Exemplar seismic retrofits of Christchurch URM buildings

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S.R. Abeling, A.N. Misnon, D. Dizhur & J.M. Ingham

Department of Civil Engineering, University of Auckland, Auckland.

ABSTRACT: Case study unreinforced masonry (URM) buildings that were seismically retrofitted prior to the 2010/11 Canterbury earthquake sequence and exhibited successful performance during these earthquakes are presented herein. Selected buildings were divided into the following categories based on size and complexity: (1) simple, single storey box type buildings (i.e. electrical substations), (2) common and simple commercial buildings, and (3) large and complex clay brick and stone URM buildings. The retrofitted case study URM buildings were evaluated based on overall structural seismic performance as well as the categories of initial seismic design, heritage preservation, architectural appeal, and cost. Detailed observations of 4 representative case study buildings and a summary of findings are reported herein.

1 INTRODUCTION

The 2010/11 Canterbury earthquakes provided a unique opportunity to investigate the overall success of retrofitted buildings following two major earthquakes, being the M_w 7.1 September 2010 Darfield earthquake and the M_w 6.2 February 2011 Christchurch earthquake. The poor performance of unreinforced masonry (URM) buildings during the Canterbury earthquakes has been widely reported (Dizhur et al., 2011; Dizhur et al., 2010; Ingham & Griffith, 2011a, 2011b; Moon et al., 2014). However, this study instead reports on case study examples of successfully retrofitted URM buildings that performed well in the Canterbury earthquakes in order to provide a retrospective inspection of the adopted design, construction, and post-earthquake repair processes. Structural, social, and economic aspects of retrofits were taken into consideration, and the findings from 4 case study retrofitted URM buildings are presented. Common themes were identified based on interviews with the architects and design engineers of these successfully retrofitted buildings.

All retrofitted URM buildings described herein were designed to between 67% and 100% of new building standard (NBS) for their importance level (IL) at the time of the seismic retrofit. Importance levels vary based on building use, with IL 1 assigned to buildings of the lowest importance and IL 5 assigned to buildings of the highest importance.

Fifty URM buildings in the Christchurch Central Business District (CBD) were known to have been retrofitted to between 67% NBS and 100% NBS before the Canterbury earthquakes (Ingham & Griffith, 2011b). After the February 2011 earthquake, only 20% of these buildings had insignificant damage, whereas 56% had moderate damage and 24% had heavy damage. Since the Canterbury earthquake sequence, over 70% of URM buildings in the Christchurch CBD that were retrofitted to levels similar to the case study buildings have been demolished, as well as over 90% of the unretrofitted URM buildings (Moon et al., 2014). The reasoning for the demolition of a building varies and is not necessarily directly associated with the extent of building damage. Buildings that were damaged such that repair costs were estimated to be approximately 75% of replacement cost were generally demolished, but other buildings were demolished for safety reason before a quote could be made (King et al., 2014). The high percentage of demolished URM buildings, particularly of retrofitted URM buildings, raises concern for the performance and preservation of New Zealand's URM building stock in future earthquakes.

2 METHODOLOGY

A list of exemplar retrofitted buildings was developed in collaboration with an advisory committee comprised of three Christchurch based engineers. The engineers were asked to identify retrofitted buildings of any construction type known to have performed well in the Canterbury earthquake sequence. They were asked to evaluate the success of a retrofit based on social and economic factors, as well as structural aspects. The engineers recommended 20 retrofitted buildings, of which 19 have loadbearing URM walls, and also recommended a group of retrofitted URM substation buildings. Three primary building typologies were identified from the recommended buildings: (1) simple, single storey box type buildings (i.e. electrical substations), (2) common and simple commercial buildings, and (3) large and complex clay brick and stone URM buildings. Buildings were selected for consideration based on a general consensus of their successful structural performance in the Canterbury earthquakes and their ability to fit into the identified typologies. Property files were obtained from Christchurch City Council for the selected buildings, and interviews were held with building engineers, property owners, and project architects.

