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Performance of as-built and retrofitted URM parapets during the 2010/2011 Canterbury earthquakes

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ABSTRACT: Unrestrained unreinforced clay brick masonry (URM) parapets are found atop a large number of vintage URM buildings. Parapets are typically non-structural cantilevered wall elements that form a fire barrier and in most cases form decorative and ornamental features of vintage URM buildings. Parapets are considered to be one of the most vulnerable elements that are prone to out-of-plane collapse when subjected to earthquake induced shaking. An in-depth analysis of the damage database collected following the 2010/2011 Canterbury earthquakes was performed to obtain information about the distribution, characteristics and observed performance of both the as-built and retrofitted parapets in the Christchurch region. Results, statistical interpretation and implications are presented herein.

1. INTRODUCTION

The etymology of "parapet" is derived from the Italian word 'parapetto' ('parare' means to 'cover/defend' and 'petto' means 'breast'), referring to the protective free-standing barrier raised above the main wall or roof of fortifications, with the word dating back to the late 16th Century. The function of the parapet has evolved over time and today included uses such as guard rails on roof terraces, decorative and ornamental building features, and fire barriers to prevent the spread of blazes in dense urban areas. The use of parapets as fire barriers dates back to the Great Fire of London in 1666 when the London Building Act (1667 and further acts, in particular the 1707 act) banned projecting and decorative wooden eaves and suggested that for separate adjoining buildings with different owners, unreinforced masonry (URM) facades and URM walls should be extended above the eaves by at least 18 inches (457 mm). The 1855 London Building Act established the minimum thickness of the parapet to be at least 8½ inches (216 mm) and the height of the parapets above the roofs of warehouse buildings that were more than 30 feet (9.0 m) in height was increased to 3 feet (915 mm) (Dicksee, 1906). Such rules of thumb for parapet construction were widely adopted in New World colonies of North America and Oceania, resulting in a large number of unreinforced masonry parapets being constructed in New Zealand between the 1880's and 1930's.

The seismic performance of parapets was typically not considered at the time of original URM building construction. Due to the elevated location and the extent of the parapets above the main street frontage and main building entrances, unrestrained parapets represent a major risk to passers-by or building occupiers trying to escape from the building during an earthquake. It was observed in multiple past earthquakes that collapse of parapets during earthquakes caused injuries and fatalities (Canterbury Earthquakes Royal Commission 2012, and Johnston et al. 2014), including in the 1989 Loma Prieta earthquake, the 1994 Northridge earthquake (ATC, 2010), the 2007 Gisborne earthquake (Davey and Blaikie, 2010), and the 2010/2011 Canterbury earthquakes (Ingham and Griffith, 2011). Numerous research studies undertaken following past earthquakes have focused mainly on the seismic performance of the global structure or on specific structural elements of URM buildings, while limited studies are available in the literature on the seismic performance of non-structural URM elements such as parapets, chimneys and building ornamental features. The observed performance of 101 URM parapets following the 2007 Gisborne earthquake (M_L 6.9) was previously reported by Davey and Blaikie (2010) and the parapet performance was compared against that predicted using the NZSEE (2006) procedures. Factors such as the parapet orientation, general parapet geometry and the height above the ground level were considered in the Davey and Blaikie (2010) study, and it was concluded that NZSEE (2006) underestimated the capacity of as-built URM parapets. In a separate study undertaken by ATC (2010), fragility curves of URM parapets were developed and presented using data collected following the 1989 Loma Prieta (California, M_w 6.9) and the 1994 Northridge (California, M_w 6.7) earthquakes. Numerous observations made following the 2010/2011 Canterbury earthquake sequence suggest that URM parapets that were previously secured performed below expectations. Based on a review of current literature, no research was found on the seismic performance of secured/retrofitted parapets.

In response to the lack of literature regarding parapet seismic performance and retrofit techniques, a database was compiled consisting of 959 parapets in the Christchurch region. Information on parapet population, geometric characteristics, orientation, adopted retrofit system and observed type and level of damage after each major event during the 2010/2011 Canterbury earthquake sequence was collected and analysed as presented herein. Data was collected using an existing inventory of URM buildings that was compiled during the post-earthquake building assessments of 627 URM buildings located in Christchurch CBD and the surrounding areas by Dizhur et al. (2010) and Moon et al. (2011). The study reported herein attempted to provide an inventory of observed parapet failure modes and to provide a critical review of commonly encountered parapet retrofits and their respective seismic performance.

2. PREVALENCE AND TYPE OF PARAPETS IN CHRISTCHURCH

For the purposes of the data reported herein, a parapet was considered to be a free-standing element located above the roof line having an approximate height greater or equal to its thickness. For example, for a two-leaf-thick (230 mm) parapet a minimum height of 200 mm was considered. Of all the URM buildings in existence in the Christchurch region prior to the 2010/2011 earthquakes, 80% (491 buildings) were identified as having parapets. A total of 959 parapets were documented, considering that typically buildings have parapets located above both the front and side walls as shown in **Figure 1**. The majority of the parapet data was collected for buildings located in the Christchurch CBD, where 63% (604 parapets) of the total parapet stock was present. The rest of the recorded parapet data derived from buildings found in the area surrounding the Christchurch CBD, including nearby suburbs and the towns of Lyttelton, Sumner, New Brighton, Kaipoi and Rangiora, see **Figure 2**. The earthquake damage to the parapets was recorded following the earthquakes that occurred on 4 September 2010 (aka Darfield earthquake, M_W 7.1), and after two main aftershocks on 22 February 2011 (M_L 6.3) and 13 June 2011 (M_L 6.4), with the last update of the data in July 2012.

