**Section 5:**

**Unreinforced masonry buildings and their performance in earthquakes**

**5.1 Unreinforced masonry buildings and their characteristics**

Unreinforced masonry (URM) buildings were built in

New Zealand primarily between 1880 and 1935. This

55-year period gives a relatively homogeneous stock

of URM buildings compared to other parts of the world.

They make up a comparatively large number of large structures in New Zealand’s buildings. They are unable to resist seismic actions in contrast to more recent structures using steel and reinforced concrete as an integral part of the building fabric. They are predominantly one, two and three storey brick buildings built for commercial purposes. Also included in this category are stone masonry buildings, churches and some important public buildings. Many URM buildings are treasured as valued records of our history and some continue to be used for the purposes for which they were built. Many others are now used as small-scale commercial premises; some are much valued for their traditional character.

These buildings were designed to resist gravity and wind loads and incorporate materials that are subject to deterioration with age: timber (subject to decay from water damage) and lime mortar. Metal fastenings are also subject to corrosion. The buildings are more than 75 years old and some more than 100 years. Many have been poorly maintained. In general, they are rigid structures with little capacity to flex when subjected to the high accelerations imparted by earthquake-induced ground motions. Unlike buildings designed with modern materials to current codes, they can change from acceptable performance to collapse with only a slight increase in the intensity of ground shaking. Collapse can occur in moderate earthquakes. The structural elements of these buildings are frequently poorly interconnected and detach from each other, resulting in catastrophic collapse under earthquake forces.

If they have not been strengthened, URM buildings are particularly dangerous as they may fail in moderate earthquakes. Because they are constructed from heavy materials, they may inflict injury, serious damage, or even death when they collapse.

It has been estimated that prior to the recent

Canterbury earthquakes, there were approximately

4,000 such buildings in New Zealand. Due to the effects of the Canterbury earthquakes, there may now be about 500 fewer.

**5.2 Earthquake performance**

The collapses of URM buildings that have occurred

as a result of the Canterbury earthquakes were mostly within the Christchurch Central Business District (CBD). As discussed in section 4 of this Volume, 39 people lost their lives due to the failure or partial failure of URM buildings in Christchurch1. Their collapse caused the death of pedestrians passing by, motorists, passengers on buses adjacent to a collapsing building, and of people inside buildings that fell. In at least three instances, failed buildings collapsed onto neighbouring buildings killing people inside. As also discussed in section 4, some of these buildings had been strengthened to varying degrees.

5.2.1 The Ingham and Griffith reports

The Royal Commission sought advice from Associate Professor Jason Ingham of The University of Auckland and Professor Michael Griffith of the University of Adelaide on the performance of URM buildings in the earthquakes. The first report that they prepared for the Royal Commission was provided in August 2011: *The Performance of Unreinforced Masonry Buildings in the 2010/2011 Canterbury Earthquake Swarm*2, covered the damage that resulted from the 4 September 2010 earthquake, and was considered in the Royal Commission’s Interim Report dated 11 October 2011. We sought a further report from Ingham and Griffith on the performance of URM buildings in the 22 February 2011 earthquake. That report, *The Performance of Earthquake Strengthened URM Buildings in the Christchurch CBD in the 22 February 2011 Earthquake*3, was dated October 2011. Both reports were published on the Royal Commission’s website.

In their August 2011 report, Ingham and Griffith explained the impact of the Canterbury earthquakes on URM buildings in the following passage:

Unreinforced masonry buildings are comparatively stiff structures, with a fundamental period typically in the range of 0.3–0.5 seconds…for this period range many URM buildings were subjected on 4 September 2010 to earthquake loads that were between 67–100% of NBS…and that the same buildings were subjected on 22 February 2011 to earthquake loads that were between 150–200% of NBS…It is well established that URM buildings perform poorly in large earthquakes and consequently the level of earthquake damage in the Christchurch CBD is consistent with expectations for loading of this magnitude.

