

In-situ Out-of-Plane Airbag Testing of Infill Masonry Cavity Walls



Testing at 151-165 Victoria Street West
Auckland, New Zealand
Automotive Garage
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Abstract

The objectives of testing were to better understand the out-of-plane behaviour of single leaf unreinforced masonry infill walls in two way bending and two leaf masonry cavity walls with original wire ties and various industry accepted ties in one way bending. One of the two single leaf URM infill walls was used as a control and the other wall contained a simulated in-plane shear crack yielding a strength decrease of 37.3%. Of the three industry accepted retrofitting ties tested, the Reid ties performed the best increasing the strength of the two leaf wall in one way bending by 44% and allowing for the most deflection before collapse. The Hilti and Helifix Ties provided little improvement when compared to the original wire ties increasing the strength of the wall by only 6% and 11% respectively.

Executive Summary

The University of Auckland was allowed by Manson's TCLM Limited to conduct in-situ out-of-plane testing on non-load bearing masonry infill walls at an automotive garage located at 151-165 Victoria Street West in the central business district of Auckland, New Zealand. The building was set for demolition due to being assessed as seismically deficient allowing the University to test the masonry walls to failure.

Tests conducted include:

- Four out-of-plane airbag tests on several isolated internal two leaf cavity infill walls to induce one-way bending fitted with various industry accepted cavity ties in addition to the original wire ties.
- One out-of-plane airbag test on an exterior URM two leaf cavity infill wall with the outer leaf removed. Tested with existing boundary conditions, inducing two-way bending type failure.
- One out-of-plane airbag test on an exterior URM two leaf cavity infill wall with the outer leaf removed. Tested with existing boundary conditions inducing two-way bending type failure with the interior leaf cut to simulate in-plane cracking.

Purpose

Based on preliminary inspections conducted by Auckland council there appears to be a large number of structures with two leaf cavity masonry infill walls that were identified in the Auckland region. A large number of such unreinforced infill walls were built prior to the 1950's and were shown to perform poorly in previous earthquakes causing significant damage and pose a severe threat to public safety due to their out-of-plane instability. Figure 1 shows a two leaf masonry cavity wall that partially collapsed during the 2011 Christchurch earthquake. Although the walls at the Victoria street automotive garage had existing wire ties' connecting the two leaves, little is known about their performance in earthquakes and the performance of proprietary retrofit tie systems.



Figure 1: Partial failure of two leaf URM wall during 2011 Christchurch earthquake.

Single leaf masonry infill walls, typically found in the interior of masonry buildings as partitions, are also prone to out-of-plane failure during earthquake induced shaking posing a great threat to buildings occupants and pedestrians. A large number of single leaf masonry walls become cracked through their mortar joints during intermittent small earthquakes posing an even greater threat during a large earthquake. The Victoria street automotive garage provided an opportunity to gain more knowledge on the performance of single leaf unreinforced masonry walls in two way bending and the effect of having pre-existing in-plane cracking.

Building Description

The automotive garage was built in 1962 in the central business district of Auckland, New Zealand. The building consists of a large open center only supported on the perimeter by a concrete encased steel frame. The concrete encased steel frame is infilled with two leaf masonry cavity walls connected to the frames using regularly spaced steel wire ties. The wire ties were placed into the mortar of the wall during construction between every fourth layer of brick as shown in Figure 3b, d. The frame and infill walls were connected via small shear keys and steel wires extruding from the reinforced concrete column into the mortar joints of the masonry walls (Figure 3a). At the base of the infill wall there was a thin aluminium sheet, to prevent the capillary action of water, placed between the mortar and cement floor slab as shown in figure 3c.

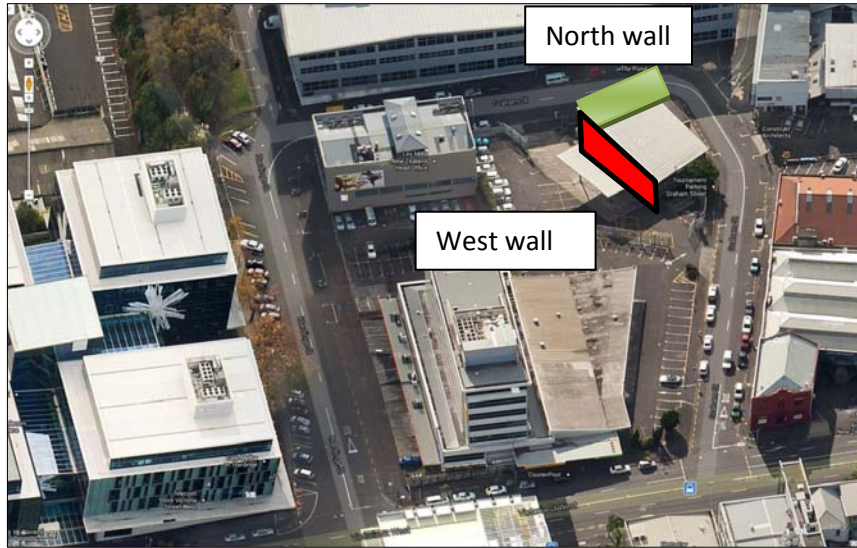


Figure 2: Ariel view of the building and location of north and west testing walls.



(A) Concrete shear key and wire tie connection to the concrete encased steel frame.



(B) Original wire ties



(C) Thin sheet of aluminium between the first and second layer of bricks.



