Performance of Unreinforced Masonry Structures in the 2010/2011 Canterbury Earthquake Sequence

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SUMMARY:
Following the magnitude 6.3 aftershock in Christchurch, New Zealand, on 22 February 2011, a number of researchers were sent to Christchurch as part of the New Zealand Natural Hazard Research Platform funded "Project Masonry" Recovery Project. Their goal was to document and interpret the damage to the masonry buildings and churches in the region. Approximately 650 unreinforced and retrofitted clay brick masonry buildings in the Christchurch area were surveyed for commonly occurring failure patterns and collapse mechanisms. The entire building stock of Christchurch, and in particular the unreinforced masonry building stock, is similar to that in the rest of New Zealand, Australia, and abroad, so the observations made here are relevant for the entire world.

Keywords: Unreinforced masonry, seismic performance, Christchurch earthquakes

1. INTRODUCTION

Since September 2010 Christchurch, the third largest city in NZ and the largest city in the South Island, has experienced a series of over 10,000 earthquakes and aftershocks, including four earthquakes with magnitudes greater the 6.0 and one with a magnitude greater than 7.0. On the 22 February 2011 a M6.3 earthquake occurred approximately 10 km away from the city centre. Although it was smaller in magnitude than the M7.1 Darfield earthquake of 4 September 2010 the effects on the city of Christchurch were much greater due to higher shaking levels in the city. Unreinforced masonry (URM) buildings performed the worst of all building types in both earthquakes, and were the only building type to sustain significant levels of shaking damage in the Darfield earthquake. A further four large aftershocks on 13 June 2011 (M 5.6 and M6.3) and 23 December 2011 (M5.8 and M6.0) caused further damage to all building types, and again the URM buildings performed the worst. Figure 1.1 shows the locations of the major earthquakes and over 10,000 aftershocks at 13 March 2012.

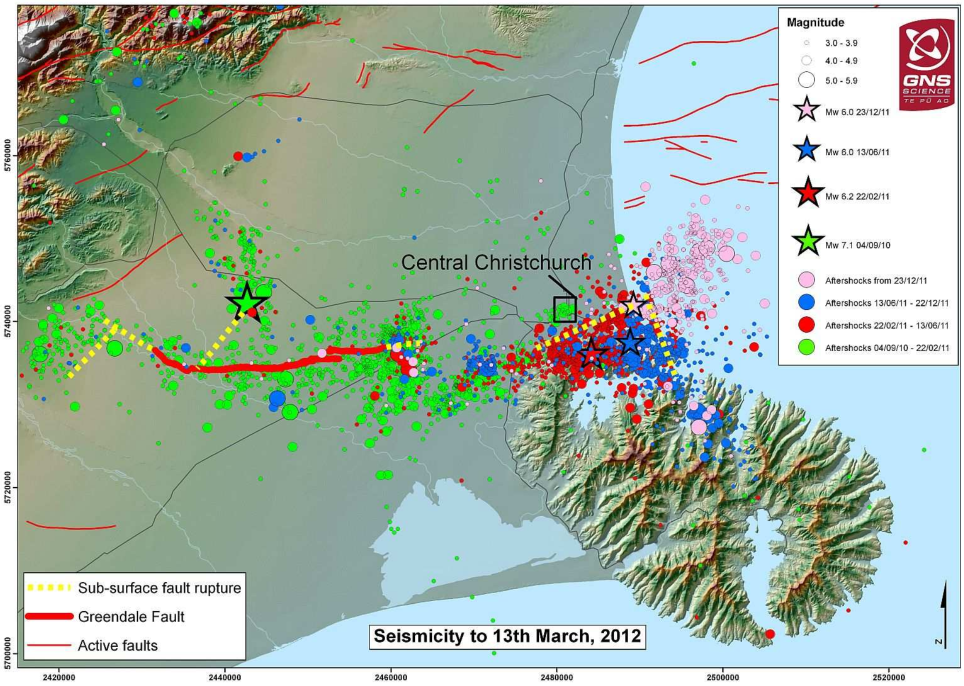


Figure 1.1. Locations of major earthquakes and aftershocks around Christchurch, New Zealand, between 4 September 2010 and 13 March 2012 [source: GNS (2012)]

