PERFORMANCE OF UNREINFORCED AND RETROFITTED MASONRY BUILDINGS DURING THE 2010 DARFIELD EARTHQUAKE

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SUMMARY

A brief history of Christchurch city is presented, including information on the introduction of unreinforced masonry as a popular building material and an estimate of the number of unreinforced masonry buildings in the Canterbury region currently. A general overview of the failure patterns that were observed in unreinforced clay brick and stone masonry buildings in the Christchurch area after the 2010 Darfield earthquake is provided. Case studies of the damage sustained to five unreinforced masonry (URM) buildings that were unretrofitted at the time of the earthquake, including photographic details, is documented. The performance of eight retrofitted URM buildings is then commented on, detailing the building characteristics and retrofit techniques. The case studies include the use of moment resisting frames, steel strong backs and strapping, diaphragm anchoring, surface bonded fibre reinforced polymer (FRP) sheets and cavity ties.

INTRODUCTION

On Saturday 4th September 2010 at 4.35 am a magnitude 7.1 earthquake occurred 40 km west of Christchurch city with a depth of around 10 km. The Christchurch Emergency Response Task Force was convened immediately with engineers, Urban Search And Rescue (USAR), building inspectors and volunteers sent to complete initial assessments of building damage that could be observed along the street front of the city centre, with the primary purpose of returning function and access to the city. Over a 72 hour period assessments and reassessments due to the aftershocks resulted in buildings being tagged red, yellow or green, and cordons were placed around buildings having potential falling hazards. Of all the damage to commercial buildings in Christchurch city, the majority was to the unreinforced masonry (URM) building stock.

Learning opportunities are still emerging from the observed earthquake damage, by investigating the failure patterns that were common in URM buildings. Five case study examples of damage to unreinforced masonry buildings are presented here to document these common failure modes, and to report on the deficiencies that contributed to the observed damage. Key to the implementation of future seismic retrofits nationwide that are effective at protecting New Zealand's remaining heritage URM buildings is an assessment of the performance of the retrofit techniques that were implemented within relevant Christchurch buildings prior to the earthquake. Consequently, eight case study examples of implemented seismic retrofits are reported, providing details on the techniques deployed and any observed earthquake damage.

EARLY CHRISTCHURCH

Moa hunters were the earliest human inhabitants of the land that now supports modern day Christchurch city. They may have arrived as early as 1000 AD and at that time the coastal wetlands were a thick forest of matai and totara, and parts of the Canterbury Plains could also have been forested. Migration of Maori in the sixteenth and seventeenth centuries from the North Island of New Zealand eventually led to the Ngai Turahuriri tribe, a sub-tribe of Ngai Tahu, controlling the coastal area from Lake Ellesmere to the Hurunui River. About five thousand Maori were living in the central Canterbury region by 1800, with large Pa at Kaiapoi and on Banks Peninsula at Akaroa, Puari, Purau and Rapaki [1]. The Maori name for Christchurch is Otautahi, meaning 'the place of Tautahi', who was a Ngai Tahu chief.

In 1835 the first Europeans that arrived in the Christchurch area did not settle, but instead used Lyttelton Harbour as a base for their whaling boats. At about that same time the Deans brothers from a Scottish farming background bought sections of land from the New Zealand Company in Britain and were planning their emigration to the new colony. William Deans arrived in Wellington, and found the local Maori to be rather hostile and his allotted parcel of land to be disappointing, so he ventured south. From Lyttelton, William travelled up the Avon River in a whaleboat until the weeds were too thick to go any further, eventually unloading his timber and supplies near the present site of Christchurch Girls' High School. The land was flat, and covered in tussock and swamp. John Deans arrived in 1843 and the brothers proved that the area had fertile land and was capable of sustaining stock. They named their farm Riccarton after their home parish near Kilmarnock, in Ayrshire, and named the river the Avon after a stream on their grandfather's farm [1].

In November 1847 John Robert Godley met the famous theorist of colonisation Edward Gibbon Wakefield in England,

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and this meeting led to the formation of the Canterbury Association in London in 1848. Godley was to found a new colony called 'Christ Church' that would follow the teachings of the Church of England. Soon after their meeting the New Zealand Company agreed to purchase land for the Canterbury Association [2]. The signing of 'Kemp's Deed' in June of 1848 by sixteen Ngai Tahu chiefs gave the New Zealand Company control of the land from Kaiapoi to Otago for £2000 [1]. In December Captain Joseph Thomas, William Fox and surveyors Cass and Torlesse arrived in Lyttelton Harbour in the 'Fly', sent by the Canterbury Association to choose a suitable site for the new colony. The current location of Christchurch city was Thomas's second choice, after eliminating Port Cooper due to the amount of reclamation that would be required in order to provide the 4,000 hectares that were specified by the Association [1]. Captain Thomas surveyed the site and laid out the streets and over the subsequent nineteen months over 3,000 settlers were shipped to Christchurch [2]. In 1875 the Christchurch drainage board was established, encouraged along due to the dangerous pollution of the Avon River after 25 years of settlement, and the regular flooding of the city [3]. Although Christchurch was the last of the main European settlements in New Zealand, it was the first City of New Zealand as decreed by Royal Charter in 1856 [2].

Construction

Construction in the early period of colonisation was primarily of timber for the residential and smaller commercial buildings due to the proximity and abundance of the local resource in the Papanui and Riccarton Forest. The simplicity of the early timber buildings was seen as imposed out of necessity, and as something to be outgrown as soon as possible [4]. In the late 1850s Christchurch prospered from the wool trade and this allowed the transition from wood to stone and clay brick masonry for the public buildings. The founders of Canterbury envisaged their colony as a direct transfer of a mature social order, intact from the old country to new. The spirit in which the Canterbury settlement was founded therefore instructed a building style that imitated the style of the home country [4]. The city's second town hall was built in stone in 1862-1863, the first stone building of Christ's College was constructed in 1863, and the city's architectural jewel, the stone Provincial Council Chambers, was completed in 1864 [4]. The aesthetic quality of Christchurch city was also regulated in terms of building size and style in order to maintain a regular appearance. In the 1860s and right through to the 1880s a vogue for Venetian Gothic architecture for commercial buildings was indulged, distinguishing the buildings of Christchurch from those of other New Zealand cities that were embracing classical and Renaissance styles. The city was populated with mostly two and three storey buildings that were complementary in height to their neighbouring buildings. This regularity in style and size was accentuated by the rigid regular gridded streets. Construction slowed during a period of economic depression in the 1870s, but allowed for a new period of design to develop by the time that prosperity returned in the late 1890s [1].

Figure 1: Victorian Christchurch in 1885 [5].

By 1914 the central area of Christchurch had been largely rebuilt, resulting in a city that was "interesting for its architectural variety, pleasing for its scale and distinctively New Zealand" [4]. Figures 1 and 2 show photos of historical Christchurch from 1885 and 1910 respectively. Two of the many influential architects of Christchurch were J.C Maddison (1850-1923), whose design focus was inspired by the Italianate style, and J.J Collins (1855–1933), who in partnership with R.D Harman (1859-1927) chose brick masonry as their medium for large commercial and institutional buildings. By the 1920s wooden structures in the city were rare, and were seen as small irregular relics of the past.

Figure 2: New Zealand Express Company building, Christchurch's first 'skyscraper', photo circa 1910 [6].

