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IN-PLANE CYCLIC BEHAVIOR OF SEMI INTERLOCKING MASONRY PANEL UNDER LARGE DRIFT

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ABSTRACT
An innovative masonry building system is being developed in the Centre for Infrastructure Performance and Reliability at The University of Newcastle, Australia. It consists of mortar-less masonry infill panels made of semi-interlocking masonry (SIM) units capable of relative sliding in-plane of a panel and interlocked to prevent sliding out-of-plane of a panel. This new system attempts to improve the earthquake performance of the framed structure by increasing the displacement ductility and the energy dissipation capacity of infill panels. A special steel testing frame with the pin connections was built to test SIM panels. The arrangement with pin connection allows application of storey drift up to 6%. Digital Image Correlation (DIC) technique is used to record the displacement behavior of the masonry panel. This paper presents the results of an experimental testing programme on SIM panels subject to cyclic in-plane lateral displacement. The primary aim of this experimental program is to obtain force-displacement relationships for SIM panel and to understand structural as well as the mechanical failure mode of the system.

KEYWORDS: *DIC, failure mode, in-plane cyclic test, semi-interlocking masonry*

INTRODUCTION
Masonry is an extremely useful construction material that has been used for thousands of years and is continually undergoing refinements to achieve better structural performance, serviceability, and affordability. It is a complex system consisting of an assemblage of solid or hollow blocks, mortar or mortar-less joints, grout and reinforced bars each with different material properties. Its behaviour is made more complex by mortar joints acting as planes of weakness due to their low tensile and shear bond strength in conventional masonry. This leads to failure and often disastrous

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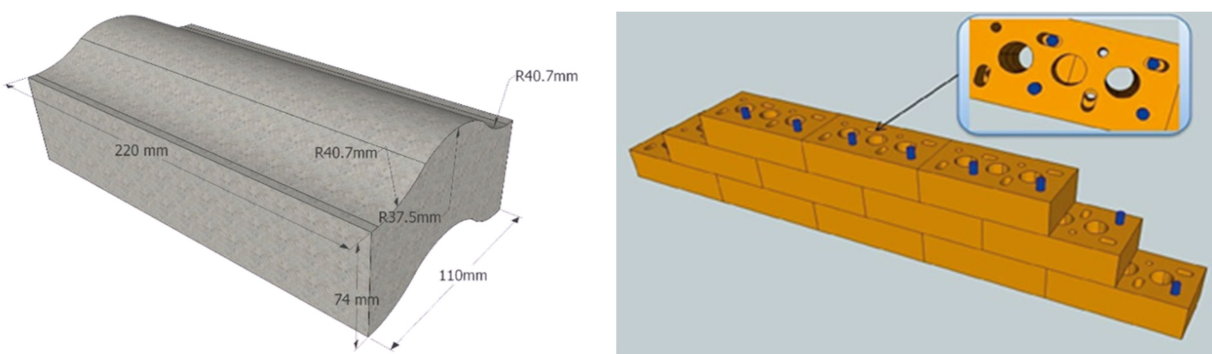
effects, including loss of life and irreparable damage to buildings. Figure 1 shows the typical damage after different earthquakes.

Figure 1: Typical Damage to Masonry Infill Panels due to Earthquake Actions

In order to prevent such catastrophic failure, Dr. Yuri Totoev invented Semi Interlocking Masonry (SIM) in 2010 [1]. In this system, units in masonry infill panels (SIM panels) are capable of relative sliding in-plane of a panel and interlocked to prevent relative sliding out-of-plane of a panel;. The SIM panels are considered as “non-gravity-load-bearing” structural elements and possess higher displacement ductility and energy dissipation to resist the lateral loads compared with traditional masonry panel [2]. It improves the earthquake resistance of the panel under lateral loading by dissipating the energy through the friction between each unit and its adjacent unit [3]. There are two types of SIM—Topological SIM and Mechanical SIM (Figure 2). Topological SIM uses the natural contours of the bricks itself to allow the relative sliding in-plane of the bricks, whilst the mechanical SIM uses dowels and slots in order to allow the in-plane sliding of the bricks.



a) Topological SIM b) Mechanical SIM

Figure 2: Types of Semi-Interlocking Masonry (SIM)

Previous investigation on SIM includes in-plane cyclic tests on a reinforced concrete (RC) frame with a SIM infill panel [3-8] and with a steel frame with a SIM infill panel [9-11], out-of- plane airbag tests on a SIM panel [9], and other supplementary tests [3, 4, 8, 10, 12]. The effect of filling the gap between the units was also studied. Totoev *et al.* [13] investigated the water penetration and thermal insulation performance of SIM panels in terms of different gap fillers e.g. linseed oil based putty, tape etc. They concluded that the panel constructed with putty exhibits better performance in terms of thermal insulation and water penetration of the panel. A larger research project based on Mechanical and Topological SIM units has been started recently at the University of Newcastle, Australia. The main points of distinction of this research project are to develop a testing setup of a SIM panel with minimal effect of the frame, to construct the SIM panel not dry stack, but with gap filler, to investigate the mechanical as well as structural failure mechanism at large level of storey drift (up to 5%), and to observe the effect of filling the gap in-between the steel frame and panel at the top of the panel.

