In-situ out-of-plane testing of unreinforced masonry wall segment in Wintec Block F building

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2010 NZSEE Conference

ABSTRACT: Most research considering seismic assessment of URM walls has been conducted using laboratory-based studies with well defined but artificial conditions. Thus, in-situ testing is required to provide data with which to validate the accuracy of laboratory-based studies of URM walls. Seismic strengthening of the Wintec Block F building in Hamilton allowed an opportunity for a team of researchers from the University of Auckland to conduct in-situ testing of a wall segment in the building. This allowed comparison with companion experiments that had previously been undertaken in a laboratory setting. This field testing involved the extraction of clay brick and mortar samples, flexural bond tests, and out-of-plane testing of a wall both in the as-built condition and after the installation of a near-surface mounted (NSM) carbon fibre reinforced polymer (CFRP) retrofit solution. Testing confirmed that the boundary conditions in real buildings can significantly affect experimental response, and also confirmed that the near-surface mounted FRP solution is an excellent low-invasive option for seismic strengthening of unreinforced masonry buildings. Details of the history of the building and the methods used to undertake the field testing are reported, and experimental results are presented.

1 INTRODUCTION

Unreinforced masonry (URM) walls were commonly used as interior partitions and/or exterior perimeter walls in buildings constructed prior to the 1931 Hawke's Bay earthquake (Dowrick 1998). These walls often have insufficient strength to resist lateral earthquake forces in high and moderate seismic zones and lack the ability to dissipate energy.

One of the most critical deficiencies of URM buildings is their out-of-plane seismic response (Griffith et al. 2003). Most research considering out-of-plane seismic assessment of URM walls has been conducted using laboratory-based studies with simulated boundary conditions. Thus, in-situ testing is required to provide data to validate the accuracy of laboratory-based studies on out-of-plane wall behaviour. In 2009, a testing opportunity became available when the lateral load resisting system of Block F of the Wintec building was scheduled to undergo seismic strengthening. The 3 storey building located in Hamilton, New Zealand, was originally built in 1917 and was comprised of unreinforced masonry perimeter walls with cement plaster on the interior and brick veneer on the exterior faces of the wall, with the interior walls plastered on both sides. The interior 2 leaf thick partition wall, scheduled for demolition, was tested in-situ in the out-of-plane loading direction, first in the as-build condition and then seismically retrofitted (repaired) with vertically positioned Near Surface Mounted (NSM) Carbon Fibre Reinforced Polymers (CFRP) strip. The in-situ test results of the as-built and the NSM retrofitted URM wall subjected to out-of-plane lateral loading, test methods used and material properties of the building are reported.

2 BUILDING DESCRIPTION

Wintec is one of New Zealand's largest Institutes of Technology/Polytechnics (ITPs) and is a provider of vocational and professional education in the Waikato region. The condition remediation and seismic strengthening of the F Block building near the corner of Anglesea and Ward Streets was part of Wintec's on-going project to modernise its Hamilton city campus (Refer to Figure 1 for building location).

The nearly 100-year-old building required earthquake strengthening to comply with New Zealand Standard NZS 1170.5:2004 – Earthquake Actions (SNZ 2004). The corner of F Block had a Historic Places Trust category B rating, implying that the facade of the former Hamilton Technical Day School had to be preserved. Additional extensions along Anglesea and Nisbett Streets were completed in 1934 and 1948 respectively, resulting in an ’L shaped’ building with approximate footprint dimensions of 31 m × 45 m that became the Hamilton Technical College in 1945. Distinctive internal features of Block F which required preservation included terrazzo flooring and a curved staircase with iron balustrades and wood banisters.

The original building was constructed of unreinforced masonry with perimeter load bearing walls comprised of 3 to 4 leaf thick masonry with cavity veneer on the exterior and cement plaster on the interior. The later additions to the south east end of the building were constructed using reinforced concrete type construction. The original URM perimeter and internal walls contained a reinforced concrete ring beam on the top portion of walls on level 1 and level 2. The concrete ring beam depth was 400 mm with thickness to match that of the walls and was located along all of the walls at a constant elevation (including the non-load bearing walls). The main masonry type for the original building consisted of dark yellow coloured bricks with hard cement-lime mortar. Some portions of walls, on the second level, consisted of a mixture of dark red and dark yellow bricks scattered around the building in clusters. The floor and roof diaphragms in the building were constructed from Matai timber and the ground floor diaphragm consisted of timber joists, 190 mm × 45 mm, spaced at approximately 450 mm c/c. A moderate number of joists were in poor condition with moisture and insect damage. The floor diaphragm on the first level consisted of 450 mm × 45 mm timber joists spaced at approximately 450 mm c/c with 45 mm thick flooring.

