Post-Earthquake Reconnaissance of Unreinforced and Retrofitted Masonry Parapets

Publisher:
Earthquake Engineering Research Institute

Published version:
DOI: 10.1193/121715EQS184M

Post-Earthquake Reconnaissance of Unreinforced and Retrofitted Masonry Parapets

Marta Giaretton,[a)] M.EERI, Dmytro Dizhur,[b)] M.EERI, Francesca da Porto,[a)] and Jason M. Ingham,[b)] M.EERI

Unrestrained unreinforced clay brick masonry (URM) parapets are freestanding wall elements found atop a large number of vintage URM buildings. Parapets are considered to be one of the most vulnerable nonstructural components that are prone to out-of-plane collapse when subjected to earthquake induced shaking. Using data collected during the earthquake reconnaissance efforts, 959 URM parapets were identify to be in existence in the Christchurch (New Zealand) area prior to 2010, with 60% (580) of them having collapsed during the 2010/2011 Canterbury earthquake sequence. Construction details and observed performance of both as-built and retrofitted parapets were documented. The reported study provides an inventory of observed parapet failure modes and a critical review of commonly encountered parapet retrofits and their respective seismic performance. [DOI: 10.1193/121715EQS184M]

INTRODUCTION

Early references to parapets in construction describe a protective freestanding barrier raised above the main wall or roof of mediaeval fortifications. As such, the etymology of "parapet," which dates back to the late sixteenth century, is derived from the Italian word *parapetto* that means "to cover/defend" (*parare*) and "breast" (*petto*). The function of the parapet has evolved over time and today includes 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 in. (457 mm). The 1855 London Building Act established the minimum thickness of the parapet to be at least 8.5 in. (216 mm), and the height of the parapets above the roofs of warehouse buildings that were more than 30 ft (9.0 m) in height was increased to 3 ft (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 areas having high seismic hazard. Furthermore, a large proportion of existing URM parapets have not been retrofitted to resist design-level earthquake forces,

[a)] Dept Civil, Enviro. & Arch. Eng, University of Padova, via Marzolo 9, 35131 Padova, Italy
[b)] Dept Civil & Enviro. Eng, University of Auckland, Private Bag 92019, Auckland 1010, New Zealand

Earthquake Spectra, Volume 32, No. 4, pages 2377–2397, November 2016; © 2016, Earthquake Engineering Research Institute

(a) (b)

Figure 1. Examples of parapet failures during the 2010/2011 Canterbury earthquakes: (a) URM parapet that has collapsed onto the street frontage; (b) URM parapet that has collapsed into the building interior.

resulting in extensive out-of-plane failure during moderate-to-high intensities of earthquake shaking (Figure 1). Due to the elevated location and the extent of the parapets above the main street frontage and main building entrances, unrestrained parapets of URM buildings represent a major risk to nearby pedestrians and building occupants. Following the 2010/2011 Canterbury (New Zealand) earthquakes, it was reported that 70% (35 people) of the deaths caused by the collapse of URM facades or wall portions occurred outside the buildings, involving pedestrians, persons in vehicles, and people who ran out of a URM building to escape (Canterbury Earthquakes Royal Commission 2012, Johnston et al. 2014).

Few earthquake reconnaissance reports have remarked on the failure of URM nonstructural elements such as parapets, domestic chimneys, and building ornamental features (Bruneau 1995, Filiatrault et al. 2001, FEMA P-58/BD-3.9.8 2010, Davey and Blaikie 2010, Moon et al. 2014). Similarly, numerous research studies have been undertaken that were focused on global seismic performance or specific structural elements of URM buildings, while comparatively little research has addressed nonstructural URM elements, specifically parapets. Fragility curves for URM parapets were developed (FEMA P-58/BD-3.9.8 2010) 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. Separate research undertaken by Davey and Blaikie (2010) presented the performance of 101 URM parapets following the 2007 Gisborne earthquake (New Zealand, M_L 6.9). Factors such as the parapet orientation, general parapet geometry, and the height above ground level were considered and the results were compared against that predicted using the national procedures (NZSEE 2006). In response to the lack of literature available regarding URM parapet seismic performance both in unreinforced and secured/retrofitted conditions, a database was compiled consisting of 959 parapets in existence in the Christchurch region prior to the 2010/2011 Canterbury

(New Zealand) earthquakes. 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 recorded and analyzed, and is presented herein.