Although the September earthquake subjected many

URM buildings to a level of shaking of the order of a

500-year return period earthquake, no lives were lost. The time of the shaking, at 4.35am on 4 September 2010, meant that commercial buildings – as most URM buildings were – were unoccupied, and there were no passers-by. However subsequent superficial examination of URM buildings resulted in many being classified as having minimal obvious damage and reoccupation was permitted. Several of those buildings were further damaged in February 2011, and the failure of some caused death. There is a discussion of each of those buildings in section 4 of this Volume. Many of the persons who were killed or injured were in public spaces alongside the failed structure.

The evidence4 is that the September 2010 earthquake created ground motions approximately *at* the design level for the ultimate limit state under the current design Standard (NZS 1170.5: 20045). This means that the shaking was appreciably greater than that of a moderate earthquake, the concept used to assess whether a building is earthquake-prone under section 122 of the Building Act 2004. Yet many URM buildings were intact after the September earthquake and may not have caused loss of life even if they had been occupied.

Over several years prior to the September earthquake, a number of buildings in the Christchurch CBD had been strengthened to varying degrees through additional structures designed to support the building fabric. This strengthening varied from building to building and included connections of walls and parapets to floors and roof, and internal frames to support brick walls. In some cases additional moment resisting structures were provided to absorb earthquake forces.

Both of the Ingham and Griffith reports, but in particular the October 2011 report, addressed the effectiveness of various levels of strengthening on the performance of structures in the earthquakes. In their October 2011 report, Ingham and Griffith analysed the performance of URM buildings that had some degree of retrofit and compared these with buildings which had no improvement. Data was collected from around 370 CBD buildings that had been subjected to the September, Boxing Day and February earthquakes. Section 6 of the October report gave an analysis of the performance of 94 buildings (taken from the 370 CBD buildings) to which they were able to assign a percentage of NBS, based on material in CCC files, information provided by building owners and engineers, or their own estimates. These 94 buildings included 31 unstrengthened URM buildings. Although the report does not set out their detailed factual basis, the conclusions about the effectiveness of retrofit are worth noting. Figures 75–82 summarise their findings in terms of the general effectiveness of the level of seismic retrofit, measured in terms of the percentage of NBS, on the level of damage that was sustained. In interpreting these figures it should be noted that the percentage of NBS was based on the then current Z factor of 0.22, which was appropriate for the near design level shaking of the September earthquake. However the shaking in the February earthquake was 1.5–2 times the design level. Hence, for this earthquake, 67% NBS as recorded in the figures corresponds to a range of 33–45%, when allowance is made for the shaking being 1.5–2 times

the design level.

80

% NBS ≥100

67 ≤% NBS < 100

60 33 ≤% NBS < 67

% NBS < 33

Percentage of buildings

40

20

0

insignificant moderate heavy major destroyed

Increasing level of damage

**Figure 76: Plot of overall building damage level for different levels of percentage of NBS earthquake strengthening**

**(source: Ingham and Griffith3)**

The data represented in Figure 76 indicate that, in the February earthquake, the URM buildings strengthened to 100% NBS performed well, those strengthened to 67% NBS performed moderately well, and the performance of those strengthened to less than 33% NBS was not significantly better than those that had not been strengthened. (In section 6 of this Volume we address various issues that we see arising from use of the ‘percentage of NBS concept’ but for present purposes we adopt it, because it is in general use, and is used in the Ingham and Griffith reports.)

The damage levels were also divided into a range of severities. The level of damage observed in buildings that had been strengthened to various percentages of NBS was compared with those buildings that had not been strengthened. The results are shown below in Figures 77, 78 and 79.