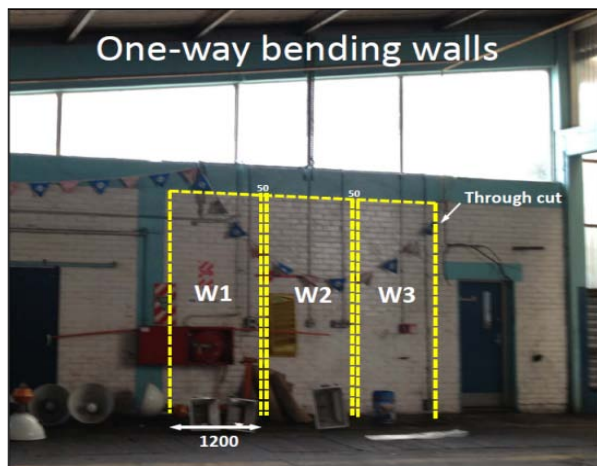
(D) Original wire tie removed from wall

Figure 3: Original wire ties and boundary conditions.

Specimen Set-up

A reaction and instrument frame was constructed on site using structural timber that was designed so that the frames were relocatable for each test wall. The exterior leaf of Wall 4 and 5, originally a two leaf infill masonry cavity wall located on the west end of the building, was removed exposing steel rods extruding from the moment frame placed into the mortar of the masonry wall and many steel ties linking the two leafs through the cavity placed into the mortar joints between brick layers of the masonry wall. The wire ties were vertically spaced every 4th brick and horizontally spaced every 5th brick in a diagonal manor throughout the entirety of the masonry infill wall. The single URM masonry leaf remaining of wall 5 was then cut using a circular saw to create a 50mm deep step crack in the shape of an “X” with the center of wall as the centroid to simulate a pre existing in-plane crack (figure 4d).

Walls 1,2 and 3 were then created by cutting through both leafs of the north wall creating three 1200mm wide by 3000mm tall sections of two leaf masonry cavity walls with original wire tie reinforcing. Hilti and Helifix then professionally inserted 14 of each tie into wall 2 and wall 3 respectively with a horizontal spacing of 600mm and vertical spacing of 330mm. The Reid ties and Hilti ties were placed into the mortar joints between brick layers whereas the Helifix ties were placed directly into the middle of the masonry bricks.



(a) North wall, Wall 1,2 and 3



(b) West Wall, Wall 4 and 5



(c) Removal of outer leaf for Wall 4,5



(d) 50mm deep simulated in-plane crack, Wall 5

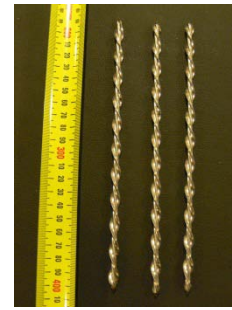
Figure 4: Wall overview and preparation.



(a) Reid Tie



(b) Hilti Tie



(c) Helifix Tie

Figure 5: Overview of industry ties.

Table 1: Tabulated conditions for each test wall.

Location	Test Id	Number of Leafs	Boundary and loading condition	Wall Condition
Wall 1	T1 - A	2	One-way bending	Original (as-built)
Wall 1	T1 - B	2	One-way bending	14 Reid ties horizontally placed at 600mm with a vertical spacing every 330mm.
Wall 2	T2	2	One-way bending	14 Hilti ties horizontally placed at 600mm with a vertical spacing every 330mm.
Wall 3	T3	2	One-way bending	14 Helifix ties horizontally placed at 600mm with a vertical spacing every 330mm.
Wall 4	T4	1	Two-way bending	Original (as-built)
Wall 5	T5	1	Two-way bending	Simulated in plane cracking

Test Setup and Instrumentation

A timber backing frame was placed on steel plates with a greased Teflon sheet separator to allow the frame to move with a small coefficient of friction when being loaded. The Backing frame was then fitted with six 10kN load cells that would transfer the load into timber diagonals. The timber diagonals were then fixed to the cement floor slab with steel plates and Reid bolts (figure 5a). Two Bigfoot™ vinyl airbags with a skin thickness of 0.25 mm were placed onto the timber backing frame in the gap between the masonry wall surface and the backing frame. The airbags could then be gradually inflated to generate an out-of-plane uniform force on the surface of the wall with an application area of 2.31 square meters each. The Airbags were connected to an air compressor using the same length and type of high pressure tubing to ensure a simultaneous inflation rate and an equal pressure level to be applied onto the wall.

Walls 1, 2 and 3 required a single instrumentation stand consisting of a single vertical axis made out of lumber (figure 5b). The vertical axis consisted of two string pots located at 1500mm and 2100mm from the floor and a single steel portal gauge 3000mm from the floor. The same instrumentation stand was used for testing of all three one-way bending walls (walls 1, 2 and 3).

Walls, 4 and 5 required a much larger instrumentation stand also made out of lumber (figure 5d). The instrumentation frame consisted of 12 steel portal gauges, and a string pot to measure the displacement of the wall. The string pot was placed at the center of the wall with the 12 Portal gauges mainly placed on three vertical axes and the rest placed as shown in figure 6a.

A National instruments high-speed data acquisition system with multiple channels was used to record the test data and the total lateral load was calculated through the summation of the force recorded by the six load cells divided by the area of the two Airbags.