PREVALENCE OF MASONRY PARAPETS IN CHRISTCHURCH

Data on URM parapet seismic performance was collected using an existing inventory of 627 URM buildings that was compiled during the post-earthquake building assessments in the Christchurch CBD and the surrounding areas as reported by Moon et al. (2014). For the purposes of the data reported herein, a parapet was considered to be a freestanding element located above the roof line and 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, including both clay brick and stone masonry constructions. A total of 959 URM parapets were documented, considering that URM buildings typically have parapets located above both the front and side walls, as shown in Figure 2. 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 (Figure 3). The earthquake damage to the parapets was recorded following the earthquakes that occurred on 4 September 2010 (known as the 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 occurring in July 2012.

The orientation of each parapet was noted and documented by considering the direction of its length. Due to the street layout of the Christchurch CBD (Figure 4a), the prevailing

Figure 2. Typical URM buildings with multiple parapets and other nonstructural elements such as chimneys and ornamental pinnacles. Images taken in Auckland, New Zealand: (a) URM parapet on street frontage; (b) rooftop view.

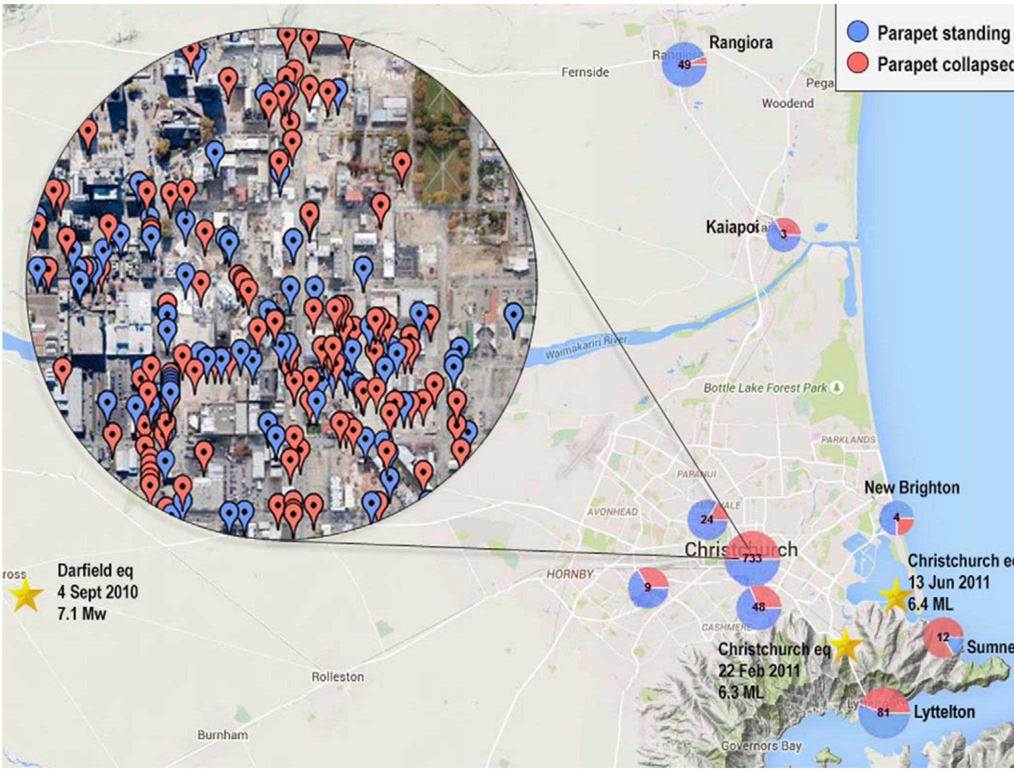
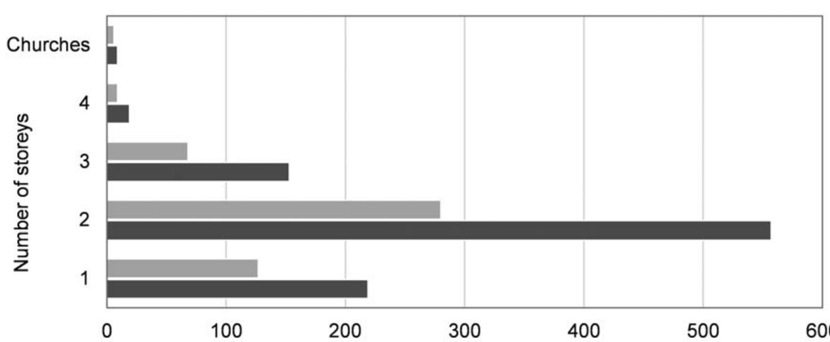


Figure 3. Distribution of surveyed parapets and corresponding damage state following the three major earthquakes that occurred in the Christchurch area on 4 September 2010, 22 February 2011, and 13 June 2011 (background map data ©2015 Google).

number of parapets were oriented north to south (NS, 43%) and correspondingly east to west (EW, 39%), while only 18% were oriented diagonally (NW and NE; Figure 4b). Sixty percent (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. Another factor that increased the hazard associated with URM parapets was that a large number (58%, 557) were located in two-story buildings (Figure 5), which is consistent with the survey performed by Walsh et al. (2014) on URM buildings in Auckland, New Zealand. Figure 5 presents the distribution of parapets in relation to the number of stories, as a function of building height (excluding parapet), being: (1) single story, 3.0 to 3.6 m; (2) two stories, 5.8 to 6.6 m; and (3) three stories, 8.6 to 9.6 m, based on (Walsh et al. 2014).

