JSEE Vol. 13, No. 1, 2011

Technical Note

Performance of Unreinforced Masonry Buildings in Canterbury Earthquakes

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ABSTRACT

This paper describes the impact of the 4th September 2010 and the 22nd February 2011 Canterbury earthquakes on masonry buildings. Christchurch and the surrounding areas have more than a thousand old buildings built of unreinforced brick and stone masonry. Several unreinforced masonry (URM) buildings were damaged (some very severely) in the September earthquake; whereas the February earthquake caused severe damage (many collapsed) to most URM buildings in Christchurch; requiring them to be demolished. As expected, retrofitted URM buildings generally performed better, but in the February earthquake several retrofitted buildings were also severely damaged. URM buildings with perimeter walls partially anchored using small and sporadic anchor bolts not extending to the full perimeter and height of the walls suffered severe damage. On the other hand, URM buildings that were systematically retrofitted to avoid the perimeter walls from detaching from each other and from the floor and roof sustained the severe shakings of the February earthquake with only minor damage.

Keywords:
Unreinforced Masonry (URM);
Seismic performance;
Retrofit; Damage;
Collapse

1. Introduction

Being in the ring of fire, New Zealand (*NZ*) has been known to be an earthquake-prone country. Nevertheless, seismic activities in the last 100 years or so have not been as frequent and severe as in other earthquake prone countries in the ring of fire (such as Indonesia, Chile, Japan, etc.). There have been some reasonably large earthquakes in the recent past (such as the *M*7.8 earthquake in the Dusky Sounds in July 2009), but because of the nearest town from the source being too far away to have any significant effect on structures, infrastructures and people, these major seismic events have not received as much attention. Before 2010, the last earthquake in *NZ* that damaged buildings and infrastructures was the *M*6.8 Gisborne earthquake in December 2007, and the last earthquake that caused casualty was the *M*7.1 Inangahua Earthquake in May 1968 (killed two people).

The seismicity of *NZ* is very unique; the boundary between the Australian plate and the Pacific plate passes right through the South Island. As shown in Figure (1), the boundary forms the Alpine fault in the middle of the South Island, which is sandwiched between two subduction zones in the north and the south. In Hikurangi trough which lies just to the east of North Island, the Pacific plate subducts underneath the Australian plate whereas in the Puysegur trench in the south west corner of the South Island, the Australian plate subducts underneath the Pacific plate. This change in relative orientation of the two plates within a short length has created a severely distorted region, giving rise to several faults in the northern part of the South Island and in the southern part of the North Island around the capital city Wellington. For this reason, Wellington has always been regarded as the most earthquake-prone city

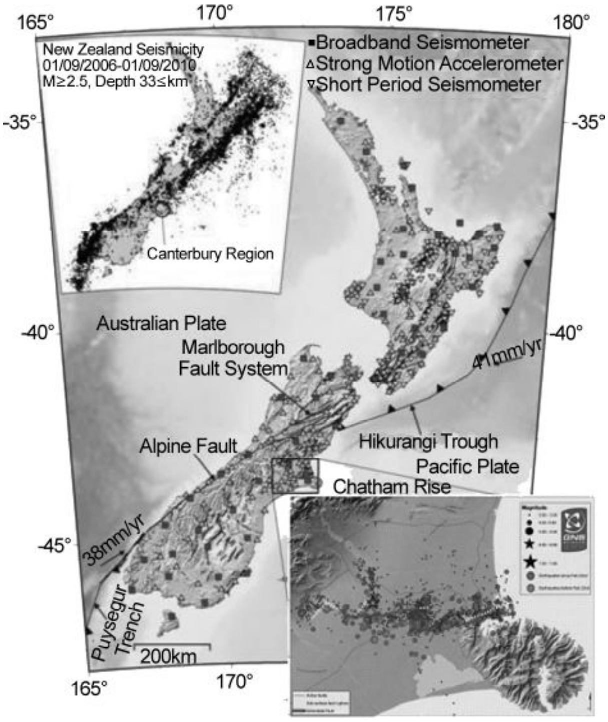

Figure 1. Seismicity of NZ and the locations of the September and February earthquakes.

among the big cities in *NZ*, and significant efforts have been put in seismic strengthening (including base isolating) of buildings in the Wellington region.

Christchurch is the biggest city in the South Island and is located about 100*km* away from the Alpine fault; which was until recently known as the only major earthquake source that could pose a genuine threat to its structures, infrastructures and residents. Although possibility of some hidden faults in the Canterbury plains has been discussed in the past [1], the seismic hazard of Christchurch and its surrounding areas was thought to be dominated by earthquakes originating in the Alpine fault. Consequently, Canterbury has always been known as a moderate seismicity region; with the design seismic hazard factor being only 55% of that for Wellington.