A team of engineers from the University of Auckland and the University of Adelaide went to Christchurch shortly after the Darfield earthquake to record the damage to URM buildings. The team returned again after the February 2011 earthquake, and were still in the city for the 13 June 2011, and have recorded a unique set of data on the performance of a large group of URM buildings through a succession of large earthquakes. A team member was visiting Christchurch again in December 2011 and recorded additional damage to some of the remaining URM buildings.

New Zealand has a comparatively homogenous URM building stock by international standards. Construction of clay brick unreinforced masonry building began in New Zealand in about 1860, and essentially ended after the 1931 Hawke's Bay earthquake, where the vulnerability of unreinforced masonry was demonstrated by the destruction of the city of Napier which had many URM buildings. Although not officially banned as a building material in New Zealand until 1976, use of URM construction phased out about this time (Megget, 2006). As a result, many of New Zealand's significant heritage buildings are of URM construction. Since 2006 all existing buildings with lateral capacity less than 33% of that required for a new building (%NBS) have been deemed earthquake prone, and are required to be strengthened to at least 33% NBS (New Zealand Parliament, 2004) (the New Zealand Society of Earthquake Engineering recommends a minimum strengthening level of 67% NBS). While most URM buildings would be classed as earthquake prone, the lack of a timeline being imposed on this requirement meant that while some of the URM buildings in Christchurch had been strengthened, many of them had not. The researchers were therefore able to study both unretrofitted URM buildings and retrofitted URM buildings.

2. THE EARTHQUAKE SEQUENCE

Prior to September 2010 the seismic risk in Christchurch, New Zealand, was thought to be relatively low, and primarily attributable to the Alpine fault, which is located approximately 100 km to the west and marks the boundary of two tectonic plates. However, the perception of seismic risk was to change shortly after 4:35 am on Saturday 4 September 2010, when a hitherto unknown intra-plate fault ruptured approximately 40 km to the west of the city of Christchurch, in the province of Canterbury.

The M7.1 earthquake resulted in severe liquefaction and lateral spreading near the Avon River in Christchurch and by the Waimakariri River in the town of Kaiapoi, to the north. The Greendale fault, as it became known, revealed a new seismic threat to the people of Christchurch. However, it soon became clear that there were more unknown faults closer to the city and indeed under the city itself, and it was one of these faults which ruptured in February 2011, causing much damage to the city and its environs.

2.1. The Darfield earthquake - 4 September 2010

The Darfield earthquake on the 4 September 2010 induced ground accelerations in the city of Christchurch of roughly 67% to 100% of the then current design standards. At the time it was hailed as the most damaging earthquake to strike New Zealand since the 1931 Hawke's Bay earthquake; miraculously, in part due to the timing of the earthquake and in part due to luck, the earthquake caused no fatalities. In general, the only building type to sustain significant shaking damage, particularly in the central business district (CBD) was URM buildings (Dizhur et al., 2010; Ingham and Griffith, 2011a). Typical damage seen included fallen chimneys and parapets, and out of plane failures of gable end walls and upper story walls. The effects of excessive diaphragm flexibility were observed, as was some in-plane shear cracking. In addition to observations made by the team on their visit to Christchurch the Christchurch City Council provided them with a copy of the database containing the damage assessment data from all the building assessments. Figure 2.1 shows the damage levels assigned to URM buildings in Christchurch after the 4 September. More than half of the buildings suffered less than 10% damage and more than three-quarters of them suffered damage levels less than 30%.