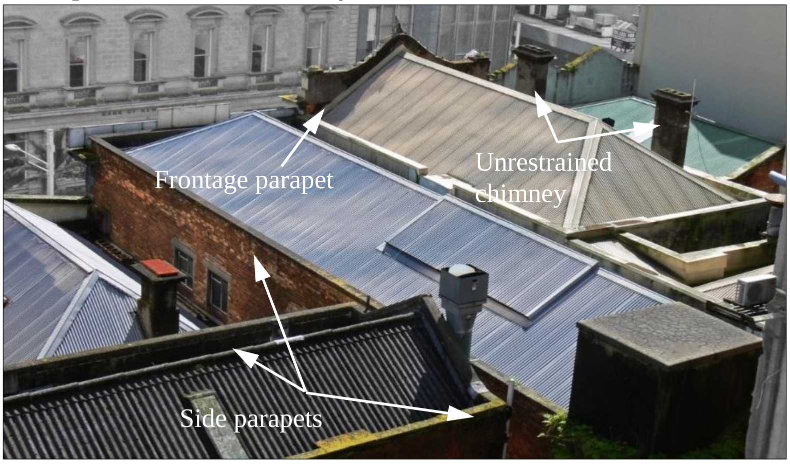


Figure 1. Typical buildings with multiple parapets and other non-structural elements such as chimneys (Image taken facing Queen Street in Auckland, New Zealand)

The orientation of each parapet was noted and documented considering the direction of its length. The prevailing number of parapets due to the street layout of the Christchurch CBD were oriented north to south (NS, 43%) and consequently west to east (WE, 39%), while only 18% were oriented diagonally (NW and NE). 60% (577) of the recorded parapets were facing publicly accessible spaces, such as streets, car parking, squares or parks, increasing the probability of injuries in the case of parapet collapse during an earthquake. A large number of parapets (58%, 557) were located in two storey buildings, see **Figure 3**, which is consistent with the survey performed by Walsh et al. (2014) on URM buildings in Auckland, New Zealand. **Figure 3** presents building height in relation to the number of storeys (excluding parapet) considering: (i) single storey, 3000 to 3600 mm; (ii) two storeys, 5800 to 6600 mm; and (iii) three storeys, 8600 to 9600 mm, based on Walsh et al. (2014).

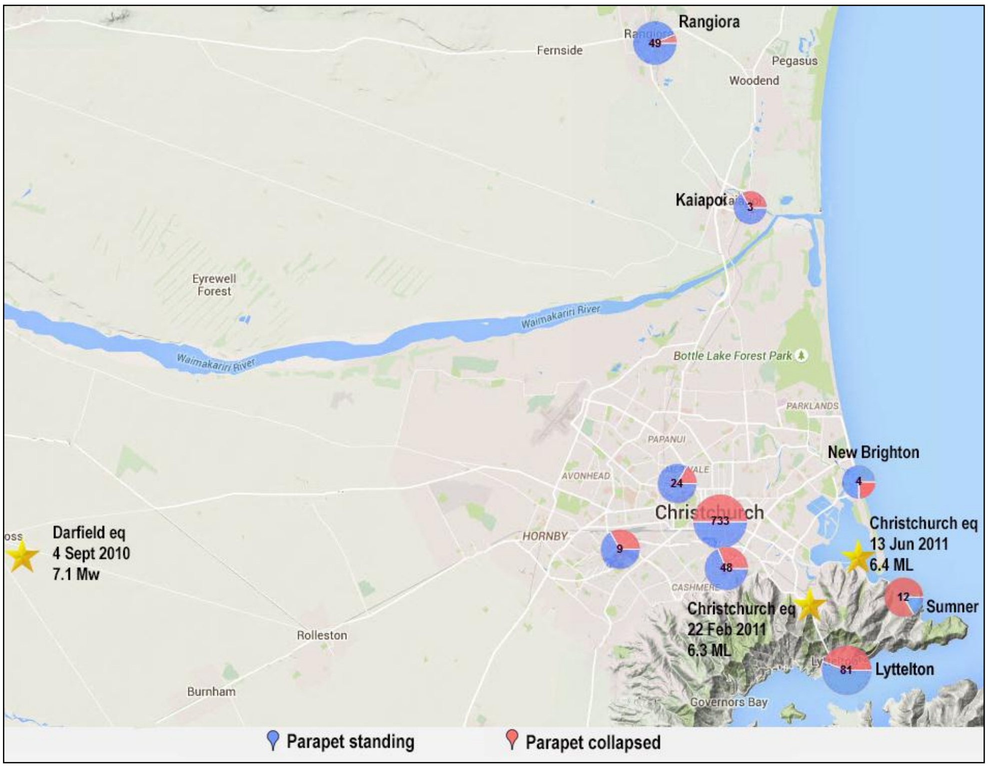
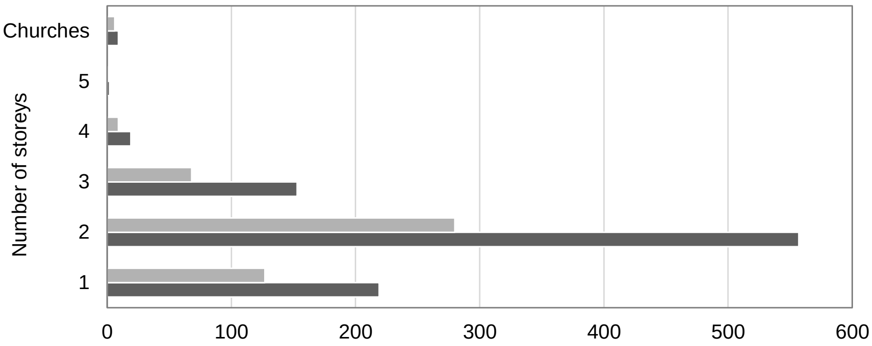