Basic facts about the two Canterbury earthquakes at 4:35*am* on Saturday, 4th of September 2010, a magnitude 7.1 earthquake occurred in Canterbury, *NZ*. The epicentre was located near Darfield, about 35*km* west of Christchurch; and the depth of the quake was 10*km*. It was predominantly a strike slip rupture of a fault spanning about 25*km*, and the maximum recorded horizontal and vertical slips were 4.5*m* and 1.5*m*, respectively. This earthquake generated severe ground shakings in the areas close to the rupture. The horizontal peak ground accelerations (*PGA*) were close to 1.0*g* in some nearby stations. The ground shakings recorded in Christchurch had *PGAs* between 0.15*g* and 0.25*g*. This earthquake was followed by more than 4000 aftershocks (the largest having a magnitude of 5.4) before another earthquake of magnitude 6.3 occurred less than 10*km* away from Christchurch at 12:51*pm* on 22nd February 2011. The focus of this earthquake was located 5*km* beneath the surface, and the rupture was not visible on the surface (i.e. subsurface fault rupture). Although the magnitude of this earthquake was smaller than the September earthquake, the resulting ground motions in Christchurch and eastern suburbs were more intense than those from the September earthquake. The horizontal *PGA* was around 1.0*g* in stations close to the epicentre and they were around 0.6*g* in the central business district (*CBD*) area. In addition, the vertical motion was also very intense. The vertical *PGA* exceeded 1.0*g* in several locations in the *CBD* and eastern suburbs. This earthquake has also been followed by hundreds of aftershocks the largest of which was measured 5.5 on the Richter scale.

Both earthquakes were of short duration; the significant shaking lasted for less than 20 seconds in both events. Nevertheless, they caused widespread damage to the ground, buildings and infrastructures in the Canterbury region. Damage to ground in the form of liquefaction and lateral spreading was prevalent in both events. In September, the ground damage (and damage to structures and infrastructures) extended to a greater area in Canterbury, but in February they were more concentrated in and around the city. In line with the level of ground shaking, the damage in Christchurch was far more severe in the February earthquake than in September. The response spectra of some records from these two earthquakes are compared against the design spectra [2] in Figure (2).

The September earthquake rendered about 2,500 houses uninhabitable; most of which could be attributed mainly to three reasons: (i) old and unretrofitted *URM* buildings lacked adequate seismic resistance; (ii) buildings located very close to the fault rupture were unable to cope with the severe ground shakings; and (iii) buildings which structurally had performed well became unusable due to ground/foundation failure. As the response spectra of typical recorded ground motions suggests, see Figure (2), the demand on long period structures

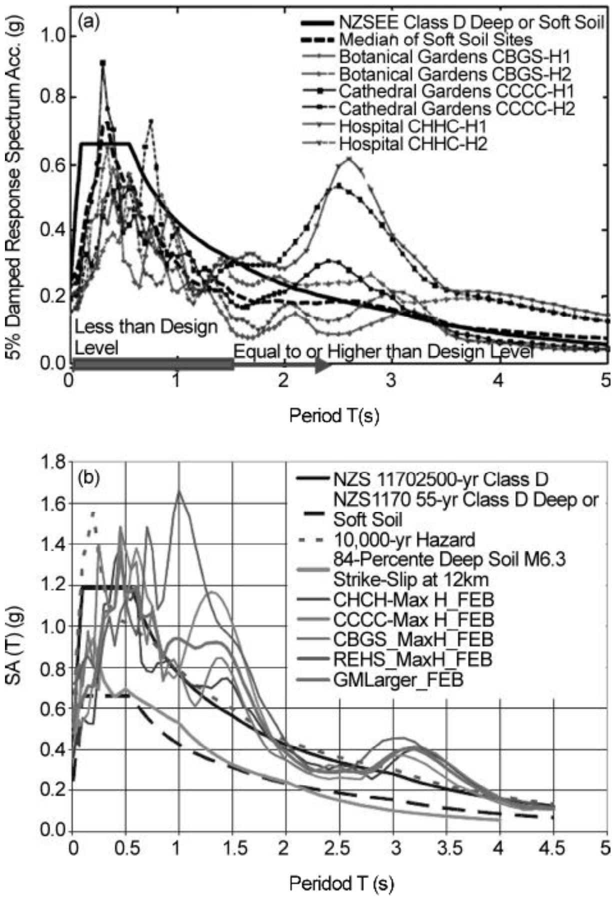

Figure 2. Comparison of response spectra of ground motions recorded in (a) September; (b) February earthquakes with the 500 and 2500 year return period design spectra.

were close to the design demand (and higher than the design demand for periods longer than two seconds); some modern high-rise buildings expectedly suffered some repairable structural damage. Excluding the *URM* buildings, the damage to other low-rise buildings and houses (which have short natural periods for which the induced demand was significantly less than the design demand as seen in Figure (2)) was mainly restricted to non-structural components such as chimneys, parapets, ceilings, facades, etc. There were some damage to roads, bridges, utilities and other infrastructures; but the extent of damage was minor to moderate. There was no casualty and only two cases of major injury was reported; whereas the number of minor injury was estimated to be around 200. There were more than 150,000 insurance claims resulting from this earthquake and the total loss was estimated to be five billion *NZ* dollars.