3 CASE STUDIES

Case study buildings were evaluated in terms of the seismic structural design, architectural appeal, heritage preservation, observed performance, and cost. Evaluation criteria for case study buildings were adapted from the assessment tool developed for appraising the seismic strengthening of heritage buildings as presented in Pattinson and Egbelakin (2016).

3.1 Orion Power Substations

Prior to the 2010/2011 Canterbury earthquakes there were 115 operational clay brick masonry substation buildings owned by Orion in the wider Christchurch region. These substation buildings act as platforms to transform high voltage energy to low voltage energy that is then distributed to Orion’s 191,000 end user customers. The considered substation buildings were typically standalone rectangular structures with a concrete floor and a rigid or flexible roof diaphragm. 110 of the substations are clay brick URM buildings that were erected between 1920 and 1960, and 5 of the substations are masonry infill buildings that were constructed after 1950. The substation buildings are important contributions to the architectural and social history of Christchurch and some of these substation buildings are listed in the City Plan as Group 4 heritage buildings due to their age, pleasing appearance and social significance (Hartrick, 2003).

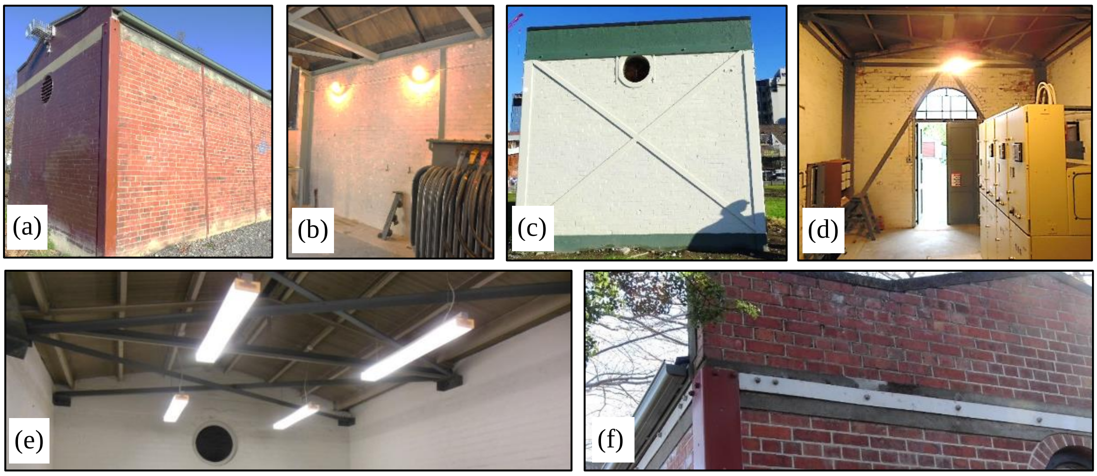

Figure 1. Orion Power substation wall and roof retrofit examples: (a) External vertical steel plates and angles; (b) Internal vertical steel plates and angles; (c) External diagonal steel plates; (d) Internal diagonal steel plates; (e) Typical roof bracing of flexible diaphragm; (f) Steel plates mounted on perimeter beam.

Seismic retrofit work on the substation buildings began in 1996 and progressed systematically for fifteen years. Walls were strengthened in-plane and out-of-plane with internal or external steel braced frames consisting of vertical and diagonal steel members. Vertical steel angles were commonly placed at the corners and vertical steel plates were located at intervals along the walls of the buildings (Figures 1a, b, c, d), with diagonal steel members generally mounted at the entrance and on the rear walls (Figures 1c, d). Frames were connected to the walls with anchored steel ties. Roofs were strengthened by either installing steel bracing across the roof diaphragm (Figure 1e), bolting steel brackets to purlins, or mounting steel plates on perimeter beams at eaves level (Figure 1f).

Most of the buildings survived the Canterbury earthquakes with minor damage and only four of the substation buildings were severely damaged (Massie & Watson, 2011). Power was restored to 90% of customers in one day following the 4 September 2010 earthquake and to all customers in ten days following the 22 February 2011 event. NZ$6 million was spent over fifteen years to strengthen the substation buildings, with an estimated cost of NZ$21,000 per building. Orion was assessed to have saved approximately NZ$60 million in direct asset replacement costs following the Canterbury earthquakes (Orion New Zealand Limited, 2012), and the community benefits associated with having the power only briefly being interrupted following the Canterbury earthquakes was clearly profound.