(a) Wintec Block F satellite view, Hamilton

(c) Wintec Block F, located at the intersection of Anglesea and Ward Streets, Hamilton

Figure 1: Wintec Block F building

3 MATERIAL PROPERTIES

The material properties of Wintec Block F were determined by conducting laboratory tests on samples that were extracted from a wall scheduled for demolition. From visual observations, the constituent materials of the building were of good quality. Figure 2 illustrates the masonry type resident within the wall that was subjected to in-situ tests and the sample extraction procedure. This type of masonry was uniform throughout the first level of the building, and consisted of dense and hard 75 mm × 220 mm × 105 mm dark yellow bricks, and 12 mm thick cement-lime mortar with wire nets embedded within the mortar joints at irregular intervals. The internal walls were covered by a 15 to 20 mm thick cement plaster (which in places had been removed for remedial work). Irregular mortar samples, single bricks and two and three brick high masonry prisms were extracted from the building and tested in the laboratory.

According to the NZSEE recommendations for assessment of buildings (NZSEE 2006), the bricks were classified as soft bricks based on their physical characteristics, with a suggested compressive strength of 1-5 MPa. Half bricks were tested in accordance with ASTM C 67 – 03a (ASTM 2003a) and an average compressive strength of 25.9 MPa was obtained, indicating that the NZSEE recommendations considerably underestimated the brick compressive strength.

The mortar compressive strength was investigated by conducting compression tests in the laboratory on irregular mortar samples. The compression test recommended in ASTM C 109 – 08 (ASTM 2008) was not possible as 50 mm cube samples are generally unattainable from existing URM buildings, where mortar joints are only 15 to 20 mm thick. Instead, irregular samples were cut into approximate cubic shapes and tested in compression as shown in Figure 2 (c) and (d).

Three brick high masonry prisms were prepared for laboratory compression testing compliant with ASTM C 1314 – 03b (ASTM 2003b).

The results obtained from the aforementioned results are summarised in Table 1.

(a) Wall subjected to in-situ tests (b) Sample extraction (c) Irregular mortar samples d) Mortar compression test

Figure 2: Materials in Wintec Block F building

Table 1: Summary of material properties

Test type	Number of Samples	Average compressive strength (MPa)	CoV	Average E (GPa)
Compression of irregular plaster cubes	7	15.1	0.31	-
Half brick compression	5	25.9	0.25	-
Compression of irregular mortar cubes	4	22.4	0.19	-
Masonry prism compression	8	9.7	0.18	2.6
Masonry flexural bond	2	0.50*	-	-

* Average flexural bond strength in MPa

4 EXPERIMENTAL PROGRAM

Due to time limitations on site, only three out-of-plane tests of the URM wall were conducted at the Wintec Block F, two being in the as-build condition and one in the retrofitted (repaired) condition. A non-load bearing, 2-leaf clay brick masonry partition wall lined with 15-20 mm thick cement plaster finish on both sides was selected for testing. In order to simplify the test and to provide direct comparison to laboratory-built companion experiments, a 1250 mm wide wall segment was isolated from the rest of the wall, to induce one way flexural bending. The wall segment was isolated by cutting vertically through the wall using a concrete cutting chainsaw, with the vertical cuts made on an inward angle to eliminate wedging effects of the wall. The location of the wall segment was selected adjacent to the door opening to minimise the length of cutting required.

Due to the presence of the concrete ring beam, the as-built testing consisted of two schemes and investigated the effects of different boundary conditions. The first scheme, designated AS-CB, involved cutting the wall segment up to the concrete ring beam and testing with the continuous concrete beam extending across the wall segment. This provided a “fixed” boundary condition at the top part of the wall, inducing arching action of the wall segment. The second scheme, designated AS-SS, involved cutting the concrete ring beam, including the beam’s longitudinal reinforcement and constructing an additional horizontal support at the top of the wall segment as shown in Figure 3.

Following the completion of the two as-built tests the wall segment was retrofitted (repaired) using the NSM technique with vertical CFRP strips embedded into the plaster layer only and the test was repeated, designated R-SS. The purpose of the repair was to observe the effects that the NSM retrofit technique had on wall flexural strength and stiffness when only the thickness of the plaster layer was utilised. The wall was loaded and unloaded several times during AS-CB, AS-SS and R-SS tests to examine if cyclic loading resulted in stiffness degradation.