(a) Test Setup (Wall 1&2)



(b) Instrumentation stand for one-way bending (wall 2)

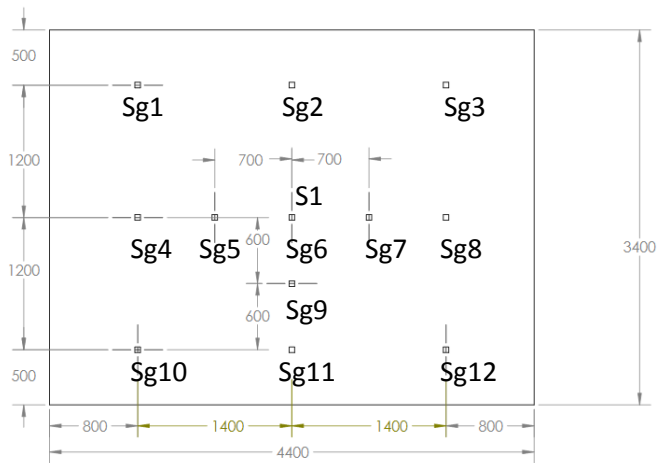


(c) Test Setup (Wall 4)

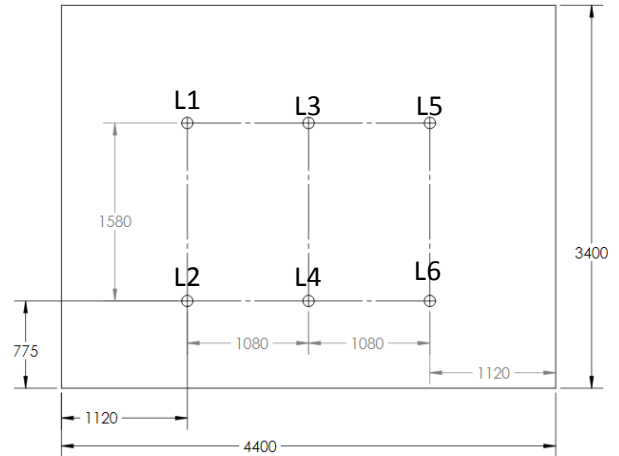


(d) Instrumentation Stand for two-way bending (Wall 4)

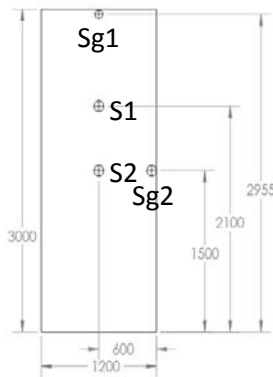
Figure 5: Test Setup and Instrumentation Stand.



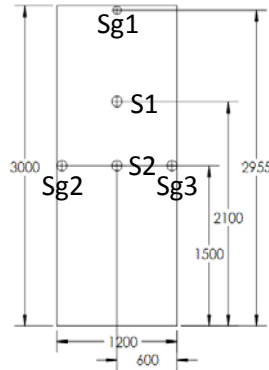
(a) Wall 3, 4 Displacement Instrumentation



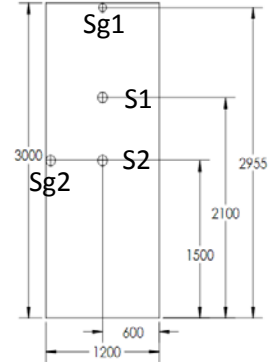
(b) Load cell Placement



(a) Wall 3 Instrumentation



(d) Wall 2 Instrumentation



(e) Wall 1 Instrumentation

Figure 6: Instrumentation Placement for all walls. All measurements in (mm)

Results

T1 – A: Wall 1, Original ties in one way bending, Two-leaf masonry cavity wall

Wall 1 is a 1200mm by 3000mm two leaf section of the north wall reinforced with original steel wire ties placed in the mortar between every 4th brick layer. Loading was applied via a single airbag which was gradually inflated followed by a slow release of pressure to load and unload the wall. This process was repeated for five cycles.

Figure 7 shows the total lateral force versus mid-height displacement for test T1-A using displacement gauge (S2) located at the center of the wall. Figure 7 shows the wall yielding on the first cycle which caused a crack at a mortar joint in the wall located between string pot 1 and string pot 2 between the 25th and 26th layer of bricks, about 2200mm above the base of the wall. The maximum force applied for subsequent cycles reached approximately 2.5 kN of force while the displacement continued to increase. This occurred due to the wall acting as if there was a hinge where the crack occurred allowing both the top and bottom sections to pivot at the crack being the top was free to lift vertically applying no compressive forces onto the wall.

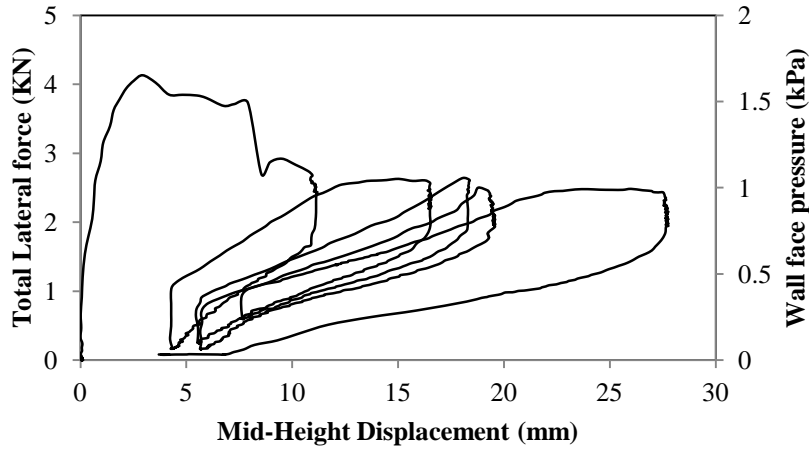
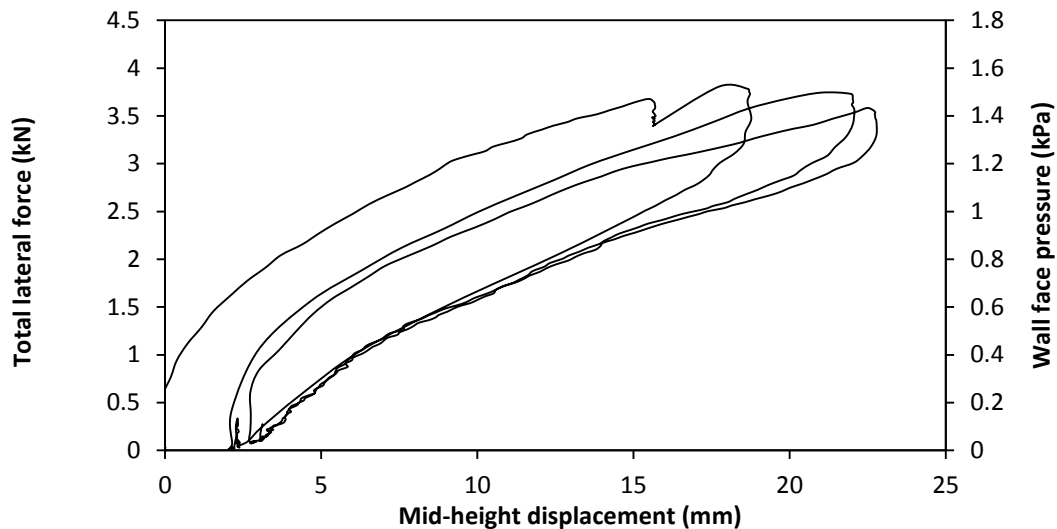