3.2 **Former 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. The building is approximately 18 m x 14.5 m along south and west elevations respectively, with a chamfered corner to the southwest and a re-entrant corner of about 8 m x 4.5 m to the northeast (Figures 2a, b). 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.

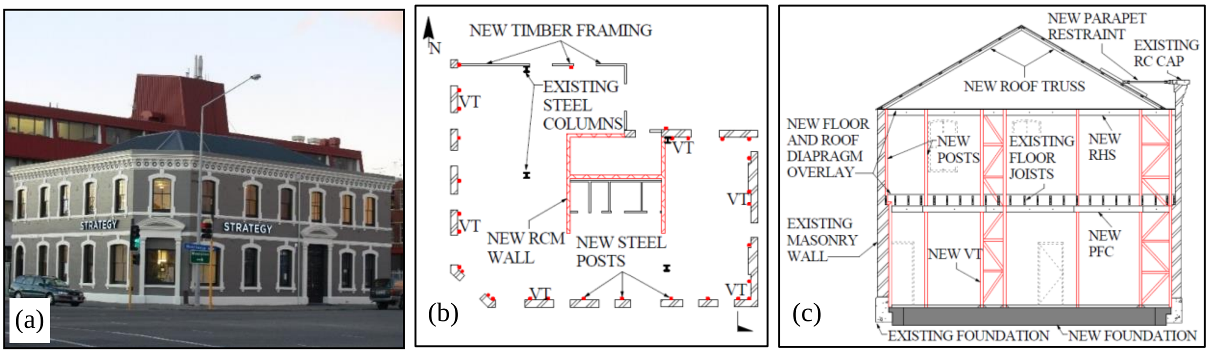

Figure 2. Retrofit of Grosvenor Tavern, 367 Moorhouse Avenue: (a) Exterior view of southwest corner after retrofit; (b) Ground floor plan showing retrofit, VT = vertical truss; (c) East elevation showing retrofit.

Work on the seismic retrofit of the former Grosvenor Tavern began when new owners purchased the property in 2010, after the building had been vacant for nine years. The first stage of the seismic retrofit involved reducing the seismic weight of the building by removing heavy clay roof tiles, lath and plaster on the interior walls, and two single storey concrete block annexes. The second stage of the retrofit combined several methods to seismically strengthen the building. Vertically oriented steel trusses were installed along the interior of the existing brick wall. New RCM walls were constructed to surround a new centrally located stair case and were topped with a concrete lid so that the area would act as a shear core. New exterior timber framed walls were installed to replace decaying timber framed walls on the north end of the building. New floor and roof diaphragms were installed over existing flooring and the parapet was restrained. (Figures 2b, c).

The seismic retrofit was designed to resist a lateral load equivalent to 70% NBS (IL 2) in 2010. The façade was determined to have the most heritage value, so minimum intervention measures were taken in order to protect its heritage value. The seismic retrofit design utilised steel lateral load resisting elements and accounted for the existing in-plane strength of the masonry.

Structural elements were strategically placed to allow for the removal of most of the interior partition walls. This approach maximised the usable floor area and created open space that permitted flexible tenancy throughout the building. Exterior staircases were removed and a new staircase was installed in a central location to provide a clear access to the upper storey.

The use of vertical steel trusses and posts as a retrofit solution allowed the interior brickwork to be maintained. On the building exterior, heritage features of the façade were accentuated by being painted a bright white against the grey paint on the masonry (Figure 2a). The vertical steel trusses and posts 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. 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 (Christchurch Civil Trust, 2011).

The first stage of retrofit work had been completed when the September 2010 earthquake occurred. The brick façade experienced only minor cracking and no further damage was reported. The seismic strengthening aspects of the building were installed before the February 2011 earthquake, including the vertical steel trusses, concrete block shear core, and new timber roof trusses, and no damage was reported in that earthquake. Steel trusses remained attached to the masonry walls, there was no cracking in the RCM walls, and there was no differential movement observed between the walls and floor diaphragm.