Rise and decline of unreinforced masonry

Brick masonry was seen as a symbol of permanency, rather than the temporary air of timber buildings. Influenced by the construction styles of the motherland, the large stone masonry gothic buildings had a positive impact on the number of more regular unreinforced clay brick masonry buildings that were constructed in the early years of settlement. The use of masonry was further justified after a number of fires in inner city Christchurch, which quickly spread along the streets between the row type timber buildings. There were severe fires firstly in Cashel Street in 1861, in Colombo Street between Hereford and Cashel Street in 1864, and then in 1866 when Armagh and Colombo Streets were destroyed. The centre of Lyttelton was also destroyed in a fire on October 24th, 1870 [2, 4]. The combustibility of timber structures therefore prompted the move to URM construction due to its fire resistant properties. The high level of seismic activity in New Zealand did not influence the decision, as the poor lateral force resisting properties of URM were unknown at this time of mass URM construction. The fire-proof nature of masonry led to it being readily adopted as the appropriate building material for high importance structures such as government buildings, schools, churches, and the Press building that housed the local newspaper company.

In Christchurch's founding forty years, the city and its surrounding boroughs were subjected to three medium sized earthquakes, and as many as seven smaller earthquakes that were centred closer to the north of the South Island [7]. The earthquake of June 5th, 1869 was the most damaging to the settlement of Christchurch, causing damage to chimneys, government buildings, churches and homes throughout the central city and the surrounding boroughs of Avon (Avonside), Linwood, Fendalton and Papanui [2]. The worst of the damage reported was to the stone spire of St John's church in Latimer Square which was cracked up its entire height [1]. In Government buildings, the tops of two chimneys came down, plaster was cracked, and several stones were displaced. Similar damage occurred in some other brick and stone masonry buildings, including Matson's building, the NZ Loan & Trust building and the NZ Insurance building. The majority of the damage to houses was the result of brick chimneys toppling and in one case the exterior brick wall of a house in Manchester Street collapsed. The damage was most intense within the inner confines of the city, decreasing from a MM 7 intensity in the city to MM 5 at Kaiapoi and Halswell. However, a few chimneys and household contents were also damaged at Lyttelton [2]. Twelve years later another earthquake was felt in Christchurch, but resulted in less damage than the previous 1869 earthquake [7]. The only reported damage from the 1881 earthquake was that to the spire of the Cathedral, which was still in construction.

The large earthquake that struck the Amuri District of Canterbury (about 100 km north of Christchurch) in 1888 is thought to have originated on the Hope Fault, which is part of the Marlborough Fault Zone [8]. The earthquake's intensity reached MM 9 in the epicentre area, and caused severe damage to buildings made of cob and stone masonry located in the Amuri District (now part of the Hurunui Territorial Authority of Canterbury), as well as in Hokitika and Greymouth. This earthquake was felt in Christchurch city, and caused minor damage to buildings [9]. A later earthquake in 1901 centred in Cheviot damaged the spire on the Cathedral for the third time in its short life and led to reconstruction of the spire in timber. Figure 3 shows the damage to the spire from the 1888 and the 1901 earthquakes.

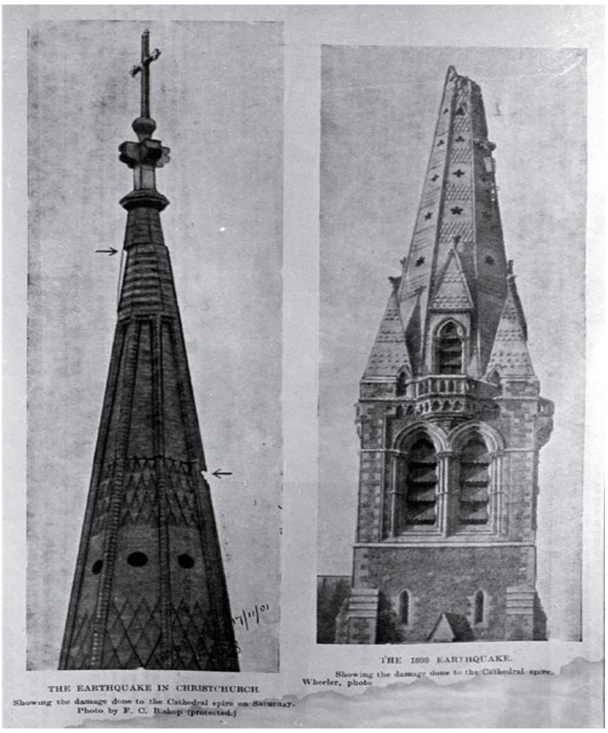

Figure 3: Damage to the Cathedral Spire in the 1888 (left) and 1901 (right) earthquakes [10].

Although these earthquakes early in the development of Christchurch did result in some damage to buildings, and in particular to stone and clay brick masonry buildings, none of these earthquakes had an effect on the construction and design of buildings as did the 1931 Hawke's Bay earthquake. On the 3rd February 1931 a magnitude 7.8 earthquake struck Napier, causing the total collapse of most URM buildings within the city's central business district, which was then followed by a fire that destroyed much of what was left [11]. During the 1931 Hawke's Bay earthquake unreinforced masonry was repeatedly proven to perform unsatisfactorily, resulting in a rapid decline in popularity and subsequent prohibition of use. Few URM buildings were constructed in New Zealand after 1931, meaning that the approximately 934 URM buildings that remain throughout the Canterbury region are now over eighty years old [12]. When compared to the vast history of URM construction worldwide, this narrow time period of approximately fifty five years over which unreinforced masonry construction was popular in New Zealand translates into a relatively homogeneous nature of the URM building stock found in New Zealand, although the early stone masonry buildings in Christchurch are distinctive. These seismically at risk buildings are a significant component of New Zealand's heritage and landmark buildings [13].

Seismic Strengthening

In response to damage in Napier from the 1931 Hawke's Bay earthquake, the Building Regulations Committee presented a report to the Parliament of New Zealand [14] that prompted formation of the New Zealand Standards Institute and led to building codes being developed and updated, with attention subsequently given to the performance of existing buildings in earthquakes. Amendment 301A to the Municipal Corporations Act in 1968 was the first legislation to address the earthquake performance of existing buildings [15]. This act empowered City Councils to require building owners to strengthen or demolish buildings which were considered earthquake prone, which resulted in a number of buildings being demolished and/or the removal of parapets and cornices. Most major cities and towns took up the legislation, with Wellington City Council taking an active approach, strengthening or demolishing 500 out of the 700 buildings identified as earthquake prone [16], whereas Christchurch City Council adopted a passive approach, generally waiting for a change in use or other development to trigger the requirements. New Zealand historian John Wilson describes this process as an effectual destruction or mutilation [4], as the elaborate facades provided by the parapets, cornices and pilasters defined the architectural style of the building. Figure 4a shows the Art Gallery on Durham Street North (constructed in 1890) as it was seen in 1905, and Figure 4b shows the current facade of the building, with its parapets and cornices removed.

The most recent development pertaining to the legislation of seismic strengthening was the introduction of the Building Act 2004, which expresses the New Zealand Government's current objective for earthquake prone buildings to be improved to appropriate seismic standards, or to be demolished [17]. The Act required all Territorial Authorities (TA) to adopt a policy on earthquake prone buildings by 31st March 2006. The policy developed by each TA first required a preliminary assessment of each district's building stock to identify potentially earthquake prone buildings. Each TA could take either a passive or an active approach to identifying and retrofitting earthquake prone buildings, depending on the size of the district under the jurisdiction of the particular TA and the number of potentially earthquake prone buildings in it. Once a building is identified as earthquake prone, significant remedial work is required to meet compliance standards. Christchurch City Council has so far taken a passive approach, having established that they have approximately 7,600 earthquake prone buildings, of which 958 were believed to be constructed of unreinforced masonry [18].