60%

% NBS < 33

No retrofit

40%

Percentage of buildings

20%

0

insignificant moderate heavy major destroyed

Damage level

**Figure 77: Damage comparison between URM buildings strengthened to 33% NBS and no retrofit (source: Ingham and Griffith3)**

60%

33 ≤% NBS < 67

No retrofit

40%

Percentage of buildings

20%

0

insignificant moderate heavy major destroyed

Damage level

**Figure 78: Damage comparison between URM strengthened to 33–67% NBS and no retrofit**

**(source: Ingham and Griffith3)**

60%

67 ≤% NBS < 100

No retrofit

Percentage of buildings

40%

20%

0

insignificant moderate heavy major destroyed

Damage level

**Figure 79: Damage comparison between URM buildings strengthened to 67–100% NBS and no retrofit (source: Ingham and Griffith3)**

Based on the data above, interpretation of the damage shows that:

• buildings that had received less than 33% NBS strengthening behaved in a similar manner to unstrengthened URM buildings, however there was a shift from major damage to moderate damage;

• a URM building strengthened to between 33% NBS and 67% NBS avoided being destroyed but otherwise the reduction in damage was not greatly better than for URM buildings that had received no retrofit; and

• URM buildings that were strengthened to between 67% NBS and 100% NBS showed a noticeable increase in performance compared to unstrengthened URM buildings.

We emphasise, as noted above, that in interpreting this data, it is important to note that the seismic hazard factor (Z) for strengthening work undertaken would have been 0.22; this factor was revised upward following the earthquakes to 0.3. Further, the direction of ground shaking in the September and February earthquakes must also be borne in mind. These matters are discussed in detail in section 2 of Volume 1 of this Report.

Other analyses in the Ingham and Griffith report compared the performance of buildings that had been subject to different kinds of strengthening, described

as Types A and B earthquake improvements. Type A involved techniques that aimed to improve connections between the walls and diaphragms: securing and strengthening building elements such as gable ends (excluding parapets, which were assessed separately); installation of connections between the walls and the roof and floor systems, so that the walls would not respond as vertical cantilevers secured only at their base; and stiffening of the roof and/or floor diaphragms.

Type B improvements were defined as strengthening techniques that sought to strengthen masonry walls and/or to introduce added structure to supplement or replace the earthquake strength provided by the original unreinforced structure. They included strong- backs installed either internally or externally; steel moment frames; steel brace frames; concrete moment frames; the addition of cross walls; post-tensioning; and the use of shotcrete, and fibre-reinforced polymer. A comparison between two types of earthquake strengthening and those with no retrofit is shown in Figure 80 below.

In the sample of 31 buildings with no retrofit, 97% suffered severe, major, or heavy damage. However, Ingham and Griffith also noted that many strengthened buildings were also damaged, in some cases to a

major extent.

60%

Types A & B Type A only No retrofit

40%

Percentage of buildings

20%

0

insignificant moderate heavy major destroyed

Damage level

**Figure 80: Plot of damage level against seismic strengthening types (source: Ingham and Griffith3)**

Figure 81 represents the conclusions in the Ingham and Griffith report about what they found was an escalating level of hazard to building occupants and passers-by caused by increased levels of building damage. Not surprisingly, the risk of fatality or injury increases with the level of damage sustained, but that is more pronounced for passers-by than building occupants.

100%

80%

Percentage of buildings

60%

40%

20%

0

insignificant 1–10% moderate 10–30% heavy 30–60% major 60–100% destroyed 100%

Damage level

(a) Risk to building occupant for different building damage levels

Unlikely

Likely

Near certain

100%

80%

Percentage of buildings

60%

40%

20%

0

insignificant 1–10% moderate 10–30% heavy 30–60% major 60–100% destroyed 100%

Damage level

(b) Risk to passer-by for different building damage levels

Unlikely

Likely

Near certain

**Figure 81: Fatality and injury risk for different building damage levels (source: Ingham and Griffith3)**

Ingham and Griffith also compared risk to hypothetical occupants and passers-by, based on an assessment of the performance of the 94 surveyed buildings that could be assigned a percentage NBS. Their findings (acknowledged to be subjective) are shown in the following diagrams, and suggest that it is generally safer to be inside a URM building during an earthquake than outside it.