The property was purchased for NZ$650,000 in 2010, and the owners report to have invested approximately NZ$1 million into the property for the retrofit and fit out. The building has remained fully tenanted since the completion of the retrofit.

3.3 **Heritage Hotel, 28-30 Cathedral Square**

The Heritage Hotel, formerly known as the Government Building, is located at 28-30 Cathedral Square in the Christchurch CBD. The north façade extends approximately 80 m along Worcester Street (Figure 3a) and the west façade extends approximately 20 m along Cathedral Square (Figure 3b). The building was designed by architect J.C. Maddison in the Italian High Renaissance Palazzo style and was built in 1913. The building has loadbearing clay brick URM walls and reasonably heavy timber flooring. It is 3 storeys and has ceiling heights up to 5.7 m and wall thicknesses up to 900 mm for exterior walls and up to 1100 mm for interior walls (Hare, 1996). The façades are heavily perforated, are ornamented with stone masonry on the ground floor, and have parapets with heights of up to 5 m. The west façade has heavy stone columns spanning two storeys to support the roof (Figure 3a). The building is listed as a Category 1 historic place by Heritage New Zealand.

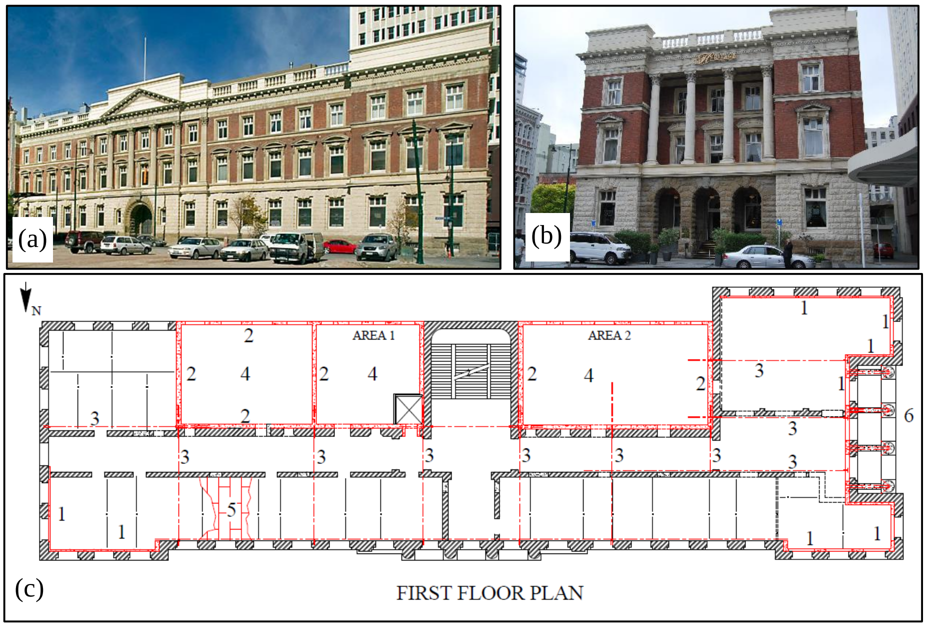

Figure 3. Retrofit of the Heritage Hotel, 30 Cathedral Square: (a) Exterior view of north elevation; (b) Exterior view of west elevation; (c) First floor plan. 1. New concrete skin walls; 2. New concrete shear walls; 3. New steel floor ties; 4. New hollow core concrete flooring; 5. New plywood overlay to existing flooring (typical); 6. Prestressing cables at centres of existing masonry columns

Seismic retrofit work was undertaken in 1995, after Christchurch City Council purchased the building to prevent its demolition. The initial project scope called for the building to be strengthened to 67% NBS (IL 3) in 1995. Two strengthening strategies were proposed, and for minimal (approximately 2%) extra cost, designers determined that the building could be strengthened to 100% NBS (IL 3). The seismic design required partial demolition of the building (Area 1 and Area 2 in Figure 3c). RC shear walls were constructed to act as shear cores in these areas. Detailing of the foundation beams under the new lateral load resisting elements utilised the full capacity of existing piles.

