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Earthquake Performance of Two Vintage URM Buildings Retrofitted Using Surface Bonded GFRP: Case Study

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ABSTRACT

As part of a seismic retrofit scheme, surface bonded Glass Fiber Reinforced Polymer (GFRP) fabric was applied to two unreinforced masonry (URM) buildings located in Christchurch, New Zealand. The unreinforced stone masonry Girls' High School and the unreinforced clay brick masonry Shirley Community Centre were retrofitted using surface bonded GFRP in 2007 and 2009 respectively. Much of the knowledge on seismic performance of GFRP retrofitted URM was previously assimilated from laboratory-based experimental studies having controlled environments and loading schemes. The 2010/2011 Canterbury earthquake sequence provided a rare opportunity for the GFRP retrofit applied to two vintage URM buildings to be evaluated and the performance when subjected to actual design-level earthquake induced shaking to be documented. Both GFRP retrofits were found to be successful in preserving architectural features within the buildings as well as maintaining the structural integrity of the URM walls. Successful seismic performance was based on comparisons made between the GFRP retrofitted Girls' High School building and the adjacent non-retrofitted Boys' High School building, as well as comparison between the GFRP retrofitted and non-retrofitted walls of the Shirley Community Centre building. Based on detailed post-earthquake observations and investigations the GFRP retrofitted URM walls in the subject buildings exhibited negligible to minor levels of damage without delamination, whereas significant damage was observed in comparable non-retrofitted URM walls.

INTRODUCTION

Most of New Zealand's URM building stock was constructed prior to 1935 and was typically designed with little or no consideration for lateral loads (Russell and Ingham 2010). In response to these deficiencies the New Zealand Building Act 2004 (NZ Parlament 2004) requires territorial authorities to adopt policies on retrofitting or demolition of buildings having deficient earthquake strength, and because many vintage URM structures are considered to be either 'earthquake prone' (satisfying 1/3 of current earthquake loading standards) or 'earthquake risk' (satisfying between 1/3 and 2/3 of current earthquake loading standards) these buildings must be either seismically retrofitted or demolished within timeframes set by the territorial authorities (NZSEE 2006), with the former scenario being favourable as many of these URM buildings are listed on the Register of the New Zealand Historic Places Trust. One retrofit option is the application of fibre reinforced polymers (FRP).

Fiber reinforced polymers consist of carbon, glass or aramid fibres embedded in a resin matrix to produce a high tensile strength, lightweight material. FRP has been commercially available since the 1940's and was originally used to improve the performance of vehicles for space exploration and air travel. Research on the use of FRP as a building material began in the late 1980's as it became more economically viable for structural engineering applications in concrete, masonry and timber materials (Bakis et al. 2002; Raftery and Whelan 2014). In addition to high tensile strength and low weight, FRP material is corrosion resistant and is simple to apply. The resulting thickness of FRP in structural applications is typically less than 3 mm (ElGawady and Lestuzzi 2004; Shrive 2006) which can be covered using plaster and other coatings to produce a desirable finish. These aforementioned attributes have resulted in FRP being perceived favourably as a seismic retrofit solution for existing buildings with deficient capacity and as an alternative to the provision of reinforced shotcrete or supplementary steel or reinforced concrete structure. Much of the research previously completed on FRP for structural engineering applications was focused on retrofit of deficient reinforced concrete frame structures. However, due to a vast number of earthquake vulnerable unreinforced masonry (URM) buildings worldwide, the use of FRP as a retrofit solution for URM structures has received increasing attention.

Past research undertaken on URM walls retrofitted using surface bonded Glass (G) FRP to enhance the in-plane seismic performance reported an increase in shear strength (Tumialan et al. ; Albert et al. 2001; Gustavo et al. 2003; Stratford et al. 2004; ElGawady et al. 2005b; ElGawady et al. 2005a; Marcari et al. 2007; Moon et al. 2007; Mosallam 2007; Alcaino and Santa-Maria 2008; Mahmood and Ingham 2011; Dizhur et al. 2013; Zhou et al. 2013). The general consensus from previous research is that application of surface bonded FRP materials reduces the effects of URM material variability and favourably improves the ductile behaviour of retrofitted URM walls. ElGawady et al. (2006) previously reported that the lateral resistance of URM walls retrofitted using surface bonded FRP was improved by a factor ranging between 1.3 and 2.9. When the FRP was detailed to cross the critical failure plane, the application of surface bonded FRP postponed the onset of in-plane failure of diagonal step cracking and also postponed the onset of rocking (flexural failure) and bed joint sliding. Collapse of tested walls was also delayed when subjected to large lateral wall deformations and the FRP fabric reduced the risk of falling debris, alleviating the potential hazard of injury to the public in the vicinity of the building (ElGawady et al. 2006).