URM building stock of Canterbury

Recent research has suggested that there are approximately 3750 URM buildings in New Zealand [19], with their distribution throughout New Zealand being aligned with the relative prosperity of communities during the period between approximately 1880 and 1930. It was estimated that there were 852 unreinforced masonry buildings remaining in the current Canterbury district, based partly on data provided by the Christchurch City Council on building population de-aggregated by construction date. It is evident that this estimate of 852 URM buildings for the entire Canterbury region results in a lower predicted number of URM buildings in Christchurch city than was reported in [18].

The estimate of building prevalence reported in [19], coupled with the official population data of New Zealand between 1886 and 1945 by county and borough [20], allowed an estimate of the distribution of URM buildings across the current Canterbury territorial authorities. This estimate assumed a uniform rate of both construction and demolition in the areas across the Canterbury province. Table 1 shows the historical populations within the current Canterbury territorial authority boundaries and the estimated number of URM buildings from each decade that today remain. The total number of 934 buildings is higher than the 852 buildings estimated in [19] due to small differences in the population data found and also as Kaikoura historically was part of the Marlborough district, and therefore not included in the total population figures reported in [19]. Figure 5 shows the projected distribution of URM buildings in Canterbury by territorial authority. Importantly, the various territorial authorities themselves do not currently have more accurate data with which to confirm or improve this prediction.

An initial evaluation procedure (IEP) is provided in NZSEE (2006) as a coarse screening method for determining a building's expected performance in an earthquake [21]. The purpose of the IEP is to make an initial assessment of the performance of an existing building against the standard required for a new building, i.e., to determine the "Percentage New Building Standard" (%NBS). A %NBS of 33 or less means that the building is assessed as potentially earthquake prone in terms of the Building Act (New Zealand Parliament 2004) and a more detailed evaluation will then typically be required. An IEP based assessment of a typical URM buildings in central Christchurch (soil type D) results in an estimated 11% NBS.

Figure 4a: Art Gallery on Durham Street North (1905) [22].

Figure 4b:282-286 Durham Street North, 2010.

Table 1: Territorial Authority populations and estimated number of existing URM buildings

Territorial Authorities		Pre-1900	1900-1910	1910-1920	1920-1930	1900-1940	Total
Kaikoura	Population	1,669	1,903	2,137	2,247	2,733	
	URM buildings	0	0	0	3	1	5
Hurunui	Population	2,781	4,838	5,596	6,336	6,415	
	URM buildings	0	6	7	7	6	25
Christchurch City	Population	83,562	94,211	110,387	131,810	152,818	
	URM buildings	4	108	134	149	138	532
Selwyn	Population	3,836	10,921	11,078	11,169	11,119	
	URM buildings	0	13	13	13	10	49
Timaru	Population	20,414	24,361	27,767	30,177	31,366	
	URM buildings	1	28	34	34	28	125
Ashburton	Population	13,457	14,845	17,002	18,514	18,937	
	URM buildings	1	17	21	21	17	76
Mackenzie	Population	1,735	2,286	3,037	3,139	3,152	
	URM buildings	0	3	4	4	3	13
Waimakariri	Population	14,934	13,243	13,157	13,304	12,904	
	URM buildings	1	15	16	15	12	59
Waimate	Population	6,711	8,330	9,343	9,462	9,002	
	URM buildings	0	10	11	11	8	40
Waitaki	Population	2,794	2,471	2,246	2,160	1,960	
	URM buildings	0	3	3	2	2	10
Total	URM buildings						**934**

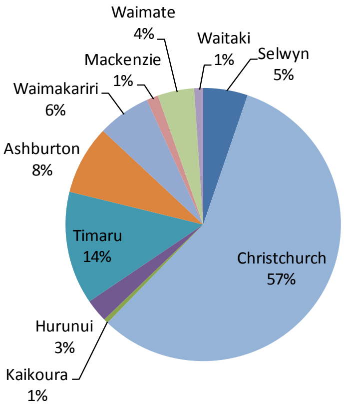

Figure 5: Projected distribution of URM buildings in Canterbury.

PERFORMANCE OF UNREINFORCED MASONRY BUILDINGS

In general, the observed damage to URM buildings in the 2010 Darfield earthquake was consistent with the expected seismic performance of this building form, and consistent with observed damage to URM buildings in past earthquakes both in New Zealand and elsewhere [23-26]. Of the 595 URM buildings that were assessed in Christchurch following the Darfield earthquake, 21% were assessed as unsafe and tagged red, 32% were assessed as yellow – limited accessibility, requiring further inspection, and 47% were assessed as green – safe for public use. Despite the known vulnerability of URM buildings to earthquake loading and the 11% NBS obtained from the IEP exercise, 395 of the 595 buildings (66%) were rated as having 10% damage or less, with only 162 (34%) of the buildings assessed as having more than 10% damage.

The weak out-of-plane strength of unreinforced masonry construction was highlighted during the earthquake, with numerous parapet and gable end wall failures observed along both the building frontages and along their side walls. These failures often resulted in further damage due to individual bricks or larger masonry sections falling through the roofs of neighbouring buildings, and also due to large sections of parapets landing on the canopies along the street frontage, resulting in overloading of the canopy braces which caused punching shear failures in the masonry. Inspection of out-of-plane wall failures typically indicated poor or no anchorage of the wall to the supporting timber diaphragm. One example was 184-186 Manchester Street where two perpendicular walls both failed in an out-of-plane mode, leaving behind anchors attached to only the roof diaphragm.

It was noted that the bricks that were lying on the ground following the earthquake were whole bricks and that failure appeared to be partly attributable to poor quality mortar. This observation was further emphasized by the failure patterns visible on a number of facade walls, that mimicked the damage observed in dry stack masonry experiments [27]. Some in-plane damage was observed, including diagonal pier cracks seen in the Manchester Courts building (formerly the New Zealand Express Company building, see Figure 2) and at 121 Worchester Street, and vertical cracks extending through the spandrels over door or window openings seen at 192 Madras Street. Unsupported or unreinforced brick chimneys performed poorly in the earthquake, with numerous chimney collapses occurring in domestic as well as small commercial buildings and some churches. A key feature of URM buildings is the presence of flexible timber diaphragms, which result in much higher lateral deflections than occurs in rigid reinforced concrete diaphragms. There was one instance where it was clear that diaphragm deformation, relative to the in-plane walls, contributed to partial failure of an out-of-plane wall. Other types of damage such as pounding due to irregularities in wall height and height of diaphragm, and return wall separation, were observed. Each of these failures are documented in reference [28] and representative case study examples of typical failure modes are provided in the following sections.

Characterisation of Mortar from Damaged Buildings

The debris from collapsed URM walls revealed that the mortar in the walls that failed during the earthquake was of poor quality, while the brick units remained in good condition. The particles in the poor quality mortars had almost zero cohesion and interlocking, and therefore these mortars often crumbled under finger compression (see Figure 6). The brick-mortar bond was almost non-existent for these poor quality mortars, as most brick units from the fallen masonry debris were separated from each other instead of remaining as larger masonry segments [29].

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Figure 6: Example of weak mortar from damaged building.