Figure 2. Distribution of surveyed parapet and damage state following the three major earthquakes that occurred on 4 September 2010, 22 February 2011, and 13 June 2011



# of storeys	1	2	3	4	5	Churches
# of buildings with parapets	127	280	68	9	1	6
# of parapets	219	557	153	19	2	9

Figure 3. Distribution of parapets in relation to the number of storeys in a building

The height of the parapet was estimated as the distance from the roof diaphragm-seating to the top of the parapet, and was clustered into four groups: (i) 200 to 499 mm, (ii) 500 to 999 mm, (iii) 1000 to 1499 mm, and (iv) 1500 to 2000 mm. **Figure 4** shows the height of the parapets in relation to the number of storeys of the building. The largest population of parapets, 48% (465), in Christchurch were between 500 to 1000 mm high, while 38% (369) of parapets were shorter than 500 mm and 13% (122) were taller than 1000 mm. Moreover 19% (108) of parapets facing public areas were taller than 1000 mm while, 24% (138) had a height ranging between 500 and 1000 mm. The remaining 57% (329) of parapets were less than 500 mm and in many cases were part of gables located above the main façade of a building. **Table 1** presents a general overview of the parapet height data collected.

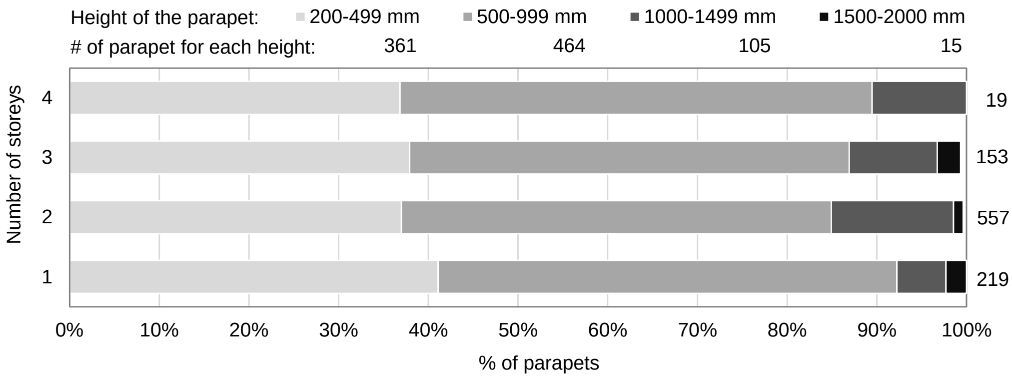


Figure 4. Parapet height and proportion in relation to the number of storeys of the building

Table 1. General overview of the prevalence of parapets in Christchurch and buildings characteristics

URM buildings with parapets	80% (491)		
Parapets recorded	959	63% (604) located in the CBD	
Parapets facing publicly accessible spaces	60% (577)	Height < 500 mm	57% (329)
		Height 500 to 1000 mm	24% (138)
		Height > 1000 mm	19% (108)
Parapets located in two storey buildings	58% (557)	Height < 500 mm	67% (374)
		Height 500 to 1000 mm	18% (102)
		Height > 1000 mm	15% (81)

3. CONSTRUCTION DETAILS

Masonry parapets were used in both clay brick and in stone URM buildings, see **Figure 5**, with a typical thickness equal to 230 mm (two-leaf-thick wall) excluding the thickness of a possible cornice. A cornice was defined as a horizontal decorative moulding that crowns a building, projecting forward from the main walls with the function of diverting rainwater away from the façade. In New Zealand, ornamental cornices were typically constructed using limestone or concrete and were present at different heights typically within the cross-section of the parapet, see **Figure 6**. In a minor number of cases the cornice was constructed using clay bricks, see **Figure 6d**. Detailed observations were made of damaged URM buildings in Christchurch, where the parapet cross-section or roof diaphragm-to-parapet connection details were exposed. The cross-section details of the parapet were identified to be consistent with those of the underlying wall, including the cases of multi-leaf stone and clay brick masonry walls or rubble stone masonry walls, see **Figure 5b,c**.

(a) Clay brick parapet

(b) Stone and clay brick parapet

(c) Rubble stone parapet

Figure 5. Example of clay brick and stone URM parapets

(a) Middle stone cornice | (b) Bottom concrete cornice, above roof level | (c) Bottom concrete cornice, under the roof | (d) Clay brick cornice | (e) Bottom limestone cornice and ornamental features at the top

Figure 6. Typical parapet cross-section and cornice positioning

A previous study undertaken by Dizhur et al. (2015) on New Zealand's clay brick cavity-walls reported that parapets can be both cavity or solid masonry. Approximately 15% (146) of the URM buildings having parapets were found to have a URM cavity wall below. Amongst this stock 70% (102) were solid parapets and 30% (44) were cavity parapets. In general, the three most prevalent types of cross-section arrangements observed in parapets were:

1. Continuous wall type (solid wall or cavity wall), **Figure 7a,b**
2. Parapet (solid or cavity) with a RC beam at roof level or a concrete/stone cornice, **Figure 6** and **Figure 7c,d**
3. Solid wall type parapet over a cavity wall, **Figure 7e**.