near certain

13%

unlikely

58% 29%

unlikely

33%

near certain

48%

likely

19%

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

**Figure 82: Risk of fatality or injury to building occupants and public space occupants (source: Ingham and Griffith3)**

They concluded that the increased risk to those in the adjacent public space was because walls are more likely to collapse outwards. Similarly parapets and gables fell onto adjacent property. These conclusions align with those of the Royal Commission, having considered the actual performance of all of the buildings whose failure in the February earthquake caused loss of life.

Ingham and Griffith also reported on the different

levels of risk to occupants and passers-by from failure of URM buildings strengthened by Types A and B strengthening works, and those that had not been strengthened. The results are presented in the following Figure 83.

80%

60%

Percentage of buildings

40%

20%

0%

unlikely likely near certain

Risk level

Types A & B Type A only No retrofit

(a) Risk to building occupants

80%

60%

Percentage of buildings

40%

20%

0%

unlikely likely near certain

Risk level

Types A & B Type A only No retrofit

(b) Risk to public space occupants

**Figure 83: Plot of seismic strengthening level vs risk to building occupants and public spaces (source: Ingham and Griffith3)**

This enhancement of safety from retrofit is noted and reinforces the imperative to strengthen buildings.

There is considerable international experience of the behaviour of URM buildings in earthquakes, especially in areas such as California and Italy where URM buildings are also common. The Royal Commission engaged two engineers based in California to peer review the Ingham and Griffith reports: Mr Fred Turner, who is a structural engineer with the California Seismic Safety Commission, and Mr Bret Lizundia, a principal

in the firm Rutherford and Chekene in San Francisco. Both are experts in this field. The peer reviews of Turner and Lizundia were also published on the Royal Commission’s website.

Turner6 and Lizundia7 discussed the Californian experience with URM buildings. Lizundia noted that in California emphasis on strengthening is primarily to reduce the risk of death and injury. He observed that it is hard to assess accurately the properties of the old materials used in URM buildings. Turner noted that in

California programmes are referred to as “conservation” rather than strengthening, and are tailored to local government discretion. Although the standards of retrofit vary, the Royal Commission was informed that, by 2006, 70% of the approximately 26,000 URM buildings in California had been either retrofitted or demolished.

Strengthening of a URM building is also considered a “risk reduction programme” by the New Zealand Society for Earthquake Engineering, a term that reflects the limitations of such work. Turner emphasised the need to acknowledge that:

…it is neither practical nor feasible to state conclusively that the public can be effectively protected from “all” falling hazards and that “strengthened URM buildings will survive severe earthquake ground motions”.

He also observed that:

…the public should be made aware of the practical limitations of seismic retrofits, considering the margins of safety from collapse and parts of buildings falling, particularly in light of the large known variability and uncertainty in the quality of building materials, the states of repair, and the integrity of connections between building components. In a retrofitted URM building, a single masonry unit that may fall from an appreciable height has the potential to be lethal or cause serious injury. Retrofits that represent best practices may not always guarantee that all masonry units will remain in place, nor that URM buildings will always avoid cost-prohibitive repairs or demolitions after experiencing severe ground motions.

Despite improvement made to many buildings, the Royal Commission is concerned to note that, from the sample of 94 URM buildings, over 60% that were strengthened to more than 67% NBS suffered moderate to heavy damage. Turner cautioned that the behaviour of URM buildings in earthquakes is difficult to predict because of the inherent weakness of component materials. This appears to be substantiated by the damage statistics derived from the Canterbury earthquakes experience. It is important to note in making this observation that the February earthquake was severe.