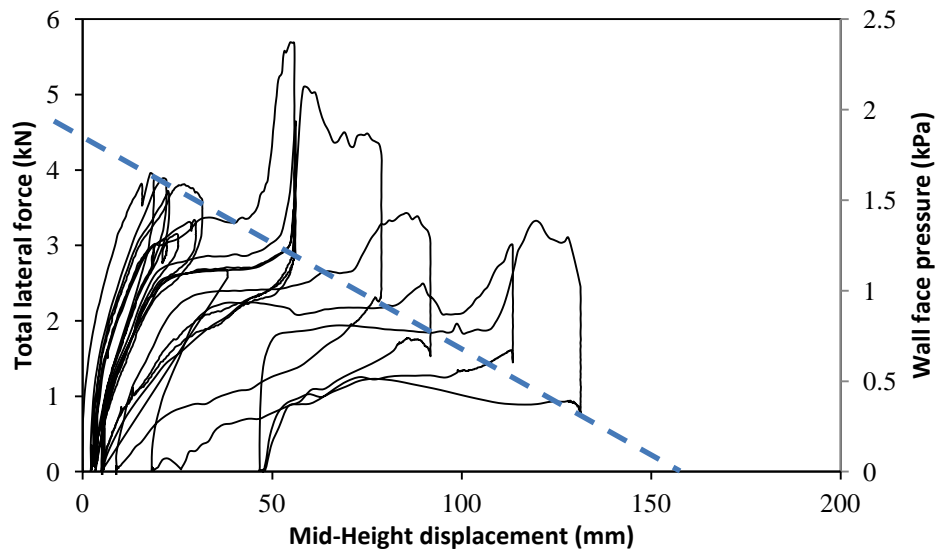
Figure 7: Force Displacement curve for wall 1 with original wire ties

T1 – B: Wall 1, Reid ties in one-way bending, Two-leaf masonry cavity wall

Wall 1, already cracked, was then retrofitted with 14 Reid ties. The Reid ties, a very robust tie, were placed with a horizontal spacing of 600mm and a vertical spacing of 330mm along the entire height of the wall. 13 loading cycles were applied by a single airbag resulting in Figure 8a which shows the total lateral force versus mid-height displacement for test T1-B using displacement gauge S2. Initially the wall resisted approximately 3.7 kN for the first three cycles however, after the third cycle something happened. The two leafs barely moved relative to each other due to the strength of the Reid ties which caused the wall to hinge at the crack completely suspending the tensile leaf as shown in figure 17 of the appendix. This caused some material from the wall to fall and get lodged into the wall causing the remaining data to become unrepresentative of just the ties. From the first three cycles the ties resisted a load of 3.5kN with minimal residual displacement.



(A) First three cycles of Wall 1 with Reid Bolts



(B) Full Hysteresis for Wall 1 with Reid bolts

Figure 8: Force Displacement curve for wall 1 with Reid ties

T2: Wall 2, Hilti ties in one-way bending, Two-leaf masonry cavity wall

Wall 2 was retrofitted with 14 Hilti ties, shown in figure 21 of the appendix, placed with a horizontal spacing of 600mm and a vertical spacing of 330mm along the height of the wall starting 490mm from the base. Loading was applied via a single airbag located on the right side of the backing frame by gradually inflating and deflating the airbag in a cyclic manor. The wall yielded on the first loading cycle at a mortar joint located between the 26th and 27th brick layers, approximately 2288mm above the base of the wall. After the fourth cycle the ties started to bend due to the eccentricity between the masonry leafs causing the walls resistance to drop. The Hilti ties began to plastically deform further with each successive cycle providing less resistance to the lateral force and increasing the residual displacement of the wall. This residual displacement caused the wall to become less stable and easier to displace with less force due to the increase in height of the center of mass gradually reaching the walls tipping point.

