A multidisciplinary evaluation of URM buildings successfully retrofitted prior to the 2010/11 Canterbury earthquake sequence

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Abstract

The 2010/11 Canterbury earthquake sequence provided a unique opportunity to analyse across a multidisciplinary framework the success of seismic retrofits of existing Christchurch buildings that were implemented prior to the earthquakes. The heritage, seismic structural and architectural attributes of three case study common clay brick buildings that were retrofitted prior to 2011 and survived the 2010/2011 Canterbury earthquake sequence are reported. To appraise the overall success of a retrofit scheme requires a multidisciplinary framework and cannot be undertaken on the basis of seismic performance alone. Interviews with building engineers, architects, and owners as well as Christchurch City Council documents were used to appraise the selected retrofits on the basis of respect for heritage, structural suitability, architectural appeal, structural performance and economic viability.

Keywords: earthquake retrofit, seismic performance, unreinforced masonry

1 INTRODUCTION

The series of earthquakes that struck the Canterbury region between September 2010 and December 2011 had a devastating effect on the building stock of the region (Moon et al. 2014). These earthquakes, referred to herein as the Canterbury earthquake sequence, are defined by two main shocks with a moment magnitude (M_w) greater than 6.0, with the Darfield earthquake on 4 September 2010 having a moment magnitude of 7.1 and the Christchurch earthquake on 22 February 2011 having a moment magnitude of 6.2 (Bradley et al. 2013). The Christchurch earthquake caused a much greater shaking intensity in the Christchurch Central Business District (CBD) than did the Darfield earthquake due to the close proximity of the epicentre (10 km) despite having a lower magnitude. Peak horizontal accelerations up to 1.41 g were recorded in the Christchurch CBD for the 22 February earthquake (Bradley et al. 2013). This magnitude of acceleration was significantly higher than the acceleration specified in design of typical buildings in the area.

1.1 PERFORMANCE OF MASONRY BUILDINGS

The poor performance of some buildings in the Canterbury earthquake sequence has been widely reported, particularly the unreinforced masonry (URM) buildings in Christchurch (Dizhur et al. 2010, Dizhur et al. 2011, Ingham and Griffith 2011, Moon et al. 2014). Rapid assessments were undertaken by engineers immediately following the September 2010 and the February 2011 earthquakes to determine the risk posed by buildings. Buildings were assigned a placard based on their damage level in accordance with New Zealand Society of Earthquake Engineering (NZSEE) guidelines. A green placard indicates that the building has been inspected and has no restrictions on use, a yellow placard indicates some building damage and only allows restricted entry, and a red placard indicates that the building is unsafe to enter (NZSEE 2009). Moon et al. (2014) report placard assignments for 361 clay brick loadbearing masonry buildings located in the Christchurch CBD. Following the September 2010 earthquake 43% of these clay brick masonry buildings received a green placard. That number was reduced to only 1% after the February 2011 earthquake, suggesting that nearly all clay brick masonry buildings suffered moderate to major damage in the Canterbury earthquake sequence.

1.2 MEASURING THE SUCCESS OF RETROFITTED BUILDINGS

A retrofitted building that survived the Canterbury earthquake sequence without being demolished is generally a good indication of an effective seismic retrofit. However, the overall success of a retrofit requires a multidisciplinary framework and cannot be determined solely on the basis of seismic performance, and instead social and economic factors must also be considered. Patterson and Egbelakin (2016) proposed a multidisciplinary framework tool to develop effective seismic retrofit solutions for heritage buildings during the design process. The assessment categories proposed have been adapted for the purpose of this study into five main categories: structural suitability; economic viability; architectural appeal; heritage preservation; and inclusion of building services. These categories were used as general guidelines to collect information on retrofitted buildings that survived the Canterbury earthquake sequence. Preliminary findings are reported here, covering the heritage, architectural, and seismic structural aspects of three clay brick unreinforced masonry buildings located in Christchurch that were retrofitted prior to the Canterbury earthquake sequence.

1.2.1 RETROFIT LEVEL

In New Zealand the level of seismic improvement of a retrofit is measured in terms of "Percentage of New Building Standard" (%NBS), with the earthquake loading standard being NZS 1170.5 (Standards New Zealand 2004). Buildings with a score of %NBS < 34 are considered 'earthquake-prone' and buildings with a score of 34 ≤ %NBS ≤ 67 are considered 'earthquake risk' (NZSEE 2016). The Z-factor (seismic zone factor) for Christchurch as specified by NZS 1170.5:2004 has increased from 0.22 to 0.3 following the 22 February 2011 earthquake (Department of Building and Housing 2011). This increase means that a building that was strengthened to 67 %NBS prior to 2011 would now only be considered to have a strength of approximately 50 %NBS.