5.2.2 Heritage buildings

The New Zealand Historic Places Trust8 (NZHPT)

provided a report to the Royal Commission cataloguing

100 heritage listed buildings. Of that number, four were in Lyttelton and 96 in the Christchurch CBD. The heritage buildings discussed in the NZHPT report were all scheduled as such in the district plan. The NZHPT report describes each building, whether it had been retrofitted, damage resulting from the earthquakes, and the present status. Many damaged buildings have now been demolished for safety reasons.

The report analyses how a select sample of 100 heritage buildings performed in the Canterbury earthquakes. The buildings were either registered by the NZHPT or listed as heritage buildings in Christchurch City Council’s District Plan. Of the 100 buildings studied:

• 72 were URM buildings;

• 15 were timber-framed buildings; and

• 13 were of other construction (i.e. reinforced concrete).

The report examined how buildings strengthened to different levels performed, grouping them by:

• earthquake strengthening of the entire building

(30% of buildings);

• partial or incomplete strengthening (16%);

• bracing and ties (8%);

• no earthquake strengthening (27%); and

• unknown if strengthened (19%).

The analysis in the report shows:

**Table 1: Numbers of strengthened buildings damaged in the Canterbury earthquakes**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Demolished** | **Demolition** | **Buildings damaged** | **Number** | **Strengthened buildings** |
|  | **pending or** |  | **strengthened** | **damaged** |
|  | **possible** | **Sept 10 Feb 11** |  | **Sept 10 Feb 11** |
| 40 | 21 | 97 95 | 54 | 54 54 |

**Notes:**

• The figures were current to January 2012.

• The damage assessment of three buildings in September 2010 was unknown.

• The damage assessment of two buildings in February 2011 was unknown.

• Three buildings collapsed in February 2011.

Although all 54 of the strengthened heritage buildings suffered damage following both the September and February events, the extent of the damage differed between the two events. The following graphs demonstrate the different impacts of the two events on the same sample of 100 heritage buildings. They also show how the different strengthening levels affected performance of the buildings.

25

20

15

Number of buildings

10

5

Unknown

No earthquake strengthening

0

Minimal damage

Moderate damage

Severe damage

Major damage

Collapse

Unknown

Bracing, ties only

Partial or incomplete earthquake strengthening

Earthquake strengthened



|  |
| --- |
| **Minimal Moderate Severe Major Collapse Unknown damage damage damage damage** |
| Earthquake strengthened 24 6 0 0 0 0 |
| Partial or incomplete earthquake 7 9 0 0 0 0 strengthening |
| Bracing, ties only 2 6 0 0 0 0 |
| No earthquake strengthening 6 17 1 0 0 3 |
| Unknown 16 3 0 0 0 0 |

**Figure 84a: Comparison between 100 strengthened and non-strengthened heritage buildings damaged in the earthquakes between September and December 2010 (source: New Zealand Historic Places Trust, March 2012)**

16

14

12

10

Number of buildings

8

6

4

2

0

Minimal damage

Moderate damage

Severe damage

Major damage

Collapse

Unknown

Unknown

No earthquake strengthening

Bracing, ties only

Partial or incomplete earthquake strengthening

Earthquake strengthened

|  |
| --- |
| **Minimal Moderate Severe Major Collapse Unknown damage damage damage damage** |
| Earthquake strengthened 4 14 9 2 0 1 |
| Partial or incomplete earthquake 1 5 9 1 0 0 strengthening |
| Bracing, ties only 1 0 1 4 2 0 |
| No earthquake strengthening 0 5 15 4 1 1 |
| Unknown 5 8 5 1 0 0 |

**Figure 84b: Comparison between 100 strengthened and non-strengthened heritage buildings damaged in the earthquakes between January and June 2011 (source: New Zealand Historic Places Trust, March 2012)**

**5.3 Observations on the behaviour of URM buildings**

There are three broad approaches to managing the risk posed by unreinforced masonry buildings in earthquakes. The first is to do nothing and accept the risk on the basis that damaging earthquakes resulting in building damage will occur infrequently. The second option is to demolish these building types, which would obviously impact on the heritage and character of New Zealand’s cities and towns. The third way forward is to install some level of earthquake strengthening in these buildings. This third option is the intent of the current law. We do not suggest that it should be abandoned.