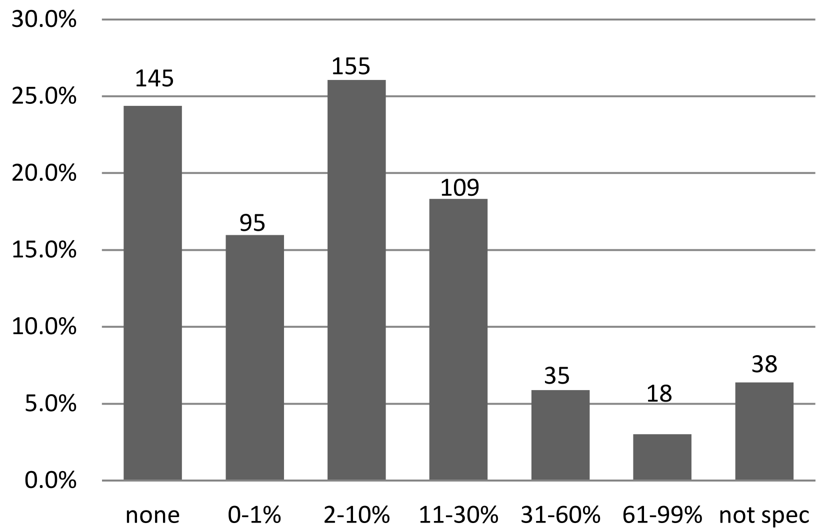


Figure 2.1. Damage levels assigned to URM buildings in Christchurch after Darfield Earthquake, 4 September 2010

Each building was also assigned a placard colour according to observed levels of structural damage. Buildings tagged green had no observed structural damage, those tagged yellow had some structural damage but were deemed safe to enter for short periods of time, for example to remove personal possessions, and those tagged red were deemed unsafe to enter. Figure 2.2, which illustrates the distribution in placard levels, shows that nearly half of all URM buildings were observed to have no restrictions on building occupation but that roughly 1 in 5 were too unsafe to be entered at all.

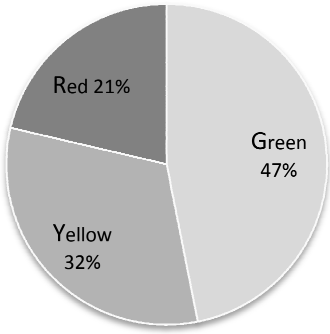


Figure 2.2. Placard colours assigned to URM buildings in Christchurch after 4 September 2010

2.2 The Boxing Day earthquake - 26 December 2010

In the weeks and months following the Darfield earthquake the region around Christchurch experienced many aftershocks. At 10:30am on Boxing Day, 26 December 2010, an aftershock occurred with an epicentre less than 2 km from the centre of the CBD. The magnitude 4.7 earthquake caused significant shaking damage in the central city and results in the closure and fencing off of several previously undamaged URM buildings.

2.3 The Lyttelton earthquake - 22 February 2011

The ground accelerations induced in Christchurch by the earthquake of 22 February 2011 were much greater than those from September 2010, and were often significantly higher than the current design level (GNS, 2011). The earthquake occurred just before 1pm, when many people were taking their lunch break, and many were caught under falling facades. The total death toll was 185, with 42 of the deaths attributable to the failure of unreinforced masonry buildings (Ingham and Griffith, 2011b).

While all building types sustained damage in this earthquake again it was the URM buildings which performed the worst (Dizhur et al., 2011; Ingham et al., 2011; Moon et al., 2011). A survey in the form of a transect of the CBD was undertaken on 24 February by two of the authors, estimated that nearly half of all URM buildings were unsafe to enter. Note that this was based on rapid external assessments only. Further details of the transect have been reported by Ingham et al. (2011) and Moon et al. (2012a, 2012b, 2012c).

The distribution in placard levels assigned to URM buildings following the February 2011 earthquake is shown in Figure 2.3. Figure 2.3 shows a significant increase in damage levels compared to those observed after the Darfield earthquake in September (Figure 2.2) with nearly 75% of all URM buildings being classed as unsafe to enter and only 1% classed as safe to occupy.

