LABORATORY TESTING OF UNREINFORCED MASONRY WALLS RETROFITTED WITH GLASS FRP SHEETS

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SUMMARY

Unreinforced masonry (URM) structures are prone to earthquake damage. The presence of a significant number of URM buildings exposes New Zealand to the possibility of substantial human and financial losses in the event of a major earthquake. A URM seismic retrofit research project is being conducted in New Zealand to investigate the effectiveness of fibre reinforced polymer (FRP) materials as a seismic retrofit solution. As part of the project, in-plane cyclic shear tests have been performed on an as-built URM wall and on a FRP-retrofitted companion wall that has been retrofitted in a manner that enhances only its shear strength. Preliminary results indicate a positive impact of the application of FRP. Further tests are planned on URM walls and assemblages retrofitted with different FRP materials and forms.

INTRODUCTION

Unreinforced masonry (URM) structures have repeatedly been shown to behave poorly in earthquakes (Bruneau 1995, Mehrabian and Haldar 2005). This is true especially for older URM structures, which were designed to withstand gravity and wind loads only. Such structures are highly susceptible to damage during an earthquake. The damage can range anywhere between minimal structural cracking to full collapse of the structure (Bruneau 1994).

New Zealand is one of the most active seismic places on the earth (Natureandco.com). It lies at the edge of the Australian and Pacific plates (Figure 1). Past earthquakes in the region have caused major losses. The most significant of these earthquakes was the 1931 Hawke's Bay Earthquake that resulted in the death of 256 people and caused widespread damage in the Hawke's Bay region (Dowrick 1998). Most of the dwellings in the area were URM. The popularity of URM in New Zealand decreased after that earthquake. Use of URM was also restricted under government regulations after the introduction of the building bylaws NZS 1900 (Holmes 1965). The current New Zealand masonry design standard NZS 4230:2004 refers only to reinforced masonry structural elements (Standards New Zealand 2004). However, the current New Zealand building stock consists of a significant number of URM structures. Many of these buildings form a part of New Zealand's architectural heritage. Unfortunately, these structures also constitute seismic hazard to New Zealand's citizens. The New Zealand Building Act 2004 (Department of Building and Housing 2004) requires such

structures to be either demolished or upgraded to ensure their safety under moderate earthquakes.

Figure 1. The geological setting of New Zealand (Reproduced with permission of GNS)

Various techniques have been employed to retrofit existing URM structures. The conventional techniques such as post-tensioning and adding steel reinforcements present complications in their application due to excessive time required for application, disruption of operations and difficulties in handling of materials. Also, the weight of conventional materials such as steel and concrete adds significant mass to a structure, resulting in the increase of inertia forces in an earthquake. Corrosion of steel reinforcement is also a concern. In recent years, FRP materials have emerged as a promising alternative retrofit solution. FRP materials are light-weight and quick to apply. They can be applied without significantly disrupting building operations. Moreover, the materials are non-corrosive and electromagnetically inert. Their cost has also dropped significantly since their introduction in the early 1990s.

FRP materials were first tested as a URM seismic retrofit solution by Schwegler (1994). Schwegler conducted in-plane shear tests on walls retrofitted on either one or both faces with carbon FRP (CFRP) plates. The test results were compared with unretrofitted walls. The comparison showed that the application of FRP significantly increased the lateral capacity of the test walls. Similar tests have since been reported by a number of other researchers (Triantafillou 1998, Holberg and Hamilton III 2002, Stratford et al. 2004, Santa Maria et al. 2006, Elgawady et al. 2007). The application of FRP retrofits has been shown to enhance the lateral load-carrying capacity of URM walls. Mixed results have been obtained for ductility. The pattern of FRP application can affect the failure mode – brittle or ductile.

Full theoretical strength of FRP is often not utilised due to premature debonding of FRP from the URM substrate. FRP debonding strength can be related to the quality of the bond between FRP and the substrate. The bond strength has been reported to vary with the surface finishing of URM walls, type of FRP (plate, sheet, near surface mounted), shape of FRP (round, rectangular) and type of substrate (clay, concrete, stone) (Tumialan et al. 2003, Galati et al. 2006, Marcari et al. 2007).

RESEARCH PROGRAMME

A research program has been designed at The University of Auckland, New Zealand to investigate the effectiveness of FRP as a seismic retrofit solution for New Zealand URM structures. The goals are to evaluate the strength and ductility capacity of URM buildings using different FRP forms and application patterns. More information about the project can be found at http://www.retrofitsolutions.org.nz.