EXPERIMENTAL PROGRAM

Hossain *et al. [14]* investigated the variation of coefficient of friction of topological SIM units with different gap fillers. The surfaces with putty possess a better coefficient of friction compared to other tested surfaces. Based on the results, the panels were constructed using the putty as a gap filler in-between the bricks in this study. In this paper, the results obtained only from topologically interlocking SIM units are presented. Other test results will be published elsewhere. The topologically interlocking SIM unit is made of concrete and therefore has high compressive strength but significantly low tensile strength. The mean compressive strength was found to be 33.75 MPa (CV = 12%) and the density is 2350 kg/m^3 [14].

Test Setup

The steel frame used in this research (Figure 3) is made of 310UC137 [15] sections. The details of the frame can be found in [11, 16]. The assembled steel frame was bolted to existing fixing points in the strong floor. The lateral hydraulic jack cylinder body was mounted on the strong wall and attached to the frame attachment plate using a single pivot pin. Four pin supports were introduced at the four corners of the frame which make the frame act as mechanism so that the applied cyclic load can be transferred directly to the masonry panel. This allows the masonry panel to move larger displacement (story drift). The pin-jointed frame allows the applied jack force to be transferred completely through the masonry without any significant loss due to the frame stiffness. Instrumentation for the cyclic load testing comprised ten linear variable differential transformers (LVDTs) and four electrical strain gauges were fitted to the steel frame as shown in Figure 3. LVDT1 to LVDT7 and LVDT8 to LVDT9 were used to record the shear displacement at various places and diagonal displacement respectively. The results from LVDT7 were used to determine the drift of the panel and represents the displacement of the panel. LVDT10 was also placed on the right side pin joints to monitor the out-of-plane movement of the panel. Strain gauges were used and monitored regularly during the test to ensure that there is no plastic damage to the steel frame. Nine targets were also placed on the backside of the panels along with a secondary camera in order to determine the relative movements of the SIM layers (Figure 5). All transducers were wired to a Data logger connected to a computer. The steel frame was then subjected to a lateral load-displacement history in cyclic form. A summary of the tested panel geometries is presented in Figure 3.