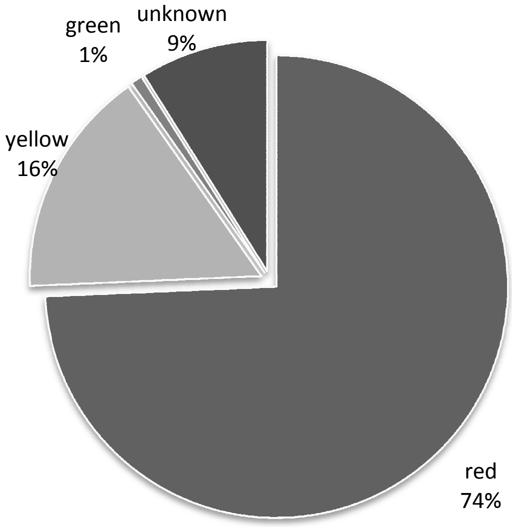


Figure 2.3. Assigned placard levels for CBD URM building after 22 February 2011

Figure 2.4 shows the additional damage sustained by one URM building due to the 22 February earthquake. The photo on the left was taken two days before the February 2011 earthquake, and the photo on the right was taken two days afterwards. The top of the gable end wall has collapsed, and some corner failure can be observed to the left of the building. The strap around the building and scaffolding to the right indicate that rehabilitation of the building was underway at the time of the February earthquake. Fortunately, the fence surrounding the building, present in both photos, meant that the public were protected from most of the falling masonry from this building. Barrier fences around many at risk buildings, combined with the loss of so many vulnerable parapets, chimneys and upper walls in September, probably helped minimise the lives lost due to falling masonry in the February aftershock (Ingham and Griffith, 2011c).

Figure 2.4. Christchurch URM building on 20 February 2011 (left) and 24 February 2011 (right)

2.4. The Christchurch earthquake - 13 June 2011

The M5.7 and M6.3 aftershocks of 13 June 2011 did not receive the same attention as the September 2010 and February 2011 earthquakes, and together with the December 2011 aftershocks are in danger of becoming the forgotten aftershocks of the Canterbury earthquakes. In a city full of damaged buildings it can be easy to overlook the effects of further large aftershocks; however, the aftershocks of 13 June, which occurred at around 1pm and 2:20pm caused widespread significant additional damage and severe liquefaction in some areas. Several previously damaged buildings suffered significant collapse, and a number of workers were treated for injury (Stuff.co.nz, 2011). The additional damage to URM buildings meant that many buildings previously planned to be saved and strengthened were damaged beyond repair. Figure 2.5 shows the progression of damage to one URM building due to the September 2010, February 2011 and June 2011 earthquakes. Minor cracks as a result of the September earthquake became significant cracks in February and resulted in partial wall collapse in June.

a) Post September 2010 b) Post February 2011 c) Post June 2011

Figure 2.5. Progression of damage to a building during the September 2010, February 2011 and June 2011 earthquakes

2.5. 23 December 2011

More than six months after the June earthquakes Christchurch again experienced two large aftershocks in one afternoon. At around 1:58pm on 23 December 2011 Christchurch was jolted by a M5.8 earthquake. This was followed about 80 minutes later by a M6.0 earthquake. Centred off the coast between 10 and 20 km east of the CBD the December 2011 earthquakes again caused significant liquefaction and further shaking damage. As with the June earthquakes, buildings which were thought to be repairable were damaged beyond repair and condemned to the demolition list. Figure 2.6 shows the progression of damage to a URM building after the February 2011, June 2011 and December 2011 earthquakes. The veneer leaf failed after as a result of the June 2011 earthquake while the internal structural wall only failed as a result of the December 2011 earthquakes. Although not visible in Figure 2.6(a), after the February 2011 earthquake wall ties were observed to be punching through the veneer layer, indicating differential movement between the two leaves.

a) Post February 2011 b) Post June 2011 c) Post December 2011

Figure 2.6. Progression of damage to a building during the February 2011, June 2011 and December 2011 earthquakes

2.6 Continuing aftershocks

In February 2012 Christchurch reached the dubious honour of having been subjected to 10000 earthquakes since September 2010. In the first two weeks of 2012 the region experienced four aftershocks with magnitude 5.0 of greater. At the time of writing the aftershocks were continuing

3. DEMOLITIONS

As at September 2011 85% of 224 buildings demolished were of URM construction (Figure 3.1). While in part this is due to the often more urgent nature of the demolition of URM buildings due to risk they present to the public, and the relative ease of demolition compared to taller buildings, it still highlights the poor seismic performance of URM buildings compared to other building types. By April 2012 the total number of buildings demolished, or scheduled for demolition, had increased to almost 1000, and many larger, newer structures had been demolished.