On the other hand, the February earthquake was more destructive for buildings, infrastructures, grounds and people in Christchurch. More than 180 people were killed in this earthquake and more than 150 people were reported to be severely injured with over 1500 cases of minor injury. The damage to buildings was not just restricted to the three categories mentioned above; even modern buildings were severely damaged. Several buildings in the downtown partially or totally collapsed among which were two high profile buildings (Canterbury Television *CTV* and Pine Gould Corporation *PGC*) in which scores of people were buried. The damage to bridges, roads, infrastructures, utilities, lifelines was much more severe this time; in many parts of the city it was several weeks before basic services like electricity, sewerage, water supply could be fully restored. The city was in a state of emergency for more than a month. Some 2 months from the earthquake a part of the city centre is still beyond the reach of general public. The estimated total loss resulting from this earthquake is about 16 billion *NZ* dollars.

2. Regulations on URM Buildings in NZ

The construction of *URM* buildings in *NZ* dates back to mid-19th century. The oldest *URM* building the author has come across in Christchurch was built in the 1860s. There are about 3750 *URM* buildings in *NZ* [3], 958 of which are in Christchurch. According to a preliminary investigation [4], about two-thirds of them are used for commercial purpose, less than 20% are residential and dwellings, and about 3% are categorised as Heritage buildings. Similarly, about 30% are single storey buildings, more than 50% are two-storeys and less than 20% have 3 or more storeys. *URM* buildings in Christchurch are at least 50 years old because since the 1950*s* construction of *URM* buildings is not permitted by *NZ* building standards. This move was triggered by the extensive collapse of *URM* buildings in the *M*7.8 February 1931 Hawkes' Bay earthquake which killed more than 250 people, a significant proportion of which originated from the collapse of *URM* buildings. Reinforced masonry construction was common for some time afterwards, but after the 1960*s* even reinforced masonry construction became obsolete.

The seismic resistance of the old *URM* buildings built before then has always been the topic of discussion in the building and earthquake engineering fraternities. In 2006, *NZ* Society for Earthquake Engineering (*NZSEE*) [5] initiated the initial evaluation procedure (*IEP*) as a coarse screening method for determining a building's expected performance in an earthquake. The purpose of the *IEP* was to assess the performance of an existing building against the standard required for a new building in terms of the "Percentage New Building Standard" (%*NBS*). A building with %NBS of 33 or less is classified as potentially earthquake prone in terms of the *NZ* Building Act [6] and a more detailed evaluation will then typically be required. Although no further action is required by law for buildings with %*NBS* greater than 33, these buildings are still considered as representing an unacceptable risk (defined by the *NZSEE* as potentially "earthquake risk") and seismic improvement may still be recommended. A %*NBS* of 67 or greater means that the building is not considered to be a significant earthquake risk. *NZSEE* [5] states that:

"A %*NBS* of 33 or less should only be taken as an indication that the building is potentially earthquake prone and a detailed assessment may well show that a higher level of performance is achievable. The slight skewing of the *IEP* towards conservatism should give confidence that a building assessed as having a %*NBS* greater than 33 by the *IEP* is unlikely to be shown, by later detailed assessment, to be earthquake-prone".

Following the September 2010 earthquake, it was reported that the Canterbury region had approximately 7600 earthquake-prone buildings, with 958 of these buildings being constructed of unreinforced masonry [4]. Significant advancement in seismic design philosophy has been made since the last construction of *URM* buildings in *NZ*. Given the very low level of seismic demand for which the *URM* buildings were designed, it is clear that these buildings are seismically very deficient compared to their modern counterparts. Earthquake and building engineers have long been advocating for the need to enhance (strengthen/retrofit) such buildings. Although several government-owned *URM* buildings have been retrofitted since, owners of private *URM* buildings have so far abstained from volunteering to strengthen their buildings without any regulatory pressure.

3. Performance of URM Buildings in the September Earthquake

Apart from buildings/houses in the liquefied areas and those located very close to the rupture, the only type of buildings to have suffered severe structural damage in the September earthquake was *URM*. Out of the 958 *URM* buildings reported to exist in Christchurch, 595 in the city centre were inspected after the September earthquake. Out of these, 47% were red-tagged (unsafe to enter until made safer or demolished); 32% were yellow tagged (accessible for short term and emergency purpose until made safer or demolished) and 21% were green tagged (safe to enter and use). It was believed that most other *URM* buildings not assessed after the September earthquake were safe.

Despite the inherent seismic deficiency of *URM* buildings, almost two-thirds of the assessed *URM* buildings were rated to have suffered 10% damage or less. This can be attributed to two reasons. Firstly, as mentioned earlier the *URM* building stock included low-rise buildings (three storeys or smaller) which have short period for which the induced demand was only about a half of the modern design demand. Hence, it may be likely that many well constructed *URM* buildings were not loaded beyond their seismic resistance. Secondly, the duration of significant ground shaking in this earthquake was short (less than 20 seconds). In several *URM* buildings, although significant structural damage was not apparent, some deterioration of the masonry was visible. It was felt that these buildings were at the verge of structural damage and could have suffered severe damage if the ground shaking had lasted for a few more seconds. This argument was justified by the fact that most of the buildings collapsed in the February earthquake which had a shorter shaking duration.