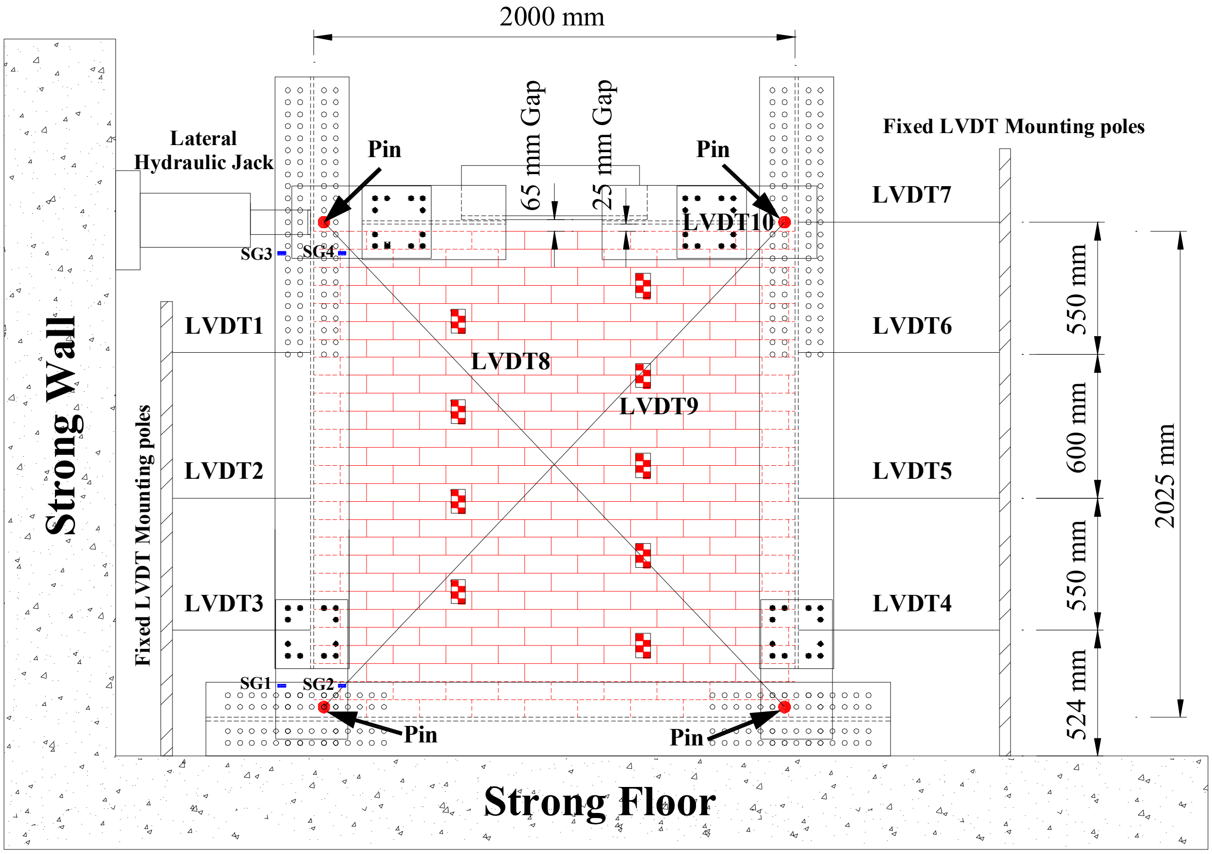


Figure 3: Experimental Set Up for In-Plane Cyclic Testing of SIM Panels

After construction of the SIM panels in the steel frame, there is a gap of approximately 25mm at each top corners and about 65mm gap in the middle of the panel as shown in Figure 3. In Panel 1, the gap remained open during testing, but in Panel 2 and Panel 3, the gap was filled by foam and grout respectively as shown in Figure 4.

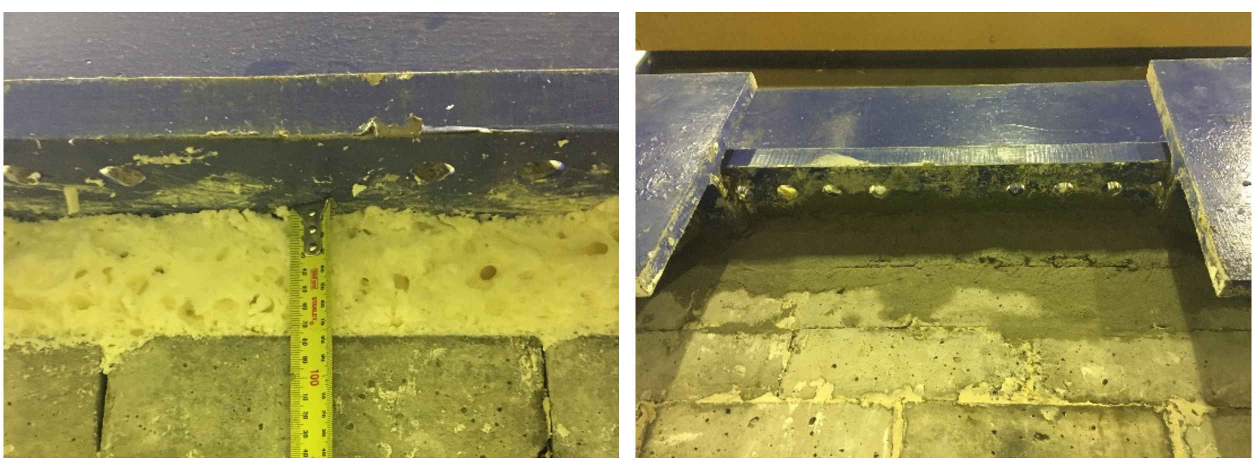
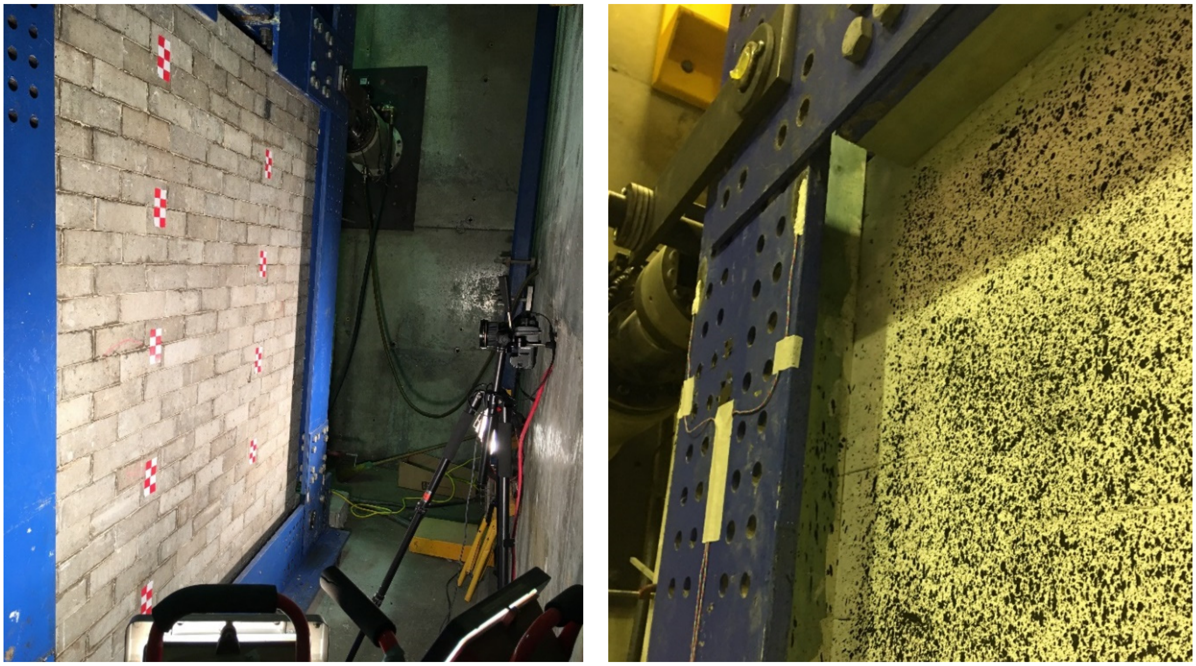