The existing flooring was strengthened with a new heavily nailed plywood overlays, and hollow core concrete flooring with a 100 mm topping was constructed in the new shear core areas. The timber diaphragms were tied to the shear cores with heavy steel flats running through the floor and into the shear walls (Figure 3c). The roof was strengthened with a RC topping over an existing lightweight concrete slab from a previous intervention and a concrete bond beam was cast around the perimeter of the roof. The stone columns of the west façade were diamond cored full height and lightly stressed prestressing cables were cast in to control cracking of the stone columns (Figure 3c).

Following the seismic retrofit, the building use changed from government offices to 54 residential and serviced apartments, a restaurant and boutiques on the ground floor, and a health club in the basement. Open and flexible spaces were created in the shear core areas, which previously housed vaults and toilets that would have been difficult spaces to utilize within the new uses of the building. Mezzanines were added at each floor to take advantage of the large storey heights and create extra bedrooms in apartments. These mezzanines are set back from the windows so that original site lines to and from the building are retained and the windows still provide an abundance of natural light.

The retrofit design protected the iconic facades of the building as well as the grand central staircase. Demolition was limited to areas in the building determined to have low heritage value, and the use of shear cores prevented the need for extra RC skin walls in areas of higher heritage significance. A new lightweight parapet that was designed to replicate the original parapet was constructed at the roof. Other heritage features throughout the building were restored during the retrofit.

The building suffered only minor cracking in the September 2010 earthquake and required minimal repairs. The February 2011 earthquake caused minor cracking in the URM walls, minor cracking in the south elevation core wall, some damage to external stonework, and flooding in the basement. Overall, the building behaved as expected, with a majority of the forces transferring to the shear core. Repairs were made following the earthquakes, and further strengthening was not necessary. The building likely would have remained operational following the earthquakes, but damage to neighbouring buildings prevented its reopening until later in 2011.

Christchurch City Council purchased the building for a cost of $735,000 in 1991 to prevent its demolition. The building was then sold in a 'package' with a neighbouring building and land to developers for $3,625,000 in 1995 (Yonge, 1996). The total final cost of the retrofit was estimated to be $3.75 million in 1995, which was approximately the same cost of a new building of equal floor area at the time of the retrofit.

3.4 **Christ's College Dining Hall, 33 Rolleston Avenue**

Christ's College Memorial Dining Hall is located at 33 Rolleston Avenue in the Christchurch CBD. The building measures approximately 33 m x 12 m and is attached to buildings on the north and south ends. The building was designed by Cecil W. Woods in the Gothic revival style as a memorial to the 'Old Boys' of the college who served in World War I and is regarded as Wood's architectural masterpiece (Wells & Hamilton, 1994). The building was constructed in 1925 and has 8 m tall loadbearing stone URM walls, and a timber roof with hammer beam trusses and buttresses. The building has two oriel-bay windows, a stone parapet, and ornately carved pinnacles (Figures 4a, c). The building is listed as a Category 1 historic place by Heritage New Zealand.