The different types of damage to *URM* buildings and components observed in the September earthquake are identified below:

Damage to gable end walls, see Figure (3): Although gable walls are known to be the weakest component in *URM* buildings [7], they were intact in many *URM* buildings. In some cases the gable walls were still in their place but in a severely damaged state with several cracks. It was unlikely that these gable walls were taking vertical loads in addition to their self weights. In several *URM* buildings, a part of the gable walls had collapsed, often onto an adjacent building.

Out-of-plane failure of solid walls, see Figure (4): Out-of-plane failure of masonry walls

Figure 3. Typical damage to gable walls in the September 2010 earthquake.

Figure 4. Typical out of plane failure of solid masonry walls in the September 2010 earthquake.

was one of the most common sights in the media following the September earthquake. In some cases, masonry walls collapsed even when they were apparently not taking any vertical loads except the self-weight (obvious from the fact that the roof structure was intact despite the collapsed walls). The main reason for out-of-plane failure of solid *URM* walls was the lack of adequate anchorage of the wall with the diaphragm. Alternately, if short masonry walls constructed with good mortar are tied firmly to the return walls at the ends, they could have satisfactory out-of-plane performance, but strong return wall connections were also missing in most cases.

Failure of cavity walls, see Figure (5): Cavity walls are not as common as solid or multi-wythe walls in *URM* buildings in Christchurch. In a few cases where cavity walls were present, the ties connecting the two leaves were found inadequately detailed or corroded. For example, in the photo shown in Figure (5), the cavity ties were made of thin steel wires embedded in the two leaves without any end hooks. It was very unlikely that the tie had any noticeable ability to resist the separating tendency of the two leaves. In such cases, it is no surprise that the front leaf collapsed in out-of-plane direction. In several cases, even the inner leaf failed because after the collapse of outer leaf, the slender inner leaf was unable to resist the vertical load imposed on it.

In-plane damage to masonry walls, see Figure (6): Diagonal in-plane cracks were visible in most *URM* walls. In infill masonry buildings too, diagonal cracks were present in the infill panels and *URM* piers between doors/windows. Diagonal cracks in *URM* walls typically started from a top corner of the wall and terminated at a window/door corner (or the apex where an arch existed above a window or door). In some walls, vertical cracks were also noticed, see Figure (6). In brick masonry, the cracks travelled in a stair-like path through the mortar joints. On-site inspection of the mortar used in some of the collapsed *URM* building was conducted, and the mortar could easily be crumbled by fingers; suggesting that the mortar had a low strength.

Other types of damage, see Figure (7): *URM* buildings also suffered other types of damage such as separation of return walls, anchorage failure,

Figure 5. Typical failure of cavity walls in the September 2010 earthquake.

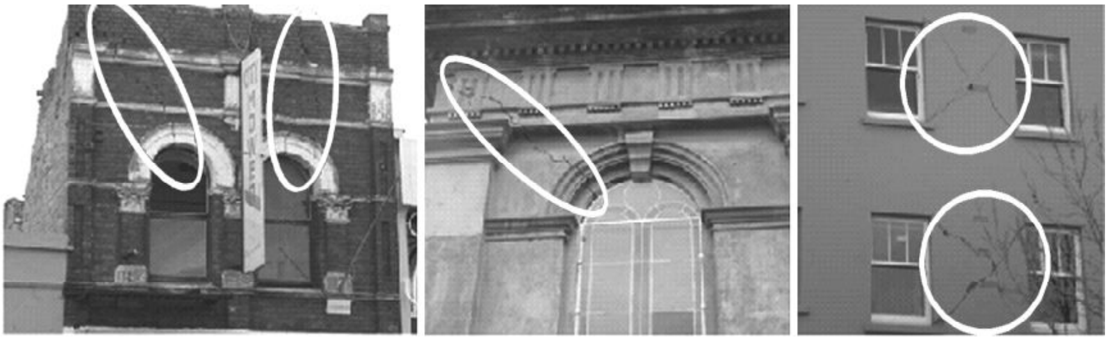

Figure 6. Typical in-plane failure of masonry walls in the September 2010 earthquake.

Figure 7. a) Separation of return walls; b) Anchorage failure of masonry wall; c) Pounding damage observed in the September 2010 earthquake.

pounding damage. In some buildings, the connection between orthogonal walls at the corner opened up, making the walls (or their parts) vulnerable to out-of-plane collapse. In several buildings, the ties supporting canopies were anchored to the walls, and the anchors suffered punching failure [8]. In some cases where buildings were in a row without any gap in between; the out-of-phase response of two adjacent buildings caused the buildings to hit against each other; thereby inducing pounding damage. Despite the presence of several pounding prone buildings, the extent of pounding damage in September earthquake was not very high [9].

