In-Plane Cyclic Testing of Non-Structural Drywalls Infilled Within RC Frames

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SUMMARY:
'Non-structural' infill walls can be defined as walls not contributing to the lateral load resistance of frame/dual structures. These walls can be constructed of both light and heavy materials. Drywalls can be given as an example of the light materials option. Unreinforced clay bricks and reinforced hollow masonry can be given as examples of heavy materials option unless they are designed to be integrated part of the structural system. Although these various wall types are assumed to be non-structural, observations made after recent earthquakes have repeatedly shown that they are easily susceptible to damage and do interact with the structural system, not necessarily improving the overall seismic performance. A research program has been initiated and currently on-going at University of Canterbury to investigate the susceptibility of these various wall types to lateral displacement reversals and develop methods to prevent/limit the damage in future practice. In this paper, the recent results of experimental quasi-static cyclic tests on light steel and timber framed drywalls within a reinforced concrete PRESSS frame are reported.

Keywords: Infill wall, non structural, drywall, partition, cyclic behaviour

1. INTRODUCTION

Early studies on non-structural infill walls focused mainly on unreinforced clay or masonry bricks used as infill material and on their structural representation for design (Smith 1967, Liauw 1972-1973). For many years, it has been recognized that infill walls can on one hand increase the initial lateral stiffness and strength of the structure, but on the other hand they can turn the structural response of a ductile design into a brittle or shear dominated behaviour. However, their contribution has been often neglected in the design phase with the assumption that their contribution is mainly positive and it would be on the conservative side. As it has been clearly defined by Park, Paulay (1975) and again by Paulay, Priestley (1992), ductility is a structure's ability to sustain its strength with increasing displacements after yielding and any brittle modification to this behaviour is unacceptable from seismic design perspective even if it causes an increase in strength.

Due to these facts and the evident brittle behaviour of unreinforced brick infill walls in that context, over the years, different practices have been adopted for infill walls. Among these practices, gypsum lined drywalls have been a common application, very popular for example both in New Zealand and in the US. These walls are usually formed by attaching gypsum linings to an underlying light framing. This light framing can either consist of light gauge steel or timber. The framing is usually bounded by the structural frame in RC/steel structures (Figure 1a) and in some cases by the upper and lower floor slabs.

Although these infill walls are not expected to be as strong as their unreinforced masonry counterparts, they have a degree of interaction with their surrounding structural framing. This can clearly be observed after earthquakes. For example, during and repeatedly after the Christchurch earthquake on 04 September 2010, most buildings did not collapse, but almost all of them suffered damage to their non-structural contents especially drywalls and ceilings (Figure 1b, 1c). Moreover, there were cases where drywalls were replaced completely after each significant aftershock occurred as part of the sequence of earthquakes (04 September 2010, 22 February 2011, and 13 June 2011).

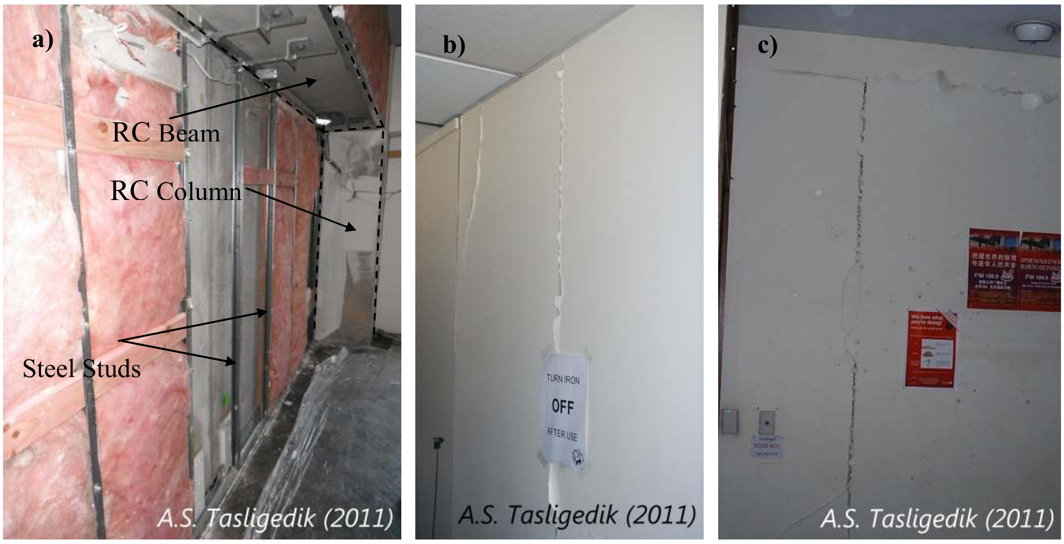


Figure 1. a) Drywall framing bounded by RC structural frame, b)-c) Observed damage at drywalls after February 2011 earthquake in Christchurch, New Zealand