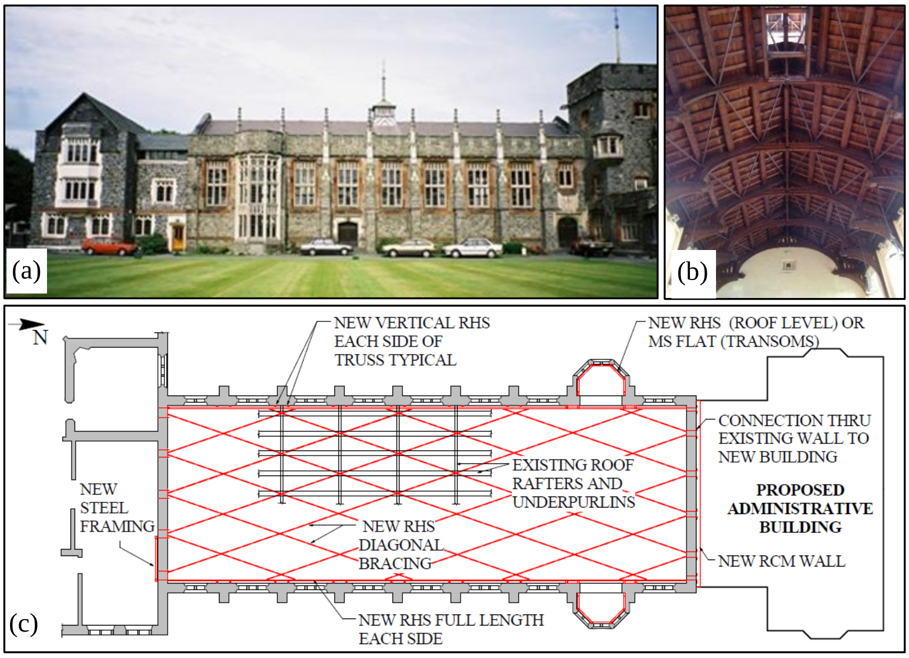

Figure 4. Retrofit of Christ's College Memorial Dining Hall, 33 Rolleston Avenue: (a) Exterior view of west façade. Taken by Melanie Lovell-Smith, NZHPT; (b) Interior view of roof strengthening; (c) Plan.

The Memorial Dining Hall was seismically retrofitted in 1988 as part of the college's ongoing effort to upgrade their buildings. Diagonal steel braces made of rectangular hollow sections (RHS) were fixed between roof trusses. The braces were connected to the east and west walls of the building by a new RHS that extends the full length of the walls and connected to the north and south walls with bolts through the existing walls (Figures 4b, c). A new reinforced concrete masonry (RCM) wall was constructed on the north wall as part of the proposed administrative building, and a new vertical steel truss comprised of RHSs was constructed on the south wall (Figure 4b). Vertical RHSs were installed internally on each side of the trusses and epoxy anchored into the existing walls. The oriel-bay windows were secured with a new RHS at roof level and mild steel (ms) flats were bolted to stone transoms. The parapets were braced, and the pinnacles were taken apart, pinned, and secured to the roof.

The seismic design achieved the desired level of seismic strengthening, being a lateral load of 0.5 g. The existing strength of the stone wall was utilised in the design to resist lateral loads in the north/south direction. Strengthening elements were strategically placed to cause only limited damage to heritage fabric. For example, the vertical RHS were positioned outside of the building in an early design iteration, but the design was modified so that the east and west facades would remain unaltered.

The Memorial Dining Hall retained the same function before and after the retrofit. Structural elements were placed in areas that did not affect natural light from the windows and still maintained the large open plan. All the internal steel work was painted to match the existing walls or was concealed by wood panelling and portraits. The use of wood panelling also conveniently allowed for extra food storage space for students (Wells & Hamilton, 1994).

Important heritage features such as the pinnacles and ornate carvings were secured in the retrofit, and the iconic east and west facades remained completely unaltered. The visual impacts of the retrofit were minimised where possible, and interventions such as the RCM wall to the north and the steel framing to the south were placed outside of the main dining hall, in areas of lower heritage value.

No damage was reported following the September 2010 earthquake and only minor damage was reported following the February 2011 earthquake. Some welds on the diagonal roof bracing fractured, but overall the bracing successfully tied the building together. A wall of an adjacent building damaged a wall of the Dining Hall due to pounding effects. Other reported damage included minor cracking to stonework, particularly around the windows, and damage to pinnacles. Damage to the windows was not unexpected because only the transoms were strengthened in the retrofit, and the mullion strengthening had been deferred for cost reasons. There was also settlement of the heavy stone walls. Overall, the damage did not disrupt use of the building, and repairs such as repointing of mortar and relevelling of the floors were made soon after the earthquake.