Figure 4: Placement of Foam (left) and Grout (right)

Figure 5(a) depicts the location of targets with the secondary camera at the back side of the panel. 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 Figure 5(b).



a) Targets on the Back Side of the Panel b) Placement of Timber Packers

Figure 5: Position of Targets and Timber Packers

The Bare Frame Mechanism is shown in Figure 6. The specified speckle pattern (Figure 6) was applied on the panel so that Digital Image Correlation (DIC) technique can be applied to measure the displacement pattern of the panel. For DIC analysis, High Definition (HD) camera was used to take photographs of the panel at the interval of 10 seconds. These photos are used as an input in DIC analysis software to determine the displacement and strain parameters of the panel.

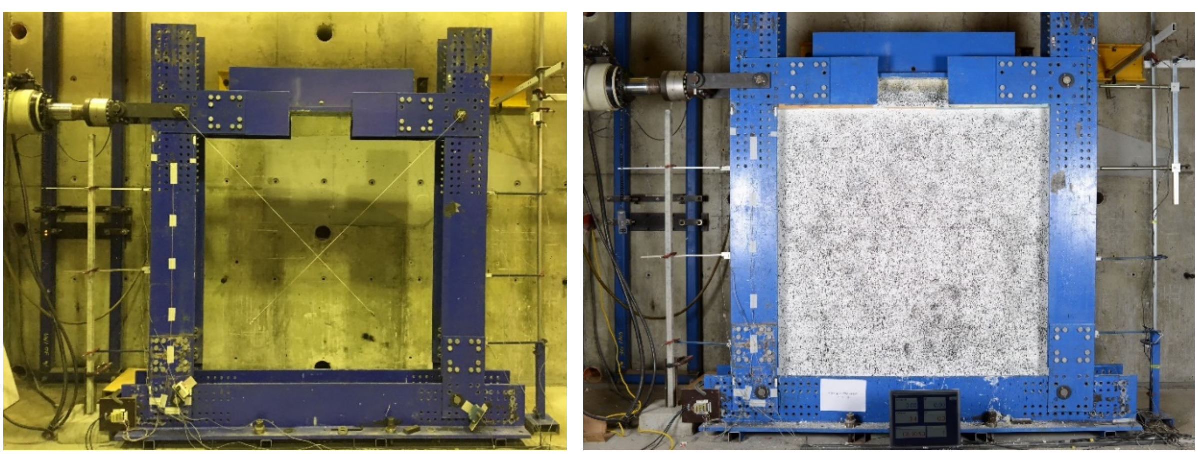


Figure 6: Photograph of Experimental Setup: Bare Frame Mechanism (left) and Frame Mechanism with Panel Showing Speckle Pattern Applied for DIC (right)

Test Procedure

This paper reports a part of the on-going experimental program on steel frames with SIM panel using in-plane cyclic 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 SIM panels. The main testing program presented in this study included four in-plane tests: (i) the bare steel frame test as shown in Figure 6 (ii) the test on the frame in-filled with the topologically interlocking SIM panel with open gap (Panel 1) (Figure 6) between the frame and the top of the panel (iii) the test on the frame in-filled with the topologically interlocking SIM panel with low compressive strength foam (Panel 2) in the gap (Figure 4) between the frame and the top of the panel. This foam is a self-expanding polyurethane foam filler that expands to 2.5 times the initially dispensed foam after being sprayed which allows a complete seal to form around all shape. (iv) the test on the frame in-filled with the topologically interlocking SIM panel with grout (Panel 3) in the gap (Figure 4) between the frame and the top of the panel. This grout is a mixture of cement and sand (Cement: Sand =1:6). The grout was allowed to cure for 28 days before testing. The mean compressive strength after 28 days of the grout was 15.40 MPa (CV = 3.44%).