Apart from a small number of previously reported seismic performance of real FRP retrofitted masonry structures (Foraboschi 2013), much of the knowledge on the seismic performance of GFRP retrofitted URM was previously assimilated from laboratory-based experimental studies having controlled environments and loading schemes. The 2010/2011 Canterbury earthquake sequence provided a rare opportunity for the GFRP retrofit applied to vintage URM walls of the Girls' High School and the Shirley Community Centre to be evaluated and the performance when subjected to actual earthquake induced shaking to be documented. Detailed earthquake damage observations, qualitative comparisons and assessment of design loads relative to experienced level of earthquake induced shaking are presented herein for the two subject buildings.

GFRP RETROFIT DETAILS

Girls' High School (GHS) Building

A detailed history of the Arts Centre of Christchurch was previously reported by Bailey et al. (2014). The specific building of interest within the Arts Centre precinct is the Girls' High School (hereafter GHS) building (see **Figure 1**), which was constructed in 1878 using unreinforced masonry consisting of Port Hills volcanic basalt stones and limestone facings in the same Gothic style as adopted for the previously completed Arts Centre buildings (Bailey et al. 2014). Additions to the building were constructed in 1893, mainly consisting of clay brick masonry construction faced with unreinforced stone masonry finish, and further additions were made in 1902.

Seismic retrofit of the GHS building began in the 1980's with bracing of the roof diaphragm being instituted throughout the structure. In 2007 the GHS building underwent further seismic retrofit, with the application of a GFRP retrofit completed in conjunction with diaphragm improvements and the addition of structural steel framework. The use of single sided surface bonded GFRP sheets was considered to be a suitable retrofit option due to the presence of URM shear walls on which extensive areas of GFRP fabric could be adhered to. In literature it is stated that single sided surface bonded GFRP sheets result in less effective improvement. In wall components found in real buildings, where restraint of all the wall edges is typically provided by the wall-diaphragm connections and/or continuity of the wall and the single sided application of GFRP sheets is of lesser concern. As can be seen in **Figure 2**, the selected walls for GFRP retrofit application provided continuous areas with few perforations. The ability for the GFRP retrofit to be applied to specific targeted areas of weakness in order to achieve the increased shear and flexural strength to contribute to the overall strength of the structure was advantageous and made GFRP an economically viable retrofit solution for the GHS building. Installation of diaphragm-to-wall anchorages and the addition of supplementary steel framework were implemented in order to suppress other failure mechanisms.

Installation of the GFRP retrofit involved removal of the internal wall linings and the use of structural putty filler applied to the underlying volcanic basalt. Application of additional putty filler was necessary in order to minimise sharp edges or protrusions that would otherwise cause voids under the GFRP sheets, as well as to minimise the potential for stress concentrations to the GFRP fibers and to enhance adhesion to the masonry surface. Approximately 200 m^2 of unidirectional woven GFRP fabric was applied, with the following technical product specifications: areal weight of 935±47 g/m^2, fiber density of 2.56 g/m^3, fabric design thickness of 0.36 mm; fibre tensile strength of 2.3 kN/mm^2 (nominal) and tensile elastic modulus of fibers of 76 GPa. The GFRP retrofit was designed with reference to ACI 440.2R-02 (2002) and the design guidelines provided by the GRFP manufacturer. Sufficient quantity of GFRP layers was applied in order to meet the required loading levels. The applied GFRP layers were not considered as upper limit and potential for higher strengthening actions existed. **Figure 3a** shows GFRP retrofit application by an accredited contractor prior to the re-lining of the walls to achieve a close-to-original finish. A first layer of GFRP sheets was applied followed by installation of GFRP splay anchors into holes drilled into the masonry. Splay anchors were installed in order to provide adequate connection between the GFRP fabrics and the masonry, and to minimise delamination (see **Figure 2e** and **Figure 3b**) and were typically spaced at approximately 500 mm centres around the GFRP sheet perimeter. A second layer of GFRP sheets was then applied.

Shirley Community Centre (SCC) Building

Shirley Community Centre (hereafter SCC) is a single storey building that was constructed in 1915 using unreinforced clay brick masonry, to be originally used as the Shirley Primary School. The building had a hipped roof and was constructed in the Georgian style with large and regular fenestrations as show in **Figure 4**. The perimeter walls of the SCC building consisted of two leaf thick solid red clay brick masonry with a veneer layer of yellow clay bricks on the exterior surface that was separated with a 50 mm wide air cavity.