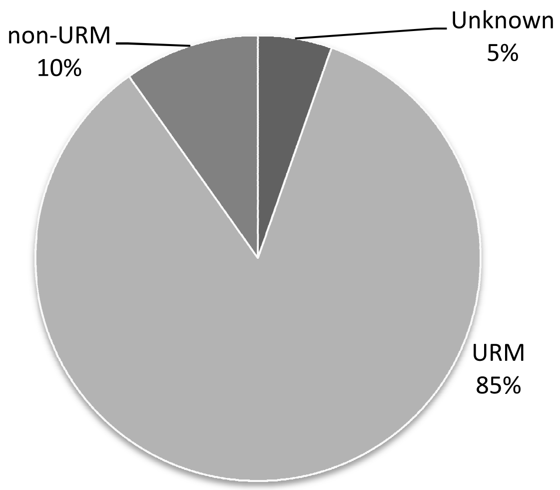
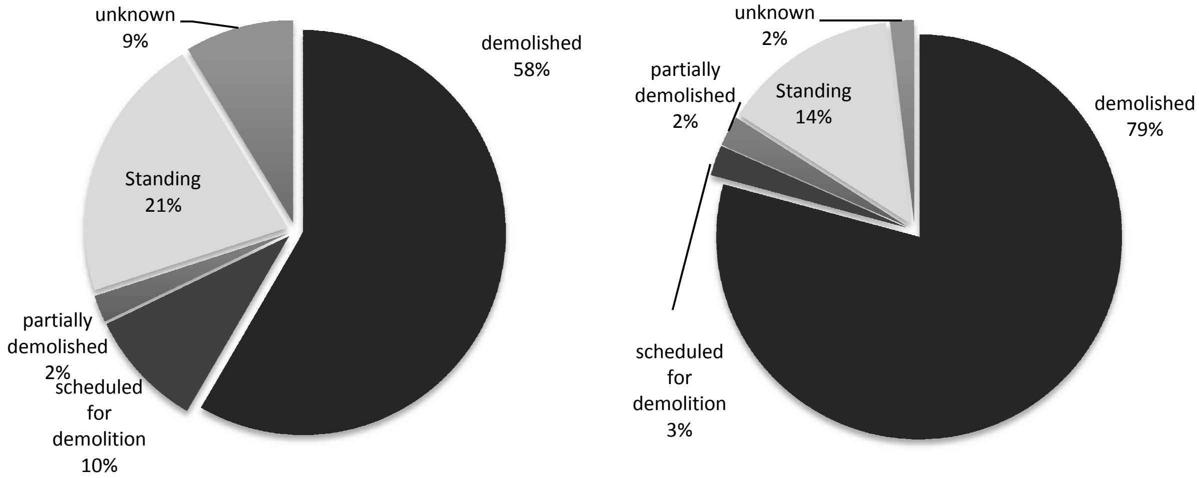


Figure 3.1. Proportion of demolished buildings which were of URM construction in September 2011.