2 CASE STUDIES

A list of 20 exemplar retrofitted buildings was developed in collaboration with an advisory committee comprised of Christchurch engineers, with 19 of the 20 buildings identified as having load bearing URM walls. Three main building groups were identified from this list: large and complex stone masonry; large and complex clay brick masonry; and common clay brick masonry. Buildings were selected for consideration based on a general consensus of their successful structural performance and their ability to fit into these categories. Property files were obtained from Christchurch City Council for the selected buildings, and interviews were held with building engineers, property owners, project architects and other relevant parties.

Three common URM buildings were selected as case studies using the described methodology. Based on findings presented in Ingham and Griffith (2011b) a common URM building in the Christchurch CBD was determined to be a multi-storey clay brick commercial building that may either stand alone or be part of a row. It is noted that the buildings presented herein were retrofitted to between 67% and 100% NBS at the time of retrofit implementations (using the pre-earthquake zone factor of Z = 0.22), and that 76% of URM buildings in the Christchurch CBD that were retrofitted to similar levels were demolished since the Canterbury earthquake sequence (Moon et al. 2014).

2.1 THE GROSVENOR TAVERN, 367 MOORHOUSE AVENUE

The building located at 367 Moorhouse Avenue was formally known as the Grosvenor Tavern and is a two storey stand-alone structure on the corner of Moorhouse Avenue and Madras Street in the Christchurch CBD. The building was constructed in 1877 using loadbearing unreinforced clay brick masonry exterior walls, timber framed interior partition walls, timber floor and roof diaphragms, and Oamaru stone ornaments (Figure 1a,b). The building is approximately 18 m x 14.5 m along south and west elevations respectively with a chambered corner to the southwest and a re-entrant corner of about 8 m x 4.5 m to the northeast (Figure 1c). The masonry walls change in thickness from three wythes (350 mm) at the ground floor to two wythes (230 mm) at the first floor.

2.1.1 HISTORY AND HERITAGE

The building located at 387 Moorhouse Avenue was designed by Canterbury architect Samuel Farr as a tavern on the ground floor and a hotel on the first floor. The Grosvenor Tavern was a popular location for railway workers in the early to mid-1900s and retained its function as hotel and tavern under a number of new owners. The building is listed as a Group 4 heritage item in the Christchurch City Plan due to its historical status as a colonial hotel on an inner-city site. This building represents early masonry commercial classicism and exhibits many features common to buildings designed by Samuel Farr. The corner location on a primary urban arterial route gives the building landmark value in addition to its public recognition value as a public house (CCC 1995).

The interior of the building has been significantly altered since its original construction, but the street facing facades still maintain a high degree of architectural integrity. Notable exterior features include a heavily corbelled parapet inlaid with wreath motifs, single arch-topped windows that are simply finished with a keystone and large segmental pediments that sit above the door cases on the corner and the Moorhouse Avenue frontage (Figures 1a,b). Alterations to the building during the 1970s tended to be architecturally unsympathetic and included the construction of two single storey concrete block annexes, an ungainly fire escape on the exterior, and several interior walls that severely segmented the space. Work during the 1970s involved removing 1200 mm of the original parapet, restraining the remaining parapet, replacing the central staircase with a staircase on the east wall, and completely remodelling the first floor. An interior wall on the ground floor that was thought to be a partition wall was removed during this renovation. The removal caused parts of the building to sag so a large steel beam was installed to prevent further damage. In 2001 the building was determined to be unsafe due to the multiple interior alterations that resulted in load paths that could not be clearly identified and land subsidence that caused differential settlement. The building was derelict until 2010 when plans for a new seismic retrofit were implemented.

2.1.2 STRUCTURAL SEISMIC UPGRADES

The seismic upgrade of the building at 367 Moorhouse Avenue combined several retrofit methods including the installation of vertically oriented steel trusses, new reinforced concrete masonry (RCM) walls surrounding a new central stairwell, new exterior timber framed walls, new floor and roof diaphragms, and new parapet restraints. The first stage of the seismic retrofit involved reducing the seismic weight of the building, with heavy clay roof tiles removed and replaced with a lightweight iron roof over new timber trusses, lath and plaster removed from the interior walls, and two single storey concrete block annexes demolished. The seismic retrofit was designed to resist a lateral load of 0.47 g (70 %NBS with a pre-earthquake zone factor of $Z = 0.22$).

VERTICAL STEEL TRUSSES AND POSTS

Vertical steel trusses comprised of 100 x 100 x 6 mm square hollow section (SHS) posts with 75 x 75 x 5 mm SHS braces offer a displacement compatible solution that provides additional in-plane stiffness to the masonry walls (Figure 1d). The two storey vertical steel trusses were prefabricated and installed by being dropped through the roof during a stage of construction when the ceiling was removed. New heavily reinforced concrete (RC) foundations were constructed along the perimeter of the building and attached to the existing foundations with 16 mm high yield reinforcement (H16) steel fixings that were epoxy anchored 200 mm deep at 600 mm centres to resist the significant uplift forces caused by the new vertical trusses. The vertical trusses are positioned such that the steel members sit against the three wythe walls on the ground floor and are offset with blocking from the two wythe walls of the first floor. The 100 x 100 x 6 mm SHS posts follow the step in the masonry at the first floor and are installed in selective URM piers to provide walls with out-of-plane stability (Figure 1d).