Factors affecting mortar quality

The poor mortar quality was partially due to deterioration over time, which is commonly caused by complex mechanisms and combination of different circumstances that are further affected by factors such as climatic variations and the variability of original material constituent. When considering old buildings, particularly those in Christchurch, seasonal variations such as snow, rain, wind and pollution are even more difficult to quantify due to many years of accumulation since the buildings were constructed [30]. However, possible causes for mortar deterioration can be addressed, and it is agreed by many authors [30, 31] that water ingress in any form plays an important part in the alteration process of mortar. Water is involved in all chemical reactions and transports one mortar compound towards another, which indirectly initiates chemical reactions between the two compounds [31].

The types of mortar deterioration that are directly or indirectly initiated by water include freeze thaw cycles, water leaching, salt crystallisation, chemical attacks and bio-deterioration. These different types of deterioration are principally similar: they affect the interior structure or surface of the mortar through volume expansion, dissolution of compounds and growth of organisms, thus decreasing the mechanical strength of the mortar. The pore structure of the mortar is one factor that determines the extent of weathering, where mortars with a high level of porosity (for instance lime mortars) are generally more prone to deterioration in comparison to low porosity mortars, such as cement mortar [31-34].

Significance of mortar deterioration in Christchurch URM buildings

Most unreinforced masonry buildings in New Zealand were constructed between the 1880s and 1930s, which coincided with the rise in popularity of Portland cement [35]. Therefore, a large proportion of New Zealand URM buildings were built using lime mortar, while the remaining proportion was built using cement-lime or pure cement mortars.

The poor quality of the mortars in URM buildings that were damaged by the Darfield earthquake suggests the use of lime-based mortars for construction of the buildings, which are generally more vulnerable to deterioration when compared to cement mortar, due to their porous nature.

Laboratory testing of extracted samples

Mortar samples from six buildings that were damaged by the Darfield earthquake were extracted for laboratory testing. The mortar compressive strength was determined by compression testing of irregular mortar samples following the procedure reported by Valek and Veiga [36]. Irregular mortar samples were collected and were cut into approximately cubical shapes having two parallel sides (top and bottom), capped using gypsum plaster and tested in compression. A Linear Variable Displacement Transducer (LVDT) was incorporated to derive the mortar stress-strain relationship and Modulus of Elasticity. The stress and strain values considered in the calculation of Modulus of Elasticity were those between 0.05 and 0.70 times the maximum compressive strength. The average irregular mortar sample compressive strength (f'_j) and Modulus of Elasticity (E) for each building are presented in Table 2.

Table 2: Mortar Properties

Building address	No of samples	f'_j (MPa) *(CoV)*	E (MPa) *(CoV)*
441 Colombo St.	6	5.86 *(0.39)*	-
113 Victoria St.	6	1.20 *(0.12)*	37.3 *(0.40)*
202 St Asaph St.	6	2.86 *(0.38)*	49.4 *(0.29)*
469 Colombo St.	7	1.86 *(0.27)*	42.2 *(0.39)*
404 Colombo St.	6	1.15 *(0.33)*	28.2 *(0.41)*
62 Ferry Road	7	1.08 *(0.22)*	44.3 *(0.29)*

Table 2 reveals that the compressive strengths of mortar samples that were extracted from the damaged buildings were mostly low, except for samples from 441 Colombo Street, which had an average mortar compressive strength (f'_j) of 5.86 MPa. The variability of mortar properties within each building was found to be high, where the Coefficient of Variation (CoV) of f'_j and E ranged from 0.12 to 0.39 and from 0.29 to 0.41 respectively. In general, the compressive strengths of mortars extracted from these damaged buildings were notably low in comparison to the mortars in other New Zealand URM buildings [37]. The general conclusion that the mortars in the damaged URM buildings in Christchurch had low average mortar compressive strengths is also in agreement with the on-site observations described previously.

Case Study Buildings

Six case studies of URM buildings that were unretrofitted at the time of the Darfield earthquake are presented below. Each building is described, including its building typology [38] and structural form and use, with photos of each case study building also presented.

Caxton Press, 113 Victoria Street

The Caxton Press building is thought to have been constructed in the 1870s. The building is a two storey isolated building (Typology C) that is now surrounded on two sides by a reinforced concrete block building as shown in Figure 7. The Caxton Press building was formerly a bakery, with the baker's oven still intact behind the modern plasterboard walls. The side walls are solid two leaf walls constructed using English bond, which has alternating header and stretcher courses, whereas the facade wall has no visible header courses.

The ground floor street-front was open, accommodating the placement of circular cast-iron columns to support the upper storey walls. The timber diaphragm joists span parallel to the facade wall, with the floorboards running perpendicular.

Damage observed

The Caxton Press building was extensively damaged during the Darfield earthquake and the subsequent aftershocks. At the time of press it was undecided which of either demolition and rebuild, or repair, was going to be more cost effective. From external observation, the parapets on the facade wall had collapsed, the top of the gabled side walls had failed due to out-of-plane loading seen in Figure 7, the perforated facade wall had developed extensive shear cracks through the spandrel over the openings, and the facade wall had pulled away from the side walls due to insufficient anchorage, as shown in Figure 8. Furthermore, pounding was evident from cracking on the side walls adjacent to where the new concrete block building butted up to the URM building. On internal inspection, evidence of diaphragm movement was apparent as indicated by displacement of the floor boards and the 15 mm displacement of the bricks in the side walls.

The building owner, who was standing outside the building at the time of the first major aftershock, recalls seeing the brick wall move in a wave pattern, which indicates possible diaphragm movement and weak cohesion between the bricks and mortar.

127-139 Manchester Street

127-139 Manchester Street is a 3 storey URM "L" shaped row building (Typology F) that was originally constructed circa 1905 and is listed by the Christchurch City Council as a protected building [39]. The building consists of 7 'bays' along Manchester Street, each having an approximate length of 5 m, with an overall building height of approximately 12 m as shown in Figure 9.

The first storey load bearing walls of the building are solid and four leafs thick and the upper storey walls are solid two leafs thick clay brick masonry. The front facade wall of the building is two leafs thick for the upper level and three leafs thick for the first level. All brickwork is constructed in the English bond pattern. Internal non-load bearing partition walls are constructed using timber studs with lath and plaster type finish. The ground floor was modified using a combination of concrete and timber supporting structure in order to provide larger open shop front space. Canopies extended along Manchester Street above the ground level and were tied back into the piers of the first level using steel rods. Decorative, balustrade type parapets extending approximately 1 m above the roof level were positioned around the street frontage perimeter.

The corner bay of the building (139 Manchester Street) was in a deteriorated condition and had been poorly maintained, with visible water damage and rot of the timber floor and roof diaphragms being evident. The floor joists and roof rafters are positioned in the North-South direction for the building portion along Manchester Street. The end gable was connected to the roof structure using only two through anchors with round end plates.

Damage observed

The building sustained considerable damage, mainly concentrated at the end bay (139 Manchester Street) where the front facade entirely collapsed out-of-plane (refer to Figure 9). The entire building sustained damage from collapsed parapets, apart from two bays (135 and 137 Manchester Street) where the parapets remained on the building as illustrated in Figure 9. From visual observations and physical assessment of the collapsed masonry the mortar was found to be in a moist condition and the mortar that was adhered to the bricks readily crumbled when subjected to finger pressure (see Figure 6), suggesting that the mortar compression strength was low (< 2 MPa). The collapsed facade wall revealed extensive water damage to the timber structure, with rotten floor joists and roof rafters. Also, it was observed that there were large patches of moist masonry on the interior surface of the building, especially around the roof area (there was no precipitation during the period following the earthquake and prior to building inspection).