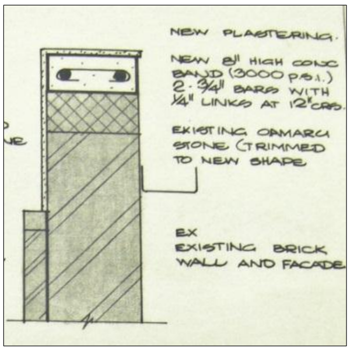
(a) Continuous solid type parapet | (b) Continuous cavity type parapet | (c) Solid parapet with a concrete beam at roof level | (d) Cavity parapet with a concrete beam at roof level | (e) Solid wall type parapet over cavity wall

Figure 7. Typical roof diaphragm-to-wall seating arrangement and parapet details

4. RETROFIT INTERVENTIONS

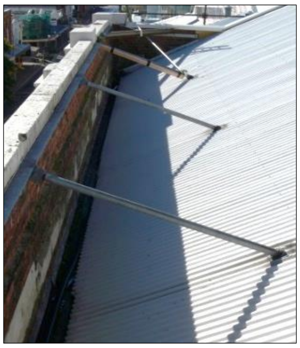
Approximately 23% (224 parapets, 124 buildings) of the surveyed parapets in the Christchurch region were found to have a form of retrofit intervention implemented prior to the 2010/2011 Canterbury earthquakes. A mixture of various types of seismic improvement techniques were observed throughout the Christchurch area, in turn leading to a wide range of different seismic performance levels of the parapets. The wide variation in retrofit techniques can be attributed to the absence of national standardisation and recommendations for the retrofit of URM parapets. Several types of techniques were adopted including (where the percentage refers to the total number of retrofitted parapets):

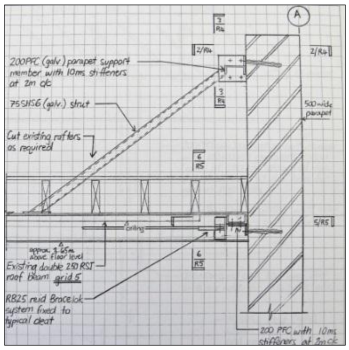
1. Concrete bond beam, **Figure 8** – 39% (87)
2. Steel brace connected to a structural element in the roof structure, **Figure 9** – 30% (67)
3. Steel strip fixed with plates or struts at the edge, **Figure 10** – 24% (53)
4. Other, such as vertical steel bars insert into the parapet, **Figure 11a,b**, corner connections, **Figure 11c,d,** and lightweight replica, **Figure 11e** – 8% (17)



(a) Typical concrete bond beam (b) Design scheme

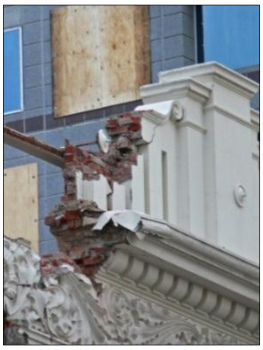
Figure 8. Example of retrofit with the addition of a concrete bond beam at the top of the parapet

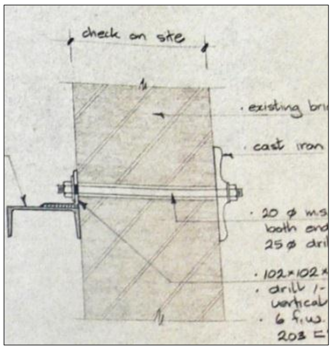




(a) Typical braced parapet (b) Parapet braced back with top connection (c) Design scheme

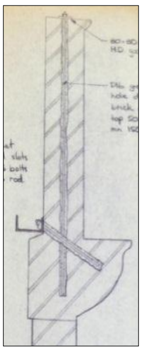
Figure 9. Examples of parapets braced back to structural elements





(a) Rear view (b) Front and damage view (c) Design scheme

Figure 10. Examples of parapet retrofit with the addition of a steel strip on the back of the parapet connected with plates



(a) Insertion of vertical steel bars (b) Design scheme (c) Corner steel bar connection (d) Insertion of horizontal corner connection (e) Lightweight polystyrene replica

Figure 11. Other types of parapet interventions to reduce the risk

5. SEISMIC PERFORMANCE

The damage to parapets was recorded following the earthquake on 4 September 2010 (aka Darfield earthquake, M_W 7.1), and after two main aftershocks on 22 February 2011 (M_L 6.3) and 13 June 2011 (M_L 6.4). **Table 2** summarises the number of parapets for each earthquake considered in the survey, clustering the data into standing and collapsed parapets and into registered Peak Ground Acceleration (PGA).

The failure categories considered in the study are clustered into two main groups:

- Standing parapets, **Figure 12**, includes: (a) no visible damage, (b) visible horizontal cracking highlighting the initiation of rocking behaviour of the parapet, and (c) other visible cracking in the parapet related to in-plane failure of the full façade or pounding effect of nearby structures.
- Collapsed parapets, **Figure 13**, includes: (a) partial collapse of the parapet, (b) full collapse of the parapet only, or (c) collapse of both the parapet and the wall.