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: (1) 200 to 499 mm, (2) 500 to 999 mm, (3) 1000 to 1499 mm, and (4) 1,500 to 2,000 mm. Figure 6 shows the parapet height in relation to the number of stories of the building. The largest population of parapets (48%, 465) in Christchurch were between 500 to 1,000 mm high, while 38% (369) of parapets were

Figure 4. Proportion of documented URM parapets in Christchurch by orientation based on the direction of parapet length. (a) Christchurch CBD pre-earthquake (Aerial photo ©2015 Microsoft Corporation). (b) Parapets orientation.



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

Figure 5. Distribution of parapets in relation to the number of stories in a building.

shorter than 500 mm and 13% (122) were taller than 1,000 mm. Moreover, 19% (108) of parapets facing public areas were taller than 1,000 mm, while 24% (138) had a height ranging between 500 and 1,000 mm. The remaining 57% (329) of parapets were less than 500 mm and in many cases were part of gables located above the main facade of a building. Table 1 presents a general overview of the parapet height data collected.

URM PARAPET CROSS SECTION ARRANGEMENTS

Masonry parapets were used in both clay brick and stone URM buildings (Figure 7), with a typical thickness equal to 230 mm (two-leaf-thick wall) excluding the thickness of a

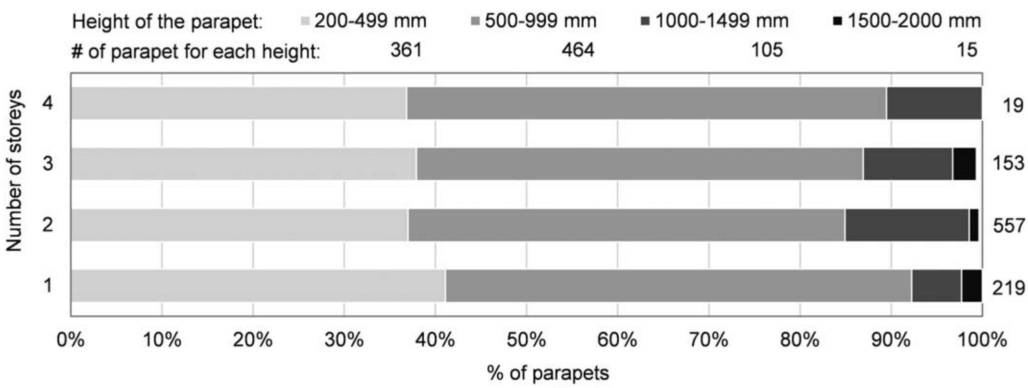


Figure 6. Parapet height and proportion in relation to the number of stories of the building.

possible cornice. A cornice is 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 facade. 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 (Figure 8). In a minor number of cases the cornice was constructed using clay bricks (Figure 8d). 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 parapets were identified to be consistent with those of the underlying walls, including the cases of multi-leaf stone and clay brick masonry walls or rubble stone masonry walls (Figure 7b, 7c). Solid clay bricks used in construction are typically of standard size (230L × 110W × 75H mm) for heritage masonry construction and were placed with approximately 15 mm collar joints. Natural stone units and their associated mortar joints are of arbitrary dimensions in relation to the type of rock and surface texture selected. Structural mortar was founded to be relatively weak, with a compressive strength ranging between 0.2 MPa and 3.5 MPa and being either lime or cement-based. Extensive characterisation of material properties have been reported in Lumantarna et al. (2014) and Giaretton et al. (2015).

Table 1. Prevalence and buildings characteristics of parapets in Christchurch

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 1,000 mm	24% (138)
		Height > 1,000 mm	19% (108)
Parapets located in two story buildings	58% (557)	Height < 500 mm	67% (374)
		Height 500 to 1,000 mm	18% (102)
		Height > 1,000 mm	15% (81)

Figure 7. Examples of clay brick and stone URM parapets: (a) clay brick parapet; (b) combination of stone and clay brick parapet; (c) rubble stone parapet.

