PERFORMANCE OF EARTHQUAKE STRENGTHENED URM BUILDINGS IN THE 2010/2011 CHRISTCHURCH EARTHQUAKE SEQUENCE

Ingham, Jason M[1]; Dizhur, Dmytro[2]; Moon, Lisa M[3]; Griffith, Michael C[4]

[1] PhD, Associate Professor, University of Auckland, Department of Civil and Environmental Engineering, j.ingham@auckland.ac.nz

[2] PhD Candidate, University of Auckland, Department of Civil and Environmental Engineering, ddiz001@aucklanduni.ac.nz

[3] PhD Candidate, University of Adelaide, Civil, Environmental and Mining Engineering Department, lmoon@civeng.adelaide.edu.au

[4] PhD, Professor, University of Adelaide, Civil, Environmental and Mining Engineering Department, mcgrif@civeng.adelaide.edu.au

Following the 22 February 2011 Christchurch earthquake a comprehensive damage survey of the unreinforced masonry (URM) building stock of Christchurch city, New Zealand was undertaken. Because of the large number of aftershocks associated with both the 2011 Christchurch earthquake and the earlier 4 September 2010 Darfield earthquake, and the close proximity of their epicentres to Christchurch city, this earthquake sequence presented a unique opportunity to assess the performance of URM buildings and the various strengthening methods used in New Zealand to increase the performance of these buildings in earthquakes. Because of the extent of data that was collected, a decision was made to initially focus exclusively on the earthquake performance of URM buildings located in the central business district (CBD) of Christchurch city. The main objectives of the data collection exercise were to document building characteristics and any seismic strengthening methods encountered, and correlate these attributes with observed earthquake damage. In total 370 URM buildings in the CBD were surveyed. Of the surveyed buildings, 62% of all URM buildings had received some form of earthquake strengthening and there was clear evidence that installed earthquake strengthening techniques in general had led to reduced damage levels. The procedure used to collect and process information associated with earthquake damage, general analysis and interpretation of the available survey data for the 370 URM buildings, the performance of earthquake strengthening techniques, and the influence of earthquake strengthening levels on observed damage are reported within.

Keywords: *unreinforced masonry, earthquake strengthening, 2010 Darfield earthquake, 2011 Christchurch earthquake, Christchurch earthquake CBD survey*

INTRODUCTION

On 4 September 2010 at 4.35 am local time, the region of Canterbury, New Zealand was subjected to a M7.1 earthquake (GeoNET, 2010). The epicentre of this earthquake was located at a depth of 10 km, 40 km west of Christchurch city in the town of Darfield, with the

event subsequently referred to as the 2010 Darfield earthquake. A series of thousands of aftershocks followed this earthquake, all varying in magnitude and location. At 12.51 pm on a busy afternoon of 22 February 2011, the city of Christchurch was subjected to a M6.3 aftershock (GeoNET, 2011). The epicentre of the M6.3 aftershock was located at a depth of only 5 km, 10 km from Christchurch city, which resulted in substantially greater shaking intensities than the 2010 Darfield earthquake, with the event subsequently referred to as the 2011 Christchurch earthquake. The combined 2010/2011 earthquake sequence caused extensive damage to many buildings in Christchurch, with the most notable damage being to the unreinforced masonry (URM) building stock (Ingham et al., 2011; Ingham & Griffith, 2011).

The use of URM in the construction of buildings in Christchurch was first seen in the late 1850s, with URM used in all important structures such as government buildings and schools. URM construction was popular due to its aesthetic and architectural qualities, and also for its fire resistant properties. The high level of seismic activity in New Zealand did not influence the city's decision to predominately build with URM as the poor lateral force resisting properties of URM were unknown at this time of mass URM construction.

Christchurch was subjected to several earthquakes during its early years. Although these earthquakes 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 earthquake which struck the city of Napier, in the Hawke's Bay region of New Zealand in 1931. On 3 February 1931 a M7.8 earthquake struck Napier, causing the total collapse of most URM buildings within that city's Central Business District (CBD), which was then followed by a fire that destroyed much of what was left. During the 1931 Hawke's Bay earthquake URM buildings were 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 (Russell & Ingham, 2010) are now over eighty years old.

In response to damage in Napier from the 1931 Hawke's Bay earthquake, building codes were developed and updated, with attention subsequently given to the performance of existing buildings in earthquakes. The first legislation to address the earthquake performance of existing buildings 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 either demolished or having their ornamental parapets and cornices removed. Most major cities and towns took up the legislation. Christchurch City Council adopted a passive approach, generally waiting for a change in use or other development to trigger the requirements.

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. 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 results in an estimated 11%NBS. Many innovations in structural engineering have been developed in order to address the issue of earthquake strengthening of old URM buildings in New Zealand, with many of these methods having been installed in URM buildings in Christchurch at the time of the earthquakes.

It is customary for innovations in structural earthquake engineering to be developed through a process of laboratory experimental testing and supplementary computer modelling, matched with a rational design procedure, such that the structural engineering community discerns the innovation to be appropriate for implementation into actual buildings. In some cases, further in-field testing may be conducted on parts of buildings in which the innovation has been installed, in an attempt to simulate the effect of earthquake loading and identify likely behaviour. Consequently, it is to be expected that many earthquake strengthening techniques are implemented primarily on the basis of laboratory evidence of their suitability, rather than their observed adequate performance in past earthquakes.

Based upon the above, it is suggested that the well documented earthquake performance of such a large number of unreinforced masonry buildings in the Christchurch region, that had received various levels of prior strengthening ranging from unstrengthened (referred to here as 'as-built') to fully strengthened (corresponding to 100%NBS) is a somewhat unique situation, particularly when accounting for the number and intensity of the aftershocks that these buildings were subjected to. Consequently, these observations are of major significance in order to gain an updated understanding of the likely seismic performance of previously strengthened URM buildings located not only throughout New Zealand, but also in countries having an analogous stock of URM buildings, such as for instance in Australia and West Coast USA. Furthermore, it may be argued that the recorded observations have relevance to the likely seismic performance of URM buildings worldwide.