Damage to secondary *URM* elements, see Figure (8): In *URM* buildings as well as other types of old buildings; secondary elements such as chimneys, parapets, facades, infill, partitions made of *URM* are not uncommon. More than half of the brick chimneys in Christchurch were reported to be damaged and/or collapsed [8]. Similarly, severely damaged and collapsed brick parapets and facades were common sights in Christchurch buildings. In many cases, blocks of collapsed brick masonry components fell off other components as they fell. A significant risk was posed by these collapsed *URM* elements to the buildings, people and vehicles in the vicinity [10].

4. Performance of Retrofitted URM Buildings in the September Earthquake

As mentioned earlier, retrofitted *URM* buildings fared a lot better than the unretrofitted ones. In general, most retrofitted buildings were not damaged beyond a minor extent. A street survey of *URM* buildings revealed different methods of strengthening/retrofitting used in *URM* buildings in Christchurch. The underlying objective of retrofitting is to quell the tendency of different components of *URM* buildings to separate and disintegrate, see Figure (9). Most of the observed retrofitting methods revolve around using a combination of steel ties/anchors/frames/plates/angles to improve the integrity of the building or its components.

The use of anchors to tie walls with the floor and/or roof was found to be the most common form of retrofitting/strengthening applied to *URM* buildings in Christchurch. In several buildings, anchors bolted against metal plates on the perimeter walls were visible. Some buildings had closely spaced anchors at each floor and roof level in both orthogonal walls, whereas some buildings had only a few anchors at discrete locations without any specific trend. The size of the anchors and the spacing differed significantly between buildings; thereby raising suspicion that the decision on how to retrofit

Figure 8. Failure of brick masonry chimneys, facades, walls and parapets observed in the September 2010 earthquake.

was based on subjective judgement rather than on quantitative design calculations. However, as the level of shaking was not very demanding, especially for this type of short period buildings, even inadequately anchored walls were not fully tested. In general, apart from a few cases (describe later) these anchors were successful in avoiding out of plane failure of the anchored walls.

Using steel plates to integrate a wall was also found to be a common approach. Figure (10) shows a 3-storey brick masonry building in which a side wall is retrofitted using bolted cross steel plates across the second storey, a three-storey *URM* building where steel tie beams are used to anchor a side wall with the floor and steel angles are used to tie the orthogonal return walls, and a single-storey brick masonry Power Station building heavily strengthened using a combination of steel braced frame and ties. All these buildings (especially the retrofitted walls) performed very well.

Figure 9. URM building with walls anchored to the floor/roof via a grid of bolted anchor ties.

In one case, a 100-year-old *URM* building was found to be retrofitted by a steel frame inside the building (not visible from outside) bolted to the brick masonry wall, see Figure (11). The building did not suffer any noticeable damage. This building was checked again after the February earthquake, and it was found to have weathered the February earthquake also very well.

In some buildings, steel plates were bolted to the wall; mainly above the arched windows, see Figure (12). These plates seemed to have worked well because no in-plane cracks were seen in these walls. The author noticed that in other similar buildings without the plates, the walls had suffered in-plane damage in the form of diagonal cracks starting from