Both the steel posts and the vertical steel trusses are connected to the URM walls with steel bolts that pass through the walls and are anchored to round steel end plates on the exterior (Figure 1f). The use of vertical steel trusses and posts as a retrofit solution allowed the interior brickwork to be maintained, whereas RC skin walls would have permanently covered interior brickwork. Steel trusses and posts are generally considered to be a heritage friendly intervention that is 'reversible' in the case that new and less invasive technology becomes available.

RCM AND TIMBER WALLS

A shear core made up of 190 mm RCM walls with H16 at 400 mm centres vertical reinforcement and H12 at 400 mm centres horizontal reinforcement was constructed around the new centrally located staircase to provide the building further lateral support (Figure 1d). The walls extend from the ground floor to roof truss level and are topped with a 150 mm thick concrete lid that is reinforced with H12 bars at 200 mm centres both ways to further increase the rigidity of the core. New timber stud braced walls were constructed on the northern most exterior wall and east side of the re-entrant corner to replace the deteriorated existing timber walls (Figure 1c). New RC footings were constructed under the new RCM walls and timber walls.

ROOF AND FLOOR DIAPHRAGMS

The existing first floor diaphragm consists of timber tongue and groove flooring over 350 x 50 mm joists spaced at 460 mm centres. New horizontal 200 mm deep parallel flange channels (200 PFC) were bolted between the vertical steel trusses and posts directly beneath the first floor joists (Figure1d) and a new diaphragm made up of 17 mm thick plywood on 45 mm battens was installed over the existing flooring. The new diaphragm was connected to the new horizontal steel members to transfer forces into the new lateral load resisting system.

The existing roof was removed and replaced with gang nail trusses spaced at 900 mm centres with a 12 mm thick plywood overlay fixed to the bottom cord of the roof trusses. The diaphragm and truss cords were connected to horizontal 200 x 100 x 4 mm steel rectangular hollow sections (RHS) bolted between the vertical steel trusses and posts (Figure 1d).

PARAPET RESTRAINT

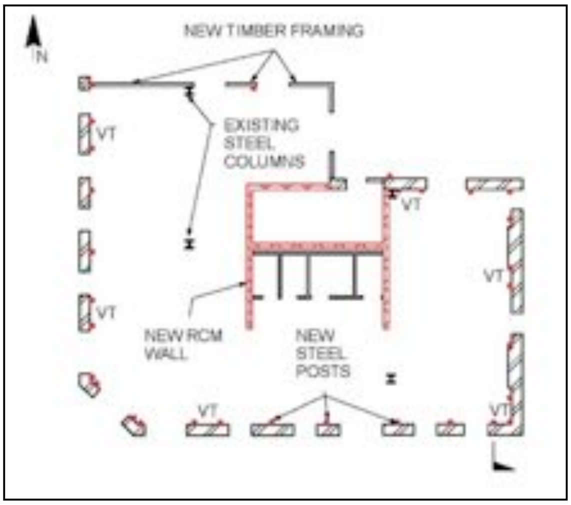
The parapet restraints from the 1970s renovation were removed and replaced with new 33.7 x 3.2 mm circular hollow section (CHS) braces. The braces were attached to a concrete cap beam that extends along the URM parapet with two 200 mm long M16 epoxy anchors and were bolted to 100 x 100 x 6 mm angles that were screwed through at least three roof purlins into the new timber roof trusses (Figure 1d).

2.1.3 **ARCHITECTURE**

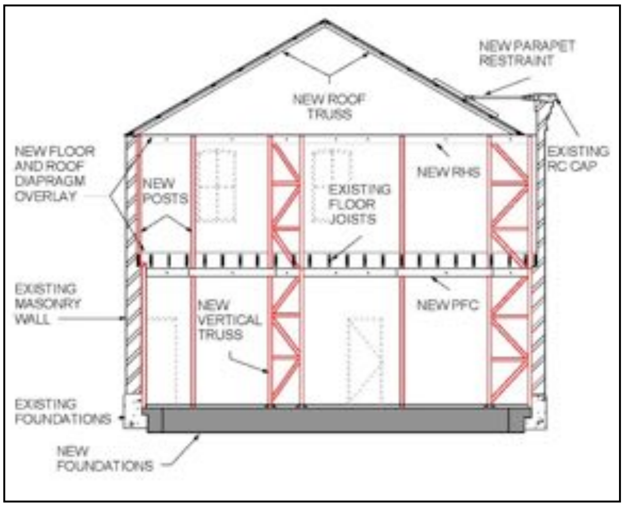
The 2010 retrofit of the Grosvenor Tavern exhibited a more concerned approach regarding the heritage features and the overall functionality of the space than had previous alterations. Structural elements were strategically placed in order to allow for the removal of most of the interior partition walls and the use of vertical steel trusses offered a solution to maximise usable floor area and create open space that permits flexible tenancy throughout the building. The staircase on the east side of the building was removed as was the fire escape on the west