However, it should be emphasised that the strengthening of URM buildings requires careful consideration. URM buildings are made up of materials that are inherently good in compression but very weak in tension. The poor performance in earthquakes of URM buildings as a class can be attributed to the buildings’ common characteristics. URM buildings are stiff, heavy and brittle structures, which attract large seismic accelerations in their structures. They have little capacity to deform once the strength of their elements has been exceeded, leading to abrupt failures.

The material properties and structural forms of URM buildings result in several potential seismic weaknesses. The deficiencies have been characterised and interpreted in the United States, for example in documents issued by the Federal Emergency Management Agency (FEMA), such as FEMA 5479. FEMA’s documents10 are also reasonably widely used in New Zealand.

When undertaking retrofit of URM buildings, it is important to understand these potential seismic deficiencies. By understanding these, a designer can determine the most critical feature of a particular structure. The most hazardous of these deficiencies are inadequately restrained elements located at height, for example, street-facing façades. Unrestrained parapets, chimneys, ornaments and gable end walls are also a high risk to public safety due to their low bending strength and high imposed accelerations. They are usually the first elements to fail in an earthquake and are a risk to people in a zone extending well outside the perimeter of the building.

The following is a general overview of common seismic deficiencies in URM structures:

**Overall strength**

Provided URM building elements are adequately tied together, the global strength of URM buildings is dependent on the in-plane shear capacity and the out-of-plane bending capacity of the walls. If these are found to be deficient, strengthening of existing elements or adding new lateral-force resisting elements will be required to cope with horizontal shear.

**Overall stiffness**

URM bearing walls are generally quite rigid. This leads to a structural system that has a low fundamental period of vibration, with higher seismic forces and lower displacements when compared to a tall flexible structure. In some buildings however, facades facing the street can be highly punctured with relatively narrow piers between openings. In addition to lacking strength, these wall lines may also be flexible, which can result in increased displacements and collapse.

**Configuration**

URM buildings vary substantially in structural layout. Buildings such as churches, which have irregular plans, tall storey heights, offset roofs, few partitions and many windows are particularly vulnerable. Many commercial URM buildings will have a fairly open street façade at ground level, resulting in a weak storey and torsional irregularity.

**Load path**

One of the most significant deficiencies in URM buildings is the lack of adequate ties between walls and floor diaphragms. Diaphragms (or floors) act as a mechanism for seismic loads to be distributed to lateral load resisting elements. Robust connections prevent forces becoming concentrated on one wall. Connections may also be used to reduce unrestrained wall heights, which increases their out-of-plane bending capacity. Older buildings that have not been maintained will have reduced material strengths due to weathering, corrosion and other processes which weaken mortar joints and connection capability. The “redundancy” of a building refers to the alternative load paths that are able to add to resistance. The ability to redistribute demands through a secondary load path is an important consideration as an earthquake-prone building with low redundancy will be susceptible to total collapse in the event of only one of its structural elements failing. Secondary load paths should be provided to increase the building’s resilience.

**Component detailing**

URM buildings do not comply with modern ductile detailing requirements. Buildings designed to current codes have the ability to withstand loads past the design ultimate limit state, whereas URM buildings will generally fail at or even below the lateral loads they were designed for originally (due to deterioration). Walls can be undesirably slender (comparing thickness to height of wall) with large spans between supports, making the walls susceptible to out-of-plane failures. Cavity walls are vulnerable as the steel ties connecting the exterior wythes to the backing wall can be weakened by corrosion. Bracing of walls, parapets and chimneys is essential in strengthened buildings.