Figure 14 presents an example of progressive damage to a parapet after different earthquakes.

Table 2. Number of parapets standing and collapsed after each earthquake and in relation to the registered PGA

	4 September 2010		**22 February 2011**		**13 June 2011**	
PGA [g]	**Standing***	**Collapsed****	**Standing***	**Collapsed****	**Standing***	**Collapsed****
0.20-0.25	24% (104)	3% (15)	4% (39)	3% (26)	13% (12)	13% (12)
0.26-0.50	63% (276)	10% (43)	11% (95)	9% (83)	19% (18)	50% (48)
0.51-0.75	n/a	n/a	26% (226)	42% (371)	0	2% (2)
0.76-1.00	n/a	n/a	2% (18)	3% (23)	4% (4)	0
Total	**87% (380)**	**13% (58)**	**43% (378)**	**57% (503+23)**	**35% (34)**	**65% (62+395)**

* Includes no visible damage and all types of cracking

** Includes partial or full collapse of the parapet or of the parapet and the wall. The total number includes all parapets that had already collapsed in the previous earthquake

(a) No damage (b) Horizontal cracking (c) Other types of cracking

Figure 12. Examples of failures categories considered in standing parapets

(a) Partial parapet collapse (b) Parapet collapse (c) Parapet and wall collapse

Figure 13. Examples of failures categories considered in collapsed parapets

(a) Former Canterbury Horse Bazaar, prior to earthquakes

(b) Partial collapse after 22 February 2011 earthquake

(c) Parapet and wall collapse after 13 June 2011 earthquake

Figure 14. Examples of progressive damage to retrofitted parapet

The 2010 Darfield earthquake did not result in as much damage to parapets when compared with the subsequent aftershocks, with 75% (327) of the recorded parapet stock not exhibiting signs of damage and only 13% (58) having collapsed. The 22 February 2011 earthquake generated higher PGAs and resulted in more damage, considering also that buildings were already weakened from the previous earthquakes. The PGA was high, with 0.7g registered in the CBD and 1.0g in Lyttelton, and both vertical and horizontal ground movements were recorded. The largest number of collapsed parapets (42%, 371) were associated with a recorded PGA higher than 0.50g, 286 (32%) of which were as-built and 85 (10%) being retrofitted parapets. Although the 13 June 2011 earthquake was comparable in terms of PGA, location, and depth of the epicentre to the 22 February 2011 earthquake, the collected data are less than for previous earthquakes because a large number of parapets (80%, 395) had already collapsed. The buildings were already heavily damaged and parapets collapsed at PGA values lower than 0.50g.

Considering the damage caused to the parapets by only the 22 February 2011 earthquake, failure was observed to be more prevalent on as-built (URM) parapets while retrofitted parapets presented an increase of horizontal or other cracking failures, see **Figure 15**. After the event 40% (269) of the as-built parapets were standing while 60% (403) had collapsed. Retrofitted parapets presented a slightly better performance with 52% (109) of parapets standing and 48% (100) of parapets collapsed. A large percentage of retrofitted parapets collapsed but it has to be considered that in many cases it was not easy to identify from the street the presence of any retrofit intervention, unless the parapet had partially or fully collapsed. **Figure 15** shows the improvement in performance of retrofitted parapets when compared with as-built parapets, with more cases standing and fewer cases collapsed. Moreover, a large number of parapets (23%, 212) collapsed due to full or partial collapse of the façade, hence the adopted retrofit intervention designed only for the parapet was not able to avoid the failure.

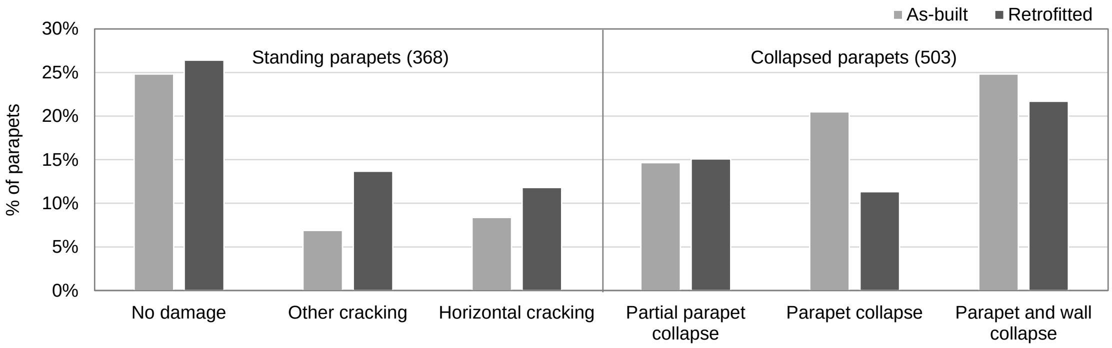


Figure 15. Observed failure categories on URM and retrofitted parapets after the 22 February 2011 Christchurch earthquake

Considering the state of the parapets after the three seismic events (after June 2011) an increase in the level of damage to parapets proportional to the height of the building (number of storeys) was observed as expected, see **Figure 16**. In the case of two storey buildings, the most populated category, 27% (153) of the parapets collapsed in conjunction out-of-plane failure of the wall, 18% (99) exhibited overturning failure of the parapet and 15% (84) partially collapsed. Of the parapets that remained standing, 9% (48) exhibited the initiation of overturning failure indicated by horizontal cracking, 8% (43) had other types of cracks and 23% (130) presented no damage.