5 TEST SETUP

Loading was applied by gradually inflating the Bigfoot™ vinyl airbag positioned in a gap of 25-35 mm between the wall segment and the plywood backing. The plywood backing consisted of an assemblage of plywood sheets and steel angles and was supported by a reaction frame consisting of vertical and diagonal timber members bolted to the timber rails to transfer horizontal loads into the masonry wall located parallel to the subject wall (shown in Figure 4). The cross-section of the setup is shown in Figure 3. The applied load from the airbags was transferred to the plywood backing and to the reaction frame using four S-type 1000 N load cells which were attached between the plywood backing and reaction frame and provided horizontal stability to the frame. To ensure that the entire load was transferred through the load cells, frictionless plates were used underneath the plywood backing. The setup closely resembled the setup successfully used to conduct previous field out-of-plane testing on URM walls (Dizhur et al. 2009, Dizhur et al. 2010a and Dizhur et al. 2010b). Out-of-plane displacement was measured using 2 Linear Variable Differential Transducers (LVDT) mounted on the opposite side of the wall. One LVDT was placed mid-height and at the wall centreline, and the second was placed 1000 mm below the top of the wall.

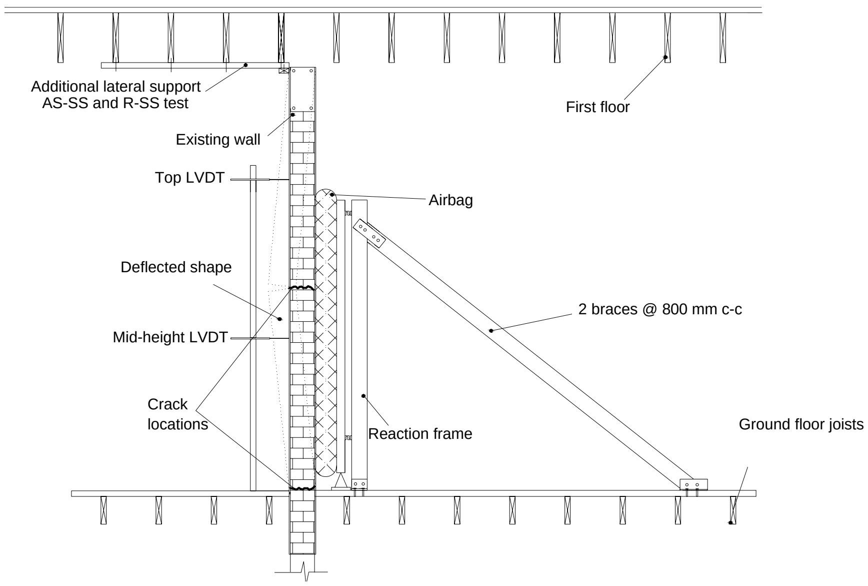
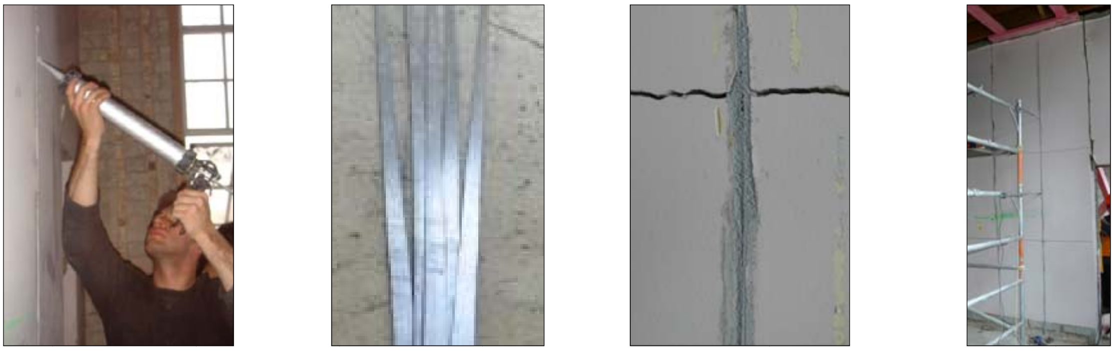


Figure 3:Cross-section of the out-of-plane test setup

Figure 4: Out-of-plane test setup

6 RETROFIT SCHEME

Using FRP material to retrofit URM walls is a technique for strengthening and increasing the ductility capacity of URM walls subjected to in-plane and out-of-plane earthquake loading. Externally bonded (EB) FRP sheets or plates and NSM FRP bars or strips are the two application techniques that are commonly used (Mosallam 2007, Yasser and Robert 2006). Using the NSM technique provides some protection from fire and the environment and if detailed correctly, does not adversely affect the aesthetics of the structure (Petersen and Masia 2008). In this field experiment, the simulated seismic performance of NSM CFRP strip was investigated.