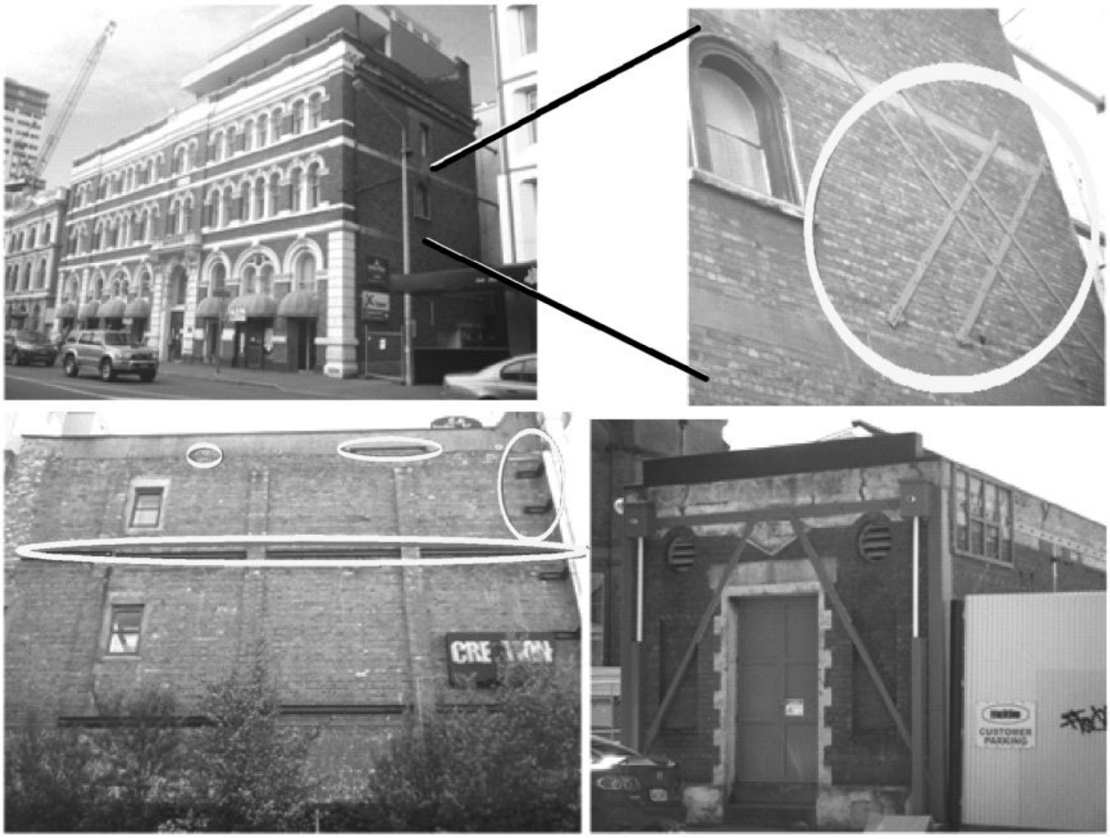

Figure 10. URM buildings retrofitted using different combinations of steel plates/ties/frames/angles.

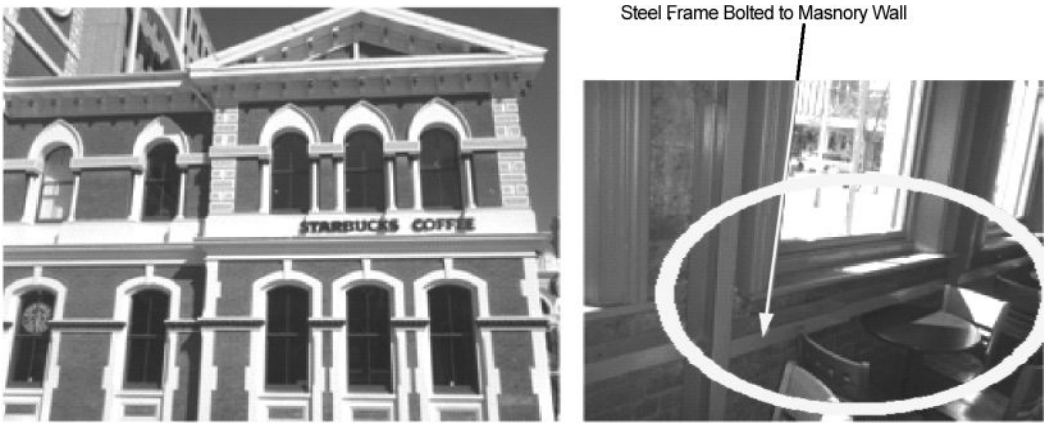

Figure 11. URM building at Cathedral Square retrofitted by steel frame bolted to the masonry wall.

Figure 12. In-plane strengthening of masonry wall using bolted steel plates.

the corner of the wall to the window arches, see Figure (6). In this case, the plates seem to have effectively arrested the weak shear plane.

Although retrofitted structures in general performed very well in the September earthquake, some buildings which had some form of retrofitting suffered some damage. These damages could be mainly attributed to two reasons. The first is insufficient anchors between the walls and the floor/roof. As shown in Figure (13) (top row), inadequate number and size of anchors could not hold the walls (including gable ends), and could not stop them from damaging. The second type of damage observed in retrofitted URM buildings was related to the failure of anchorage. As shown in Figure (13) (middle and bottom rows), the anchor plates punched through the wall in several buildings; and in some cases the anchor plates moved. A proper design using a better estimate of the likely force could have resulted in a larger anchor plate which could have avoided these punching failures.

5. Performance of URM Buildings in the February Earthquake

The February earthquake posed a much greater demand (than the current design level demand) even on low-rise buildings with short natural period; a category in which most *URM* buildings fall. As the *URM* buildings are inherently weaker than what we currently design for, it was not a surprise that most *URM* buildings either collapsed or were very severely damaged. The building inspection record showed that out of 471 *URM* buildings inspected, only 58 (12%) were green-tagged, 122 (26%) were yellow-tagged and 291 (62%) were red-tagged. The total number of inspected *URM* building is significantly less than the number of *URM* buildings in Christchurch. This may be due to a number of *URM* buildings demolished after the September earthquake. Among the remaining *URM* buildings, many completely collapsed and did not need any formal inspection/evaluation. It is believed that most of the green tagged *URM* buildings had been retrofitted. Apart from some heritage buildings for which economic considerations are secondary, it will be very difficult to economically justify repair of most other yellow-tagged *URM* buildings. Hence, it is very likely that there will be very few unretrofitted *URM* buildings left in Christchurch when the post-earthquake rebuilding is completed. In the absence of slightly or moderately damaged *URM* buildings, it was impossible to deeply analyse what features of *URM* construction worked well and what did not. In most cases, unretrofitted *URM* buildings collapsed partly or wholly, see Figure (14). To some extent, the extensive collapse of *URM* buildings may have been contributed by the September earthquake and the following aftershocks which may already have

Figure 13. Typical damage to anchored walls observed in the September 2010 earthquake.