It appears that the through steel anchors at the gable did not provide sufficient restraint to the masonry, with the brickwork being pulled around the steel anchor plates (refer to Figure 10). Furthermore, from images prior to the earthquake it is evident that there were significant cracks through the spandrel and the parapet over the top corner window of 139 Manchester Street. Falling parapets landed on the canopies, resulting in an overloading of the supporting tension braces that led to canopy collapse. The connections appeared to consist of a long, roughly 25 mm diameter rod, with a rectangular steel plate (approximately 5 mm thick) at the wall end that was approximately 50 mm wide x 450 mm long and fastened to the rod, and was anchored either on the interior surface or within the centre of the masonry pier or wall. The force on the rod exceeded the capacity of the masonry, causing a punching shear failure in the masonry wall (refer to Figure 11).

Welstead House, 184-188 Manchester Street

Welstead House was originally constructed in 1905 and is a corner building located at the intersection of Manchester Street and Worcester Street. The building was designed in Edwardian Baroque style by architect Robert England with an 800 m^2 gross floor area [40]. The building was occupied by seven tenancies in total, and was a standalone 2 storey URM building (Typology C) with a regular rectangular plan and no vertical irregularities. A photograph of the building prior to the Darfield earthquake is shown in Figure 12.

The roof of the building was constructed in three gabled sections, with the parapet enclosing the roof gables and estimated to have a height of 1.6 m. The wall thickness was three leafs, increasing to four leafs at the parapet. The parapet was secured by a single through anchor plate at the apex of each roof gable (i.e. a total of three anchors on the Manchester Street side). A concrete frame was placed at the bottom floor level to allow for large open shop fronts.

Damage observed

The building experienced a complete out-of-plane collapse of the street front corner facade walls (refer to Figure 13). Anchors in the gables did not provide sufficient restraint, as they remained in the timber roof structure following the earthquake as shown in Figure 14. Steel anchor plates which were observed along the Worcester Street roof were positioned between the masonry leafs. These anchors remained in the timber roof structure, indicating that insufficient out-of-plane restraint was provided. Due to excessive damage and safety considerations the building was subsequently demolished.

192 Madras Street

This building was designed by the Christchurch architectural firm of England Brothers and was constructed in approximately 1918-1919 on a narrow plot on the east side of Madras Street (refer Figure 15). The building is not listed with the New Zealand Historic Places Trust but has significant historical and social significance as the original headquarters of the Nurse Maude Association. The building was gifted to the Nurse Maude Association and Nurse Maude herself lived in the building's upstairs flat and died in the property in 1935. The building was turned into office space in the mid 1990s [41].

The building has a footprint of approximately 8.8 m by 27 m, with one heavily perforated wall located on the eastern side (facade) and the other three walls having minimal perforations. The construction is unreinforced masonry with wooden diaphragms and a lightweight roof. The external walls are solid load-bearing masonry and step from three leafs to two leafs at the first floor level and to one leaf at parapet level. Diaphragm anchors at the first floor and roof level were installed in 1998, providing some earthquake strengthening, but no remedial strengthening work was applied to the facade wall [41].

Damage observed

Comprehensive damage was visible to the facade wall, with the spandrel panels at the first floor and roof level having extensive cracking, both vertically and diagonally. There appeared to be some movement of the facade at the diaphragm level in the horizontal direction perpendicular to the plane of the wall. The side walls suffered diagonal shear failures that were visible internally, extending into the stairway wells [41]. The parapet remained attached, as it is supported to some extent by masonry columns that are an extension of the side walls. A diagonal crack extended from the intersection between the top east corner of the side wall and the masonry column diagonally down (seen in Figure 15 and 16), indicating possible rocking of the parapet block out-of-plane.

Cecil House / Country Theme Building, 68-76 Manchester Street

The Cecil House / Country Theme building is an "L" shaped corner building located at 68-76 Manchester Street, on the corner of St Asaph and Manchester Streets (Typology C3) (refer to Figure 17). The building has two stories, was constructed in 1877 in the neo-classical style, and is not listed by the New Zealand Historic Places Trust [42] but is believed to significantly contribute to the heritage value and character of the Commercial Urban Conservation Area [43].

It appears that the front façade of the building is a three leaf URM wall, with two leaf parapets located along the street-facing perimeter. The parapet had a poorly reinforced (approximately 6 mm round bars at each corner) concrete beam on top.

Damage observed

The most apparent earthquake damage was the toppled parapets around the street frontage as illustrated in Figure 17 and 18, with a lightly reinforced concrete beam on top of the parapet providing insufficient restraint. Falling parapets landed on the canopies below, resulting in an overloading of the supporting tension braces that led to a punching shear failure in the masonry wall and resulted in canopy collapse. The connections appeared to consist of a long, roughly 25 mm diameter rod, with a round steel plate (about 10 mm thick) at the wall end that was approximately 150 mm in diameter.

No evidence of through anchors connecting the roof diaphragm to the wall structure was observed. Some in-plane damage to the far end of the building along Manchester Street was evident, mostly consisting of cracking through the spandrel and some horizontal cracking through the piers.

463-469 Colombo Street

This building was constructed in approximately 1905, and is located at the corner of Colombo Street and Sandyford Street. The building is a 2 storey URM "L" shaped row building (Typology F) and is listed by the Christchurch City Council as a protected building [39]. The building consists of 6 bays along Colombo Street and 2 bays along Sandyford Street, each having an approximate length of 6 m with an overall height of approximately 7.5 m, as shown in Figure 19. The external canopy extends along Colombo Street and is supported by a column structure.

The ground floor along Colombo Street consists of concrete frame construction, and the upper floor consists of a two leaf veneer masonry construction with an approximate 80 mm cavity and regularly spaced wire veneer ties for the upper storey. The parapets are solid two leaf construction supported on the stone cornice. The bays are separated with a solid two leaf masonry wall constructed using weak lime based mortar (see Table 2).

The top part of the building consists of a roof space that decreases in height from approximately 1.2 m to the ceiling level, due to the sloping roof away from Colombo Street. The top storey ceiling and floor diaphragm consists of timber rafters/joists pocketed into the masonry wall to a depth of one brick and oriented in the North-South direction, with lath and plaster type finish. Internal partition walls consist of timber studs with lath and plaster type finish.

Damage observed

The majority of the observed damage was concentrated along Sandyford Street (end two bays) where complete collapse of the parapets, the wall section in the roof space and delimitation of the external veneer were the main damage that was observed (refer to Figure 19 and 20).

The collapsed external veneer layer revealed that the wire veneer ties were generally in good condition, with a few ties being affected by rust. It was also observed that most of the ties remained in the internal layer as illustrated in Figure 21 and 22, and that the internal surface of the cavity wall was constructed to a poorer quality in comparison to the external layer, indicated by a large number of visible voids and broken bricks used. It is believed that the pocketed ceiling rafters provided sufficient support to the internal leaf of the cavity wall, preventing out-of-plane collapse. It was also observed that some of the roof structure members in the vicinity of the drainage gutters were in a poor condition.

PERFORMANCE OF RETROFITED URM BUILDINGS

In general, the retrofitted URM buildings performed well, with minor or no earthquake damage observed. Partial or complete collapse of parapets and chimneys were amongst the most prevalent damage observed in retrofitted URM buildings, and was attributed to insufficient lateral support of these building components. Out-of-plane separation of the façade from the side walls was observed in some URM buildings, and was the result of insufficient wall-diaphragm anchorage.

Figure 7: Caxton Press, 113 Victoria Street.