Seismic improvement work was undertaken on the SCC building in 2009. In order to enhance the rocking and shear capacity of the URM piers along the interior wall of the northern wing corridor of the SCC building, seven individual wall areas were strengthened using surface bonded GFRP. Single layer GFRP sheets were applied onto the full height of each individual wall area with approximately 60 m^2 of fabric in total being applied throughout the SCC building. GFRP sheets used in the SCC building had the same technical product specifications as the sheets used in the GHS building. The GFRP retrofit was applied to the corridor side of the walls only, with the retrofit locations shown in **Figure 5**.

Prior to the application of GFRP fabric, the original rendering plaster was removed from the application area and the wall surface was made smooth and as flat as possible. Installation of the

GFRP fabric prior to reapplication of the rendering plaster is illustrated in **Figure 6**. The application of one layer of GFRP sheets was predominantly intended to improve the shear capacity of the individual piers. To increase the rocking capacity of the piers, approximately 12 mm diameter GFRP anchor rods were embedded 300 mm deep at 150 mm centres into the concrete strip foundation beams. A localised strip of the timber flooring was removed to allow the anchor rods to be drilled and epoxied into the concrete foundation beam. The top ends of the GFRP anchor rods were fanned out and positioned at the base of each retrofitted pier and oversplayed with the aforementioned GFRP sheets (see **Figure 6c**). In addition to the GFRP anchor rods, the rocking capacity of the piers was further enhanced by providing extra 150 mm wide strips of GFRP fabric bonded along the full height of the pier edges (see **Figure 6b** and **c**).

The out-of-plane stability to the perimeter walls of the SCC building was enhanced by using vertically oriented steel hollow sections as strong backs regularly fixed to the URM walls. To ensure sufficient lateral load resistance in the north-south direction, a reinforced concrete shear wall was also added at the location shown in **Figure 5**. The external veneer brick layer was secured to the main wall using stainless steel helical veneer ties installed at regular spacing.

CANTERBURY EARTHQUAKES

The Canterbury earthquake sequence began on 4th September 2010 and was followed by a large number of aftershocks including the more damaging 22nd February 2011 Christchurch earthquake. Bailey et al. (2014) have reported the main events of the earthquake sequence and their significance to the Arts Centre of Christchurch. Further information relevant to the general performance of URM buildings was also previously reported by Dizhur et al. (2010), Dizhur et al. (2011), Senaldi et al. (2012) and Moon et al. (2014).

The 22nd February 2011 tremor, although of shorter duration, had peak ground accelerations (PGA) equivalent to or of greater intensity than that considered in new building design standards at the time (Bradley et al. 2014) . Christchurch Hospital (CHHC) was identified as the location of the closest strong motion recording station to the Christchurch Arts Centre, where a PGA of 0.17g and 0.37g was recorded, with the principal motion felt in the east-west direction during the 4th September 2010 and 22nd February 2011 earthquakes respectively (Bradley et al. 2014). The design level PGA for new construction at the time of the earthquake was equivalent to 0.36g (Standards Association of New Zealand 2004), but it is understood that the design PGA used at the time of the retrofit for the GHS building was 1/3 of the 0. 36g earthquake loading specified in the loadings code at the time.

Shirley Library (SHLC) was identified as the location of the closest (less than 1 km) strong motion recording station to the SCC building, where a PGA of 0.18g and 0.33g were recorded during the 4th September 2010 and 22nd February 2011 earthquakes respectively (Bradley et al. 2014). The retrofit of the SCC building was designed to 2/3 of the loading standard (Standards Association of New Zealand 2004) based on NZSEE (2006) recommended loading at the time of the design in 2007, with a horizontal design PGA of 0.25g.

PERFORMANCE OF GFRP RETROFITED WALLS

Performance of GHS Building

The interior plasterboard covering the GFRP retrofit was removed following the 22nd February 2011 earthquake in test locations throughout the GHS building in order to observe the performance of the retrofit. From the exposed locations there was no evidence to suggest delamination of the GFRP from the stone masonry substrate. Minor cracks were observed in the interior plasterboard in localised areas. One of these areas was around the chimney that acted as a heavy weight cantilever, resulting in significant cracking throughout the surrounding area.

Overall, the GFRP retrofit contributed to the preservation of a number of architectural features, such as the pressed ceiling detailing, with the building requiring only minor repair. Although the retrofit of the GHS building significantly improved the seismic performance of the building and resulted in an overall global minimisation of structural damage, the building's connection and proximity to the substantially damaged nearby West Lecture building resulted in the GHS building having limited access while the remainder of the centre underwent repair and stabilisation work. The Boys' High School building is located within the same complex as the GHS building and was analysed in detail in order to provide a benchmark comparison for the performance of the GFRP retrofit. The construction of these two buildings was completed at approximately the same time (Bailey et al. 2014) and as can be seen from the aerial view of the Arts Centre (see elevation view GHS **Figure 7**), the two buildings have similar features and layouts. **Figure 8** shows selective examples of damage in the shear walls that was identified throughout the Boys' High School building and **Figure 9** shows comparison images of the GHS building. The Boys' High building had no FRP installed and a number of areas were identified where the retrofit may have been beneficial through increasing the shear capacity and integrity of some lateral load resisting URM walls. Although a number of minor cracking locations caused by large shear forces and differential movement between floors was identified throughout the GHS building, the level of earthquake damage was minimal when compared to that observed in the Boys' High building.