(a) Before retrofit, June 2010

(b) After retrofit, September 2011



(c) Ground floor plan, showing retrofit, VT = vertical truss



(d) East elevation, showing retrofit

(e) Cracking in exterior façade, after 4 September 2010

(f) Wall achors painted to match façade, 2011

(g) Undamaged building, days after the 22 February 2011 earthquake.

Figure 1. Views and retrofit details of the building located at 367 Moorhouse Avenue

side, and a new staircase was installed in the location of the original staircase on the interior of the building to provide a clear path to the upper storey.

Heritage features of the façade are accentuated by being painted a bright white against the grey paint on the masonry, and the anchor end plates that connect the steel frames to the masonry wall are painted to match the façade so that they are hardly noticeable from a distance. The vertical steel trusses are evenly spaced between windows in order to retain views from the building. Windows in the new timber walls are detailed such that they are nearly identical to the façade windows.

2.1.4 SEISMIC PERFORMANCE

The Grosvenor Tavern was in the initial stages of the retrofit work when the September 2010 earthquake occurred. The brick façade experienced minor cracking as seen in Figure 1e but no further damage was reported. The retrofit work quickly resumed and the vertical steel trusses were installed in November 2010. The building was undamaged in the February 2011 earthquake such that the vertical steel trusses remained attached to the masonry walls and there was no differential movement observed between the walls and floor diaphragm. The structural seismic system of the retrofit was proven effective when the building received a green placard upon post-earthquake inspection (Figure 1g). The seismic retrofitting work and building alterations were fully completed in June 2011 and the building is now operational. The Grosvenor Tavern is now the last remaining 19th century URM building on Moorhouse Avenue. The building was awarded a Civic Trust award in 2011 for significant restoration of a heritage building and for the maximisation of complimentary use of a heritage building.

2.2 THE SMOKEHOUSE, 650 FERRY ROAD

The Smokehouse is a two storey standalone clay brick masonry building located at 650 Ferry Road on the corner of Ferry Road and Catherine Street in Woolston, Christchurch. The original building footprint measures approximately 10 m x 13 m with a chamfered corner to the north. The ground floor URM walls are three wythes (350 mm) thick and the first floor walls are two wythes (230 mm) thick.

2.2.1 HISTORY AND HERITAGE

The Smokehouse building was constructed in 1903 in the Victorian style as a combined shop-residence for coal merchant and carter James Cunningham. The site continued to house a coal yard until the 1960s and a cartage firm until the 1980s. The building remained in near original condition until 2007 when work began on a building extension and seismic retrofit. The building at 650 Ferry Road is listed as a Group 4 heritage building by the Christchurch City Council (May 2006). The unpretentious façade has large windows on the ground floor street facing corner, a chambered entry, and detailed brickwork that forms corbelled eaves and a string course (Figure 2a). The relatively simple architecture of the red clay brick masonry structure is given prominence by the corner location of the building on a major suburban arterial route.

2.2.2 STRUCTURAL SEISMIC UPGRAGES

The building at 650 Ferry Road underwent major upgrades in 2007 including the addition of a new building extension and the seismic retrofit of the original building (Figure 2a,b,c).

Large portions of the original exterior URM walls were removed to create openings that provide access between the original building and the new extension (approximately 346 m^2 of additional ground floor area) (Figure 2b,c). The new building extension is seismically independent of the existing building and therefore its load resisting systems is not discussed. Seismic retrofit work to the original building included the installation of new steel moment resisting frames (MRFs) in the newly created openings and the stiffening of the first floor and roof diaphragms. Work also included infilling one window on the second floor, repointing the original lime based mortar, and moving the staircase closer to the main street entrance. The existing masonry building was retrofitted to withstand a peak ground acceleration of approximately 0.46 g (67 %NBS with a pre-earthquake zone factor of Z = 0.22).