DATA COLLECION PROCESS

Commencing in March 2011 a team of researchers was deployed to document and interpret the observed earthquake damage to masonry buildings in the Canterbury region, by investigating the failure patterns and collapse mechanisms that were commonly encountered. The procedure used by Urban Search and Rescue (USAR) was adopted, where the Christchurch CBD was discretised into numbered blocks. Building surveys were primarily external only, with all building elevations surveyed where this was safe and access was available. However, when safe, and when access was available, internal building inspections were also undertaken.

Throughout the CBD numerous active demolition sites were visited and inspected. In many cases these inspections allowed the building's internal structure to be partially inspected during the demolition process, which otherwise would not have been possible due to safety considerations. This exercise also allowed for relatively straightforward collection of small building samples from building demolition sites, including: brick and mortar samples, through ties with timber assemblages, adhesive anchor rods, and cavity ties. Inspection of demolition sites also proved to be valuable when attempting to identify the seismic strengthening systems within the internal parts of the building, and when seeking to investigate the quality of earthquake strengthening installations, particularly for adhesive type anchors.

Google maps were extensively used throughout the survey for identifying building addresses, business names, building boundaries, providing imagery prior to the earthquake, and allowing identification of buildings and of building elevation types, for buildings that suffered extensive damage such that details were unrecognisable following the earthquake. Also post-earthquake aerial photography was extensively used throughout the damage analysis stage of this survey. In particular, post-earthquake aerial photograph was used for identification of out-of-plane cantilever type failure modes and identification of parapet failures and other building components in the regions of buildings otherwise not visible from the street elevation.

Christchurch City Council (CCC) property records were requested and reviewed in order to confidently identify cases of earthquake strengthening, with 82 URM buildings located in the Christchurch CBD selected. Time constraints restricted a greater number of records from being reviewed. However, in some cases the CCC records lacked information about earthquake assessment and strengthening, or any structural aspects of the building. Therefore only 74 sets of records were used in the study, representing 20% of the 370 URM buildings in the CBD database.

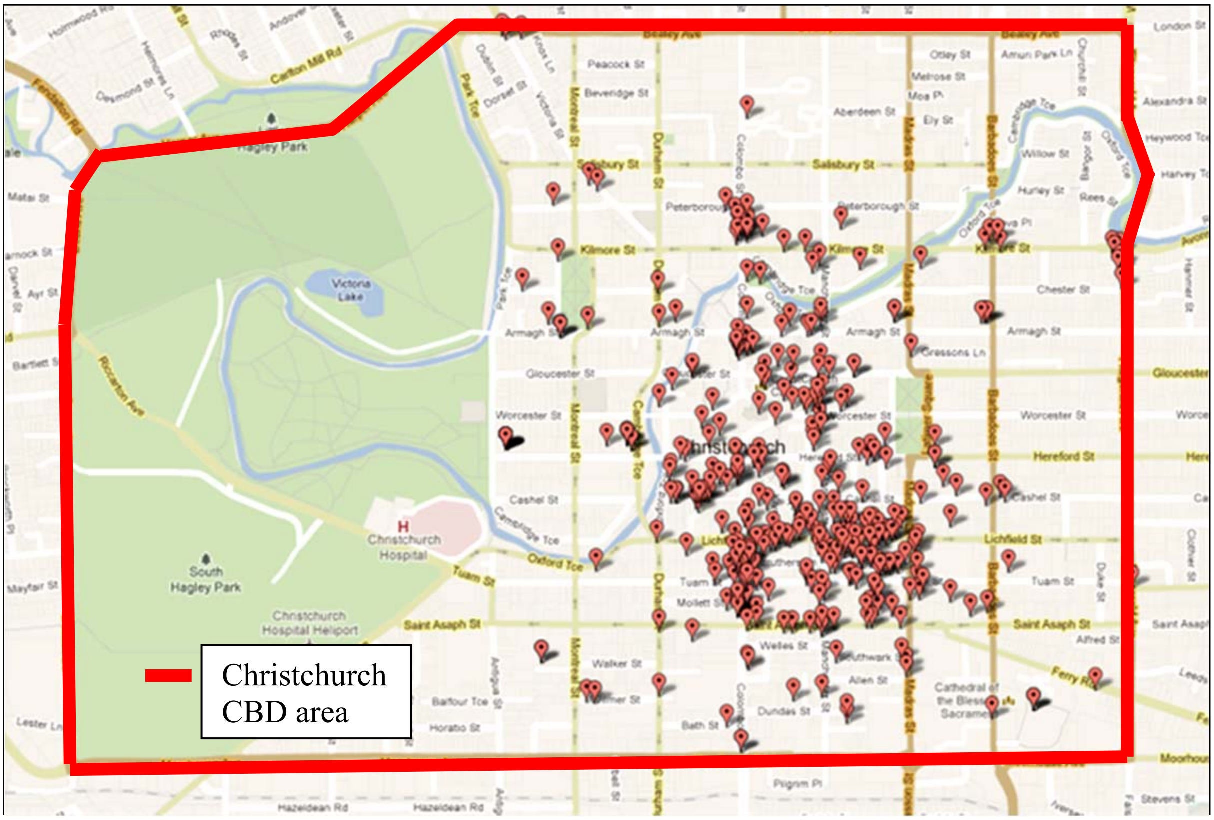


Figure 1: Location of URM buildings included in this study

SURVEY POPULATION

Only buildings located in the Christchurch CBD area (outlined in Figure 1) were included within the survey, with Figure 1 showing the specific location of all the 370 buildings in the Christchurch CBD database. All surveyed buildings were constructed of load-bearing

unreinforced clay brick or natural stone masonry, with no building that was constructed having a concrete frame with masonry infill being incorporated into the study. Significant effort was made to ensure that all URM buildings located in the Christchurch CBD were incorporated into the survey. However it is known that approximately 10 buildings were not incorporated into the survey database due to limited available information on these buildings.

SURVEY DATA

Survey assessment forms were specifically developed for assessment of the earthquake performance of Christchurch URM buildings. General building information was recorded, such as the location of URM buildings included in this study, the address, the building's original name and current name as of February 2011, the name of the business(es) operating within the building as of February 2011, and if known, the date of construction. Further information was also noted such as the number of storeys, the presence of a basement, the occupancy type, the type of elevation, whether the buildings was a row building or a stand-alone building and if the building was a row building, whether it was located mid-row or end-of-row. Earthquake strengthening methods that were encountered were also recorded.