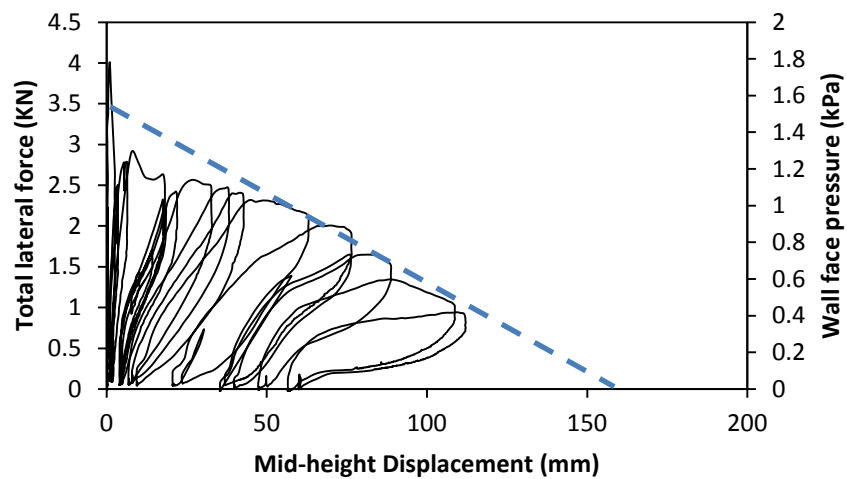


Figure 9: Force Displacement plot for wall 2 in one-way bending with Hilti Ties

T3: Wall 3, Helifix Ties in one-way bending, Two-leaf masonry cavity wall

Wall 3 was retrofitted with 14 Helifix ties, shown in figure 18 of the appendix, placed with a horizontal spacing of 600mm and a vertical spacing of 330mm along the height of the wall starting 440mm from the base. Loading was again cyclic consisting of loading and unloading of a single airbag to apply a uniform distributed lateral load to the wall. The masonry wall yielded on the first cycle at a mortar joint between the 23rd and 24th brick layers, about 2024mm above the base of the wall on the tensile masonry leaf. The stiffness of the wall decreases linearly as the displacement increased with the ties providing less resistance with each cycle due to yielding of the ties or their connection to the masonry. On the 7th cycle of loading the Helifix ties couldn't even resist 1kN of force causing a displacement of more than 100 mm.

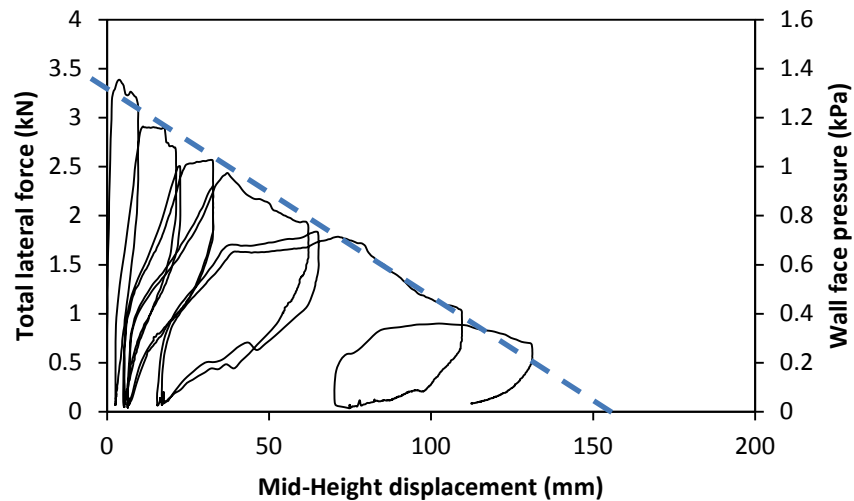


Figure 10: Force Displacement plot for wall 3 in one-way bending with Helifix ties

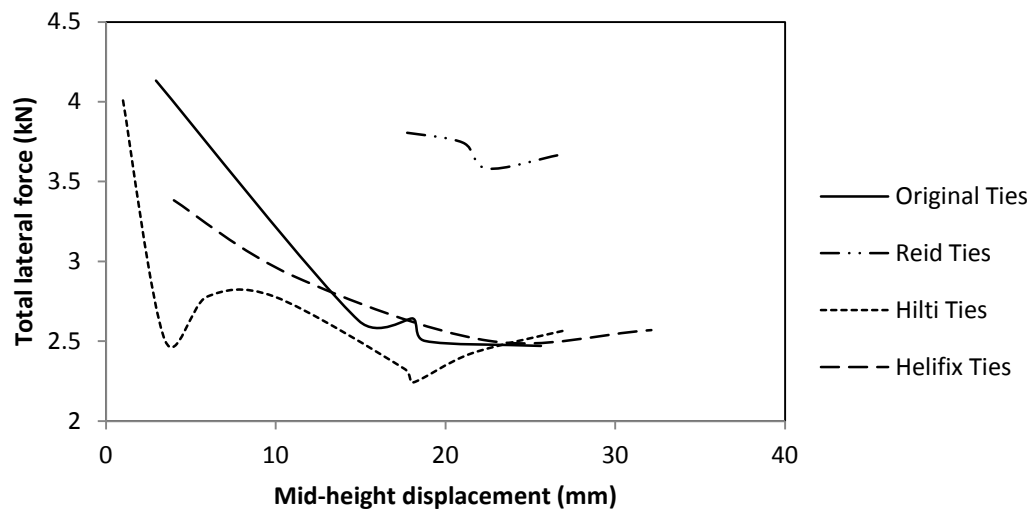


Figure 11: Force displacement envelope curve showing all ties.

Table 2: Tabulated tie performance.