STEEL MOMENT RESISTING FRAMES

New openings were created in the original southeast and southwest exterior ground level URM walls and MRFs made up of universal columns (200 UC 52) were installed to support the lateral and gravity loads of the new openings. The MRFs were designed to be sufficiently stiff such that they are displacement compatible with the existing masonry walls. The beams are each topped with a 400 x 10 mm mild steel flat bar that is epoxy anchored to the existing masonry with 12 mm diameter threaded anchor bolts (M12) 300 mm long at 600 mm centres (Figure 2d) and the columns are secured to the existing masonry walls with 300 mm epoxy anchor bolts. The original wall foundations under the new MRFs were thickened on both sides by 400 mm of new concrete secured with 12 mm diameter steel reinforcing Grade 300 bars (D12) epoxy set into the existing foundation at 200 mm centres top and bottom. An additional MRF made up of 250 PFCs was constructed on the northeast wall. New beams (250 UB 31 or 200 UB 30) were installed under the existing floor joists in locations where interior masonry walls were removed.

ROOF AND FLOOR DIAPHRAGMS

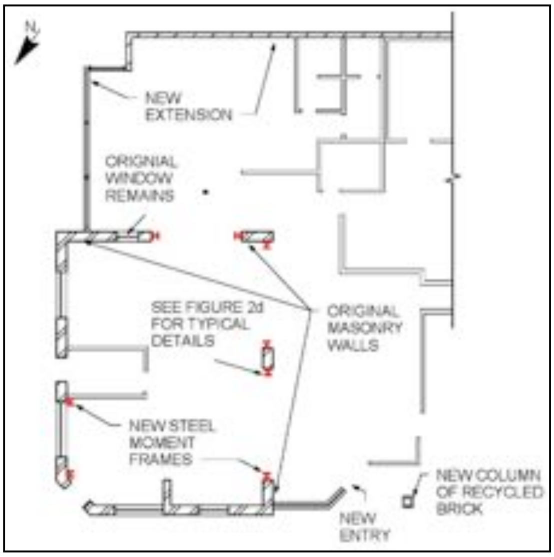
The first floor diaphragm was retrofitted by removing the existing flooring and installing a 12 mm thick plywood diaphragm over the existing floor joists (Figure 2d). 12 mm thick plaster board was fixed to the underside of the floor joists with metal battens in sections of the building where the original lath and plaster ceiling was not retained, and the original timber framed roof was retained and topped with corrugated iron roofing.

2.2.3 **ARCHITECTURE**

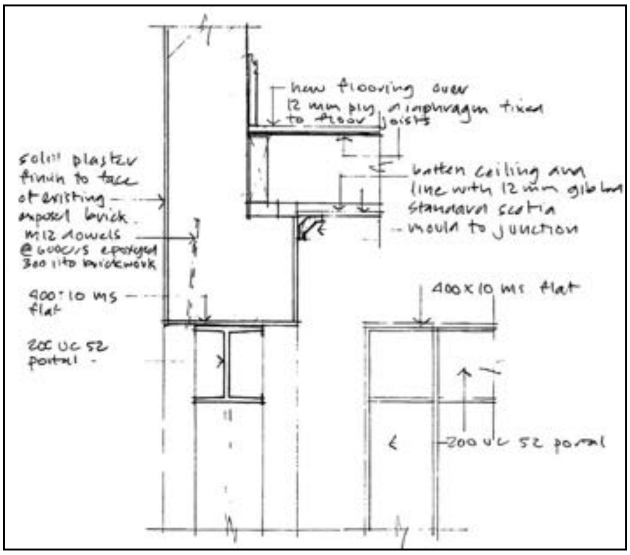
The Smokehouse building won the New Zealand Architectural Award in 2008 for initiative, enterprise, and restoration. The existing red clay brick masonry and new steel frames were left exposed and provide a cohesive transition between the existing building and the new building extension. The removal of internal masonry walls and fireplaces maximises usable space and natural light is abundant from the many windows and the skylight. Heritage features such as the original parlour ceiling rose and cornice were retained, and authentically sized rimu flooring boards were obtained and recycled from Bethany hospital in Auckland. Brick was recycled from the demolished parts of the walls to construct the new column and wall at the new entry on the west side of the building (Figure 2c). The new Catherine Street entry was set back approximately one metre from the existing façade in order to retain the original sight line of the building from Ferry Road. The red clay brick masonry walls of the existing building are complemented by the red tin exterior of the new building extension.