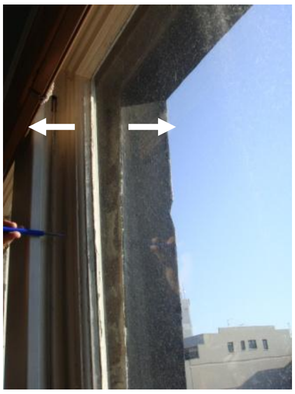

Figure 8: Caxton Press, 113 Victoria Street, facade wall pulled away from the side walls.

Figure 9: 135-139 Manchester Street, out-of-plane facade collapse.

Figure 10: 139 Manchester Street, through steel anchors and rotten timber roof diaphragm.

Figure 11: 137 Manchester Street, pull out of the canopy supports.

Figure 12: Welstead House, 184-188 Manchester Street, before the earthquake.

Figure 13: Welstead House, 184-188 Manchester Street, after the earthquake.

Figure 14: Welstead House, 184-188 Manchester Street, side view, showing steel anchors.

Figure 15: 192 Madras Street, cracking through top spandrel.

Figure 16: 192 Madras Street, in-plane diagonal cracking through top spandrel.

Figure 17: Cecil House / Country Theme Building, 68-76 Manchester Street, parapet collapse.

Figure 18: Cecil House / Country Theme Building, 68-76 Manchester Street, concrete beam on the ground.

Figure 19: 463-469 Colombo Street, collapse of the veneer.

Figure 20: 463-469 Colombo Street, exposed wire veneer. ties

Figure 21: 463-469 Colombo Street, rear view of the building.

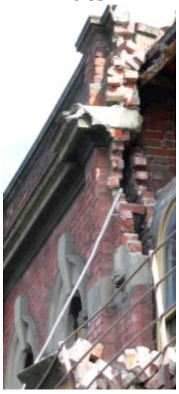

Figure 22: 463-469 Colombo Street, cavity between wall and veneer, with solid parapet above.

Most of the retrofitted URM buildings had significant heritage value based on their era of construction and aesthetic quality and therefore a carefully considered, minimally invasive retrofit solution had been preferred. The addition of a secondary structural system was found to be a common retrofit solution, with fewer buildings adopting alternative solutions such as steel strapping, the addition of surface bonded fibre reinforced polymer (FRP) sheets, and post-tensioning. Case study examples of the performance of retrofitted URM buildings that were inspected following the Darfield earthquake are briefly reported below.

The Malthouse, 71 Colombo Street

The Malthouse is a stone masonry building that was constructed in 1867-1872 (see Figure 28). It is one of New Zealand's oldest buildings and has been recognised as a category II heritage building by the Historic Places Trust [44]. The building has three levels, with a half basement, timber diaphragms and an irregular floor plan. The building was used as a Malthouse until 1955, when it was converted to the Canterbury Children's Theatre.

Retrofit:

Between 1972 and 1984 the Malthouse went through several architectural renovations that included seismic retrofit. The roof was raised in two stages: the first stage involved raising half of the roof in 1992 and the second stage involving raising the remainder of the roof in 2003. Seismic retrofit of the Malthouse in 2003 was found to be insufficient and consequently the building's lateral load resisting system was again updated in 2008. The seismic retrofit involved injecting grout into the rubble masonry walls, installing new wall-diaphragm anchors (see Figure 31), strengthening of the floor diaphragms by replacing the plywood and introducing additional timber blockings as shown in Figure 30, and strengthening the roof by introducing new steel trusses (see Figure 29). It was established from discussions with the manager that the cost of retrofit was approximately $NZ 750,000.

Performance:

The building performed well and no signs of damage were observed during post-earthquake inspection.

The Smokehouse, 650 Ferry Road

The Smokehouse, located at 650 Ferry Road, is a two storey isolated (Typology C) URM building as shown in Figure 32. The building's exact construction date is unknown but can be confirmed as pre-1930s, and the building has been categorised as a heritage building by the Christchurch City Council. The building's foot print is approximately square, having dimensions of 13 m along Ferry Road and 10 m along Catherine Street. The original mortar is a weak lime/cement mortar with large grain size sand. In places the original mortar was re-pointed with strong cement mortar.

Retrofit:

The Smokehouse was seismically retrofitted in 2007 by introducing secondary moment resisting steel frames. This retrofit also included alternations to the internal layout, which involved partial removal of original external walls and replacement with moment resisting steel frames that created openings into the adjoining new section of the building (see Figure 23 and 33), and also infilling one window at the second floor level. The retrofit design of the building won the New Zealand Architectural Award in 2008 for initiative in retention, restoration and extension of a significant building and its adaption to new uses [45].

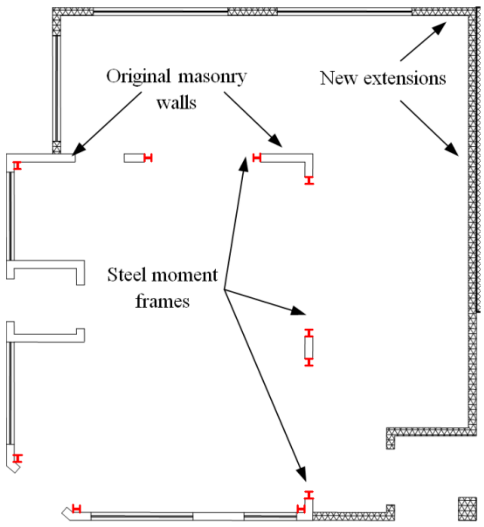

Figure 23: Floor plan of Smokehouse, showing retrofit.

Performance:

The building performed well, with no signs of earthquake damage observed on the exterior of the building. However, some minor vertical cracks at the wall corners, minor cracks around the perimeter of the in-filled window, and one minor horizontal crack slightly above the base of one pier at the second floor level were observed during internal inspection.

X Backpackers, 56 Cathedral Square

This four storey URM building located in the northeast corner of Cathedral Square was constructed in 1902 (see Figure 34). The building, formerly known as the Lyttelton Times building and now occupied by X Backpackers, is the last in a row of multi-story buildings on Gloucester Street and butts up to the original Canterbury Press building. The building's exterior aesthetics are similar to the nineteenth century Chicago high-rise buildings (i.e., Romanesque style), with heavy vertical URM piers ending in round headed arches on the front façade and two leaf thick solid brick URM walls on the periphery. The facade of the building is shown in Figure 34. The building was registered as category I heritage building with the New Zealand Historic Places Trust in 1997 and therefore an application for its demolition was declined and the building was instead purchased by the Christchurch Heritage Trust [44]. The building was constructed using bright red burnt bricks, laid in a common bond pattern. From preliminary scratch tests it was established that a weak lime/cement mortar was used in construction, with variation in the mortar strength in upper floors.

Retrofit:

The former Lyttelton Times building was seismically retrofitted in 2001 using steel moment resisting frames. The moment frames, as seen from the fourth floor of the building, are shown in Figure 37. As part of the seismic retrofit scheme, the parapets were tied back to the roof structure using hollow steel circular sections (seen in Figure 36). In a recent inspection of the building, steel straps anchored to the side walls in an X pattern were also observed (shown in Figure 35) and were possibly part of an earlier retrofit scheme.