Moreover, the costs associated with the non-structural elements are usually higher than those of structural elements (Glogau 1975). Although there are researches focusing on non-structural elements, usually in those researches the structural frame-non-structural infill wall interaction has not been taken into account in the experimental phase (Filiatrault et. al.2010). Until now, the effects of drywalls on the global response have been assumed to be negligible and no literature could be found regarding their cyclic behaviour infilled within an RC frame. As a result, in the light of the given observations and facts above, for the development of low damage solutions, it is vital to understand the following properties of these walls infilled within a structural frame:

a) Cyclic behaviour
b) Drift based damage states
c) Failure mechanisms
d) Effects of interaction with the surrounding frame

Therefore, two types of drywalls infilled within a unique RC frame were tested as part of a wider research project on the development of low damage solutions for different vertical non-structural elements (Tasligedik et. al. 2011, Baird et. al 2011). One of the specimens was prepared using light steel framing and the other specimen was prepared using timber framing. The testing was carried out by using quasi-static reverse cyclic displacement reversals applied to the structural frame. In this paper, the preliminary results and observations of these experimental tests are reported.

2. EXPERIMENTAL PROGRAM

In order to test the cyclic performance of various infill wall typologies, a unique test setup has been developed at University of Canterbury in New Zealand. The setup comprised two precast columns and two precast beams connected by 40 mm diameter post tensioning bars in order to achieve a rocking/re-centring behaviour, PRESSS technology Pampanin 2010, at beam column connections. Due to the characteristics of the test setup, it was possible to test many types of infill walls within this unique RC frame without causing any damage to the structural frame at all. Moreover, the behaviour of the infill wall could easily be extracted from the global behaviour since the bare frame behaviour remained basically linear elastic at each test.

In the setup, possible out-of-plane deformations were prevented by providing four rollers on a secondary steel frame at the second level RC beam. In order not to cause incompatible beam elongation between the first and second level beams and clamping of the first level, pivot points were provided at the central ends of the first level beam so that the beam contacted the columns at these points. In Figure 2 and 3, front view, side view and isometric view of the setup are shown.

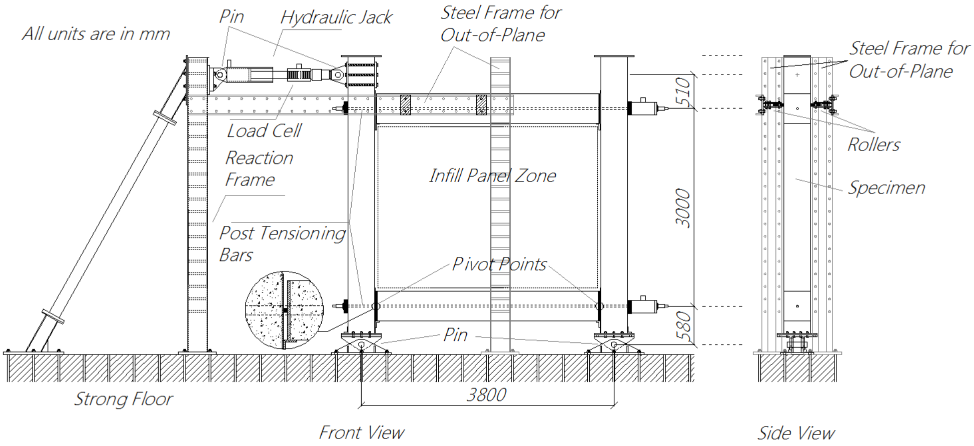


Figure 2. Test setup, front and side view

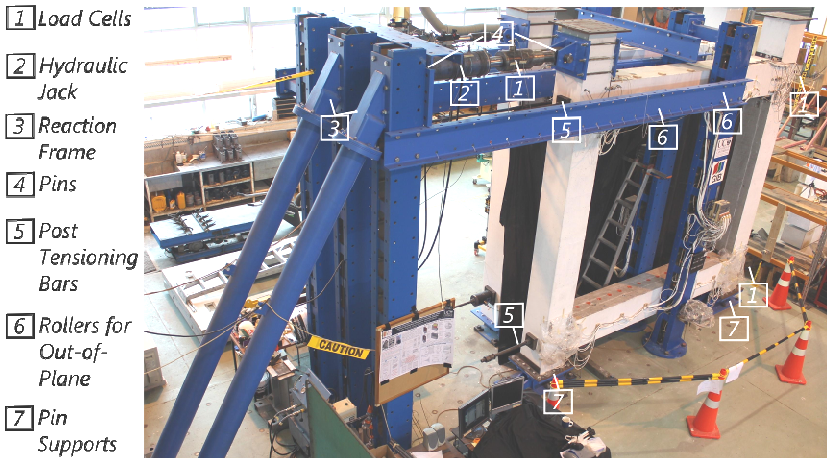


Figure 3. Isometric view of the setup

The frame replicated the deformed shape of an inner storey in a multi storey building. If the performance of the frame were to be tested, the ideal loading and supporting points would be the middle height of the upper and lower storey columns in a prototype building, or inflection/contra-flexure points. However, since the performance of the infill walls was the main focus of this particular research, this requirement was not seem necessary, provided that a realistic shear deformation could be imposed to the infill wall. The height limitation of the laboratory was also considered; it was felt more important to test the infill walls in full-scale rather than scaling down the frame.