Applied Displacement History

Cyclic lateral displacements were applied at the pin support of the steel frame by a hydraulic jack. The cyclic lateral displacements consisted of a pull cycle (Frame goes leftward-negative) and a push cycle (Frame goes rightward- positive). The cyclic lateral displacement was applied in computer controlled displacement steps. Each displacement was repeated three times in the cyclic form and the results of the LVDTs, visual crack of the panel and strain gauges were monitored carefully. The loading speeds were changing over the displacement but the cycle period was kept 800 sec for all the target displacement except for 1 mm displacement. The induced horizontal force and displacement measured by LVDT7 were recorded and represents the controlled displacement. The story drift was calculated by dividing the measured displacement at LVDT7 by the story height of 2 m. Table 2 shows the amplitudes, the average loading speed, and the duration of each cycle. Using this procedure, the test duration varied from 450 to 500 min. The adopted lateral displacement of this testing is presented in Table 1.

Table 1: Displacement Amplitude

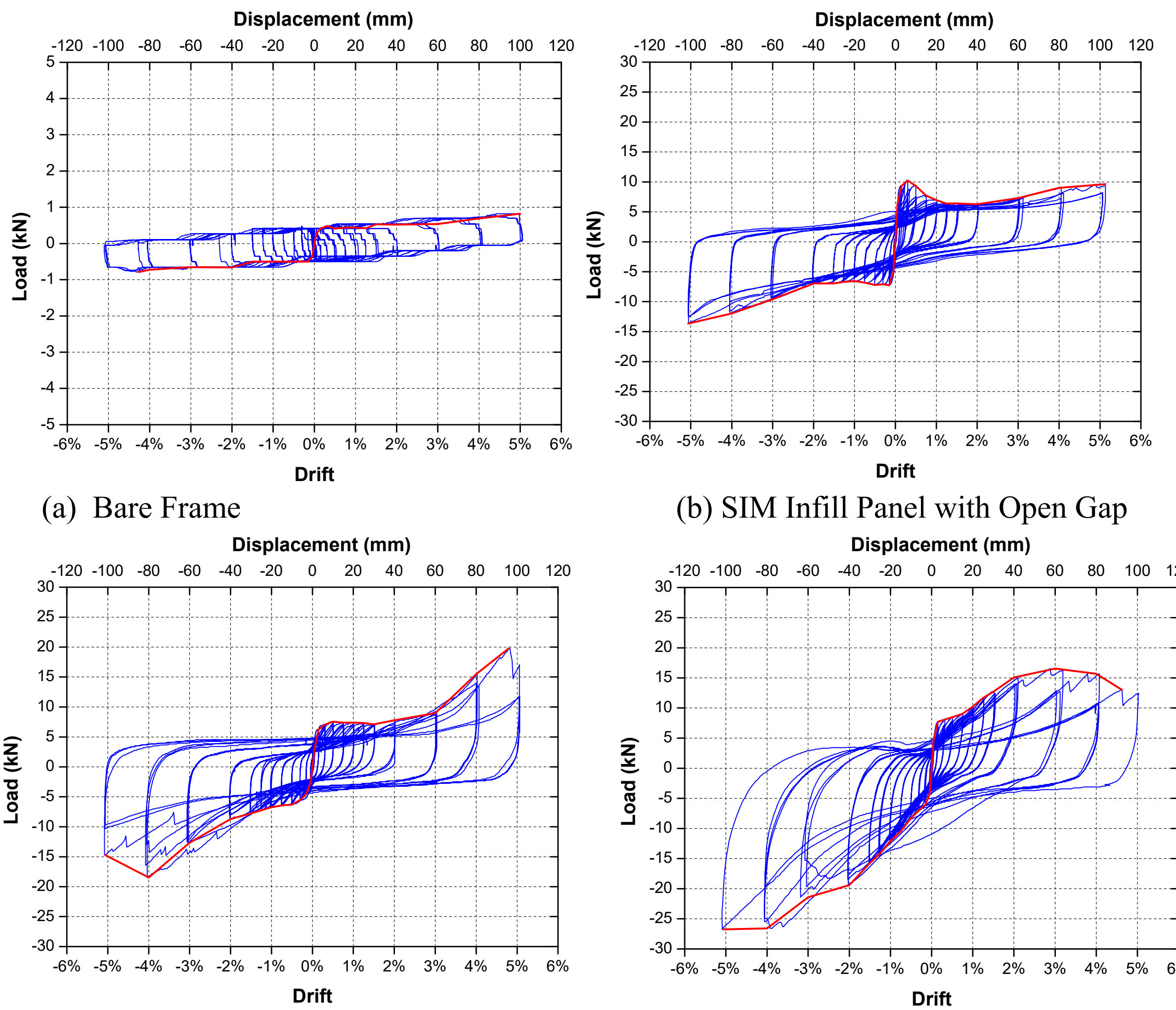
Drift (%)	Displacement (mm)	Loading Speed (mm/sec)	Period (sec)		Drift (%)	Displacement (mm)	Loading Speed (mm/sec)	Period (sec)
0.01	1	0.01	400		1.25	25	0.125	800
0.015	3	0.015	800		1.5	30	0.15	800
0.3	6	0.03	800		2.0	40	0.2	800
0.5	10	0.05	800		3.0	60	0.3	800
0.75	15	0.075	800		4.0	80	0.4	800
1.0	20	0.1	800		5.0	100	0.5	800

RESULTS AND DISCUSSION

The primary function of the SIM unit as a structural element is to dissipate energy when a lateral load is applied to it. The bed joint sliding that is utilized by the SIM panel to absorb this load classifies it as a mechanism. Three panels were constructed and tested along with steel frame in this study. The pin jointed steel frame allows the panel to undergo large drift.