As part of the initial investigations, cyclic in-plane shear tests were conducted on two URM walls. The main purpose of these tests was to study the cyclic shear behaviour of URM walls built using New Zealand materials. One of the walls was tested as-built. The other wall was retrofitted externally with glass FRP (GFRP) sheets. The displacement-controlled lateral force was applied to the top of the test walls using a hydraulic actuator. Description of the test walls, test setup, testing procedure and preliminary results is given in the subsequent sections.

TEST WALLS

The test walls were built by a professional bricklayer using recycled bricks. The bricks were obtained from demolished buildings and cleaned for use in the tests. A weak mortar mix, ASTM type 'O' (1:2:9 cement/lime/sand by volume) was selected to simulate decayed mortar in old URM structures. Each test wall measured 1970 mm long × 1970 mm tall × 240 mm thick. The walls were built two leaves thick in the common bond pattern, with header courses every fourth course. The masonry materials and bond pattern were selected to replicate the construction materials and practices most commonly encountered in old New Zealand URM structures. The walls were built intentionally in a way that closely reproduced the observed, often deteriorated, finish quality of walls in real buildings.

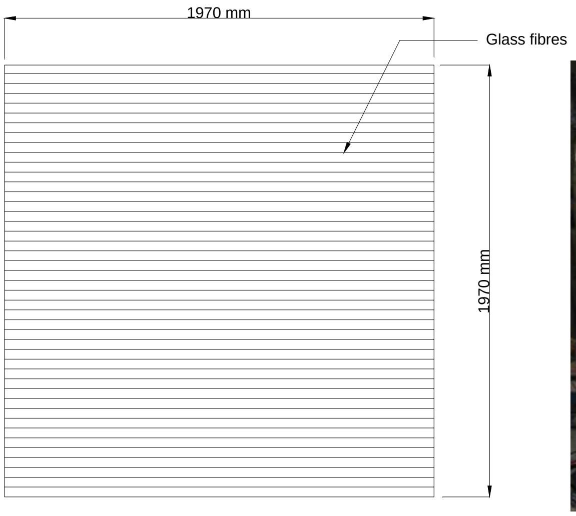
One wall was left as-built for comparison of the test results and behaviour with the retrofitted wall. Figure 2 shows the as-built test wall. The other wall was retrofitted using uni-directional glass FRP (GFRP) sheets. The manufacturer-provided typical properties of the sheet are given in Table 1. The decision to use GFRP was taken on the basis of cost and often-reported lack of additional strength gain with the more expensive alternative, carbon FRP (CFRP) (e.g. Albert et al. 1998). The wall was retrofitted on one face only. This is consistent with FRP retrofit practice. FRP is generally applied only on the inside face of URM walls in a building in order to preserve the architectural façade. The test wall was strengthened in shear only to allow the wall to fail in a flexural mode, which is a ductile/pseudo-ductile mode of failure. Due to time constraints, the retrofit was applied before the as-built test had proceeded. Two layers of GFRP sheet were applied for the retrofit. The glass fibres were oriented horizontally for both sheets. Figure 3 shows the fibre layout and the retrofitted wall.

Figure 2. As-built wall

The GFRP sheets were applied using a multi-stage process. First, the wall surface was ground level by an angle grinder. After grinding, the imperfections in the wall surface were filled with putty to obtain a near smooth surface. The primer epoxy coat was then applied to the wall using paint rollers. Separately, a GFRP sheet was saturated with epoxy. The saturated sheet was positioned on the wall by hand and worked against the wall by paint rollers to achieve a good bond. The sheet was anchored at its ends to the wall by fibreglass anchors to avoid premature delamination failures. The second sheet was bonded to the first sheet using epoxy. The FRP sheets were left to dry for a period of two weeks. During this period, heating lamps were used to accelerate the curing process.