Using 50 MPa concrete and 500 MPa reinforcing steel, all members of the RC post tensioned frame were designed to withstand the resulting shear forces and bending moments without yielding such that they could remain elastic. In the design phase, all future tests on clay brick or reinforced hollow masonry infill walls were also taken into consideration. Moreover, since beam to column connections were obtained by using unbonded post tensioning bars (Macalloy 1030), special care was necessary to account and design for the increase of post tensioning force due to the rocking mechanism at different drift levels. This required additional helix confinement in the post tensioning zones (Macalloy ETA 07/0046). The resulting detail for beam to column connection and reinforcement details of columns and beams are shown in Figure 4.

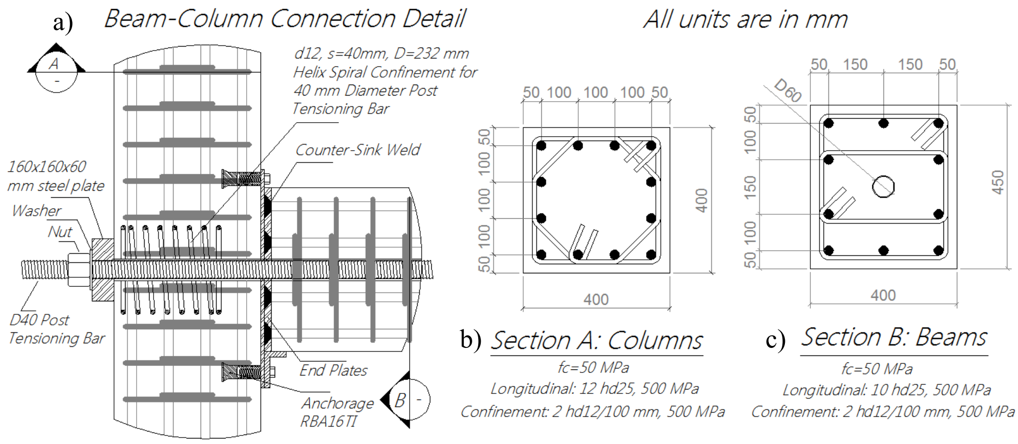


Figure 4. a) Beam-column connection detail, b) Column reinforcement detail, c) Beam reinforcement detail

The tests were carried out using reverse cyclic quasi-static loading protocol in accordance with ACI 374.1-05. However, no intermediate cycle was applied between drift increments. During the tests, no axial load was applied. There were three reasons for this:

- The most pronounced (undesirable) deformation on the frame, affecting the infill, can be imposed under zero axial load.
- As stated in ACI 374.1-05, the absence of axial load on the system produces conservative results in the structural performance.
- Due to the height limitations of the laboratory crane and for simplicity

The specimens were instrumented to observe the behaviour of both the rocking structural frame and the infill wall. For the infill walls, measurement of the diagonal deformations was critical. Figure 5 shows the drift protocol and a typical instrumentation scheme.

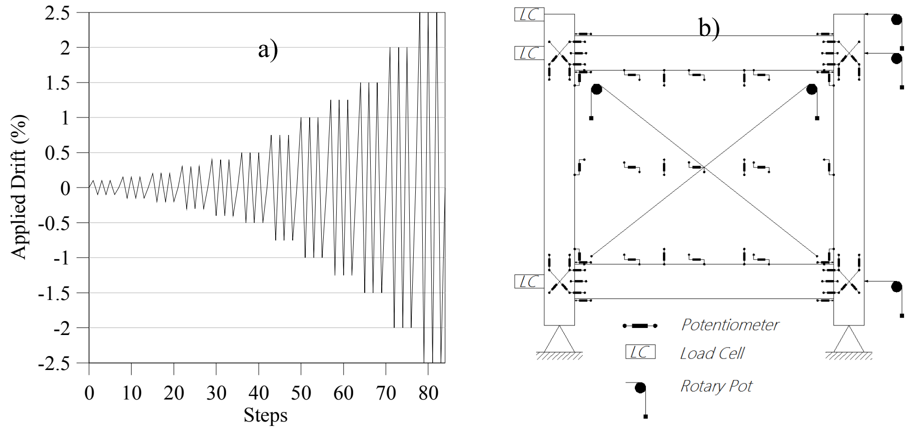


Figure 5. a) Applied drift history (Compatible with ACI374.1-05), b) Typical instrumentation layout

3. TEST SPECIMENS

Three types of specimens were tested. The first specimen consisted of the bare frame without any infill walls (BF) in order to obtain the force-displacement behaviour of the frame. The second specimen consisted of a fully infilled frame (FIF) with steel framed drywall (STFD). The third specimen consisted of a fully infilled frame with timber framed drywall (TBFD). An overview of the test specimens characteristics and dimensions is shown in Figure 6 and summarized in Table 1.