Reinforcing tie	Max post cracking load	Improvement %	Collapse displacement	% Drift
Original wire	2.627 kN	Control	N.A.	N.A.
Reid	3.782 kN	44%	293 mm	15.5%
Hilti	2.787 kN	6%	216 mm	11.9%
Helifix	2.908 kN	11%	246 mm	14.25

T4: Wall 4 two-way bending, Single leaf URM wall

Wall 4, located on the west side of the building, is a 3400 X 4400mm single leaf URM masonry wall surrounded by a reinforced concrete moment frame. Loading was applied via two large airbags placed at the centroid of the wall to apply a lateral force to an area of approximately 4.62 square meters located on the interior of the wall. The airbags were gradually inflated and deflated in a cyclic manor.

Figure 12 shows the total lateral force versus the mid-height displacement for T4. The displacement gauge used was initially a steel portal gauge (SG6) located at the center of the wall however, on the 5th cycle it was changed to a string pot (S1) to account for larger displacements. The wall reached a maximum load of 61.28kN on the fourth cycle displacing 60.51mm with a residual displacement of approximately 19mm with no applied load. At this point the wall yielded along a step crack in the mortar joints between bricks originating from the centroid of the wall as shown in figure 13a. The wall was then pushed past its stability point to a mid-height displacement of 100mm with a force of approximately 54 kN causing a residual displacement of 28.5mm. The crack pattern was then amplified and revealed a non-regular crack pattern for a rectangular section. The typical crack pattern for rectangular wall in two-way bending with a larger base than height would yield figure 13c however our crack pattern has no central horizontal crack and instead has multiple in-plane cracks in all directions.

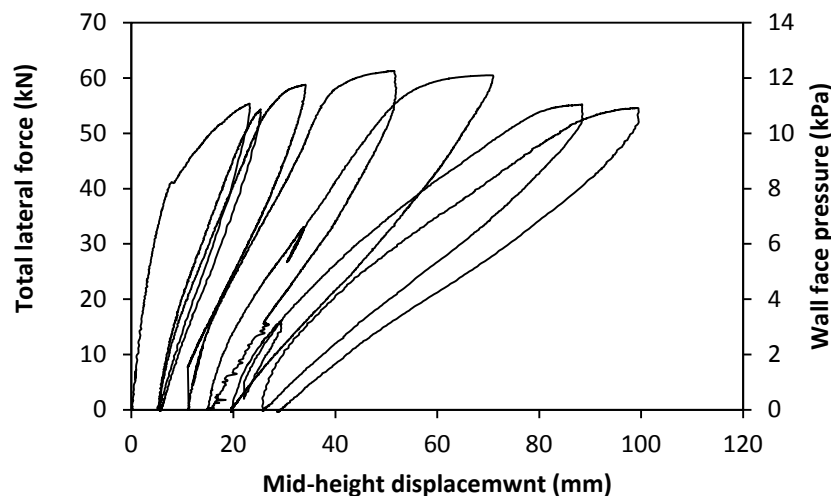


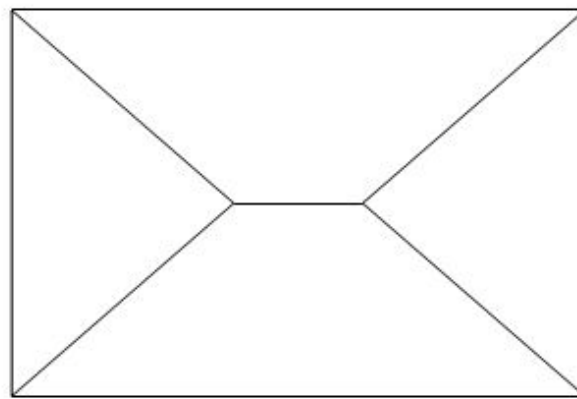
Figure 12: Force Displacement curve for Wall 4 in two-way bending



(a) Crack Pattern of wall 4 on tensile side



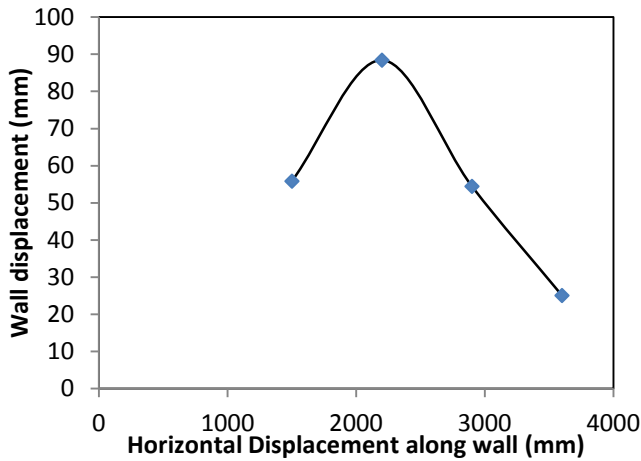
(b) Crack pattern of wall 4 compressive side



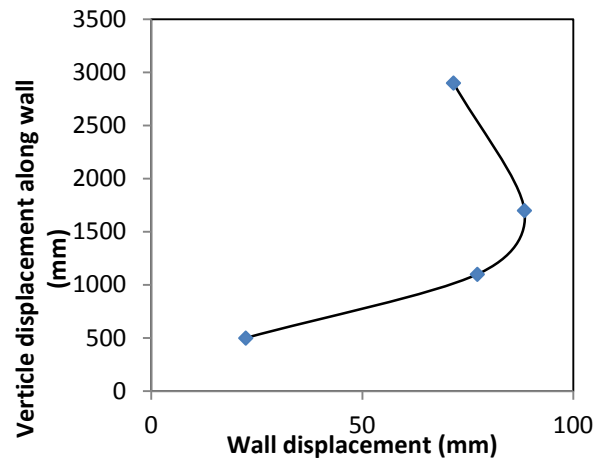
(c) Typical two-way bending crack pattern for a rectangular wall

Figure 13: Crack patterns for wall 4.