Table 1: Typical properties of GFRP sheet (Material data sheet)

Property	*Typical test value*
Ultimate tensile strength in primary fibre direction, MPa	575
Ultimate tensile strength perpendicular to primary fibres, MPa	43
Elongation at break, %	2.2
Tensile modulus, GPa	26.1
Laminate thickness, mm	1.3



(a) schematic FRP layout

(b) FRP-retrofitted wall

Figure 3. FRP configuration

TEST SETUP

Figure 4 shows the test setup. The test walls were built directly on the strong floor. A layer of strong cement/sand mortar was spread on the strong floor before laying the first course of the wall, to provide adequate bonding with the strong floor. Two loading systems were incorporated into the test setup: to apply lateral forces and provide axial loads. Displacement-controlled lateral forces were applied by means of a hydraulic actuator. The hydraulic actuator was connected between the strong wall and a steel beam bonded to the top of the test wall, for uniform distribution of the lateral force over the length of the wall. This arrangement approximated the diaphragm-wall earthquake force transfer mechanism in a URM building. Vertical load was simulated using four external stressing tendons, two on each side of the wall. The tendons were anchored to the strong floor. The required stressing force was applied to the top of the tendons by a hydraulic jack. The force was transferred to the test walls by stiff steel beams pivoting on the steel beam bonded to the wall top. Coil springs were provided to facilitate the maintenance of a constant prestress load.

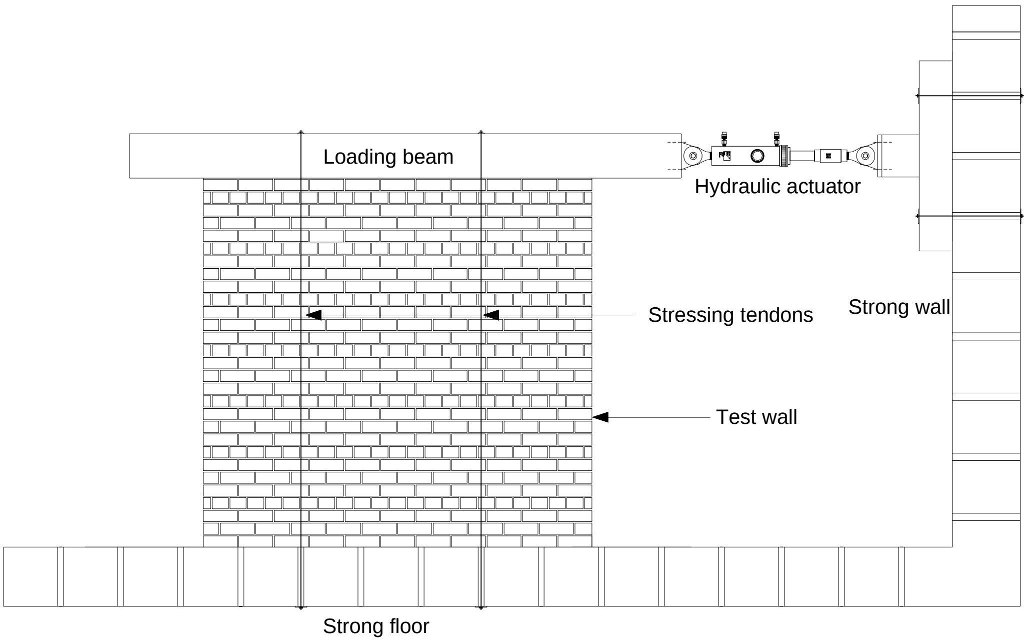


Figure 4. Test Setup

INSTRUMENTATION

The following instrumentation was used:

Load cells: One load cell was connected to the hydraulic actuator to measure the lateral force applied to the walls. Two load cells were used to monitor axial forces in the stressing tendons during the test.

Portal transducers: Portal transducers were used to measure displacements in the test walls. Top lateral displacement was measured by connecting a portal transducer between the end

face of a wall and a stiff frame. In-plane wall displacements were determined by mounting portal transducers on one face of a test wall.

Strain gauges: Foil-type strain gauges were fitted on the sheet-face of the retrofitted wall. The gauges were oriented parallel to the direction of fibres to monitor strains in the GFRP sheet at different loading intervals.

Data acquisition: Test data was acquired by an electronic data logger.

TESTING PROCEDURE

Axial load was applied to the test walls before the application of lateral forces. A superimposed axial load of 160 kN (0.34 MPa) was applied to the wall. This corresponds to the superimposed axial loads on the URM walls in the lowest storey of a 5-storey building with timber floors. After stressing the tendons to the required level of force, an initial load cell reading was taken.