Hysteretic Behaviour

Since SIM primarily depends on friction as a means of energy dissipation during a seismic event, it is important to develop an understanding of the load-displacement behavior during the testing. Figure 7 illustrates the load–displacement diagrams from all the tests, as well as associated envelope curves of the 1st cycle at each displacement increment. Note that the vertical axis scaling in this figure is not same for all graphs. 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) Bare Frame

(b) SIM Infill Panel with Open Gap

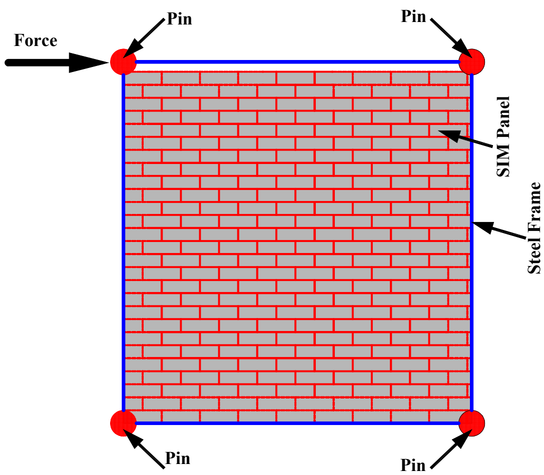
(c) SIM Infill Panel with Foam in the Gap

(d) SIM Infill panel with Grout in the Gap

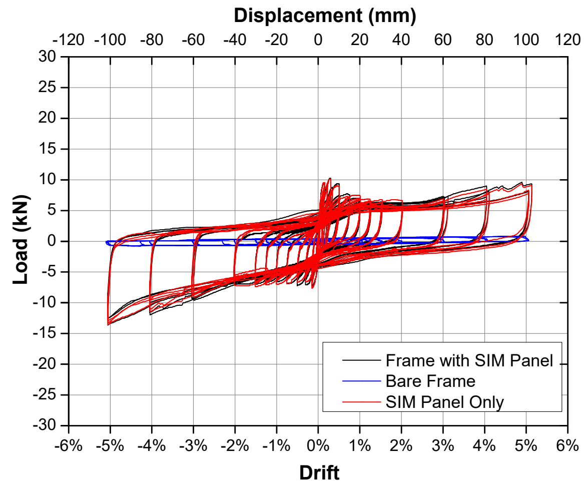
Figure 7: Force–Displacement Response Hysteresis of the Tested Panels

Energy dissipation

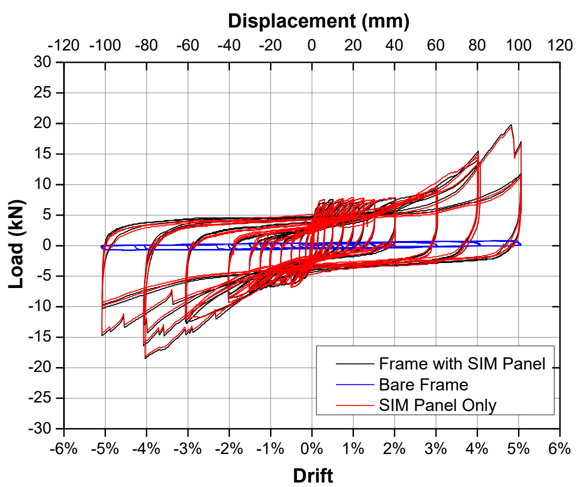
Since SIM primarily depends on friction as a means of energy dissipation during a seismic event, it is important to determine the contribution of SIM panel itself when it is tested with frame mechanism. To assess the contribution of SIM panels to the overall structural response the difference between the response of the bare frames and the SIM infilled frames were studied. It can be seen from Figure 8 that the contribution of the bare frame in terms of energy dissipation (represented by the area under the hysteresis loop shown on the graphs) is insignificant compared to SIM panels. This happens because of the introduction of the pin supports in the steel frame.