Figure 14. Collapse of URM buildings in the February 2011 earthquake.

softened these buildings significantly.

In *URM* buildings which did not completely collapse, different damage mechanisms were prevalent. There were out-of-plane wall failures, see Figure (15), collapse of gable walls and parapets, see Figure (16); damage to in-plane masonry walls/columns/piers arches, see Figure (17); anchorage failure, see Figure (18); and cavity wall failure due to inadequate interleaf tie, see Figure (19). In most buildings, more than one form of the aforementioned damages occurred.

Figure 15. Out-of-plane failure of URM walls observed in the February 2011 earthquake.

Figure 16. Failure of gable walls and parapets observed in the February 2011 earthquake.

Figure 17. In-plane damage to walls/piers/columns/arches observed in the February 2011 earthquake.

Figure 18. Punching failure of masonry walls due to inadequate anchorage (February 2011 earthquake).

Figure 19. Failure of cavity walls due to inadequate ties (February 2011 earthquake).

A form of building damage that was significantly more pronounced in the February earthquake compared to the September earthquake was building pounding damages [11]. During a rapid pounding survey conducted within the *CBD* after the earthquake, about 120 buildings were identified to have suffered damages of different extent due to pounding with the adjacent building. This is more than a quarter of the total buildings surveyed; pounding damage of this extent is unheard of in previous earthquakes. Some typical building pounding damages are shown in Figure (20).

6. Performance of Retrofitted URM Buildings in the February Earthquake

As the ground shaking was more intense than what the modern buildings are designed for, even systematically retrofitted *URM* buildings suffered damage in the February earthquake. *URM* buildings which had retrofit measures other than the traditional wall anchors did well. Retrofitted by an internal steel frame, the two-storey *URM* building in Cathedral Square, see Figure (11), did not have any damage noticeable from outside.The one-storey *URM* Powerhouse buildingin Madras Street, see Figure (10), which was retrofitted using steel braced frame on the front wall and a combination of steel tie beams on the side walls, was intact. The three-storey *URM* building in Gloucester Street which had steel cross plates bolted on the side walls, see Figure (10), also withstood the February earthquake with minor damage.

On the other hand, several buildings which had walls (in one or both directions) anchored to the floor suffered damage of different extent. One of the lessons taught by this earthquake is that we should not be fooling ourselves that so-called retrofit solutions, which tie into one or two bricks, will work. There were several *URM* buildings in Christchurch which had used some anchors to tie the wall with the floor. However, looking at the size, number and spacing of the anchors a question on its effectiveness would immediately come to the mind. Some inadequately anchored walls, which expectedly suffered damage, are shown in Figure (21). In some buildings, the anchors were of very thin size, in

Figure 20. Building pounding damage observed in the February 2011 earthquake (Photos: Greg Cole).

Figure 21. Performance of inadequately anchored masonry walls in the February 2011 earthquake.

some others a number of anchors were concentrated in a small region and other parts of the wall were left unanchored; in some buildings the anchors were too far apart; in some the anchors were provided only at one level, and a number of buildings had only the side walls anchored. Obviously, in a strong shaking, these solutions will not be able to securely hold of all portions of the perimeter masonry walls, gable walls and the parapet in place. Unsurprisingly, the walls of such buildings suffered partial or complete out-of-plane collapse.

In many *URM* buildings in which the perimeter walls had an extensive grid of two-dimensional anchors, the performance was very good. Some such buildings are shown in Figure (22). In a very few buildings, the visible damage was almost non-existent despite the external walls not showing a very efficient anchorage system. The author suspects that these buildings may have some other form of retrofitting in addition to the sporadic wall anchors visible from outside.

Several *URM* buildings, despite having a reasonable anchorage system, suffered significant damage. Some such cases are shown in Figure (23). In some buildings, although the anchors seemed to be of good size and well distributed throughout the length and height of the building, parts of the perimeter walls still suffered out of plane failure. In some cases, the part of gable wall above the line of highest anchor bolts collapsed; probably, this could have been avoided by providing one or more anchors close to the apex. In some buildings, the anchors were sufficiently provided in the side walls but very few and sporadic in the front wall; which resulted in the out-of-plane failure of the front wall. As the anchor bolts are aesthetically less appealing, in deciding the retrofit system it is normally the tendency to use as few anchors/plates as possible in the front wall. The February earthquake exposed the inherent deficiency of such retrofit solutions used in several *URM* buildings in *NZ*.

7. Conclusions

This paper has presented a detailed account of the performance of unreinforced masonry (*URM*) buildings in the last two earthquakes in Christchurch, *NZ* (the *M*7.1 earthquake of 4th September 2010 and the *M*6.3 earthquake of 22nd February 2011).