Figure 14 shows the horizontal and vertical displacement profiles of wall 4 on the second to last cycle due to portal gauges 5 and 7 being disconnected as to not exceed their capacity. The horizontal profile shows relatively symmetric bending across the mid-height of the wall however, only four fifths of the curve could be shown due to portal gauge 4 malfunctioning. The vertical displacement shows that the bottom of the wall was much more rigid than the top with gauge 2, located 1200mm above the center, measuring approximately 50mm more of displacement than that of gauge 11 located 1200mm below the center. This shows that the connection to the top of the reinforced concrete moment frame is not very rigid being it was only connected via a single layer of mortar whereas both sides are reinforced with the wire ties. Also the bottom has a compressive force due to all of the bricks above making a better connection to the ground than just mortar.



(a) Horizontal displacement profile wall 4



(b) Vertical displacement profile wall 4

Figure 14: Wall 4 horizontal and vertical displacements and crack patterns

T5: Wall 5, two-way bending with simulated in-plane cracking, single leaf URM wall

Wall 5, also located on the west side of the building, is a 3400 X 4400mm infill wall encased by a reinforced concrete moment frame with a 50mm deep step crack cut through the mortar joints to simulate pre-existing in plane cracking across the entire width and height of the wall as shown in figure 4d above. Loading was applied via two airbags, covering an area of 4.62 square meters, located on the interior of the wall in a cyclic pattern consisting of gradual inflation and deflation.

Figure 15 shows the total force versus the Mid-height displacement for wall 5. The displacement gauge used was initially a steel portal gauge (SG6) located at the center of the wall however, on the 6th cycle it was changed to a string pot (S1) to account for larger displacements. The wall reached a maximum load of 38.4 kN on the fifth cycle with a displacement of around 38mm causing the wall to yield. The wall primarily cracked along the mortar joints on the tensile side of the simulated in-plane step crack allowing for the wall to displace a great amount with little force due to each section moving nearly independent of one another as shown in figure 16c. Once the wall yielded the wall became easier to displace and began to deform plastically with large residual displacements.

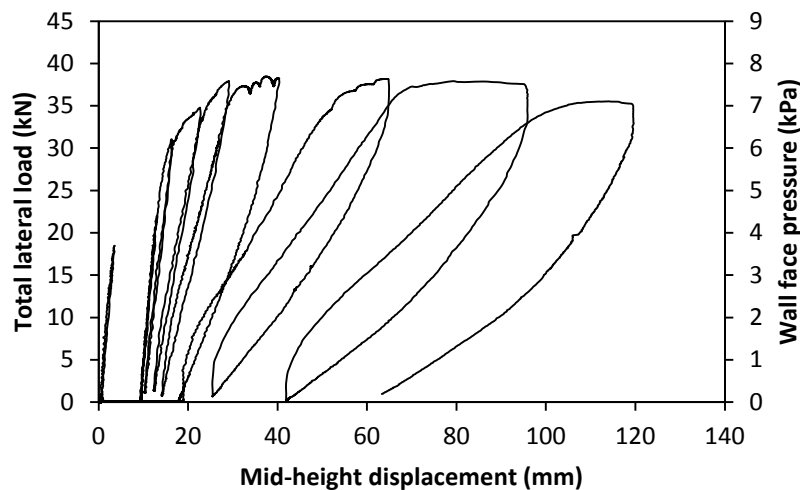
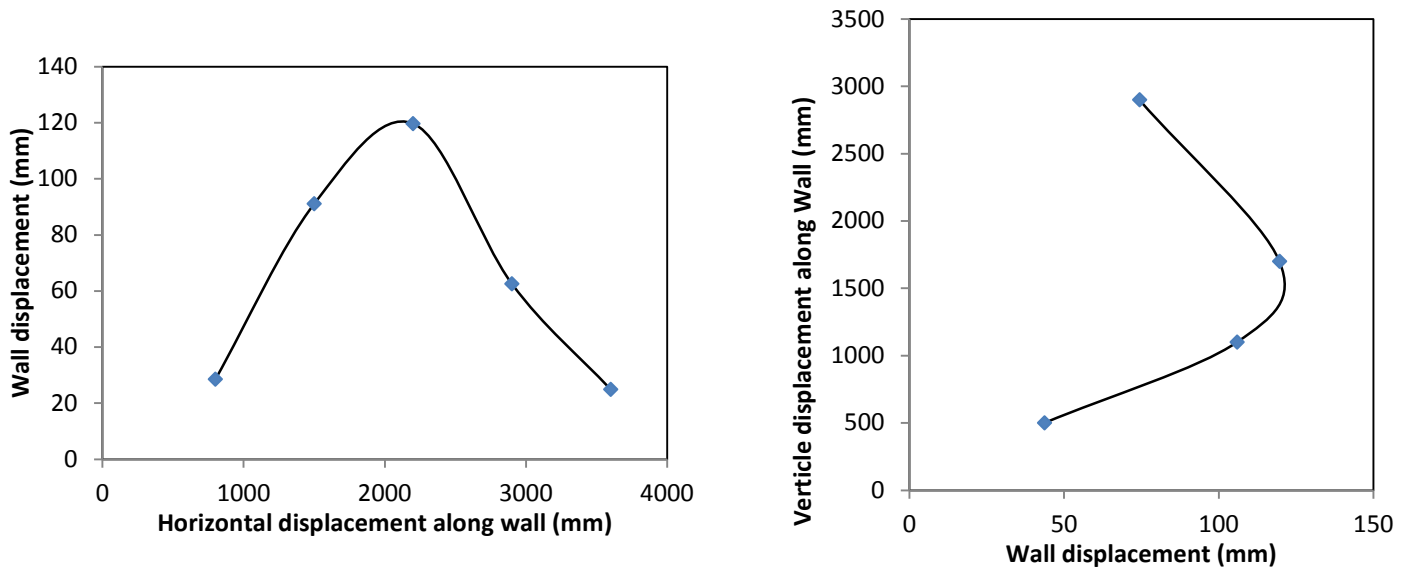