The overall damage observed for each building was recorded using two damage scales. The protocols developed by the Applied Technology Council (ATC) were used because of their widespread use in past post-earthquake damage inspections, with the damage scale shown in Table 1.

Table 1: ATC 38/13 General Damage Classification (ATC, 1985)

Classification	Extent of damage
None	0%
Insignificant	1-10%
Moderate	10-30%
Heavy	30-60%
Major	60-100%
Destroyed	100%

The second damage scale adopted was that developed by Wailes and Horner (1933), which was specifically developed to describe damage to URM buildings. Details of this damage scale are reported in Table 2. Figure 2 shows examples of damage levels A-D using the Wailes and Horner (1933) damage scale.

Table 2: Wailes and Horner (1933) Damage Scale

Damage level	Damage description
A	Undamaged or Minor Cracking, No Significant Structural Damage, Minor Veneer Damage
B	Parapet Failure or Separation of Veneer, Major Wall Cracking and Interior Damage
C	Failure of Portion of Exterior Walls, Major Damage to less than 50% of walls
D	Major Damage to more than 50% of walls
E	Unrepairable Damage, Demolition Probably Appropriate

(a) Damage classification - Insignificant
Damage level – A
(292 Kilmore Street)

(b) Damage classification - Moderate
Damage level – B
(200 Madras Street)

(c) Damage classification - Heavy
Damage level – C
(120 Manchester Street)

(d) Damage classification - Destroyed
Damage level – D
(202 Hereford Street)

Figure 2: Damage classification examples

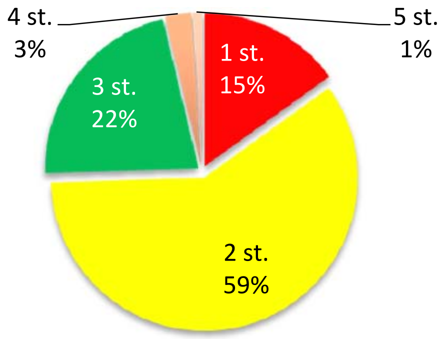
As well as the overall building damage level, the level of damage to each building elevation was also assessed based upon an adaption of the ATC 38/13 classification detailed in Table 1, using the damage levels unknown, non-visible, insignificant, moderate, heavy and extreme. The level of damage to parapets and the parapet orientation were recorded using similar classifications of none, minor, moderate, heavy, partial collapse and full collapse. Other recorded damage included the level of damage due to falling debris from adjacent buildings. Damage was recorded and classified as none, minor, moderate and severe. Earthquake strengthening systems that were encountered were also recorded in detail, and assigned to various categories for analysis.

GENERAL STATISTICS

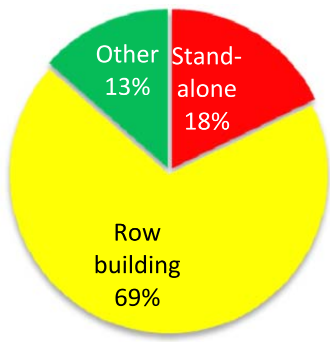
The year or decade of construction of each building surveyed was recorded where possible (154 (42%) buildings), and ranged from 1864 to 1930. The data showed that the construction of URM buildings peaked in the Christchurch CBD during the first decade of the 20th century. 333 (90%) of the surveyed URM buildings were constructed using clay brick masonry as the principal construction material type, with the remaining 37 (10%) buildings being constructed of either natural stone or a combination of clay brick and natural stone masonry. The most common occupancy type was commercial/offices, with 323 (87%) buildings being assigned

this classification. This finding is consistent with the fact that the survey was confined to the CBD area, but is also likely to be true for the New Zealand national URM building stock.

The distribution of above ground number of storeys is presented in Figure 3(a), where it can be seen that 59% of the surveyed buildings had two storeys and 22% of buildings surveyed had 3 storeys. Consequently two storey buildings were most prevalent and 85% of all URM buildings surveyed were multi-storey. Figure 3(b) shows the distribution of row buildings and stand-alone buildings, again illustrating the predominance of URM row buildings in the CBD. Of the 254 (69%) row buildings, the distribution between buildings classified as being either end-of-row or mid-row was approximately equal, with 130 (51%) being end-of-row buildings and 124 (49%) being mid-row buildings.



(a): Number of storeys



(b): Row buildings

Figure 3: General building statistics

A total of 922 building elevations were surveyed. When accounting for the mix of row and stand-alone buildings, the 922 surveyed building elevations is thought to represent approximately 84% of all building elevations associated with the 370 surveyed URM buildings. Missing data was due to restricted access for some buildings. The distribution of elevation types is presented in Table 3, showing that 391 (42%) of the surveyed elevations were perforated masonry frames and a further 383 (42%) building elevations were walls that were either solid (without openings) or had few openings.

Table 3: Data distribution by elevation type

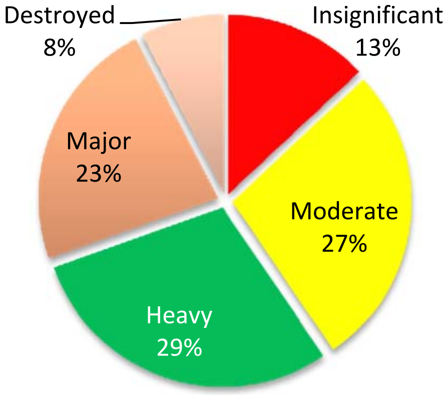
Elevation type	No. of elevations	% of elevations
Perforated frame (piers/spandrels)	391	42%
Solid wall	120	13%
Solid wall with a few openings	263	29%
Not identified	148	16%
Total	**922**	**100%**

GENERAL DAMAGE STATISTICS

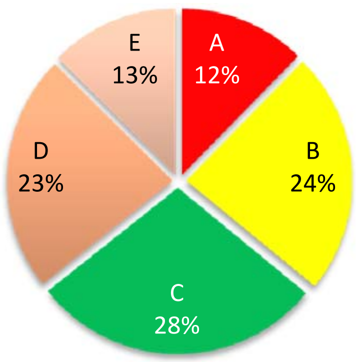
The damage recorded using the ATC general damage classification scale can be seen in Table 4 and Figure 4(a). The ATC scale reported damage in excess of moderate for 219 (60%) of all surveyed buildings, and damage in excess of insignificant for 320 (87%) of all surveyed buildings.