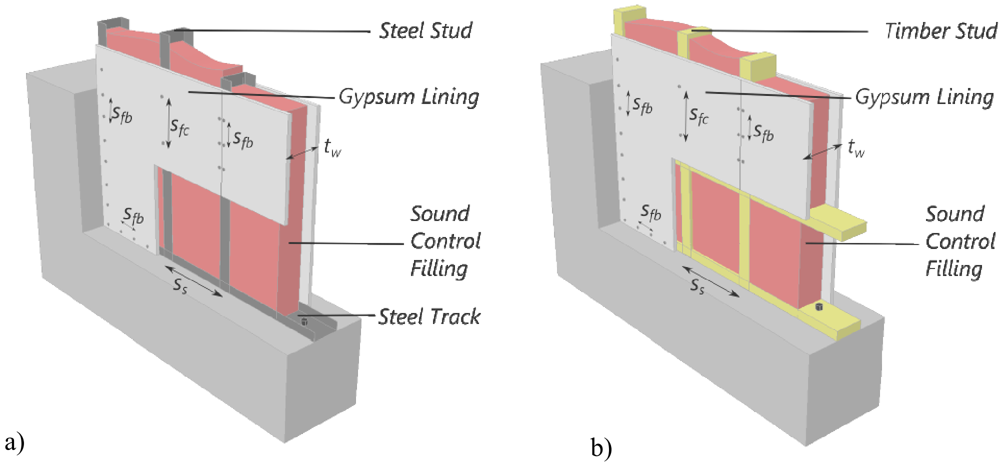


Figure 6. a) Typical steel framed drywall detail (i.e. FIF1-STFD), b) Typical timber framed drywall detail (i.e. FIF2-TBFD)-Note: Refer to Table 1 for dimensions.

Table 1. Summary of test specimens with typical dimensions

Test	*Name*	*Post Tensioning (kN)*	*Wall Thickness t_w (mm)*	*Stud Section Dimensions (mm)*	*Stud Spacing s_s (mm)*	*Fastener Spacing at Lining Borders s_{fb} (mm)*	*Fastener Spacing at Lining Center s_{fc} (mm)*
Test 1	*BF*	*80*	-	-	-	-	-
Test 2	*FIF1-STFD*	*80*	*120*	*20 × 90 × 0.55*	*600*	*200*	*400*
Test 3	*FIF2-TBFD*	*80*	*120*	*50 × 90*	*600*	*200*	*400*

BF: *Bare frame*
FIF1-STFD: *Fully infilled steel framed drywall*
FIF2-TBFD: *Fully infilled timber framed drywall*

3.1 Construction of Fully Infilled Steel Framed Drywall FIF1-STFD

The steel framed drywall was constructed using typical construction practice. The steel tracks were first fixed to the upper and lower RC beams (Figure 7a-b). After that, the steel studs were fitted into these tracks and connected to the tracks (Figure 7c-d) and the studs adjacent to the RC column surfaces were then fixed to the columns. Then gypsum linings were fixed over the formed steel framing on each side using self drilling gypsum lining screws (Figure 7e-f). At the end, the lining interfaces were plastered using paper tape and plaster (Figure 7g). The most common anchors for fixing the steel tracks to the upper and lower beams are the first two anchors shown in Figure 7h. Due to ease of removal, the second one was used in this test specimen, which is HRD frame anchor. The third type is philips self drilling screws used for fixing the steel studs to the tracks.

3.2 Construction of Fully Infilled Timber Framed Drywall FIF2-TBFD

The construction of a timber framed drywalls slightly differs from that of steel framed drywalls. Resembling the construction practice, first the timber members at the borders were fixed to the surrounding RC frame by drilling and inserting the required anchors (Figure 8a-d). Then the vertical timber studs were fixed to the boundary timber members at the upper and lower beams (Figure 8e). After that, the horizontal timber members were fixed between each stud (Figure 8f). Then gypsum linings were fixed using the same screw type as STFD (Figure 8g). The four anchor types used in this specimen are shown in Figure 8h. The first two are the common anchors used in fixing the timber to concrete. Due to ease of removal, the second type was used, which is HUS-H universal screw. The third type is the nail used in fixing the timber members to each other. The fourth and last one is the self drilling fasteners used for fixing the gypsum linings to the timber framing.