Performance:

Some minor internal cracks were observed on the side of the building facing Cathedral Square, and large interior cracks at the top of the façade (separation of front facade from the in-plane walls of nearly 100 mm) were attributed to insufficient wall-diaphragm anchorage (refer Figure 38). Damage to the wooden partition interior walls was also observed, which provided evidence that large out-of-plane deformation of the front façade wall occurred. As a post earthquake hazard mitigation measure, the front façade was secured by introducing temporary steel rod anchors and the unstable façade top was tied to the diaphragm at the roof level. Figure 39 shows minor in-plane cracks that were observed in the spandrel of the front facade wall at ground level.

TSB Bank Building, 130 Hereford Street

130 Hereford Street is a 1920s 3+ storey isolated (Typology E) URM building, currently owned and occupied by TSB Bank Limited. The original structural system consisted of URM load bearing walls, built in the Chicago style architecture as shown in Figure 40. The estimated footprint area of the building was approximately 450 m^2. The ground floor has been re-furbished and is occupied by the TSB Bank, whereas the upper levels required refurbishment at the time of the earthquake and therefore the retrofit structure was exposed at the time of inspection. From preliminary scratch tests it was established that a weak lime mortar (can be scratched with a finger nail) was used in construction. The bricks used were bright red burnt bricks, laid in a common bond pattern. The building has flexible wooden diaphragms that consist of plywood sheathing resting over wooden joists that are supported on the load bearing URM walls.

Retrofit:

The building was seismically retrofitted by the new owner (TSB Bank) in 2009, which involved the introduction of secondary frames. The facade is strengthened by concrete columns and beams at the floor levels (forming a concrete frame) and the side walls are strengthened using steel frames with diagonal braces that are anchored into the masonry as shown in Figure 24 and 41. The floor diaphragms on levels 2 and 3 were stiffened with plywood sheets and 'X' pattern steel plates, with fixings spaced at approximately 20 mm as show in Figure 42. Figure 44 shows the roof diaphragm strengthening using steel tie rods and Figure 43 shows strengthening of the gable, consisting of steel frames with anchor bolts. The walls are supported by newly added concrete beams at the basement level, further resting over old concrete basement walls.

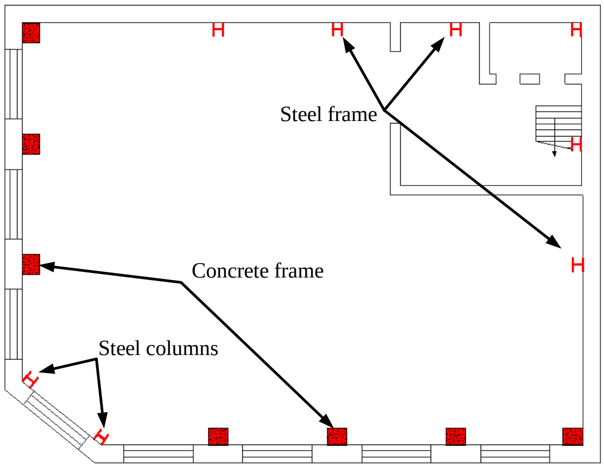

Figure 24: Floor plan of TSB Bank Building, showing retrofit.

Performance:

No visible cracks in the walls were observed, although some minor vertical cracks were visible in the basement beams (probably not caused by the earthquake).

Joe's Garage Cafe, 194 Hereford Street

At the time of construction in the 1920s, 194 Hereford Street was the end building in a row of two storey buildings. The building is a two storey isolated (Typology C) URM building now occupied by Joe's Garage Cafe and Miles Construction, and is isolated from the neighbouring building by a seismic gap (see Figure 45). The original structural system consisted of load bearing external URM walls, with timber diaphragms and a concrete lintel beam running the full length of the building on the Hereford Street and Liverpool Street sides. The street-facing facade walls are perforated URM walls whereas the rear of the building consists of stiff solid shear walls. The building has a sloping roof and the parapet height varies from zero to about 1 m at the side adjacent to the neighbouring building. From preliminary scratch tests it was established that a lime based weak mortar having coarse aggregate was used in the original construction.

Retrofit:

The building was seismically retrofitted in 2004 using large steel portal frames oriented in the transverse direction of the building, that are spaced at approximately 4 m centres as shown in Figure 46. The building floor plan is shown in Figure 25. Diaphragm strengthening was not observed in the interior of the building.

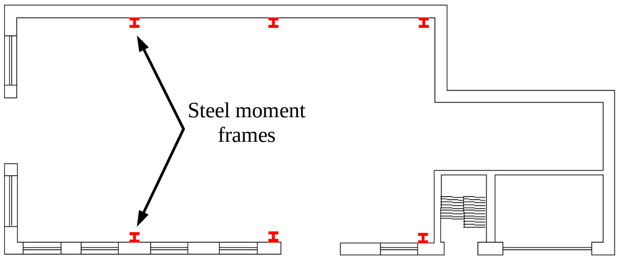

Figure 25: Floor plan of Joe's Garage Cafe, showing retrofit.

Performance:

The retrofit increased the stiffness in one direction only, creating differential stiffness between the building's two principal axes which may have accentuated the building's torsional response, resulting in diagonal shear cracks at the rear face of the building as shown in Figure 47. Some localised punching of bricks away from the steel moment frame was also observed and was attributed to the frame pounding against the URM wall at the locations adjacent to the beam-column joint. However, no cracks were visible at the ground floor level. The parapet was cracked at the roof line and had been temporarily strengthened using steel tie backs to the roof (see Figure 48). The occupants stated that the parapet crack appeared in the Wednesday (8th September 2010) M5.0 aftershock [7], and that the displacement amplitude of the building was small with high frequency vibrations. Pounding damage was also observed due to twisting of this building towards the neighbouring building, which exceeded the seismic gap allowance. Damage is shown in Figure 48.

Vast Furniture / Freedom Interiors, 242 Moorhouse Avenue

Vast Furniture / Freedom Interiors (shown in Figure 59) is a single storey masonry building, with its roof supported on strong steel trusses that were laterally braced by connecting steel section trusses. Masonry materials observed were bright red bricks and a weak lime mortar, with URM laid in a common bond pattern.

Possible Retrofit:

The trusses are further supported on steel portal frames, but the frames had more modern welded joints than the old fashioned riveted joints used in trusses, which suggests that the portal frames were added later to the building as a seismic retrofit solution (see Figures 60 to 62).

Performance:

The parapets collapsed out-of-plane and wall-diaphragm anchors pulled out from the wall, with the anchors punching through the brickwork and creating localized wall damage (refer to Figure 60). The building was cordoned off as falling hazards had been identified during post-earthquake evaluation.

Environment Court Ministry of Justice/ Former Canterbury Society of Arts Gallery, 282-286 Durham Street North

The Environment Court building is a one storey isolated (Typology A) URM building that was constructed in the 1890s. The building was originally constructed as an art gallery, with street facades divided into a series of bays and decorated with patterned cornices. A wooden truss supports a gable roof and rests on load bearing URM walls. Due to the building's historic value it is identified as a Category I historic place on the New Zealand Historic Places Trust register [44].

Retrofit:

The building was seismically retrofitted in 1972 by the Justice Department. The seismic retrofitting scheme involved the addition of cross walls and strapping of the building with steel plates, as shown in Figure 4b and Figures 49 to 51.

Performance:

During the post-earthquake inspection no cracking was observed.

Shirley Community Centre, 10 Shirley Road

Shirley Community Centre is a single storey Typology G (institutional) URM building that was constructed in 1915 to be the Shirley Primary School. The building has a hipped roof and was constructed in the Georgian style with large and regular fenestrations [44] as show in Figures 52 and 53. This historic building was registered under the Historic Places Act in 1993. The perimeter cavity walls consist of two leaf thick solid red clay brick masonry with a single veneer yellow brick layer on the exterior surface.