Table 4: ATC 38/13 general damage classification

Classification	Associated damage value	No. (%) of buildings
None	0%	0
Insignificant	1-10%	48 (13%)
Moderate	10-30%	101 (27%)
Heavy	30-60%	107 (29%)
Major	60-100%	84 (23%)
Destroyed	100%	28 (8%)
Total		**368 (100%)**



(a) ATC 38/13 Classification



(b) Wailes and Horner Scale

Figure 4: Damage level using two different classifications schemes

The damage statistics as classified using the Wailes and Horner General Damage Classification scheme are reported in Table 5 and in Figure 4(b). It can be seen that 322 (88%) of all buildings were classified as having suffered significant structural damage (Level B, C, D or E) when using the Wailes and Horner damage scale.

Table 5: Wailes and Horner damage scale

Damage Level	Damage description	No. (%) of buildings
A	Undamaged or Minor Cracking, No Significant Structural Damage, Minor Veneer Damage	46 (12%)
B	Parapet Failure or Separation of Veneer, Major Wall Cracking and Interior Damage	88 (24%)
C	Failure of Portion of Exterior Walls, Major Damage to less than 50% of walls	106 (28%)
D	Major Damage to more than 50% of walls	86 (23%)
E	Unrepairable Damage, Demolition Probably Appropriate	42 (13%)
Total		**368 (100%)**

Correlation between the two damage scales

As noted above, it was determined that when using the ATC 38/13 damage classification there were 320 (87%) surveyed buildings that suffered damage in excess of insignificant, and when using the Wailes and Horner damage scale there were 322 (88%) surveyed buildings that suffered significant structural damage (Level B, C, D or E). Clearly this comparison indicates a high level of correlation between the two survey methods. This high correlation can be further identified by considering the two charts in Figure 4, where it can be seen that comparable numbers of buildings were assigned for each of the incremental damage levels within the two scales.

Damage for different building forms

The ATC 38/13 damage classification was used to investigate any possible relationship between the number of stories and the level of damage (see also Figure 3(a) for the distribution of storey heights for the entire URM building population). As shown in Figure 5, and specifically neglecting the case for 5 storey buildings due to this category representing only 1% of the building population, it was concluded that there was no distinct relationship between overall building height and the level of sustained building damage.

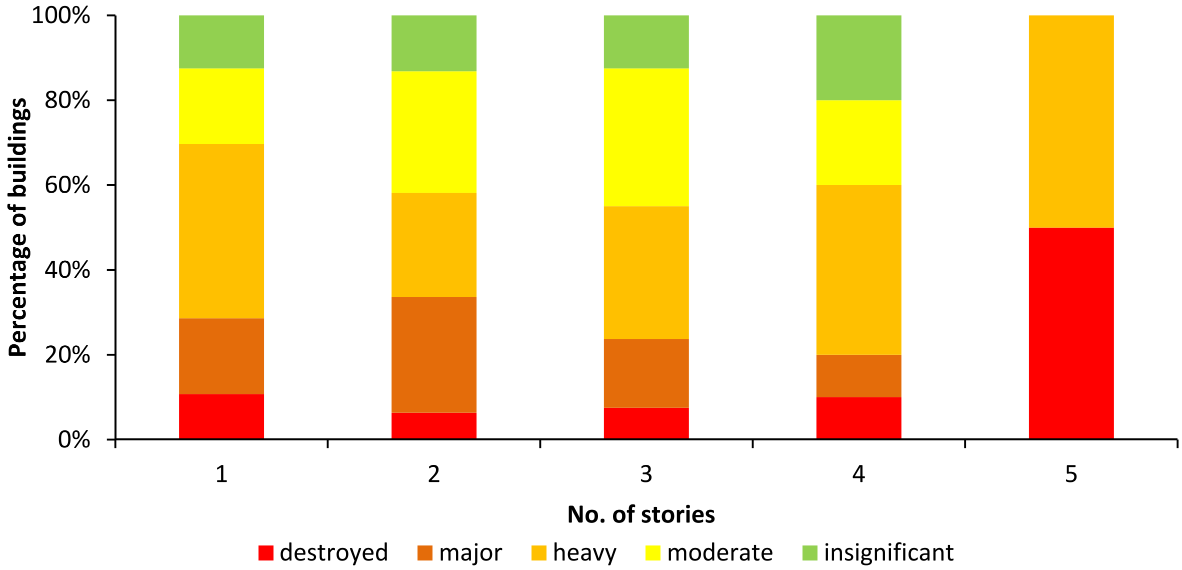
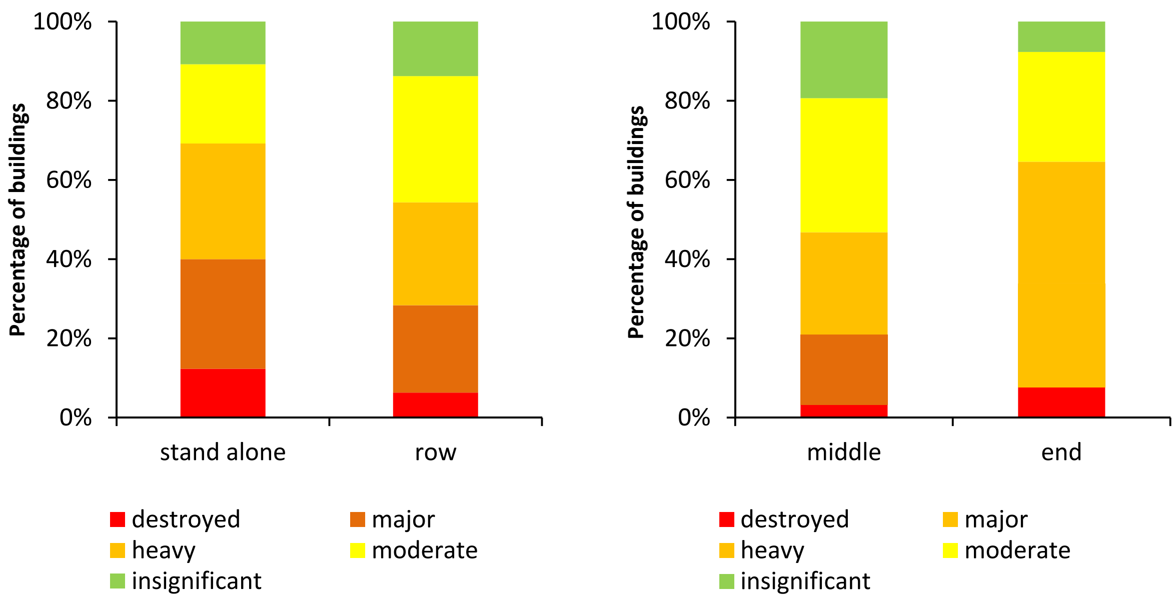