(a) Exterior northwest elevation, 2011

(b) Interior looking east, 2011

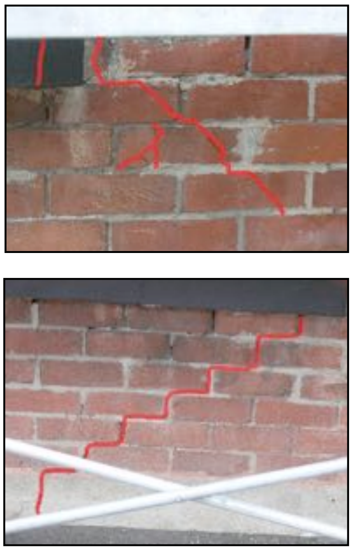


(c) Ground floor plan, showing retrofit locations



(d) Detailing of MRFs

(e) Exterior repairs underway after 22 February 2011



(f,g) Cracks in exterior walls, after 22 February 2011

Figure 2. Views and retrofit details of the building located at 650 Ferry Road

2.2.4 SEISMIC PERFORMANCE

The exterior brickwork of the Smokehouse building did not experience any visible cracking in the September 2010 earthquake. However, vertical cracks at the front corner section, minor horizontal cracks above one of the piers on the second level, and minor cracks around the in-fill window were found on the interior. Repair work was underway when the 22 February 2011 earthquake occurred (Figure 2e). Additional cracking on the interior and new damage to the exterior brickwork was found (Figures 2f,g) and the building received a yellow placard (restricted use – short term entry). The damage was readily repaired and the Smokehouse building reopened soon after the earthquake. The performance of the retrofitted building that resulted in minimal interruption to the business operations, coupled with the architectural attention to heritage features, allow this retrofit to be regarded as an exemplar.

2.3 URBAN WINERY, 208 MADRAS STREET

The building located at 208 Madras Street in the Christchurch CBD is a two storey building that measures approximately 8.5 m x 30.5 m in plan. The building is the last in a row of multi-storey buildings on Madras Street as it shares an URM party wall with the building to the north and the building to the south has been demolished. The original building is comprised of timber roof and floor diaphragms supported by timber interior columns and URM exterior load bearing walls that are three wythe (350 mm) thick on the ground floor and two wythe (230 mm) thick on the first floor and parapet.

2.3.1 HISTORY AND HERITAGE

The building at 208 Madras Street was constructed in 1908 and includes significant heritage features such as the Madras Street façade (Figures 3a,b) and original timber flooring but is not listed as a heritage building by the Christchurch City Plan. The building originally functioned as offices on a site owned by Turner and Growers, a New Zealand based produce company. Christchurch City Council acquired the Turner and Growers site in 2002 as part of a proposal to revitalise and enhance the eastern side of the central city and developers purchased part of the site that included 208 Madras Street from Christchurch City Council in 2006. The building had not undergone any major seismic strengthening work or alterations and was considered unsafe and derelict. The building at 208 Madras Stress was to be the first of several building and site upgrades to create the Urban Winery development.

2.3.2 STRUCTURAL SEISMIC UPGRADES

The retrofit of the building at 208 Madras Street was a highly tailored solution that utilised several retrofit methods and made major modifications to the building fabric. The south and east URM walls were demolished and replaced by steel MRFs; steel MRFs, RC skin walls, and parapet restraints were used to strengthen the remaining URM walls; and the floor and roof diaphragm connections were strengthened (Figures 3a,c,d). The retrofit was completed in 2008 to withstand a peak ground acceleration of approximately 0.46 g (67 %NBS with a pre-earthquake zone factor of Z = 0.22).

STEEL MOMENT RESISTING FRAMES

The existing gravity supporting structure consists of 200 x 190 mm timber posts spaced approximately 4.4 m to 4.7 m apart with a 235 x 190 mm timber beam spanning between posts. The columns of the new steel MRFs were installed in line with the existing timber columns (Figure 3d,g). The MRF along the north wall is made of full height 310 UC 97 columns with 200 x 6 mm SHS beams positioned below the roof truss (Figure 3g) and the UCs are connected to the masonry wall with two epoxy set M12 bolts at 400 mm centres. The SHS beams are welded to 100 x 10 mm plates at 750 mm centres that are fixed to the masonry wall with epoxy set M16 bolts. The MRF to the south is made up of full height 250 UC 73 columns with 310 UB 40 beams at the roof and 250 UC 73 beams with 150 x 6 mm mild steel (MS) flat collectors at the first floor (Figure 3g). Single story 310 UC 97 columns were installed next to the existing interior timber columns and are connected to the north wall with 460 UB 67 collector beams and to the south wall 150 x 6 mm MS flat plate collectors (Figure 3g). The north and south MRFs are connected with 250 UB 37 collector beams at the roof (Figure 3g).

REINFORCED CONCRETE SKIN WALL

An RC skin wall was constructed against the interior masonry of the west wall from the ground floor to the top of the parapet in order to preserve the Madras street façade. The RC skin wall is typically 150 mm thick with 300 mm thick pilasters and is connected to the existing masonry by D12 bars epoxy set at 600 mm centres each way (Figure 3d). The wall is reinforced with 10 mm diameter reinforcing Grade 300 bars (R10) at 200 mm centres horizontally and 20 mm diameter reinforcing Grade 500 bars (XD20) with various spacing vertically. The wall is 300 mm thick from the step in the masonry wall to the bottom of the first floor windows (approximately one metre). This thicker portion of wall is reinforced with R10 bars at 200 mm centres vertically and four rows of two XD20 bars horizontally. A second 1500 mm long RC wall was constructed on the west side of the north wall (Figure 1d). This RC skin wall is 150 mm thick and is reinforced with XD16 bars at 150 mm centres horizontally and 200 mm centres vertically.