Retrofit:

Seven individual wall areas were strengthened with surface bonded FRP sheets using Sikawrap 100G (the application of FRP retrofit is shown in Figures 54 and 55) in the locations shown in Figure 24. FRP rod anchors were installed to bond the applied Sikawrap 100G sheet to the concrete foundation beams [46]. The out-of-plane stability to the perimeter wall was provided by using steel hollow sections as strong backs fixed to the URM walls. To ensure sufficient lateral load resistance in the North-South direction a concrete shear wall was also added at the location shown in Figure 26. The veneer brick layer was secured to the main wall using helical veneer ties at regular spacing.

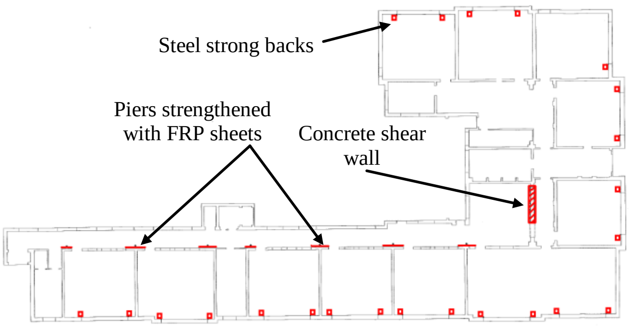

Figure 26: Floor plan of Shirley Community centre showing retrofit.

Performance:

Overall the building performed well, with no significant damage, and was tagged green during initial 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 FRP sheets, as shown in Figure 56, 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, as shown in Figure 27 (no cracks were detected through the veneer at the same locations). Horizontal cracking and spalling of the plaster layer was observed at the north east wall (see Figure 57). In addition, a minor step-wise crack through the veneer was observed in the south-west corner of the building.

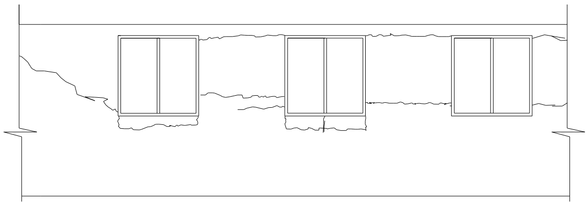

Figure 27: Shirley Community Centre; crack pattern in the plaster layer around the window openings in the external wall of the south corridor

Figure 28: Malthouse, 69-71 Colombo Street.

Figure 29: 69-71 Colombo Street, interior view of the Malthouse.

Figure 30: 69-71 Colombo Street, additional blocking at ground floor.

Figure 31: 69-71 Colombo Street, wall to diaphragm connections.

Figure 32: Smokehouse, 650 Ferry Road.

Figure 33: 650 Ferry Road, interior steel frames visible.

Figure 34: X Backpackers, 56 Cathedral Square.

Figure 35: 56 Cathedral Square, 'X' steel brace fixed into wall.

Figure 36: 56 Cathedral Square, parapet restraints.

Figure 37: 56 Cathedral Square, steel frames at interior.

Figure 38: 56 Cathedral Square, façade separation.

Figure 39: 56 Cathedral Square, cracking through the spandrel on ground level.

Figure 40:TSB Bank Building, 130 Hereford Street.

Figure 41: 130 Hereford Street, steel brace frame.

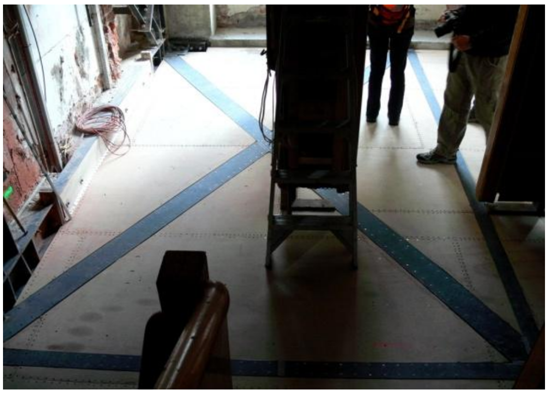

Figure 42: 130 Hereford Street, floor diaphragm strengthening.

Figure 43: 130 Hereford Street, gable strengthening.

***Figure 44**: 130 Hereford Street, roof diaphragm strengthening.*

***Figure 45**: Joe's Garage Cafe, 194 Hereford Street.*

***Figure 46**: 194 Hereford Street, steel moment frame.*

***Figure 47**: 194 Hereford Street, highlighted crack location at the rear of building.*

***Figure 48**: 194 Hereford Street, reduction of seismic gap.*

***Figure 49**: 282-286 Durham Street North, Armagh street view.*

***Figure 50**: 282-286 Durham Street North, strap detail around openings.*

***Figure 51**: 282-286 Durham Street North, side view with gable.*

***Figure 52**: Shirley Community Centre, 10 Shirley Road.*

***Figure 53**: Shirley Community Centre, rear view showing gable strengthening.*

***Figure 54**: Shirley Community Centre, FRP sheet strengthening (2009) [46].*

***Figure 55**: Shirley Community Centre, FRP sheet strengthening (2009) [46].*

***Figure 56**: Shirley Community Centre, FRP strengthening after earthquake, no visible cracking.*

***Figure 57**: Shirley Community Centre, loss of plaster in north east wall.*

***Figure 58**: Vast Furniture / Freedom Interiors, 242 Moorhouse Avenue.*

Figure 59: 242 Moorhouse Avenue, wall-diaphragm anchor punching.

Figure 60: 242 Moorhouse Avenue, wall strengthening using steel sections.

Figure 61: 242 Moorhouse Avenue, interior of the building (location where anchor plate pull out occurred).

CONCLUSIONS

- Christchurch City Council has previously undertaken a passive approach towards seismic assessment and subsequent retrofit of the city's earthquake prone building stock, having established that they have approximately 7,600 earthquake prone buildings, of which 958 were thought to be constructed of unreinforced masonry.
- An independent analysis of the URM building stock for the Canterbury region using a previously developed methodology has suggested that there may be approximately 532 URM buildings in Christchurch and 934 URM buildings in the Canterbury region. However, as 595 URM buildings were assessed during post-earthquake inspections, this analysis appears to under-predict the actual number of URM buildings in Christchurch. Actual data on the number of URM buildings in other territorial authorities of the Canterbury region currently are not available.
- In general, the observed damage to URM buildings in the 2010 Darfield earthquake was consistent with the expected seismic performance of this building form, and consistent with observed damage to URM buildings in past earthquakes both in New Zealand and elsewhere. The main failure types observed were: parapet failure, chimney failure, out-of-plane facade wall failure and in-plane damage.
- Water ingress has a significant effect on mortar deterioration, with the main causes being directly or indirectly initiated by water ingress.
- Mortar samples extracted from 6 damaged URM building were tested in compression and resulted in low average mortar compressive strengths (generally < 2 MPa), which is with agreement with the on-site observations.
- Presented preliminary case studies investigated the performance of URM buildings and illustrated examples of each failure mode, with each being briefly discussed.
- In general, retrofitted URM buildings performed well, with minor or no earthquake damage observed. Partial or complete collapse of parapets and chimneys were amongst the most prevalent damage observed in retrofitted URM buildings and was attributed to insufficient lateral support.
- Case studies of the performance of buildings retrofitted using steel and concrete moment frames, steel brace frames and surface bonded FRP materials were presented and briefly discussed.

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