Figure 3.2(a) shows the proportion of the 368 URM buildings in the CBD demolished or scheduled for demolition at September 2011. By September 2011 over half of all URM buildings in the CBD had already been demolished, and another 10% were on the demolition list. Figure 3.2(b) shows the proportion of URM buildings in the CBD that were scheduled for demolition or had already been demolished in April 2012. As can be seen more than 80% of all URM buildings have either been demolished or are scheduled to be demolished in April 2012. It should be noted that the demolition list is updated fortnightly, so these figures are subject to change.



a) September 2011 b) April 2012

Figure 3.2. State of URM buildings in Christchurch CBD in September 2011 and April 2012

4. PERFORMANCE OF SEISMIC RETROFITS

As can be expected URM buildings which had been seismically retrofitted performed better than those which had not. The damage levels for the URM buildings in the Christchurch CBD were plotted against the level to which they had been seismically enhanced (%NBS), shown in Figure 3.3, and clearly shows the buildings which were seismically retrofit to higher levels of %NBS sustained less damage than those strengthened to lower levels. Preliminary findings on the performance of seismic retrofits are reported by Ingham and Griffith (2011c), and work in this area continues.

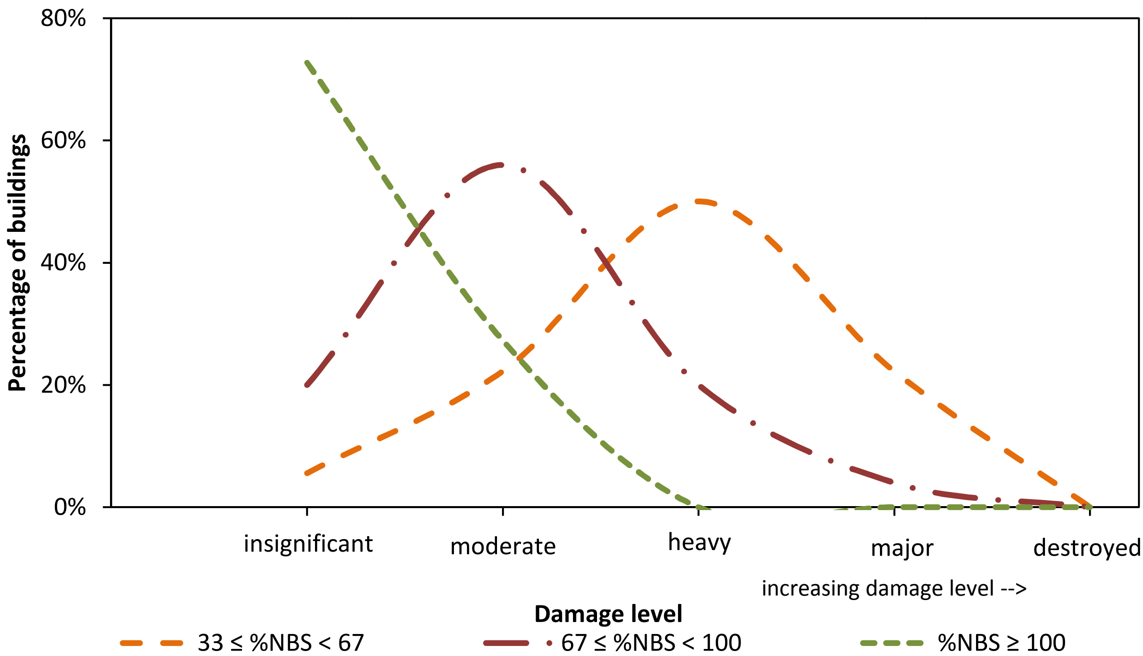


Figure 3.3. Level of damage sustained by URM buildings that had received different levels of seismic retrofitting

5. SUMMARY AND CONCLUSIONS

The 2010 and 2011 Canterbury earthquakes had a devastating effect on the city of Christchurch, and particularly on its URM building stock. Many historically significant URM buildings have been damaged beyond repair, and the future of many others remains uncertain. While the majority of URM buildings have been or will be demolished, observations made by research engineers throughout the earthquake sequence have allowed for a unique study into the effects of multiple large earthquakes in the range and greater than design level of a large population of URM buildings. A database of damage to all the URM buildings in the Christchurch region is being developed by Universities of Adelaide and Auckland, and will eventually be made publically available. Lessons learnt from the study of damage progression and the relative performance of different levels of retrofit strengthening will help engineers secure and save historically valuable URM building stock in other New Zealand cities and across the world.

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