Figure 5: ATC 38/13 damage classification for number of stories

The level of damage was investigated by separating the damage data into stand-alone versus row buildings (see Figure 6(a)), where it was established that there was a greater degree of damage to stand-alone buildings than to row buildings. Similarly, the performance of row buildings was considered based upon damage correlated to whether the building was located mid-row or end-of-row (see Figure 6(b)), where it was found that greater damage was sustained to end-of-row buildings. These findings are consistent with the generally held view that mid-row buildings are somewhat protected from damage by the end-of-row buildings (occasionally referred to as 'bookend' behaviour) and similarly that the practice of constructing multiple URM buildings connected together provides additional robustness when compared to the earthquake performance of stand-alone URM buildings.



(a) Damage levels for stand-alone vs. row buildings

(b) Damage levels for row buildings depending on position

Figure 6: ATC 38/13 damage classification for stand-alone and row buildings

Damage to individual building elevations

The damage levels for individual building elevations using the ATC damage scale are presented in Table 6. Also reproduced in the far right column of Table 6 are the damage statistics previously reported in Table 4 for entire buildings.

Table 6: Damage levels for all elevations

Elevation damage level	No. (%) of elevations	No. (%) of buildings
None visible	68 (7%)	0
Insignificant	127 (14%)	48 (13%)
Moderate	237 (26%)	101 (27%)
Heavy	204 (22%)	107 (29%)
Extreme	286 (31%)	112 (31%)
Total	**922 (100%)**	**368 (100%)**

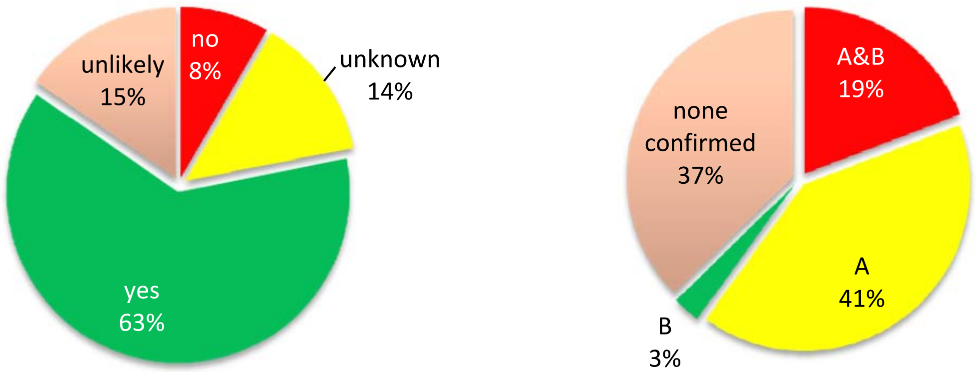
It is evident in Table 6 that there is a strong correlation between the percentages of damage recorded for each damage level when comparing the data for individual building elevations and overall building response, as would be expected.

PERFORMANCE OF EARTHQUAKE STRENGTHENING TECHNIQUES

The various forms of earthquake strengthening of URM buildings were categorised into three types, being parapet restraints, Type A seismic retrofits, and Type B seismic retrofits. Type A retrofits securing/strengthening of URM building elements such as gable ends, installing connections between the walls (excluding parapets) and the roof and floor systems of the URM building so that walls no longer respond as vertical cantilevers secured only at their base, and stiffening of the roof and/or floor diaphragms. Type B earthquake improvements

were defined as strengthening techniques that sought to strengthen masonry walls and/or introduce added structure to supplement or replace the earthquake strength provided by the original unreinforced masonry structure. Examples of Type B earthquake improvement are, strong-backs installed either internally or externally, steel moment frames, steel brace frames, concrete moment frames, addition of cross walls, shotcrete, FRP, and post tensioning. The term shotcrete was used to not only describe added concrete walls that have been 'shot' onto the URM wall using high pressure pumping equipment, but also cast concrete walls. This decision was made in order to avoid having an increased number of classifications that each had a minimal number of recorded cases of implementation.

As can be seen in Figure 7(a), 231 (62%) of all URM buildings in the Christchurch CBD had some form of earthquake strengthening installed at the time of the 22 February 2011 Christchurch earthquake (in addition to parapet restraints possibly being installed also), with 82 (22%) buildings identified as having one or more Type B earthquake strengthening methods installed.



(a) Proportion of earthquake strengthened buildings

(b) Identified type of earthquake strengthening

Figure 7: Distribution of installed earthquake strengthening types

Table 7: Distribution of earthquake strengthening types

Type of earthquake strengthening	No. of buildings	% of buildings
A&B	82	22%
A	149	40%
none confirmed	139	38%
Total	**370**	**100%**

PARAPET RESTRAINTS

A total of 435 records of parapets were associated with the surveyed buildings, with some buildings having multiple parapets, such as those on street corners or for end-of-row or stand-alone buildings. Of these 435 parapets only 149 (34%) parapets could be positively identified as having parapet restraints installed. Unfortunately, it was not possible to definitively identify a sufficient sample size of specific types of parapet restraint systems from building inspections. As expected, restrained parapets performed significantly better than parapets having no restraint, with 75 (84%) unrestrained parapets suffering full or partial collapse

while only 65 (44%) restrained parapets suffered similar damage. Furthermore, 71 (48%) restrained parapets suffered no or moderate damage while only 12 (13%) unrestrained parapets achieved such good response, such that 86% (71/83) of those parapets that performed satisfactorily were restrained. Overall it may be concluded that unrestrained parapets were twice as likely to collapse as were restrained parapets. It would seem that this is a disappointing finding as it would have been sensible to assume that the majority of restrained parapets would have performed satisfactorily. This finding suggests that further investigation is required to better understand why parapet restraints were not more uniformly successful in preventing damage.