Due to the successful performance of the GFRP retrofit in the GHS building, the Old Registry building that is located at the northwest side of the Arts Centre Complex has since undergone FRP retrofit as part of the post-earthquake repairs and rehabilitation that was completed in mid-2013.

Performance of SCC Building

The SCC building performed well during the 4th September 2010 earthquake without incurring significant earthquake damage, and following the earthquake the building was reoccupied after an initial engineering inspection. Minor cracking was observed at the ceiling level and at the wall-ceiling corners. There was no visible cracking at the location of surface bonded GFRP sheets, as shown in **Figure 10a**, although there were visible cracks in the plaster in the external piers along the corridor running east-west in the south part of the building. Minor horizontal cracking and spalling of the plaster layer was observed at the northeast wall of the SCC building. In addition, a minor step-wise crack through the veneer layer was observed in the southwest corner of the SCC building.

Following the 22nd February 2011 Christchurch earthquake and subsequent aftershocks, the SCC building sustained considerably greater damage in comparison to that observed following the 4th September 2010 earthquake. However, most of the wall segments that were retrofitted using GFRP fabric overlays sustained no to minimal cracking, as shown in **Figure 10b**. In some cases (see **Figure 10c**) a vertical crack was developed at the locations where the GFRP sheets terminated, indicating minor relative movement. In two out of seven piers where GFRP fabric was applied there was minor horizontally oriented cracking observed, as shown in **Figure 10d**, with the crack widths measured as approximately 0.25 mm and predominantly extending the entire width of the wall segment. In the same wall segments, horizontally oriented hairline cracking was also observed on the opposite side of the wall to where GFRP sheets were applied (see **Figure 10e**). In places where relative movement of the timber floor diaphragm occurred the GFRP fabric was inspected for visual signs of delamination, as shown in **Figure 10f**. Movement of the timber floor diaphragm relative to the URM walls was attributed to moderate liquefaction that was observed on site.

In many cases the URM walls in the SCC building that had no GFRP fabric sustained significant irreparable earthquake damage. Perforated corridor external walls that were directly opposite to the GFRP retrofitted walls along the east wing of the SCC building provided a good benchmark comparison of performance. The corridor external walls suffered significant damage due to rocking and sliding failure of the URM piers (see **Figure 11a and d**). Significant shear cracking and disintegration of masonry was observed in solid URM shear walls in other parts of the SCC building as shown in **Figure 11**. Due to the severe damage to the unretrofitted URM walls and differential settlement of the building foundations, repair of the building was deemed uneconomical and the SCC building was subsequently demolished.

CONCLUSIONS

The 2010/2011 Canterbury earthquake sequence provided an opportunity for the performance of surface bonded GFRP retrofit applied to two vintage URM buildings to be evaluated. GFRP retrofits were found to be successful in preserving architectural features within the buildings as well as maintaining the structural integrity of the URM walls. Successful seismic performance was based on comparisons made between the GFRP retrofitted Girls' High School building and the adjacent non-retrofitted Boys' High School building, as well as comparison between the GFRP retrofitted and non-retrofitted walls of the Shirley Community Centre building. Based on detailed post-earthquake observations and investigations the GFRP retrofitted URM walls in the subject buildings exhibited negligible to minor levels of damage without delamination, whereas significant damage was observed in comparable non-retrofitted URM walls.

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Figure 1. GHS building at Arts Centre of Christchurch

Figure 2. Details of GFRP retrofit implemented at the GHS building

Figure 3. Installation of GFRP retrofit at the GHS building in 2007

Figure 4: External and internal views of the SCC building, 10 Shirley Road, Christchurch

Figure 5: Floor plan of the SCC building showing retrofit locations (highlighted) as well as the direction and location of previous/subsequent figures

Figure 6: Installation of GFRP retrofit at SCC building (photos taken in 2009)

Figure 7. North elevation of the Boys' High School building pre and post 22nd February 2011 earthquake. Note the collapse of the turret and gable end walls

Figure 8. Observed earthquake damage in the Boys' High School building

Figure 9. Post-earthquake damage observations in GHS building

Figure 10. Observed performance of GFRP retrofitted walls at SCC building (photos b-f taken November 2012)

Figure 11. Observed damage to walls at SCC building having no GFRP retrofit