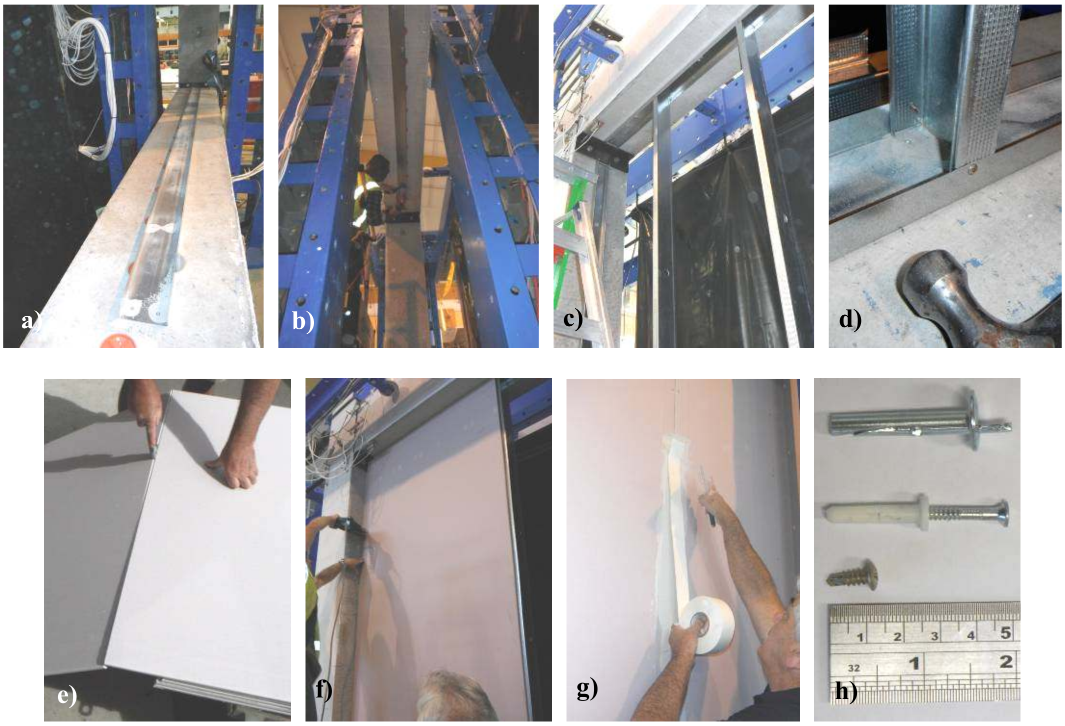


Figure 7. Construction sequence for the steel framed drywall FIF1-STFD, a-b) Top & bottom track installation, c-d) Stud installation into tracks, e-f) Gypsum lining installation, g) Plastering, h) Anchors/fasteners used

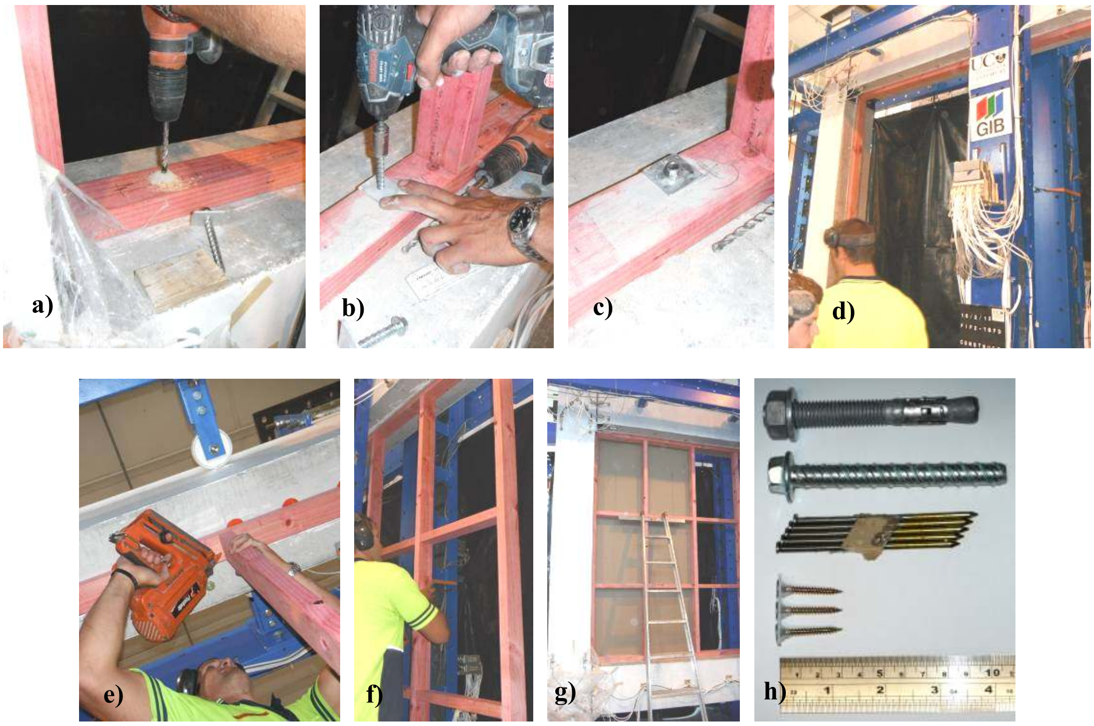


Figure 8. Construction sequence for the timber framed drywall FIF2-TBFD, a-d) Installation of timber at the borders, e) Installation of vertical studs, f) Installation of horizontal members, g) Gypsum lining installation, h) Anchors/fasteners used

4. TEST RESULTS

4.1 Bare Frame BF

The bare frame was tested three times. In each of these tests, the same displacement history was applied. As expected, the frame remained elastic with minor cover cracks. It should be noted that the amount of post tensioning to be applied was determined at this stage. In order not to force the setup to its limit, an initial post-tensioning force of 80 kN was used, which correspond to approximately 10% of the yield for the post tensioning bar. Also, the supplied central pivot points at the level 1 beam proved to work well to prevent beam elongation and thus clamping of level 1 to occur. In Figure 11a and 11b, the hysteresis curve and post tensioning vs. drift curves are shown.