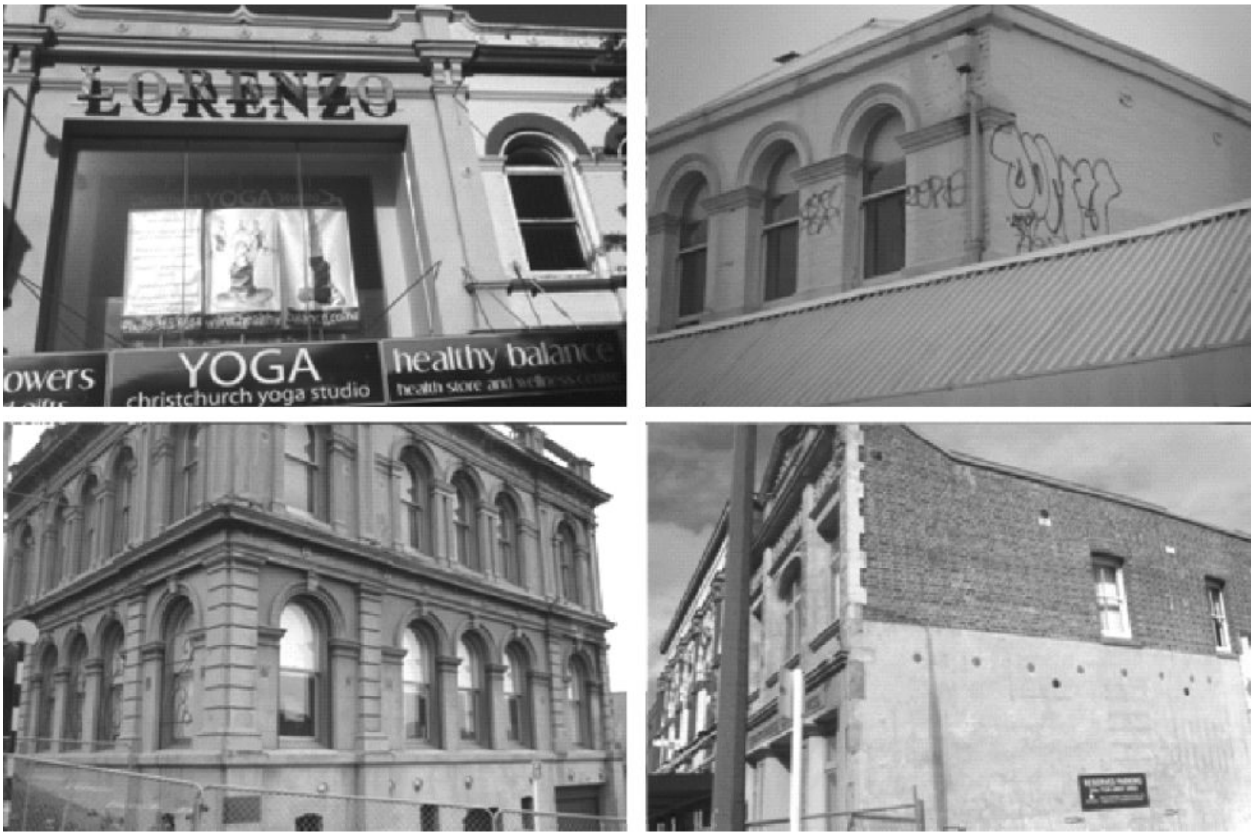

Figure 22. Good performance of some URM buildings with anchored perimeter walls in the February 2011 earthquake.

Figure 23. Damage to systematically anchored masonry walls in the February 2011 earthquake.

In both earthquakes, *URM* buildings suffered more damage than any other building type did. Several *URM* buildings were severely damaged in the September earthquake, leaving demolition as the only viable option. Many damaged *URM* buildings were planned to be repaired before the February earthquake. *URM* buildings which were already damaged/softened to different extent by the September earthquake and the subsequent aftershocks were not in a healthy state to cope with the much more violent shakings induced by the February earthquake. Not surprisingly, in the February earthquake most *URM* buildings either collapsed or suffered severe damage requiring demolition. It is believed that there will be very few (if any) unretrofitted *URM* buildings left in Christchurch when the city emerges from the aftermath of the two earthquakes.

Prior to these earthquakes, several *URM* buildings had been intervened with an aim to improve their seismic performance. Nevertheless, in the absence of a retrofitting/strengthening standard the methods applied to retrofit different *URM* buildings varied significantly; both qualitatively and quantitatively. In general, all strengthening approaches try to enhance the integrity of the perimeter walls and the connection between the wall and the floor/roof by applying a combination of steel ties/anchors/angles/beams/frames etc. In the September earthquake, most retrofitted *URM* buildings performed well. Only in a few cases, retrofitted buildings suffered minor-moderate damage which was greatly within the repairable limit. On the other hand, February earthquake, in line with its level of shaking which was more severe than the current design level, damaged even the retrofitted buildings to different extents. The buildings which had inadequate anchoring could not stop the walls/gables/parapets from collapsing in the out-of-plane direction. On the other hand, *URM* buildings which were adequately and systematically retrofitted were rewarded with a very good performance involving little damage. The February earthquake proved that intuitively intervening *URM* buildings with a few anchors here and there are not sufficient to limit the damage to *URM* buildings in large earthquakes and a proper retrofit design standard is needed to safeguard existing *URM* buildings in *NZ* from future earthquakes.

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