FLOOR DIAPHRAGM AND ROOF

The close spacing of the new steel MRFs allowed the original timber floor diaphragm and roof to be preserved. The first floor diaphragm is made up of tongue and groove flooring over 300 x 50 mm floor joists at 400 mm centres that span north to south. 600 mm of the existing flooring was removed along the north wall and replaced with 19 mm thick plywood infill nailed to the existing floor joist. 200 x 50 mm blocking is nailed to the existing boundary joist on the north wall with 3 rows of 75 x 3.3 mm diameter nails at 100 mm centres, and the blocking is secured to the existing masonry wall with M16 bolts epoxy set at 450 mm centres drilled 22.5 degrees to horizontal and secured with tapered washers in order to connect the diaphragm to the existing URM wall. On the south wall the existing floor joists sit on joist hangers that are connected to the UBs through timber blocking with M16 bolts at 800 mm centres. The existing floor diaphragm is nailed with 15 mm diameter nails at 150 mm centres to 50 mm timber plates that are connected to the top flange of the beams with counter sunk M12 bolts at 800 centres.

The existing timber roof trusses span north to south and are spaced at approximately 3.3 m centres. 100 x 6 mm plates were welded to the UB or SHS beams and connected each side of the truss chord with M20 bolts. Solid nogging was inserted between roof purlins for the full width of the building in the line of the collectors.

PARAPET RESTRAINTS

The parapet along the west wall was strengthened by the RC skin wall but the party wall to the north extends higher than the MRFs and required additional restraint at the top. The party wall is secured with 76 CHS 3.2 braces with a 100 x 6 MS cleat slotted into and connected with two M16 bolts to each end. The cleat is welded to a SHS that is welded to a 100 x 10 mm MS plate that is bolted with two M12 anchor bolts epoxy set 150 mm minimum into the existing wall. The other end of the brace passes through the roof and the cleat is connected to a 6 mm MS plate that is welded to the 250 UB 37 collector.

2.3.3 **ARCHITECTURE**

The selected seismic strengthening plan preserved the Madras street façade and was determined to be the least invasive to the interior of the building. The close spacing of the MRFs allowed the existing timber flooring to be retained without the addition of interior walls which would have severely segmented the space. New awnings were installed to shift the focus of the building to the south side where the developers planned to transform the empty lot into a walkway to a central plaza. The use of steel MRFs allowed for the installation of large windows on the south wall that created an abundance of natural light in the interior (Figure 3e,f) and the east wall was replaced with tin sheeting and a brick masonry veneer (Figure 3c). The first floor was designed to be office suites and the ground floor was made into a flexible hospitality space with centralized toilets to allow the possibility of multiple tenants.

2.3.4 **SEISMIC PERFORMANCE**

The building performed well in both the September 2010 and the February 2011 earthquakes. Partition walls suffered minor cracking, but the brickwork was not damaged, no structural damage was reported, and there was no differential movement between the floor diaphragm and the masonry walls or the new steel MRFs. The building was given a yellow placard after the February 2011 earthquake due to a falling hazard created by the parapet of the building to the north. The parapet was repaired and the building was fit-out as a brewery that opened in 2012.

3 **DISCUSSION AND LIMITATIONS**

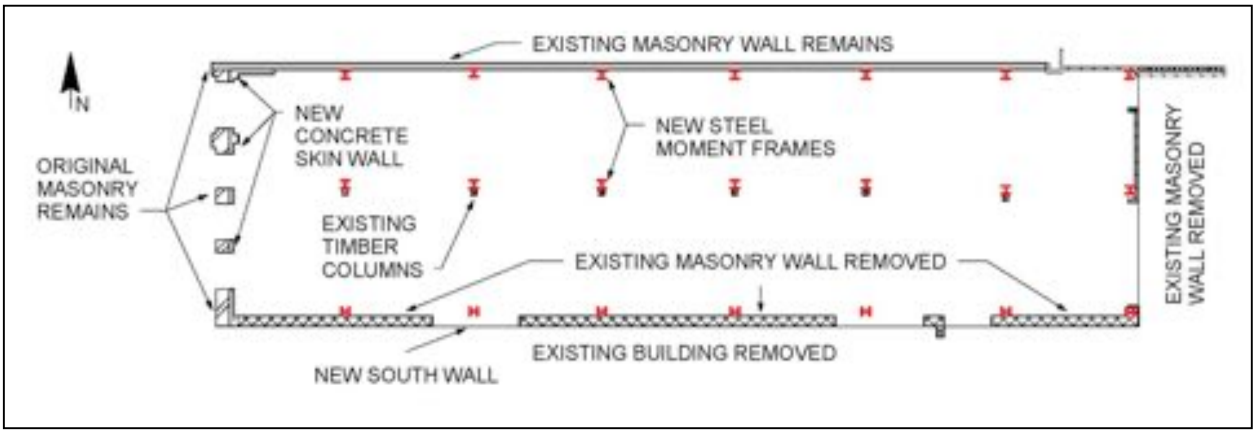
The success of the retrofits can largely be attributed to careful planning and collaboration of the building owners, architects, and engineers during the design process. Engineers in all interviews discussed developing several alternative retrofit schemes before deciding on the implemented retrofit. Design iterations were updated to create a strategy that was seismically compatible, aesthetically pleasing and economically feasible while still protecting key heritage features and capitalizing on available space. It is likely that the buildings described would had been demolished had it not been for the building owner's early intervention based on demolition statistics from Moon et al. (2014). Several building owners described their initial economic investment as worthwhile due the ability of the building to reopen soon after the earthquakes.