The Memorial Dining Hall building was again retrofitted in 2013 to comply with the change in the seismic zone factor (Z factor) for Christchurch following the Canterbury earthquakes (NZS 1170.5) from 0.22 to 0.30. Retrofitting and repair works were scheduled to take place over school holidays to prevent disruption of use to the building. Comments regarding the cost of this retrofit were not able to be made at the time of submission.

4 SUMMARY OF COMMON THEMES OF SUCCESSFUL RETROFITS

The presented case studies investigate structural, social, and economic aspects of the design, construction, and post-earthquake repair processes of retrofitted URM buildings. Interviews were conducted with the intention of identifying why the case study retrofits were successful in the 2010/11 Canterbury Earthquakes. No one-size-fits-all approach to developing a successful retrofit was discovered. Instead, the success of the case study retrofit tended to be based on a number of factors relating to the design and construction processes. Common themes identified from the presented case study retrofits as well as from interviews with engineers and architects of other retrofitted buildings include:

1. Motivated owner
2. Team approach
3. Multiple retrofit solutions explored
4. Attention to detail

4.1 Motivated Owner

A motivated owner was a common theme among all of the case study retrofits. The most common reasons for the considered buildings to undergo retrofit work was because the building underwent a change of use, and this required the building to be strengthened to a minimum of 33% NBS. However, motivated owners often felt some connection to the building and its place within the community and were willing to invest extra effort and cost to strengthen the building above the minimum.

Owners of earthquake prone buildings may require education by design engineers and other professionals on the positive aspects of seismic retrofits so as not to view a required retrofit solely as a financial burden. Positive aspects of retrofits include the viability of strong return on investment, the creation safe spaces for building occupiers and public, as well as the preservation of heritage.

4.2 Team approach

In almost all the interviews, building owners, engineers and architects described close collaboration during the early phases of design. Economic cost was weighed against the heritage value of the building and desired level of strengthening during the decision-making process. A heritage architect was often a valued member of the team who was contacted early and often in the design process. Strengthening solutions developed by engineers and architects both protected and celebrated the heritage fabric of the retrofitted buildings. The important heritage features were repaired, maintained, reinstated, and strengthened during the retrofit process as necessary.

4.3 Multiple retrofit solutions explored

In most cases, the engineer developed alternative retrofit designs before selecting the best design in terms of cost, level of earthquake resistance, and protection of heritage building fabric. Economic cost was weighed against the heritage value of the building and desired level of strengthening during the decision-making process. Costs were generally kept at or below the cost of constructing a new building.

The type of retrofit was often influenced by the required level of protection of heritage components. The addition of steel bracing, steel strong backs, or steel moment resisting frames is generally considered to be a heritage friendly intervention that is ‘reversible’ in the case that new and less invasive technology becomes available (Robinson & Bowman, 2000). RC skin walls or RCM walls were typically placed in areas where the heritage fabric of the building was of low importance. Shear cores were used in building areas of least heritage value as partial demolition of the building portions was required.

The creation of open spaces for flexible tenancy was a priority in most of the commercial case study buildings. The optimum placement of structural walls and braces was explored to achieve the desired aesthetic and to retain views inside and outside of the case study buildings.

4.4 Attention to detail

Structural engineers generally described that a high level of quality control was undertaken onsite during retrofit implementation, particularly in cases were adhesive anchors were used. Adequate on-site inspection was undertaken to ensure that the steel components are securely anchored to the existing URM walls. Improper installation was commonly observed to lead to premature failure of adhesive anchors (Dizhur et al., 2016).

The important heritage features were repaired, maintained, reinstated, and strengthened during the retrofit process as necessary. Architectural detailing was generally designed to match the existing heritage aesthetic. Most buildings expressed the seismic intervention appropriately, with structural elements either hidden and discrete or visible and transparent.

5 CONCLUSION

Seismic design, architectural appeal, heritage preservation, observed performance and cost were investigated for case study URM retrofits that performed well in the 2010/11 Canterbury earthquakes. Common themes identified in the case studies of successfully retrofitted buildings were (1) a motivated owner, (2) a team approach, (3) multiple retrofit solutions explored, and (4) attention to detail.

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