TYPE A EARTHQUAKE STRENGTHENING TECHNIQUES

As shown in Table 7, 231 (62%) of all URM buildings in the Christchurch CBD had some form of Type A earthquake strengthening installed. The use of through ties was the most commonly encountered form of Type A earthquake strengthening. In addition, 52 URM buildings (14% of 370 total population) had diaphragm stiffening installed, with 18 buildings being identified as having both floor and roof diaphragm stiffening.

A total of 185 wall elevations having gables were identified in the survey, with 129 (70%) gable end walls having gable restraints installed. A total of 108 (84%) of the identified gable restraints were ‘through ties’. It should be noted that ‘through ties’ are more readily identifiable than many other restraint types, especially adhesive anchors, and so the reported distribution is likely to under-count securing types such as adhesive anchor systems that are less readily identified. It was concluded that restrained gables performed better than for situations where no gable restraint was identified. However, 74 (57%) restrained gables suffered partial or full collapse.

The 108 gable elevations having ‘through ties’ to provide restraint allowed the specific performance of through ties to be further analysed. From this analysis it was determined that this securing technique resulted in mixed success, with 58 (54%) gable elevations suffering in excess of moderate damage. Further correlation between damage levels and the spacing of through tie anchors would assist in determining future recommendations for earthquake strengthening procedures, but was beyond the scope of the study reported here. Nevertheless, the finding that approximately half of all restrained gables sustained either heavy damage or collapse suggests that further investigation of appropriate procedures for the earthquake protection of unreinforced masonry gable end walls is merited.

Roof diaphragm improvement was identified in 37 (17%) URM buildings where Type A earthquake strengthening was implemented. The most common roof diaphragm improvement type was steel bracing (19 cases), followed by steel brace frames (12 cases) and plywood overlay (6 cases). However, for 162 (70%) earthquake strengthened buildings it was not possible to confirm whether roof diaphragm improvements were implemented. Floor diaphragm improvement was confirmed in only 32 (14%) buildings where Type A earthquake strengthening was implemented, and was not able to be confirmed in 187 (81%) of the surveyed URM buildings. For those buildings where floor diaphragm improvement had been implemented, plywood overlay was the most common stiffening type, with 20 (9%) cases identified. Four (2%) cases each of steel bracing, steel brace frames and the addition of concrete were also identified. Of the four concrete floor improvements identified, three were

in-situ concrete floors over the full floor area to replace the original timber floor diaphragm and one floor was a concrete overlay above the original timber floor, with supplementary steel beams added to support the added weight of the concrete overlay.

Type B earthquake strengthening techniques

Within 82 URM building having Type B earthquake strengthening, there were some cases where multiple Type B strengthening techniques were used, such that overall a total of 109 Type B installations were surveyed. T he most common Type B earthquake strengthening technique surveyed was the addition of steel moment frames, followed closely by concrete moment frames. The overall building damage levels for 97 (89%) of the 109 identified cases of Type B earthquake strengthening were considered. The Type B strengthening methods of Fibre Reinforced Polymer (FRP), post-tensioning, and external strong-backs were not included in as the number of surveyed cases of implementation was small.

As might be expected, the two Type B earthquake strengthening methods that resulted in the least damage were shotcrete and the addition of cross walls. The two methods are somewhat analogous as the former involves the application of new reinforced concrete walls adhered to the exterior of existing URM walls and the latter involves the installation of new walls. The data also shows that the damage statistics for buildings having internal strong backs, steel moment frames and concrete moment frames was comparable.

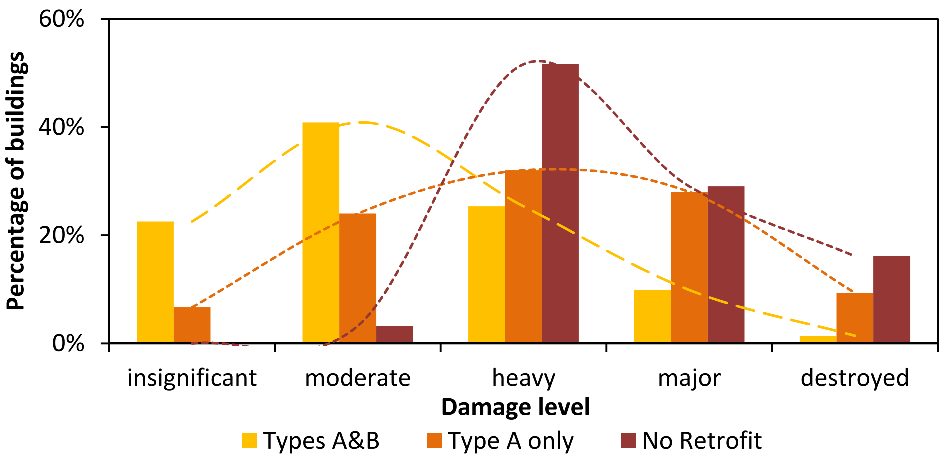


Figure 8: Plot of damage level against seismic strengthening types

COMPARISON BETWEEN EARTHQUAKE STRENGTHENING SCHEMES AND OVERALL BUILDING DAMAGE

The data showed that URM buildings having no earthquake strengthening suffered greater damage than those buildings that had received some form of earthquake strengthening. Of the 31 URM building confirmed to have no earthquake strengthening, 30 (97%) suffered heavy, major or severe damage (see Figure 8). Similarly, of the 149 buildings that had a Type A earthquake strengthening scheme installed, 104 (70%) suffered heavy, major, or severe damage whereas for combined Type A&B strengthening only 29 (35%) buildings suffered this level of damage. From this data it is clear that Type B earthquake strengthening was more successful at minimising building damage than were Type A earthquake strengthening improvements. This observation is to be expected, recognising that the aim of Type B

earthquake strengthening improvements is to increase the global earthquake capacity of the building, and consequently reduce the expected overall building damage level.