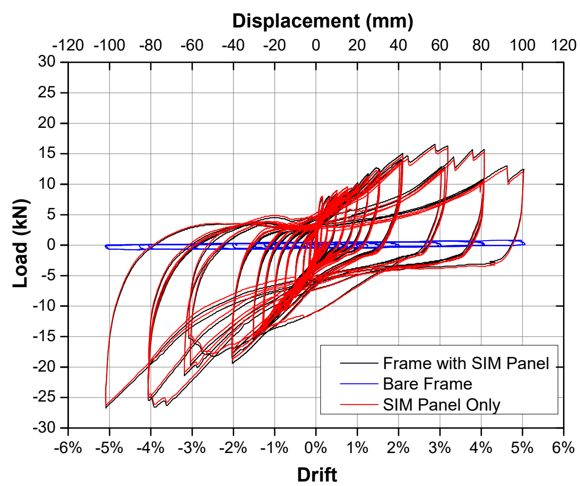
a) Mechanism of SIM Panel with Frame



b) SIM Infill Panel with Open Gap



c) SIM Infill Panel with Foam in the Gap



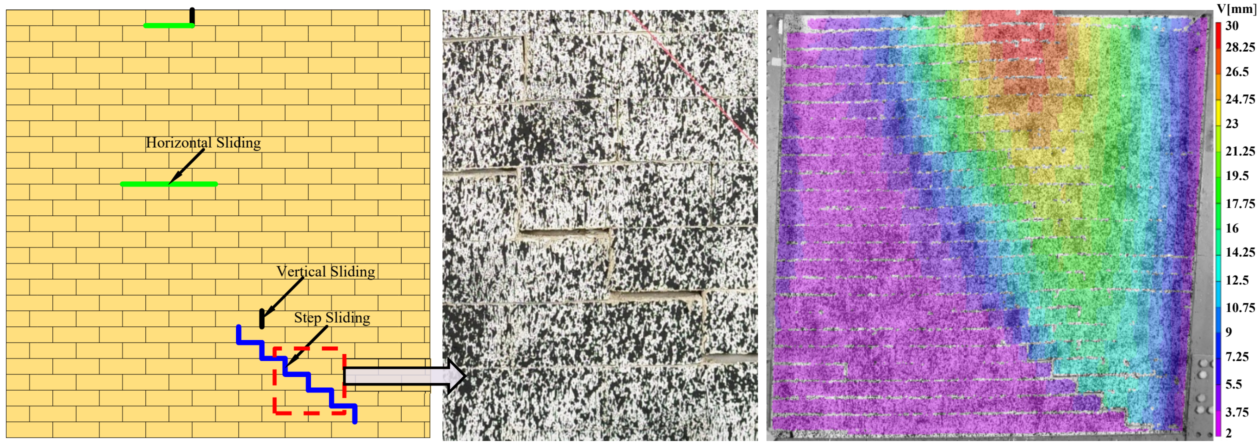
d) SIM Infill panel with Grout in the Gap

Figure 8: Overall Structural Response of the SIM panels

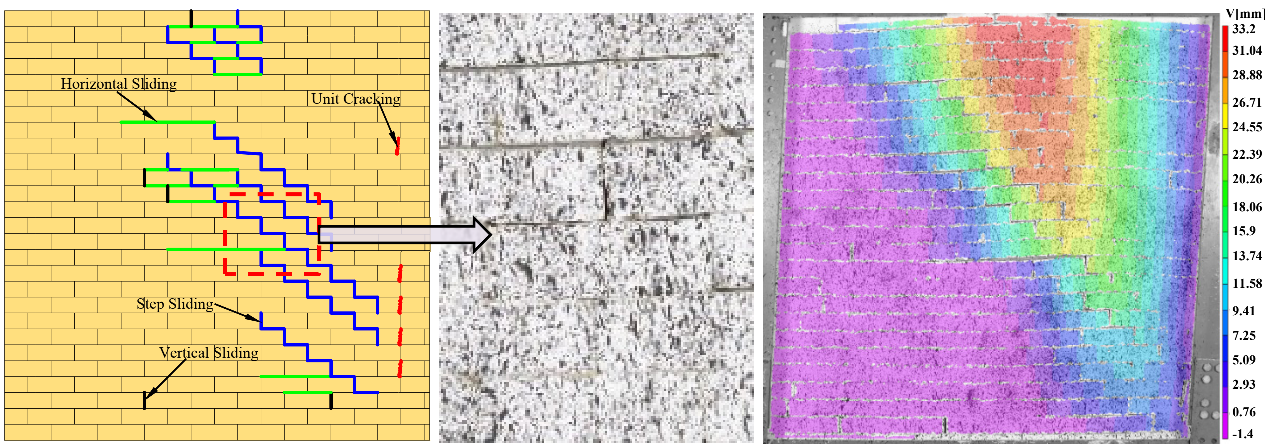
Furthermore, the energy dissipation capacity of different Panels can be seen in Figure 8. It is observed that material placed in the gap in-between the steel frame and SIM panel had a considerable impact on the energy dissipation behavior of the SIM panels. The SIM panel with grout in the gap exhibits better dissipation of energy compared to SIM panel with foam in the gap. This is because the grout is much stiffer (resists more load) than foam.