**Diaphragm deficiencies**

Diaphragms in URM buildings are usually floors constructed of wood and may lack both strength and stiffness. Diaphragms are essential for tying the building together and ensuring the lateral loads are transferred to the lateral load resisting elements, such as walls. If diaphragms are too flexible then their ability to do this will be compromised. Large displacements of these diaphragms can also lead to wall failures.

**Foundation deficiencies**

Differential settlement, liquefaction and lateral spreading will all have detrimental effects on URM buildings.

**Material properties**

Observations in the Ingham and Griffith reports based on what was observed in the Canterbury earthquakes indicate that in general, walls of URM buildings are made of weak mortar and strong bricks. Bricks that had fallen from considerable height had not fractured and were in reasonably good order, whereas the mortar could be crushed simply under finger pressure.

**Vertical acceleration**

The ground motions recorded in the CBD during the February earthquake had very high vertical components of acceleration due to the close proximity of the fault. In assessing the seismic performance of a number of URM buildings for the Royal Commission, Mr Peter Smith observed that the vertical acceleration temporarily reduced the gravity and compression forces in walls. This was particularly significant in the higher levels of the walls. The temporary reduction in this compression reduced the stability of the walls, which depended on gravity actions, and it reduced the pull-out strength of the ties that had been installed to restrain the walls and parapets.

5.3.1 Observed damage and modes of failure. Based on the Ingham and Griffith reports, and the evidence we heard about the individual buildings discussed in section 4 of this Volume, we note that the Canterbury earthquakes resulted in common modes of URM building failure. We now describe these damage patterns and collapse mechanisms.

**Parapet and chimney failures**

A parapet is the vertical wall element that protrudes above the roofline. These, along with chimneys and ornaments, have little lateral load capacity and present the greatest hazard to life due to their location at height. Numerous unrestrained parapets, as well as some that had been strengthened, collapsed during the Canterbury earthquakes. If unrestrained, a parapet will act as a vertical cantilever that rocks at its base. Parapets were seen to fail around their roof line both inwards onto the buildings as well as outwards onto streets and public spaces. Before and after photographs of the building at 386–406 Colombo Street in Figures 85 and 86 illustrate that parapets were some of the most vulnerable, and generally the first, building elements to collapse.



**Figure 85: 386–406 Colombo Street before the September**

**2010 earthquake (source: Ingham and Griffith)**



**Figure 86: 386–406 Colombo St after the February 2011 earthquake (source: Ingham and Griffith)**

**Awning failures**

Falling parapets tended to land on the awnings and verandahs, causing the overload of the supporting tension rods. These typically collapsed due to a punching shear failure at the anchorage into the wall above.

**Wall and gable end failures**

The failure of URM walls may be in-plane or out-of- plane or a combination of these two mechanisms.

**Façades**

The façades of commercial URM buildings invariably incorporate large openings for windows and doors to the street, which make these wall structures particularly vulnerable. The balance of the wall was mostly comprised of brick columns and arch lintels above windows. While providing adequate vertical support for roof, ceiling and wall members, there was often no robust connection between façades and building side walls, and the floor and roof diaphragms behind.

The evidence presented to the Royal Commission in the hearings about individual URM buildings that failed causing loss of life (discussed in section 4) also clearly demonstrated these failure modes. We considered 25 individual buildings or structures, but omit from this discussion the free-standing wall that collapsed at 90 Coleridge Street, the interior chimney that collapsed in St Albans and the spandrel panel that fell from the carpark building at 43 Lichfield Street. Of the 22 remaining buildings, 19 had weak walls. Eleven were cases where the façades failed and rotated outwards onto the street. In seven cases the side walls failed and collapsed onto an adjacent building or inwards on the building itself. The Durham Street Methodist Church was another building that had weak walls, and it collapsed completely.

We note that there is an extensive review of various failure modes for URM buildings in FEMA 30611. This is an important reference source for those needing to assess buildings and design strengthening measures. We address these subjects in section 6 of this Volume.