Figure 17 shows the results for only the collapsed parapets, where the data are clustered based on height of the parapet and number of storeys of the building, with separate graphs presenting as-built and retrofitted parapets. For each horizontal bar the number outside parenthesis represents the total number of collapsed parapets and the number within parenthesis represents the number of parapets for each category, including both collapsed and standing cases. The data shows a reduction of collapsed parapets when a retrofit system is applied, in particular in the cases of single or two storeys buildings. Similar graphs are presented in **Figure 18**, were data collected after the 22 February 2011 earthquake are clustered by height of the parapet and recorded PGA, both for as-built and retrofitted parapets. The addition of the retrofit system significantly reduced the collapse, in particular at PGA lower than 0.50g.

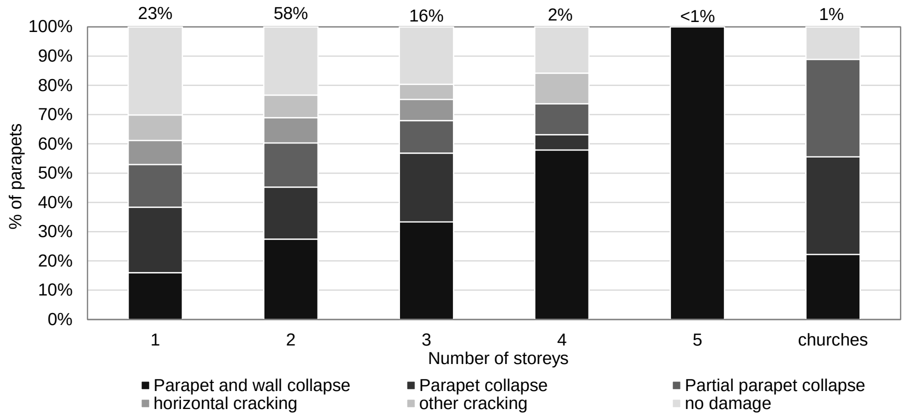
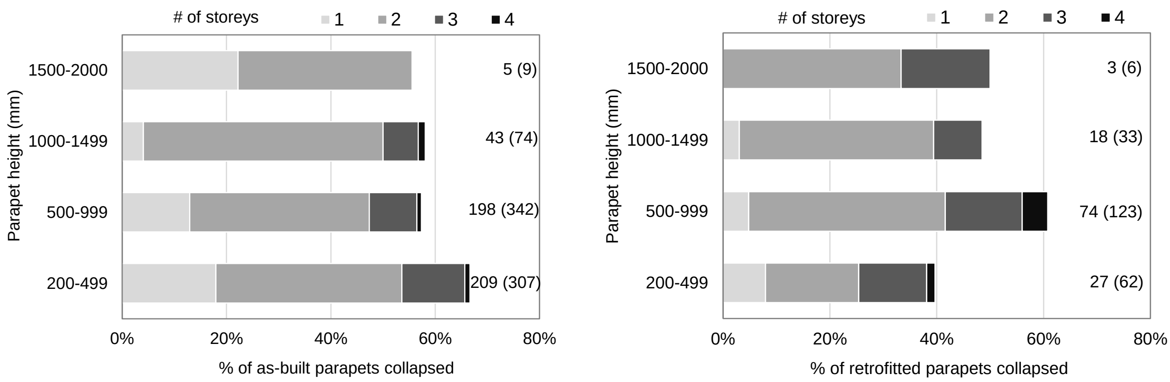
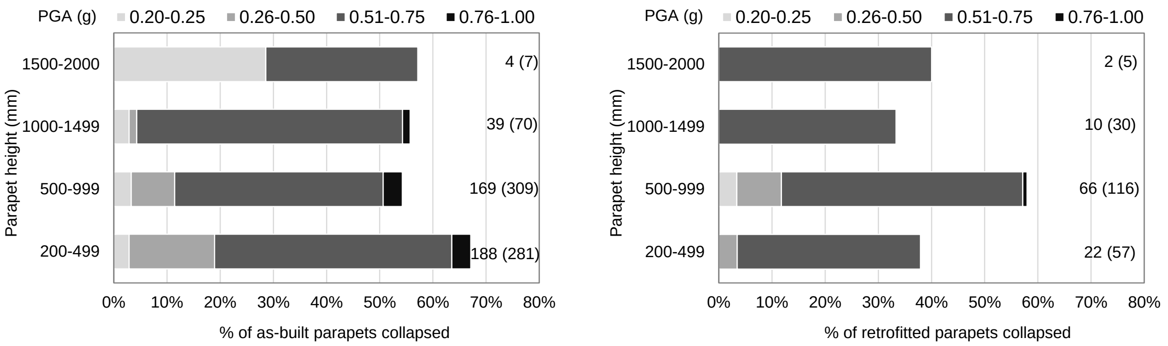


Figure 16. Observed parapet failure categories and proportion in relation to the number of storeys of the building



(a) As-built parapets (b) Retrofitted parapets

Figure 17. Parapet collapse in relation to parapet height and the number of storeys of the building



(a) As-built parapets (b) Retrofitted parapets

Figure 18. Parapet collapse during the 22 February 2011 Christchurch earthquake in relation to parapet height and the registered PGA

In relation to the types of retrofit presented in Section 4, the addition of a concrete bond beam or a brace fixed back to a structural element was widely adopted as a retrofit solution, with the latter performing better than the former, see **Table 3**. The addition of a concrete beam at the top of the parapet was often the cause of collapse of the masonry parapet under the beam or the collapse of both the parapet and the concrete beam due to the increased mass, see **Figure 19a**.