4.2 Fully Infilled Steel Framed Drywall FIF1-STFD

The first damage observed was given by the separation/cracking at the interface between the drywall and the RC frame at 0.15% drift. At 0.2% drift, the interface cracking occurred between lining panels A and B. At 0.3% drift, the interface cracking between lining panels A and B progressed and caused bowing on the surface of the interface. At this drift state, a drywall in real life would require definite repair or replacement. Moreover, this level of damage (and associated drift) corresponds to a sudden drop in lateral load (Figure 12a). After that, further damage concentrated on this lining-to-lining interface and lining A began to rock, causing toe crushing of lining A (Figure 9). Once mobilized, this interface had the most significant damage and controlled the failure mechanism of the drywall. An overview of the level of damage for this specimen at the end of the test is shown in Figure 9. The global lateral force vs. lateral displacement hysteresis curve is shown in Figure 12a. The behaviour of the post tensioning was the same as per the bare frame specimen BF.

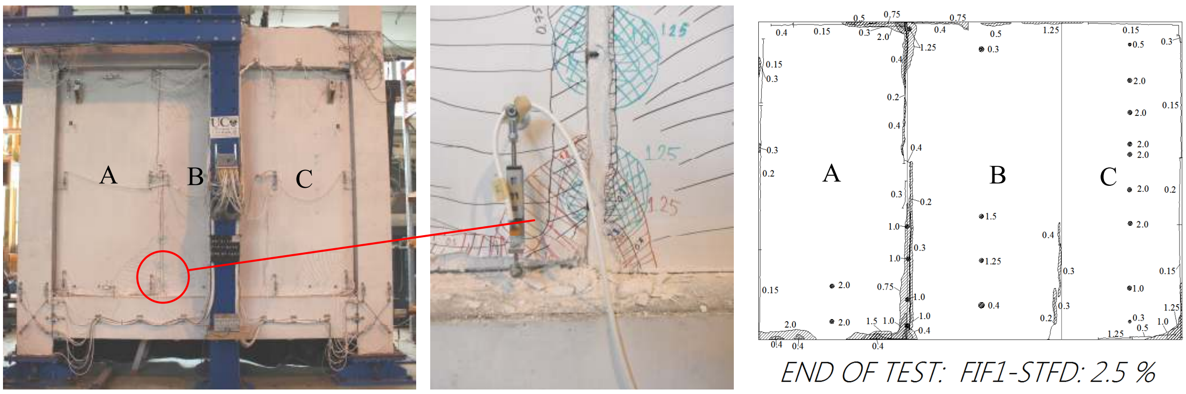


Figure 9. Damage state of steel framed drywall FIF1-STFD at the end of test

4.3 Fully Infilled Timber Framed Drywall FIF2-TBFD

At the first drift level of 0.1%, the interface between the drywall and the RC frame cracked and separated. No additional damage was observed until 0.3%. At 0.3%, minor cracking occurred at the corners of the drywall and gypsum lining fasteners began to get damaged. At 0.75%, the corners of the drywall started to bow due to the compression strut and a sudden drop in lateral force was observed. Based in this test, 0.75% drift would thus correspond to a drift-level (limit state) where a drywall would need repair/replacement in real life. After this drift level, damage concentrated at the corners of the wall and bowing/crushing damage progressed further (Figure 10). An overview of the level of damage for this specimen at the end of the test is shown in Figure 10. The global lateral force vs. lateral displacement hysteresis curve is shown in Figure 12b. The behaviour of the post tensioning was the same as per the bare frame specimen BF.