After the application of axial load, the lateral cycles were commenced. All loading cycles were displacement-controlled, with two cycles at each displacement level to obtain a stabilised crack pattern. This also verified the lateral force values at each displacement level. A test wall was initially pushed to 0.5 mm. The test was paused at this displacement level to inspect the wall and FRP sheet for any damage/debonding. The displacement was then released to bring the wall back to the original position. After this, the wall was pulled to 0.5 mm and the procedure was repeated. The displacement increment was maintained at 0.5 mm up to a displacement of 2 mm. For displacements greater than 2 mm, the increment was increased to 1 mm. The complete displacement cycle history is shown in Figure 5. The test was stopped after a definite failure mode was established.

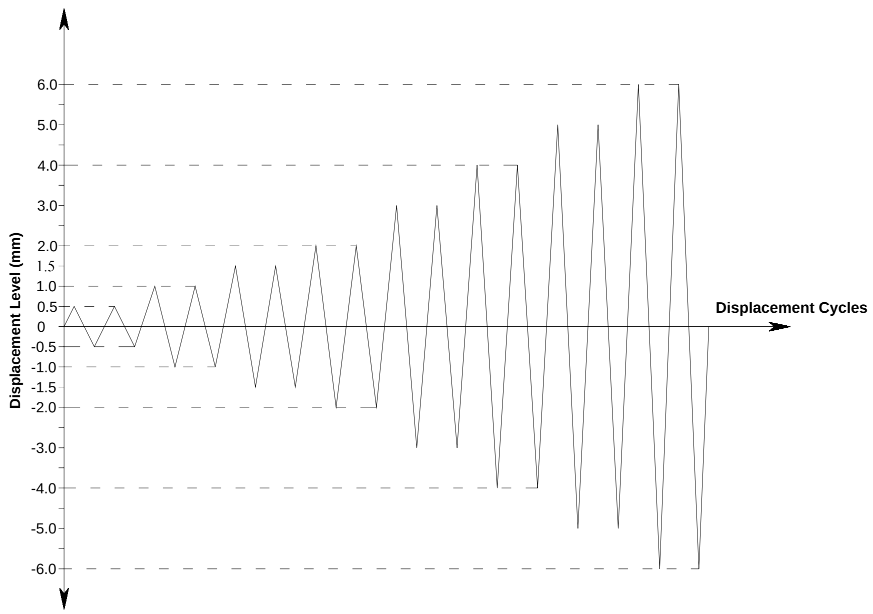


Figure 5. Displacement cycles

PRELIMINARY TEST RESULTS

As-built Wall: The as-built wall deformed by rocking. Initial cracking was observed at a displacement of 2 mm. The first crack appeared at the right edge of the wall, three courses above the wall base. The corresponding lateral force was 74 kN. With increasing displacements, the crack propagated towards the other edge of the wall. Another crack appeared on the left side of the wall at 5 mm push displacement. At larger displacements, both cracks joined and the wall started to rock at 3-4 courses above its base. This test was continued beyond 6 mm displacement. However, results only up to 6 mm displacement are reported here. An increase in lateral force was observed after initial cracking

Lateral strength of the rocking as-built wall, V_r was computed per FEMA 356 (ATC 2000) as

$$V_r = 0.9\alpha P\left(L / h_{eff}\right) \quad (1)$$

where α = factor equal to 0.5 for fixed-free cantilevers; P = total gravity load on the cracked section = 184 kN for this wall; L = length of the wall = 1970 mm; and h_{eff} = height to the resultant of lateral force = 1760 mm, smaller than the total wall height due to failure three courses above the wall base. Using the above values, the rocking capacity, V_r, of the wall was computed equal to 92.70 kN. The actual strength of the wall, 74 kN, was about 20% lower than the computed lateral strength.

Retrofitted Wall: The retrofitted wall also deformed by rocking. However, unlike the as-built wall, rocking occurred at the wall base. This was attributed to the presence of FRP sheet which held together the upper masonry courses. The initial crack appeared in a pull cycle at a displacement of 2 mm. The corresponding lateral force was 79.5 kN. The first crack on the left edge of the wall was observed at a push displacement of 4 mm. Both cracks joined at the base of the wall at a displacement of 5 mm. The test was stopped at a displacement of 6 mm when the wall visibly started to rock at its base.