The typical failure modes of steel braces mounted behind the parapet were: (i) horizontal cracking corresponding to the location of the horizontal steel beam, followed by collapse of the remaining un-retrofitted part above, **Figure 19b**, (ii) failure due to short embedment of the ties adopted to fix the beam to the parapet, and (iii) horizontal cracking at the base of the parapet. Typically collapse was observed when the parapet was retrofitted using only steel braces locally fixed with ties and plates, without the presence of a horizontal steel beam, as shown in the building in **Figure 20** where both systems were adopted. The use of horizontal steel strips fixed to the parapet with plates resulted in the collapse of the parapet due to the absence of connection to a primary structural element, **Figure 19c**. Horizontal cracking at the location of the steel strip was observed when the steel strip was applied to all the perimeter parapets as a ring beam. In some cases it was recognised that the horizontal steel strip had occasional vertical steel bars acting as struts.

Table 3: Standing and collapsed parapets in relation to the type of retrofit

	Standing	**Collapsed***	**Wall and parapet collapse**
As-built:	38% (277)	36% (268)	26% (190)
Retrofitted:	46% (102)	26% (58)	29% (64)
Concrete bond beam (39%)	12% (26)	10% (23)	
Bracing back to structural element (30%)	17% (39)	6% (14)	
Steel strip (24%)	9% (21)	9% (20)	
Other (8%)	7% (16)	<1% (1)	

* Excluding the parapets collapsed due to the collapse of the wall above

(a) Concrete bond beam (b) Bracing back to structural element (c) Steel strip

Figure 19. Typical examples of failure observed for the adopted retrofit interventions

(a) With a horizontal steel beam (b) Without a horizontal steel beam

Figure 20. Comparison between parapets braced back to a structural element with and without a horizontal steel beam

A final comparison was carried out considering the orientation of the parapets versus the direction of the earthquake in respect to the data collected after the 22 February 2011 earthquake. As previously described, the orientation of the parapet was identified by the direction of its length and was clustered into four groups: north-south (NS), east-west (EW), north-west (NW), and north-east (NE). The angle between the epicentre and each building was calculated using GPS coordinates. The resulting angles were then clustered into four groups: (i) “0 degrees” that includes the angles from 337.5° to 22.5° and the opposite 154.5° to 202.5°, (ii) “45 degrees” between 22.5° to 67.5° and 202.5° to 247.5°, (iii) “90 degrees” from 67.5° to 112.5° and 247.5° to 250.5°, and (iv) “-45 degrees” considering the angles from 112.5° to 154.5° and 250.5° to 337.5°, see **Figure 21**. In each group, parapets were clustered as perpendicular, parallel or diagonal with respect to that angle. For example, in the case of group “-45 degrees” that includes most of the CBD (6-12 km from the epicentre) and Lyttelton (5-6 km from the epicentre), all the parapets oriented NE are perpendicular (⊥), parapets NW are parallel (//), and parapets NS and WE are considered diagonal (∠). **Figure 21** summarises the results using pie charts divided into sectors representing each angle group. The pie charts present standing (blue portions) and collapsed (red portions) parapets considering their orientation being perpendicular, parallel or diagonal. In the CBD it was observed that the urban pattern was mainly oriented NS and EW and as a consequence a large number of parapets were diagonal to the direction of the earthquake and most of them collapsed. The area called “0 degrees” includes Rangiora and Kaiapoi located respectively at 32 km and 22 km from the epicentre, and the western suburbs where most of the parapets were perpendicular and parallel and the recorded PGA was less than 0.50g, resulting in a large number of parapets standing. **Table 4** presents the results and the number of parapets considered for each group.