Figure 15: Force Displacement curve for wall 5 in two-way bending

Figure 16 shows the horizontal and vertical displacement profiles of wall 5 on the last loading cycle at the walls maximum deflection. The horizontal profile shows that the left side of the wall deflected slightly further than the right side of the wall due to the different sections of the wall being more or less independent of one another due to the simulated in-plane crack. The vertical displacement shows that the bottom of the wall was much more rigid than the top with the top displacement gauge (SG2) located 1200mm above the center of the wall displacing approximately 30mm further than SG11 which was located 1200mm below the center again due to the single layer of mortar connecting the masonry wall to the reinforced concrete moment frame and lack of a compressive force.



(c) Crack pattern of wall 5 on the tensile side



(d) After complete failure of wall 5 compression side.

Figure 16: Wall 5 Horizontal and Vertical displacements and crack patterns.

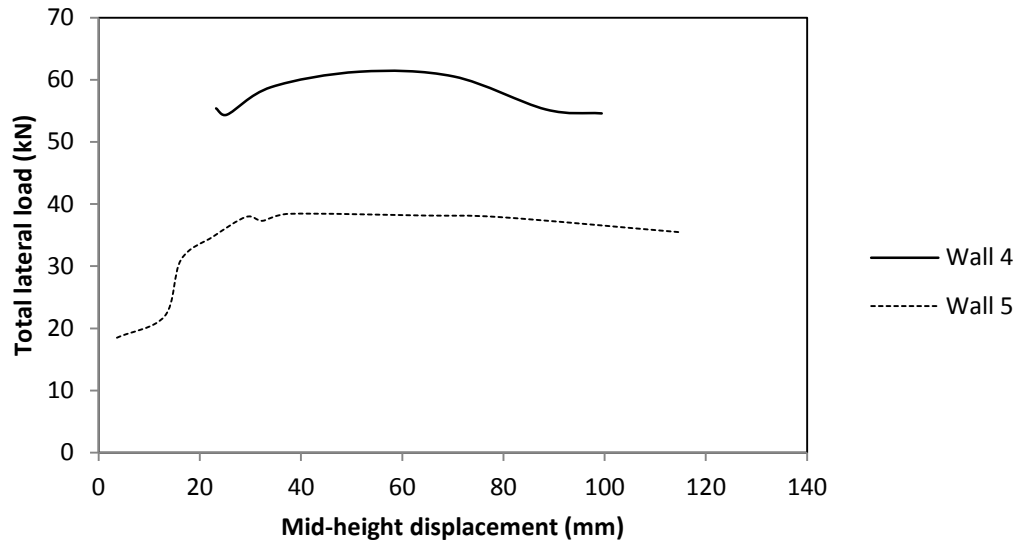


Figure 17: Force displacement envelope curve for Wall 4 and 5.

Table 3: Tabulated results of tests 4 and 5.

Wall	Max force	% Loss of strength
4	61.29 kN	Control
5	38.44 kN	37.3%

Conclusion:

Both the single leaf URM walls and two leaf masonry walls deflected much further than expected while remaining intact. All of the two leaf walls transferred the lateral load applied by the airbags via the ties to the tensile leaf before the ties yielded themselves. The original ties performed well in the one way bending tests resisting a lateral load of approximately 2.5kN which is comparable to the walls with the aftermarket retrofits. Of the aftermarket ties the Reid ties provided the most stiffness and were the only tie that didn't yield during testing. The Helifix and Hilti ties increased the stiffness of the wall initially however their strength linearly decreased as the deflection increased due to plastic deformation of the ties occurring between the two leafs of the walls. The single leaf URM wall in two way bending performed in a very ductile manor deflecting a distance greater than the width of a brick at mid-height yet remaining intact with minimal residual displacement when unloaded. However, if a single leaf URM wall contains a pre-existing in-plane crack than the wall is significantly weaker and deflects much farther being the crack is amplified by the lateral loading causing each section of the masonry wall to act as nearly independent sections of brick.

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[1] Dizhur, Dmytro. "In-situ Out-of-plane Airbag Characterization Report." *WILISCOURT APARTMENTS*

[2] Walsh, Kevin, Dmytro Dizhur, and Jason Ingham. "Testing of 151-165 Victoria Street West, Auckland CBD Automotive Garage: Proposed Work Programme."

Appendix:



Figure 18: Reid Bolts placed in wall 1.



Figure 19: Reid ties just before complete failure of wall 1. Complete separation of tensile leaf at crack.



Figure 20: Hilti ties during testing of wall 2.



Figure 21: Hilti Tie after complete failure of wall 2.



Figure 22: Wall 3 Helifix ties just before complete failure



Figure 23: Helifix tie still in place after failure, slightly bent.



Figure 24: Crack placement on wall 3 (left), wall 2 (middle), and wall 1 (right)



Figure 25: Wall 4 crack pattern during testing.



Figure 26: Wall 4 bulging at the center during testing.



Figure 27: Wall 5 with simulated in-plane crack just prior to complete failure.



Figure 28: Wall 5 after failure of wall.