Lateral strength of the wall was computed using FEMA 356 (Eq. 1) by instituting the following parameters: α = 0.5; P = 187 kN; L = 1970 mm; and h_{eff} = 2040 mm. Note that the effective height of 2040 mm of the wall is greater than the actual wall height of 1970 mm due to the application of lateral forces at the centre of the loading beam (Figure 4). The rocking strength, V_r, of the wall was computed equal to 81.3 kN. The actual strength of the wall, 79.5 kN, compared well with the computed value.

Fig. 6 shows a comparison of the hysteresis plots for the both walls. The ratio of lateral force and computed lateral strength for each wall is plotted along the y-axis. Wall tip displacement is plotted along the x-axis.

Some preliminary observations have been made by comparing the hysteresis behaviour of both walls. First, the slope of the retrofitted wall is much steeper, indicating a higher stiffness than for the as-built wall. This can be attributed to the presence of vertical fibres holding the main glass fibres. Second, the graph ordinate for the retrofitted wall corresponding to first displacement level of 0.5 mm is about 25% greater in value than that for the as-built wall. This difference in ordinate values is constant until the end of the displacement cycles. Reasons for this are still being investigated. Third, a strain-hardening type behaviour is observed following the initial displacement level of 0.5 mm. This is due to increase of the post-tensioning forces as the walls rocked.

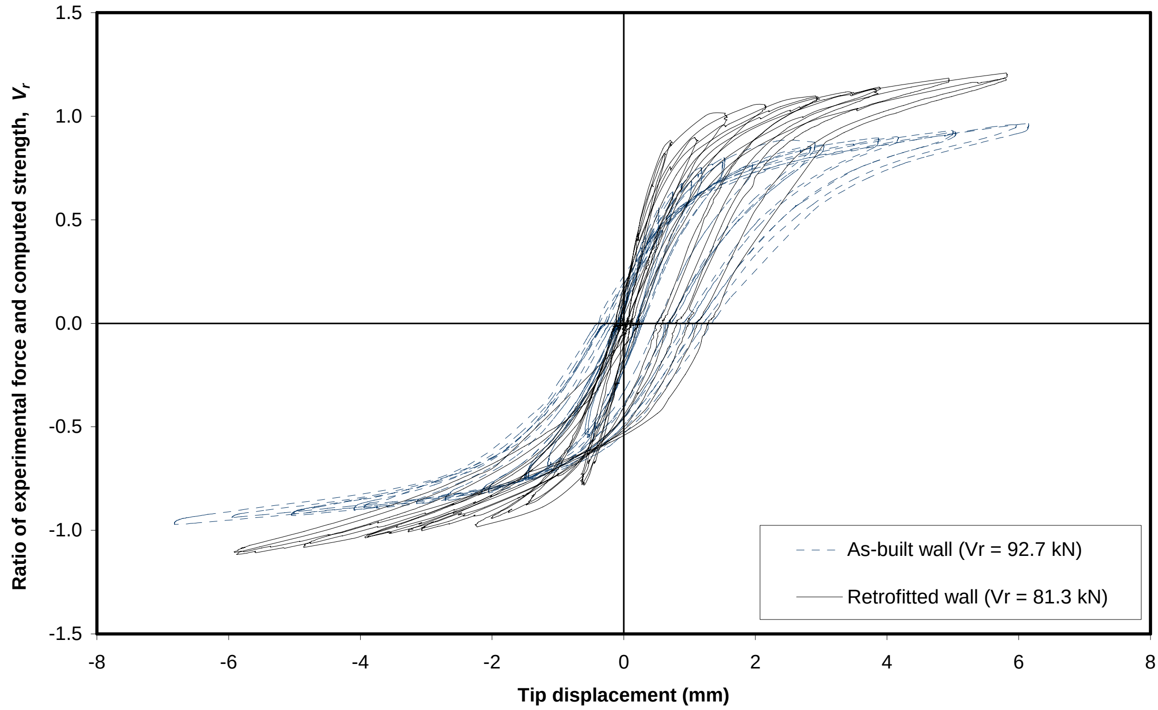


Figure 6. Ratio of the experimental force and computed strength versus tip displacement

CONCLUSIONS

This paper presents the test setup, testing procedure and preliminary test results for two almost-identical URM walls, one retrofitted with GFRP sheets, which were subjected to cyclic in-plane displacement-controlled forces. The objective was to allow rocking of the retrofitted wall, which is a suitable mechanism for dissipating earthquake energy. An increase in the lateral force capacity and stiffness of the retrofitted URM wall was achieved. Further tests are planned with different FRP retrofit schemes and forms.

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