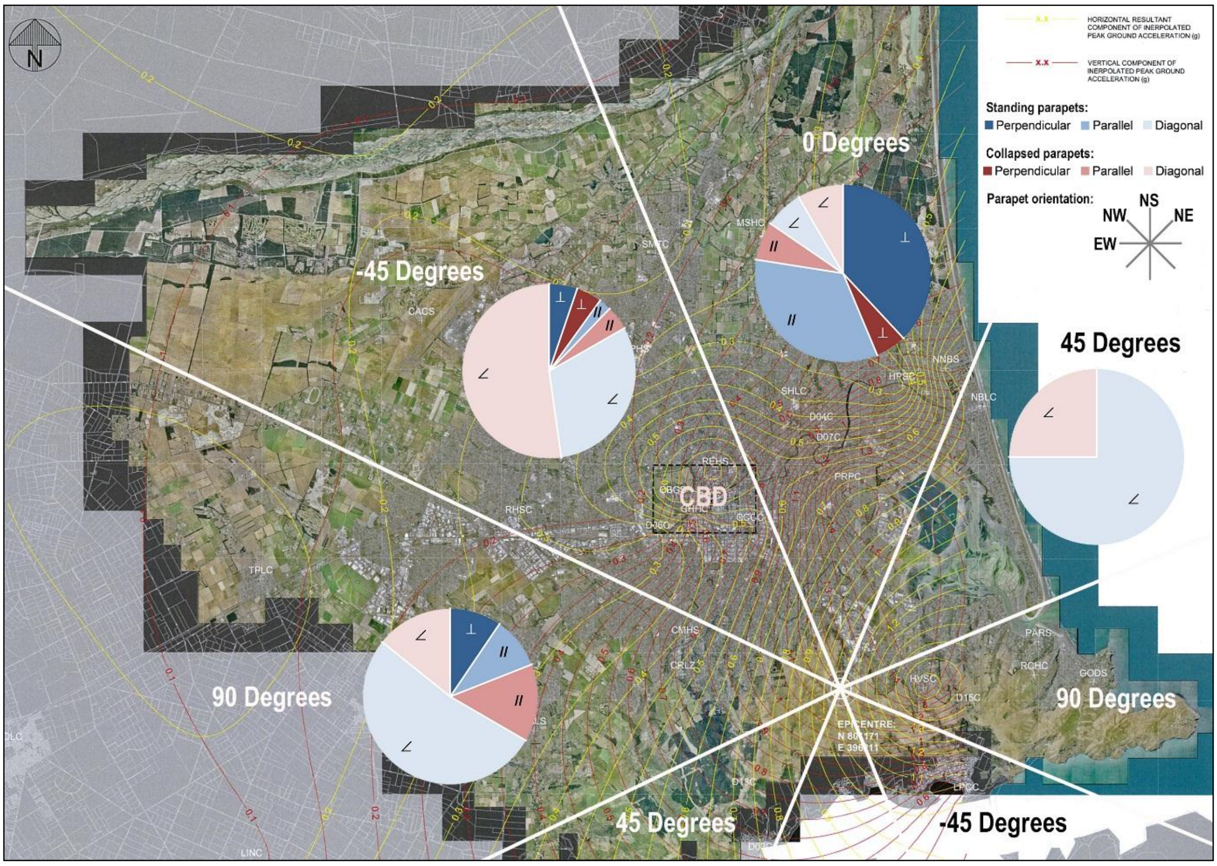


Figure 21. Map showing the epicentre and PGA contours (Source: Christchurch City Council), and for each considered angle group a pie chart showing standing and collapsed parapets for each orientation

Table 4. Orientation and state of parapets with respect to the angle between the building and the epicentre of the 22 February 2011 Christchurch earthquake

	Perpendicular	Parallel	Diagonal

Angle	Standing	Collapsed	Standing	Collapsed	Standing	Collapsed	Total
0	38% (27)	6% (4)	34% (24)	7% (5)	7% (5)	8% (6)	**71**
45	0	0	0	0	75% (3)	25% (1)	**4**
90	10% (2)	0	10% (2)	14% (3)	52% (11)	14% (3)	**21**
-45	5% (41)	5% (37)	2% (18)	5% (35)	31% (242)	52% (408)	**781**

6. CONCLUSIONS

A database of 959 URM parapets in existence in Christchurch and surrounding towns prior to the 2010/2011 Canterbury earthquakes was collected and the following results were obtained.

- Construction details. A large number of parapets were located in two storey buildings, approx. 5800 to 6600 mm above ground level, and often facing publicly accessible spaces such as streets, car parking, squares or parks. The height of the parapet from the roof line was estimated to be between 200 mm to 2000 mm, with the largest population being 500 to 1000 mm high (48%, 456). Parapet thickness was typically equal to a two-leaf-thick wall, excluding the presence of a possible cornice, and the cross-section often reflected the wall composition directly below. Three types of cross-section arrangements were identified: (i) continuous wall type (solid or cavity wall), (ii) solid or cavity wall parapet with RC beam at roof level or cornice, (iii) solid wall parapet over cavity wall. Limestone, concrete or sometimes a clay brick cornice was observed at different heights of the parapet, occupying the full cross-section.

- Retrofit intervention. 23% (224) of the documented parapets had been retrofitted prior to the 2010/2011 earthquakes. The techniques adopted to mitigate the seismic risk included: (i) concrete bond beam at the top, 39%, (ii) steel braces fixed to a structural element, 30%, (iii) steel strip fixed with plates or struts at the edge, 24%, and (iv) other solutions, 8%, such as vertical steel bars inserted into the masonry, corner connections or replacement with a lightweight replica. Approximately 50% of the parapets retrofitted with a concrete bond beam or a steel strip collapsed during the earthquakes due to the increase of mass or the absence of connection to a structural element respectively. The presence of the brace behind the parapet allowed better performance to be achieved, reducing the percentage of collapsed parapet to 25%.

- Seismic performance of both as-built and retrofitted parapets was recorded after the 4 September 2010 earthquake and after the two main aftershocks, 22 February 2011 and 13 June 2011. The 22 February 2011 earthquake was the more damaging event with the collapse of 60% (403) of the as-built parapets and 48% (100) of the retrofitted parapets. Failure categories were analysed in relation to the recorded PGAs, the number of storeys, the height and orientation of the parapet, and the retrofit system. It was confirmed that the level of damage increased with the increasing number of storeys and the height of the parapet.

- During the 22 February 2011 earthquake, the largest stock of collapsed parapets was correlated to PGA values higher than 0.50g, with 286 (32%) of the collapsed parapets being as-built and 85 (10%) being retrofitted. The addition of a retrofit system significantly reduced the chance of parapet collapse, in particular at low PGA values. Considering the effect on heavily damaged buildings, PGA values lower than 0.50g were sufficient to cause collapse of the parapets. In the Christchurch CBD, the majority of collapsed parapets were oriented diagonally to the direction of the earthquake.

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