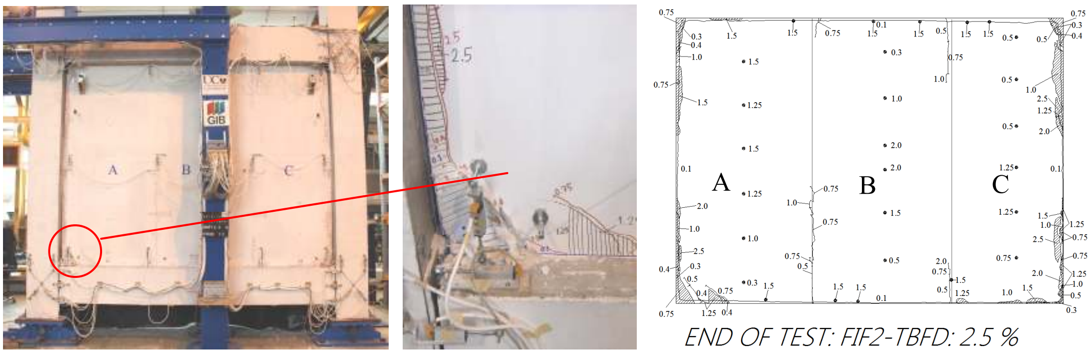


Figure 10. Damage state of timber framed drywall FIF2-TBFD at the end of test

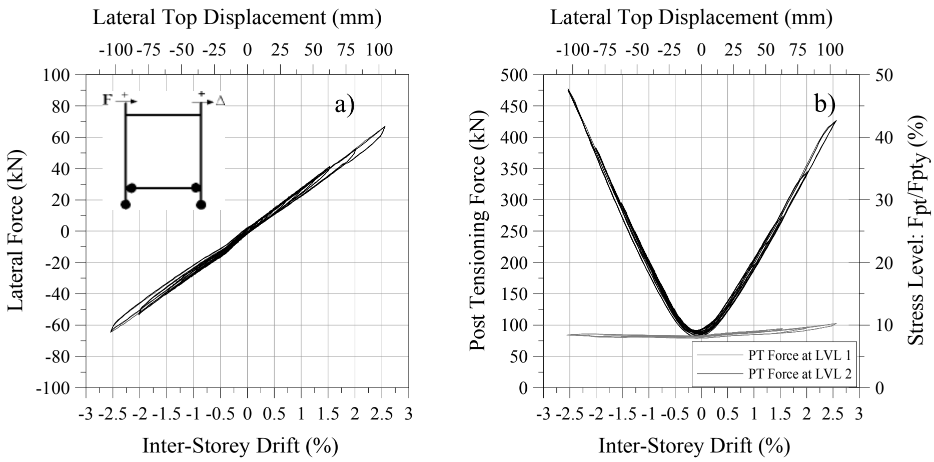


Figure 11. a) Hysteresis curve of bare frame, BF, b) Post tensioning vs. drift curve of bare frame, BF –Note: the post tensioning curves are the same for each test

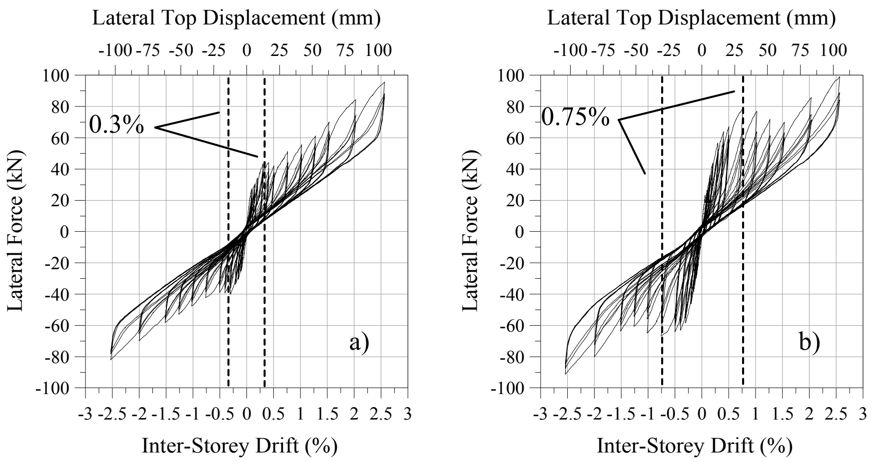


Figure 12. Global Hysteresis curves for a) Steel framed drywall, FIF1-STFD, b) Timber framed drywall, FIF2-TBFD (Dashed lines correspond to damage limit state of the infill wall)

5. EVALUATION OF RESULTS

The test results confirmed first of all that the bare frame behaved as expected. No damage occured and it could be used repeatedly without having to replace it. Its behaviour was be represented by a linear force displacement curve and be subtracted from the total behaviour in order to obtain the contribution of the infill wall itself.

The steel framed drywall FIF1-STFD showed that this type of drywall is expected to get damaged at 0.3%, which is a very low drift level for these walls. At this drift, the observed damage would require repair or complete replacement in daily practice. When the bare frame behaviour is subtracted from the total response, it can be seen that the steel framed drywall infill behaved in a relatively ductile manner (Figure 13b). It should be noted that the pinching of the curve is due to the self centring capability of the structural frame and ductility is referred as the envelope behaviour of the specimen.

On the other hand, timber framed drywall FIF2-TBFD showed a rather different behaviour when compared to the steel framed counterpart FIF1-STFD. The wall was damaged at 0.75% drift with a higher force capacity. Although the damage occurred at a higher drift level, the timber framed drywall TBFD behaviour was more brittle than the steel framed drywall STFD and changed the global response into a brittle one (Figure 13c). The resulting loss of strength and thus stiffness at a storey level associated to the damage of the infill could possibly lead to the development of a soft-storey mechanism. As part of the project, non-linear static and dynamic analyses are under-going to investigate this possibility.

An important observation can be made by checking the residual force capacity (F_{Iu}) exerted by the infill walls at 2.5% drift (Table 2). After 1.5% drift level, both steel framed drywall FIF1-STFD and timber framed drywall FIF2-TBFD have the same residual force capacity, which is approximately around 40 kN. Envelope curves, lateral force contributions exerted by the infill walls are shown in Figure 13. In addition, values at the observed damage limit states of the tests are given in Table 2.

