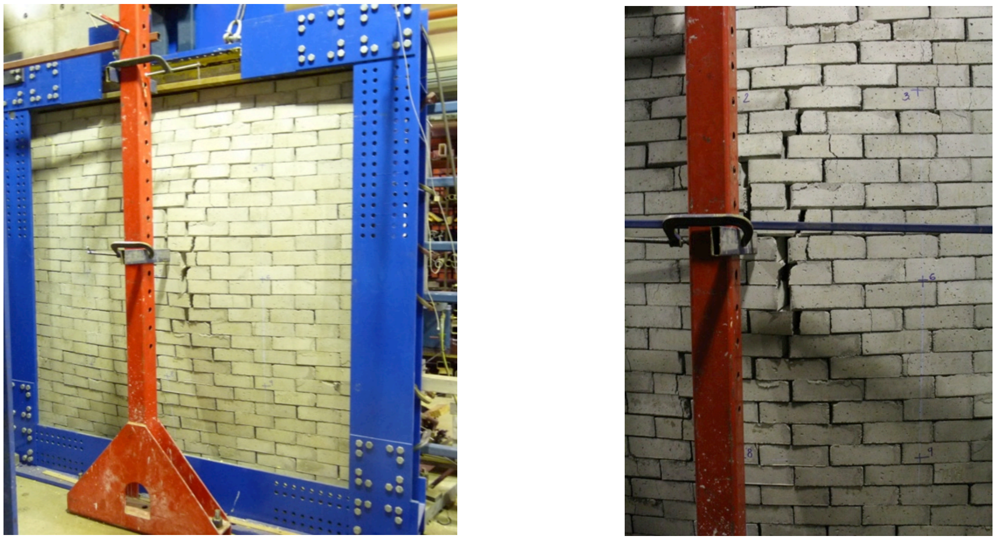


a) Out-of-Plane Displacements of SIM Panel



b) Layout of Potentiometers

Figure 7: Out-of-Plane Results



a) Crack Pattern **b) Cracks in the Centre of the Panel**

Figure 8: Out-of-Plane Damage

The last test in the program was the repeat of the in-plane bare frame test (Figure 5c). It was performed to check how well this universal testing frame maintains its strength and stiffness during tests. It was found that the hysteretic curves are very similar to the first bare frame test. It was noticed that the frame maintained the strength and stiffness up to about 0.2% storey drift. However, the frame had lost some stiffness at that level of drift resulting in about 6.6 kN loss of strength. Because there was no steel yielding in the frame, it was assumed that this happened because of slipping in some bolted connections.

COMPARISON TO PREVIOUS IN-PLANE TESTS

The RC frame with the prototype SIM panel was tested in-plane previously [8]. Those results are shown in Figure 6b. Comparison of the envelope curves indicates that response mechanisms of SIM are essentially the same in both studies.

It is obvious that a gap between the top of the SIM infill panel and the frame plays a key role in the response of this dual system. Before this gap is closed only the constant friction response mechanism could be formed in the panel. In this stage panel contributes very little to the strength and the stiffness of the system. Its contribution is mainly to the damping. When the frame and the SIM panel are in contact the response mechanism is of Mohr-Coulomb type. Increased compression on bead joints results in higher friction forces and panel contribution to the strength, stiffness and dumping becomes much greater. In our tests 2.4x2.4 m SIM panel contributed about 24 kN to the strength of the structure. It amounts about 42% of the RC frame assembly strength and about 35% of the stronger steel frame assembly. Panel contribution to the system energy dissipation was also significant: about 78% with RC frame and about 52% with steel frame.

In RC frame tests, the gap was small and there was a clear transition from the constant friction response mechanism to the Mohr-Coulomb response mechanism. In steel frame tests, there were two separate tests (with and without the gap) with two very different results each representing a clear case for the corresponding response mechanism.

CONCLUSIONS

Results of this experimental study can be summarised in following conclusions:

- A universal steel testing frame was developed for multiple tests on masonry panels from 1570×1570 mm to 2470×2470 mm and up to 277 mm thick. It performed well through the tests. However, it was found that bolted connections should be tightened for future tests;
- In order to evaluate the structural potential and the cyclic behaviour of the topologically interlocking SIM infill panels, a series of in-plane and out-of-plane tests was performed;
- The force-displacement behaviour of the structure, its stiffness degradation, energy dissipation, and the response mechanisms have been studied and compared to the behaviour of the bare frame and to the previous tests on the RC frame;
- The out-of-plane displacement capacity of the confined square SIM panel was found to be more than 1.5 times the thickness of the masonry panel;
- Two distinct linear stages of the out-of-plane response have been identified. We are assuming that the first stage is governed by compressive forces in the SIM panel due to arching between supports and the second stage by torsional forces between SIM units on the bead joints;
- It was confirmed that gap between the frame and the panel had significant influence on the composite response of the structure. Practically, it is difficult not to have the gap between the top of the panel and the frame during infill panel construction. Therefore, the constant friction mechanism should be considered typical for infill SIM panels. On the other hand, construction of confined masonry panel ensures perfect frame-panel contact. This triggers Mohr-Coulomb response mechanism with greater SIM panel contribution to the strength, stiffness, and energy dissipation of the structure.

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