(a) Two part epoxy application

(b)15 mm × 1.2 mm CFRP strips

(c) CFRP strip continues through the crack

(d) CFRP strip extends full wall height

Figure 5: CFRP retrofit application procedure

A single CFRP strip (Young's modulus of 165 GPa) 15 mm wide × 1.2 mm thick was positioned vertically in the centre of the wall test section and extending from top to bottom following AS-CB and AS-SS tests, as shown in Figure 5. A groove was cut into the 15-20 mm plaster layer only, using an angle grinder (6 mm thick blade) to a depth of approximately 15 mm and a two part epoxy was used to bond the CFRP strip into the groove. Prior to insertion of the CFRP strip the groove was entirely filled with epoxy to ensure maximum bond area and 72 hours were allocated for the epoxy to set.

7 EXPERIMENTAL RESULTS

7.1 Testing of as-built wall segment

Test AS-CB test was performed by uniformly increasing the pressure in the airbag until the capacity of the setup was reached. At the maximum loading pressure no evidence of wall movement at the boundaries and no cracks were visually detected on the wall surface. Due to a potentially explosive brittle failure of the wall, attributed to the sudden release of potential energy stored in the airbag and limitations of the setup, the airbag pressure was not further increased. Consequently, the obtained results (shown in Figure 6) for AS-CB test were within the elastic range.

Following the preparation for the AS-SS test, the pressure in the airbag was again gradually increased until the sudden formation of a large crack and a displacement of approximately 30 mm was observed. The force to develop the crack was not only attributed to the bond strength of the mortar joint but also to the relatively small portions of brick that remained uncut within the vertical wall segment. The single crack was located at 2250 mm above the floor level, at 56% of the wall height as shown in Figure 7. The test was continued until mid-height wall displacements of up to 135 mm were reached, at which point the testing was stopped and the air bags deflated. Three semi-cycles were performed with the resulting total lateral force - mid-height displacement response is shown in Figure 6. The wall segment had 19 mm of residual displacement after the completion of test AS-SS.

The location of crack formation at 56% of the strip height during test AS-SS was comparable to the results obtained during laboratory testing of walls with similar geometry. Also, the measured post-cracking behaviour of the tested wall (AS-SS test) closely matched the corresponding prediction using a tri-linear model (shown in Figure 6) developed based on laboratory testing conducted at the University of Auckland (Derakhshan et al. 2009). It is clear that boundary conditions that are encountered in real buildings are different from those simulated in the laboratory. Therefore, further investigation and analysis is required prior to establishing any recommendations on the assessment of such walls.

Using the New Zealand Standard, NZS 1170.5:2004 - Earthquake Actions (SNZ 2004), assuming a shallow soil site, an annual probability of exceedance of 1/500 and a near-fault factor of 1.0, the wall strip was predicted to encounter a face pressure loading of 2.93 kPa during a design level earthquake. Figure 6 clearly shows that during testing, the face pressure value specified by NZS 1170:5 was exceeded for the AS-CB test, but not for the AS-SS test. This indicated that the simply supported walls required seismic strengthening (all walls in the building were bounded by a concrete ring beam).

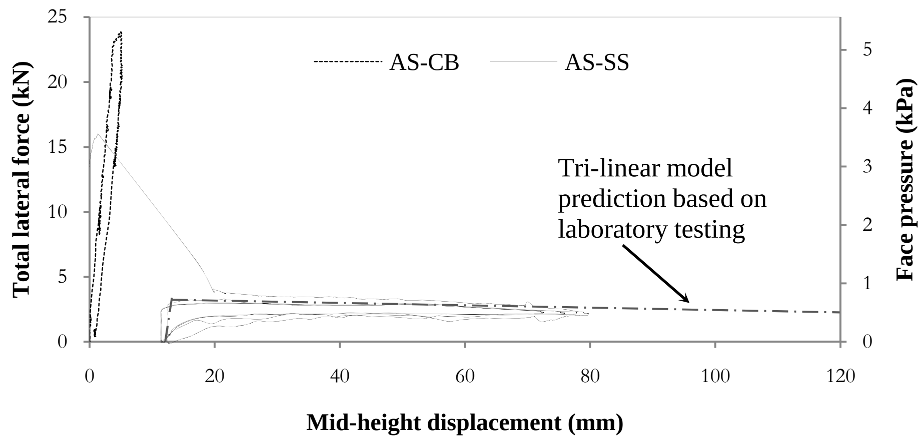


Figure 6: Total lateral force - mid-height displacement response for AS-CB and AS-SS tests

(a) Cutting through concrete ring beam (b) AS-SS test crack location

Figure 7: Out-of-plane tests

7.2 **Testing of retrofitted wall segment**

The repaired wall segment was tested using the same setup and boundary conditions as used for the AS-SS test. The pressure was increased until visible cracking in the vicinity of the strip occurred, the airflow was then paused (without releasing the airbag pressures) and crack locations (as shown in Figure 8) were observed and marked.