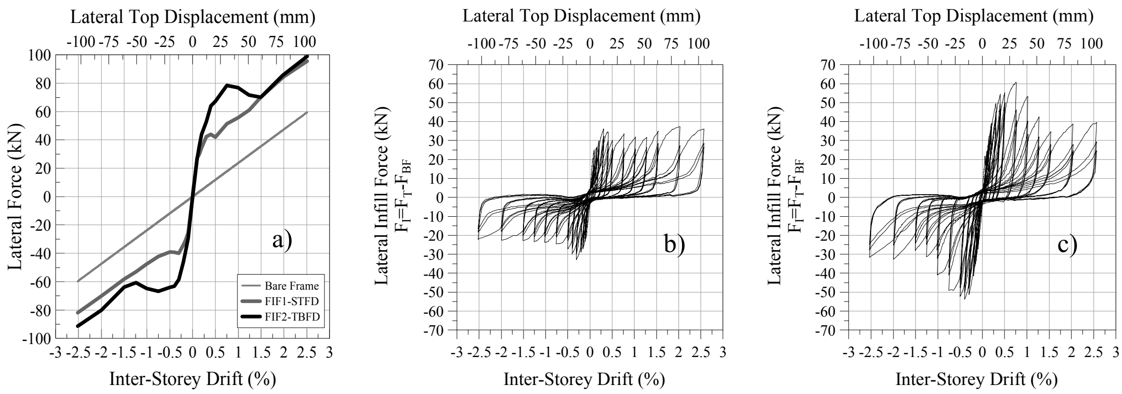
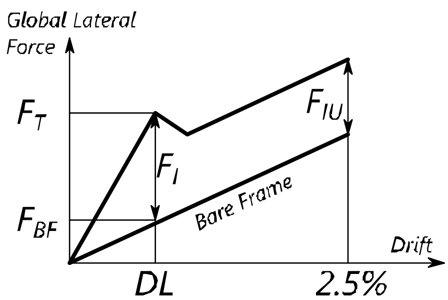


Figure 13. a) Force vs. drift envelopes of the tests, b) Lateral force exerted by only the steel framed drywall infill FIF1-STFD (=F_T-F_{BF}), c) Lateral force exerted by only the timber framed drywall infill FIF2-TBFD (=F_T-F_{BF})

Table 2. Drift, force values and comparisons at damage limit states

Name	*DL (%)*	*F_T (kN)*	*F_{BF} (kN)*	*F_I (kN)*	*F_{Iu} (kN)*	*F_D (kN)*	*F_I/F_{Iu}*
FIF1-STFD	*0.3*	*42.3*	*7.2*	*35.1*	*36.1*	*45.5*	*1*
FIF2-TBFD	*0.75*	*78.4*	*17.8*	*60.6*	*39.5*	*78.6*	*1.5*

DL: *Drift limit in terms of inter-storey drift, requires repair or*
F_T: *Total lateral force on the setup=$F_{BF}+F_I$*
F_I: *Lateral force carried by infill wall =F_T-F_{BF}*
F_{Iu}: *Lateral force exerted by the infill wall at 2.5% ultimate drift*
F_D: *Approximate Diagonal force carried by infill wall=$F_I/\cos\alpha$*
F_I/F_{Iu}: *Lateral infill force level exerted relative to residual infill wall strength at 2.5% drift*



6. CONCLUSIONS

Drift-based damage limit states of two different types of drywalls infilled within an RC frame were obtained. Based on the observations made, as-built steel framed drywalls suffered significant (enough to require repairing if not complete replacement in daily practice) damage at 0.3% drift level. Timber framed drywalls, on the other hand, suffered the same level of damage at higher level, 0.75%, of drift.

Information on the reverse cyclic behaviour of these two types of drywalls was obtained. The steel framed drywall specimen tended to behave in a ductile manner, while the timber framed drywall specimen tended to behave in a brittle manner. In this specific case, and in the light of the use of a peculiar low-damage but also lightly reinforced testing frame, the lateral force (F_I) carried by each wall (see Table 2) are substantial when compared to the total force carried by the system (F_T). More investigations are required and are on-going based on numerical simulation to confirm the actual extent of interaction between these 'non-structural' walls and the main 'structural system'. The common belief that light infill walls can be neglected in the structural design might need to be revisited. On the other hand, after 1.5% drift, both drywall type showed same cyclic behaviour and residual strength (approximately 40kN).

These tests highlighted the importance of considering the effect of interaction between the structural system and the non-structural infill walls, even when considering light steel or timber framed drywalls. In particular, the reported 'non-structural' drywalls suffer significant damage at a very low drift level and in most cases requires repair or complete replacement, which as recently once again proven by the Canterbury earthquake sequence in 2010-2011, and can be very costly. There is a clear need to develop and implement solutions to prevent or minimize the damage to non-structural infill walls, either consisting of light-medium or heavy materials.

As a final remark, it has been confirmed that the RC frame constructed of precast members connected with unbonded post tensioning tendons/bars (PRESSS-system) works well as a test rig for infill walls in reverse cyclic loading protocol. The frame does not get any significant damage and shows a linear elastic behaviour at each test and can be used multiple times. Moreover, these types of structures can be the "ultimate earthquake resisting system" due to their low damage and high seismic performance.

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