INFLUENCE OF EARTHQUAKE STRENGTHENING LEVEL ON OBSERVED DAMAGE AND ASSESSED HAZARD

Earthquake strengthening levels in terms of %NBS were identified for 94 (26% of the 368 total) URM buildings, either by consulting CCC records, by personal communication with building owners, engineers and heritage personnel, or in cases where sufficient details about the building were known was based upon estimation. The distribution of %NBS data is reproduced in Table 8 where it is shown that 61 (65% of 94) URM buildings had been earthquake strengthened to at least 67%NBS and a further 18 (19%) URM buildings had been earthquake strengthened to at least 34%NBS. 15 (16%) buildings had been strengthened to less than 33%NBS, and 31 (8% of the 368 total) URM buildings were positively confirmed to have received no earthquake strengthening.

Table 8: Distribution of %NBS classifications for 94 earthquake strengthened URM buildings

%NBS Retrofit level	No. of buildings	% of buildings
%NBS < 33	15	16%
33 ≤ %NBS < 67	18	19%
67 ≤ %NBS < 100	50	53%
%NBS ≥ 100	11	12%
Total	**94**	**100%**

The performance of these 94 earthquake strengthened buildings and 31 unstrengthened buildings was analysed by determining the damage distribution for each category of %NBS as shown in Table 9 and reproduced in Figure 9.

Table 9: Damage levels for different %NBS categories

	%NBS ≥ 100		**67 ≤ %NBS < 100**		**33 ≤ %NBS < 67**		**%NBS < 33**		**No retrofit**	
Insignificant 1 - 10%	8	73%	10	20%	1	6%	1	7%	0	0%
Moderate 10 - 30%	3	27%	28	56%	4	22%	5	33%	1	3%
Heavy 30 - 60%	0	0%	10	20%	9	50%	5	33%	16	52%
Major 60 - 100%	0	0%	2	4%	4	22%	1	7%	9	29%
Destroyed 100%	0	0%	0	0%	0	0%	3	20%	5	16%
Combined Heavy, Major and Destroyed	**0 of 11**	**0%**	**12 of 50**	**24%**	**13 of 18**	**72%**	**9 of 15**	**60%**	**30 of 31**	**97%**
Total	**11**		**50**		**18**		**15**		**31**	

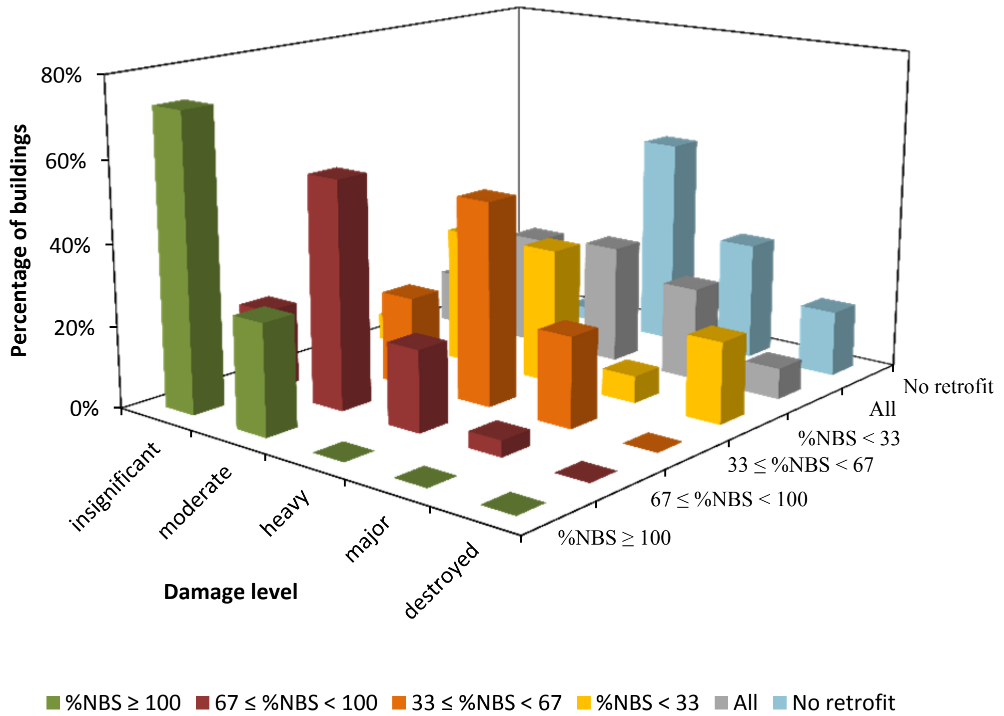


Figure 9: Damage levels for different levels of %NBS earthquake strengthening

From Table 9 and Figure 9, it can be determined that those URM buildings strengthened to 100%NBS performed well, that buildings strengthened to 67%NBS performed moderately well, but that buildings strengthened to less than 33%NBS collectively exhibited no significant improvement in performance when compared with buildings that had received no earthquake strengthening.

DAMAGE INTERPRETATION

Based upon the data presented in Table 9 and Figure 9 the following interpretations can be made:

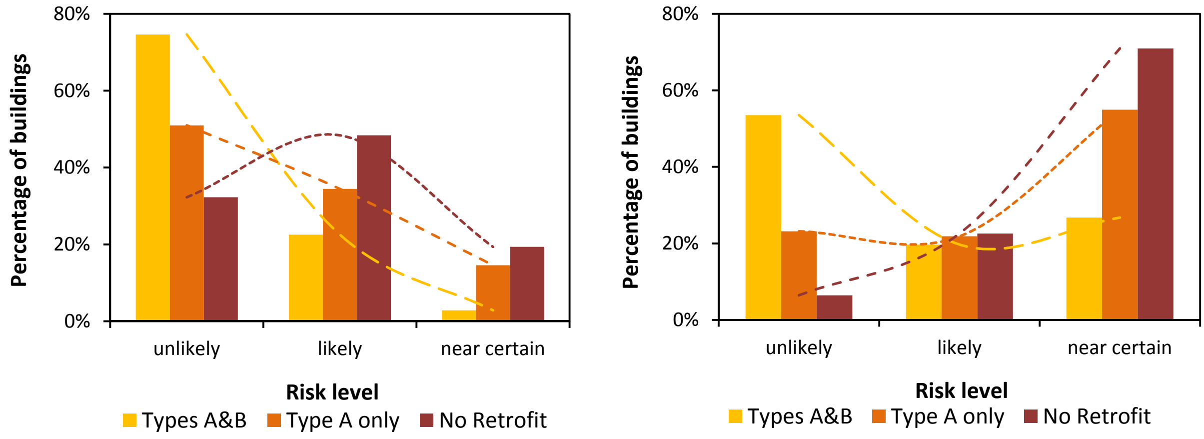
1. It can be determined that URM buildings that were strengthened to less than 33%NBS performed in an approximately similar manner to unstrengthened URM buildings. However, this level of strengthening did result in a significant reduction from major damage to moderate damage.
2. It can be determined that URM building strengthened to 33-67%NBS avoided being destroyed (100% damage), but that otherwise their performance was not greatly better than for unstrengthened buildings. The category 'Combined Heavy, Major and Destroyed' in Table 9 provides further clarification of this matter, which reports 72% damage for 33-67%NBS and 60% damage for 0-33%NBS, representing an increase in damage of 20% for the 33-67%NBS earthquake strengthening class.
3. It can be seen from Figure 9 that URM buildings strengthened to 67-100%NBS performed much better than both URM buildings having no strengthening and URM buildings strengthened to lower levels of earthquake resistance.