**5.4 Some conclusions**

(a) URM buildings depend on gravity load for their stability. Ground motion can temporarily reduce this load and hence the buildings’ stability. The Canterbury earthquakes have shown that high accelerations can occur in the region close to faults. Consequently, where fault lines are close to or suspected to be close to CBDs, allowance should be made for the likely high ground accelerations in an earthquake.

(b) The majority of the deaths and injuries caused by the failure of URM buildings in the February earthquake occurred when building façades collapsed onto adjacent footpaths and roads. The Royal Commission considers that in a situation where there are limited resources it is logical to provide a greater level of protection against collapse of elements that threaten the public than to the buildings as a whole.

(c) If the Ingham and Griffith figures are adjusted to reflect the fact that the shaking level in the February earthquake was between 1.5–2 times the design level, it may be observed that a retrofit level of 33% NBS gives a marked improvement against collapse or major damage to a building, compared with retrofit between 0 and 33% NBS. On this basis it appears the minimum retrofit to 33% NBS could be maintained as an appropriate level for the building as a whole.

**References**

1. Excluding the PGC and CTV buildings and the death of an infant caused by an internal exposed brick chimney breast collapsing, the majority of other fatalities (39 out of 41) were caused by typical unreinforced masonry buildings failing in some way. The other two deaths were caused by a free-standing concrete block wall collapsing onto the victim, and a concrete spandrel falling onto the victim’s vehicle.

2. Ingham, J.M. and Griffith, M.C. (August 2011). *The Performance of Unreinforced Masonry Buildings in the*

*2010/2011 Canterbury Earthquake Swarm: Report to the Royal Commission of Inquiry*. Christchurch, New Zealand: Canterbury Earthquakes Royal Commission.

3. Ingham, J.M. and Griffith, M.C. (October 2011). *The Performance of Earthquake Strengthened URM Buildings in the Christchurch CBD in the 22 February 2011 Earthquake: Addendum Report to the Royal Commission of Inquiry.* Christchurch, New Zealand: Canterbury Earthquakes Royal Commission.

4. See section 2 of Volume 1 of this Report.

5. NZS 1170.5:2004. *Structural Design Actions, Part 5: Earthquake Actions – New Zealand*, Standards New Zealand.

6. Turner, F. (2011). *Review of “The Performance of Unreinforced Masonry Buildings in the 2010/2011 Canterbury*

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Royal Commission, 30 September 2011.

8. New Zealand Historic Places Trust. (2012). *Heritage Buildings, Earthquake Strengthening and Damage: The Canterbury Earthquakes September 2010–January 2012: Report for the Canterbury Earthquakes Royal Commission.* Christchurch, New Zealand: Canterbury Earthquakes Royal Commission.

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Edition). Washington D.C., United States of America: Federal Emergency Management Agency.

10. Examples include Rutherford and Chekene. (2006). *Techniques for the Seismic Rehabilitation of Existing Buildings* (FEMA 547/2006 Edition). Washington D.C., United States of America: Federal Emergency Management Agency. And Rutherford and Chekene. (1990). *Seismic Retrofitting Alternatives for San Francisco’s Unreinforced Masonry Buildings*. San Francisco, California, United States of America: Author. And Federal Emergency Management Agency. (2004). *Primer for Design Professionals: Communicating with Owners and Managers of New Buildings on Earthquake Risk* (FEMA 389). Washington D.C., United States of America: Author. And Applied Technology Council. (2009). *Unreinforced Masonry Buildings and Earthquakes: Developing Successful Risk Reduction Programs* (FEMA P-774/October 2009). Washington D.C., United States of America: Federal Emergency Management Agency.

11. Applied Technology Council. (1998). *Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings; Basic Procedures Manual* (FEMA 306). Redwood City, California, United States of America: The Partnership for Response and Recovery.

Note that Standards New Zealand was previously known as the Standards Institute of New Zealand.