Crack pattern at 100 mm push cycle

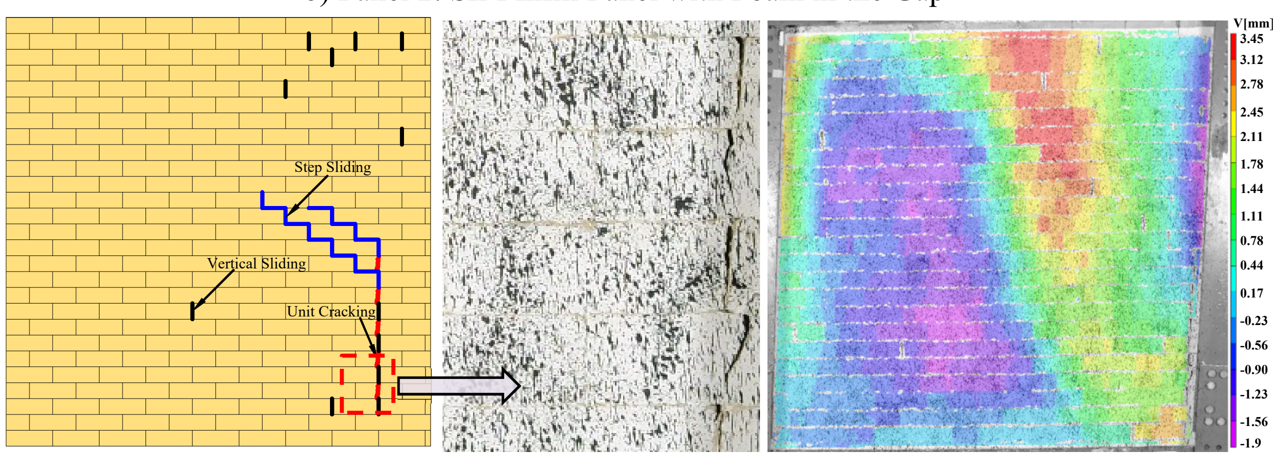
Figure 9 illustrates the crack pattern for 100mm (push cycle) displacement of the three panels. The crack pattern is also mapped by plotting the vertical displacement output from the 2D Digital Image Correlation analysis (right-side image). The maximum vertical displacement of the Panel 1, Panel 2 and Panel 3 are 30mm, 33.2mm, and 3.5mm respectively.



a) Panel 1: SIM Infill Panel with Open Gap



b) Panel 2: SIM Infill Panel with Foam in the Gap



c) Panel 3: SIM Infill Panel with Grout in the Gap

Figure 9: Displacement and Cracks in the panels

From Figure 9, it can be concluded that the crack propagation and modes of failure of the SIM panels were somewhat affected by the gap in-between the steel frame and SIM panel, though all of the panels were predominantly displaced by step sliding. Large drift capacity and energy dissipation are achieved due to the step sliding. All the tested panels showed horizontal sliding first along the head and bed mortar joints at the first loading stage (at drift about 2%), regardless of the presence of foam and grout in the gap. No visual SIM unit cracking appeared in Panel 1, but in Panel 2 and Panel 3, the occurrence of the unit cracking was induced due to a rocking of the SIM panels. It is also noted that the gap in-between the steel frame and panel has an effect on the vertical movement of the panel which is obvious. The vertical displacement of the panel with grout exhibits very low value compared to the panel with open gap and panel with foam. This occurs due to the availability of the space in the gap. For panel with foam, when the load is applied, the foam compressed but in the panel with grout, there is not enough room to displace the panel vertically.

CONCLUSIONS

An investigation on the behaviour of SIM panels subjected to cyclic lateral displacement is underway in the Centre for Infrastructure Performance and Reliability at The University of Newcastle, Australia. As explained before, the aim of this testing is to observe the failure mechanism of the SIM infill panel and to test whether the infill panel can remain structurally sound both during and following an earthquake event. Based on the present study, the following conclusions may be drawn:

- The new testing set up minimizes the influence of the frame in terms of load –displacement behavior due to the introduction of the pins. This frame has a much lower force resistance than a rigid steel frame.
- Type of the gap filler has the potential to change the load bearing response as well as failure mechanism of the SIM panel. The maximum vertical displacement of the SIM panel with grout (stiff filler) is quite small compared to SIM panel with foam (soft filler).
- The SIM Panel with grout in between the steel frame and the top of SIM panel exhibits better performance in terms of energy dissipation compared to other tested SIM panels.

Major issues deserving further research include tests on Mechanical SIM units that could be used to extend the presented findings and to gain additional insight into the behaviour of SIM panels with linseed oil based putty as a gap filler. Further, a subsequent theoretical investigation to determine the mechanical model for SIM panels with gap filler is envisaged. Finally, the numerical modelling, and analysis of seismic response of buildings with such panels as well as the development of design recommendations for SIM panel deserve attention.

ACKNOWLEDGEMENTS

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