RISK TO BUILDING OCCUPANTS AND SIDEWALK PEDESTRIAN

From survey observations and a critique of photographs of damage taken for each building, a hazard analysis was performed to consider the risk posed to people if they had hypothetically been inside or directly outside (such as on the footpath) each URM building during the earthquake, with the latter scenario referred to here as a 'sidewalk pedestrian'. When considered in greater detail, it was identified that buildings which posed a near certain risk of fatality or injury to their occupants also posed a comparable risk for anyone occupying the public space directly adjacent to the building. However, buildings which posed a risk to sidewalk pedestrians were not necessarily a risk to the building's occupants. This finding is attributable to the observation that walls are more likely to collapse outwards, due to restraint provided by contact with roof and floor diaphragms for wall deformations directed towards the building interior. Interior falling debris is less likely to be due to falling masonry parapets, gables and walls as usually roofs, upper storey floors, and even interior partitioning provide some protection to the building occupants. From this hazard analysis it is identified that the risk to the general public 'sidewalk pedestrian' and the risk to the building occupants differ, and that both hazard scenarios need to be considered. Directly outside the building the public are at greater risk due to falling masonry parapets, gables and walls.

The analysis described above was extended to consider the escalating hazard to building occupants and to sidewalk pedestrians for increased levels of building damage. Obviously, as the overall building damage level increases, so too does the risk of fatality or injury to the public and to the building occupant. However, the danger to the sidewalk pedestrian increases more significantly with increasing damage than does the risk to building occupants.

The correlation between earthquake strengthening levels and the hazard to building occupants and to passers-by was assessed. As expected, and as shown in Figure 10(a), buildings that had undergone Type A + B earthquake strengthening posed significantly less risk to their occupants when compared to buildings that had undergone Type A earthquake strengthening only, with the greatest risk being for buildings that had received no earthquake strengthening. In Figure 10(b) it is particularly evident that buildings that have undergone Type A + B earthquake strengthening were much less likely to pose a risk to passers-by than were buildings having only Type A earthquake strengthening or buildings having no earthquake strengthening.



(a) Risk to building occupants (b) Risk to public space occupants

Figure 10: Plot of seismic strengthening level vs. risk to building occupants and public spaces

DAMAGE DUE TO NEIGHBOURING BUILDINGS

Of the 370 buildings surveyed the majority (260, 70%) suffered no damage from neighbouring buildings, as shown in Table 10. However, the remainder (110, 30%) of the surveyed buildings sustained damage levels due to neighbouring buildings, ranging from minor to severe. In a number of cases damage that otherwise would not have occurred to earthquake strengthened buildings was attributable to full or partial collapse or to falling debris from neighbouring buildings that had received no or little earthquake strengthening.

Table 10: Damage level due to neighbouring building

Damage level	No. of buildings	% of buildings
Severe	21	6%
Moderate	42	11%
Minor	47	13%
None	260	70%

CONCLUSIONS

Following the 2010 Darfield earthquake and the 2011 Christchurch earthquake, a team of researchers was deployed to document and interpret the observed earthquake damage to masonry buildings in the Canterbury region, by investigating the failure patterns and collapse mechanisms that were commonly encountered, and documenting building characteristics and any seismic strengthening methods encountered. Based on data collected and further data analysis for URM buildings located in the Christchurch CBD, it was concluded that:

- 62% of all URM buildings in the Christchurch CBD had received some form of earthquake strengthening.
- 97% of URM buildings that had received no prior earthquake strengthening were either seriously damaged (i.e. suffered heavy or major damage) or collapsed.

With respect to URM buildings that had received some form of earthquake strengthening:

- Of those URM buildings that had been earthquake strengthened to less than 33%NBS, 60% were seriously damaged (i.e., suffered heavy or major damage) or collapsed.
- Of those URM buildings that had been earthquake strengthened to 34-67%NBS, 72% were seriously damaged or collapsed.
- Of those URM buildings that had been earthquake strengthened to 67-100%NBS, only 24% were seriously damaged or collapsed.
- Of those URM buildings that had been earthquake strengthened to 100%NBS or greater, none were seriously damaged or collapsed.

With respect to earthquake strengthening methods:

- 44% of restrained parapets failed, compared with failure of 84% of unrestrained parapets. Whilst parapet restraint generally improved earthquake performance, it is clear that many parapet restraints failed to perform as intended. Clearly, parapet retrofits provided some earthquake resistance but probably less would be expected. This somewhat surprising result was partly attributable to the observed poor performance of adhesive anchorage systems and may have also been due to parapets being secured to roof systems having diaphragms that were too flexible.
- 57% of restrained gable end walls failed, compared with 88% of unrestrained gable end walls. Similar to parapets, whilst gable restraint also generally improved earthquake performance, it is clear that many gable restraints also failed to perform as intended.
- Further investigation should be conducted to ascertain which parapet and gable wall retrofit techniques were most effective and why, in order to improve the effectiveness and reliability of earthquake strengthening solutions in the future.
- There is clear evidence that installed earthquake strengthening techniques reduced damage levels, that Type A+B retrofits were significantly more effective at reducing overall structural damage, and that shotcrete strengthened wall retrofits and added cross wall retrofits appeared to be more effective than steel strongback retrofits, again probably due to better material deformation compatibility with masonry.

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