The test was continued until moderate cracking in close proximity to the CFRP strip occurred and a total mid-height lateral wall displacement of 60 mm was reached, with five additional semi cycles performed to the same displacement level. The resulting lateral force - mid-height displacement response is shown in Figure 9. It should be noted that the noise in the data was due to timber floor vibrations (foot traffic) on which the LVDT's support frame was resting.

The pressure in the airbag was increased further until a total displacement of 100 mm was achieved, at which point severe cracking and spawling of the plaster layer occurred. Most of the severe cracks were concentrated at the lower portion of the wall strip (refer to Figure 8). The total lateral force - mid-height displacement response for the severe cracking stage is shown in Figure 8, which illustrates that there was a dramatic decrease in the stiffness with increasing displacement. The residual displacement was approximately 60 mm following completion of the R-SS (severe damage) test. Figure 8 shows the cracking pattern for the tension side of the wall segment.

(a) Moderate cracking during R-SS test | (b) Severe cracking of the plaster during R-SS test | (c) Close-up of the crack pattern | (d) Close-up of the CFRP strip

Figure 8: Crack pattern for R-SS test

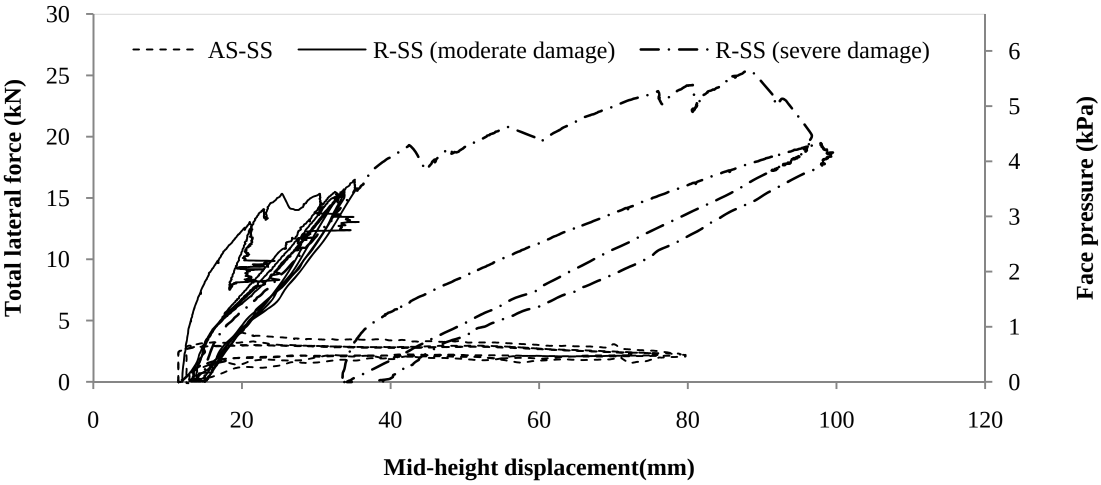


Figure 9: Total lateral force - mid-height displacement response for R-SS test

8 CONCLUSIONS

The material properties of Wintec Block F were determined by conducting laboratory tests on extracted samples. The average brick compression strength was determined to be 25.9 MPa while the average three brick high prism compression strength was 9.7 MPa, with a Young's Modulus of 2.6 GPa. The average compressive strength of irregular mortar cubes was 22.4 MPa and the average flexural bond strength was 0.50 MPa. It was concluded that NZSEE recommendations considerably underestimated the brick compressive strength.

The AS-SS test verified a previously obtained laboratory-based wall behaviour model, and the experimental test results showed that the wall segment satisfied the current New Zealand seismic load requirements with original top support condition only.

A single CFRP NSM strip was shown to dramatically increase the post-cracking wall strength. As shown in Figure 8, the flexural strength increased by over 5.25 times. Also, it has been shown that a strong cement plaster layer does not require removal and could be utilised for the NSM seismic strengthening technique. It has been shown that a single CFRP strip embedded into the plaster layer provides sufficient increase in flexural strength to meet the current New Zealand seismic load requirements. Even though further research is required to accurately establish the design guidelines for this type of retrofit, this testing has illustrated that this retrofit technique provides a simple and cost effective alternative to seismically strengthen URM buildings and their components.

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