A method for determining the economic feasibility of these retrofit is under development. Retrofit costs were not described in this study due to the uncertainty of whether costs reported in interviews were comparable (i.e. if costs reported were construction costs or total

(a) Façade and south wall, before retrofit

(b) West façade, after retrofit

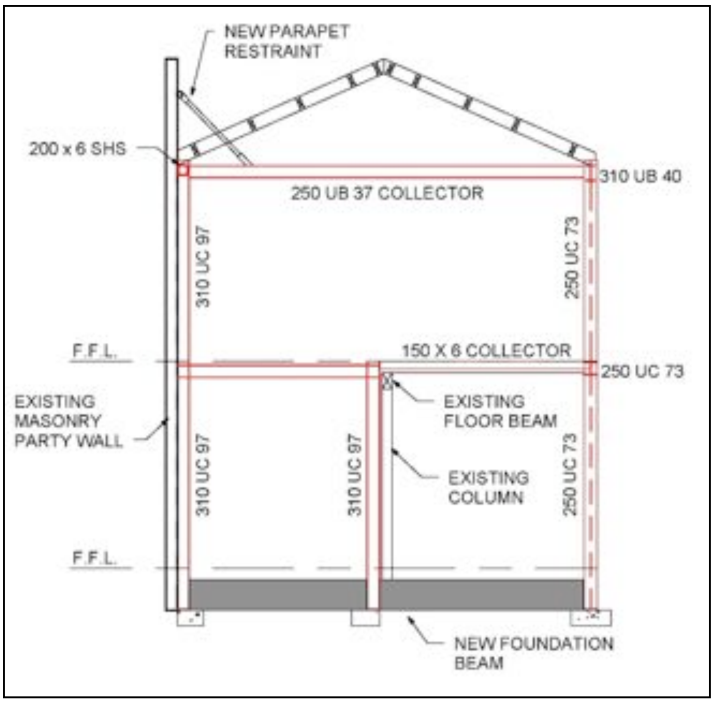
(c) New south and east walls, after redevelopment



(d) Floor plan, showing retrofit

(e) First floor interior looking east, after retrofit

(f) Ground floor interior looking east, after retrofit



(g) Typical frame elevation looking east, showing retrofit

Figure 3. Views and retrofit details of the building located at 208 Madras Street

seismic retrofit costs). Jafarzadeh et al. (2014) discusses a method to determine the seismic retrofit construction cost of Iranian public school buildings with a framed structure based on construction tender documents. Cost information from each of the discussed retrofits is being collected to determine if a similar method can be applied to these case studies.

4 CONCLUSIONS

Three common clay brick masonry commercial buildings are described that were each seismically retrofitted prior to the Canterbury earthquake sequence and that performed well in the earthquakes. These retrofitted buildings are located at 367 Moorehouse Avenue, 650 Ferry Road, and 208 Madras Street and were identified as exemplars based on multidisciplinary criteria. This study includes information on the heritage, seismic structural, and architectural aspects of the retrofits. The retrofit and upgrades of the described buildings had aesthetically pleasing architectural detailing, plans that allowed flexible tenancy, and minimal intervention to the heritage fabric. Each of the three buildings had retrofitting work performed to strengthen the first floor diaphragm connections. The stiff vertical steel trusses and RCM shear core installed in the building at 367 Moorehouse Avenue proved to provide displacements that were compatible with the original URM walls such that the building was undamaged in the 22 February 2011 earthquake. The MRFs used in the retrofit of the building at 650 Ferry Road performed well in the Canterbury earthquake sequence, with the only damage being cracking of the brickwork that was readily repaired and only resulted in minor interruption to business operations. The building at 208 Madras Street was also successfully retrofitted with closely-spaced MRFs and RC skin walls and had no exterior damage in the Canterbury earthquake sequence. Further case studies are to be completed on other successfully retrofitted buildings identified in the beginning stages of this research.

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