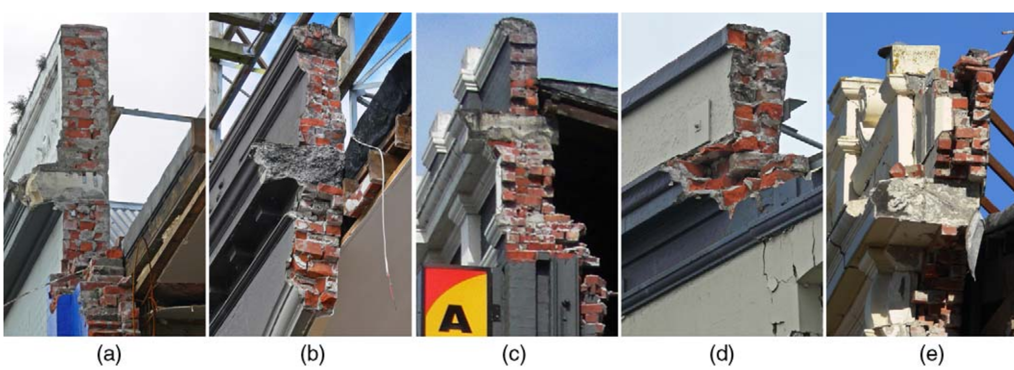


Figure 8. Different positioning of cornice within parapet cross section: (a) limestone cornice, above roof level; (b) concrete cornice, above roof level; (c) concrete cornice, under roof level; (d) clay brick cornice, above roof level; (e) limestone cornice and ornamental features at the top.

A previous study undertaken by Dizhur et al. (2015) on New Zealand's clay brick masonry cavity walls reported that a parapet constructed above a cavity wall can be either 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 wall parapets. In general, the three most prevalent types of cross section arrangements observed in parapets were:

- Continuous wall type (solid wall or cavity wall; Figure 9a, 9b)
- Parapet (solid or cavity) with a RC beam at roof level or a concrete/stone cornice (Figure 8 and Figure 9c, 9d)
- Solid wall–type parapet over a cavity wall (Figure 9e)

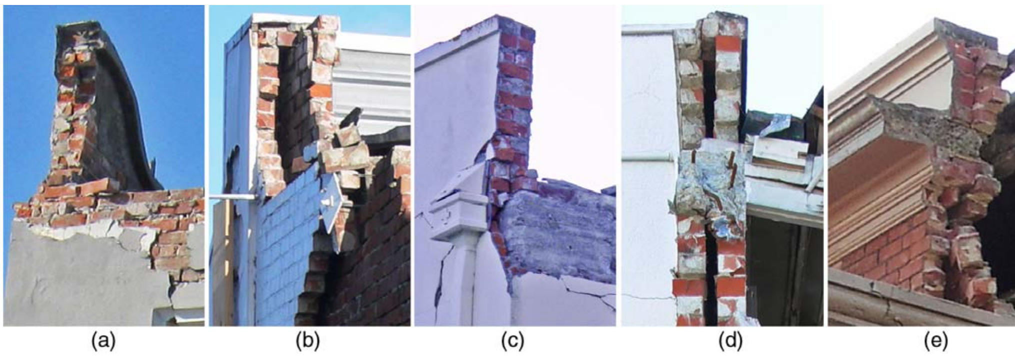


Figure 9. Typical parapet cross section and roof diaphragm-to-wall seating arrangement: (a) continuous solid wall–type parapet; (b) continuous cavity wall–type parapet; (c) solid parapet with a concrete beam at roof level; (d) cavity parapet with a concrete beam at roof level; (e) solid wall parapet over cavity wall.

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, with the first interventions being dated back to the 1970s. Note that from the street level and from aerial photos taken pre- and post-earthquake, it was not easy to identify the presence of retrofit intervention, unless the parapet was damaged, hence could be that a larger number of parapets was retrofitted. A mixture of various types of seismic improvement techniques were observed throughout the Christchurch area, in turn leading to a wide range of different engineering details and 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 identified, and were clustered into the following four main groupings (where the percentage refers to the total number of retrofitted parapets):

- Concrete bond beam, Figure 10: 39% (87)
- Steel brace connected to a structural element in the roof structure, Figure 11: 30% (67)
- Steel strip fixed with adhesive anchors or struts at the edge, Figure 12: 24% (53)
- Other, such as corner connections, Figure 13a, lightweight replica, Figure 13b, and vertical steel bars inserted into the parapet, Figure 13c, 13d: 8% (17)

U.S. guidelines (FEMA E-74 2011) provide detailing and construction considerations for braced parapets, while (FEMA 547 2006) gives information on parapet removal and replacement with a concrete cap beam.

OBSERVATIONS ON PERFORMANCE OF MASONRY PARAPETS FOLLOWING THE 2010/2011 CANTERBURY EARTHQUAKES

The damage to URM parapets was recorded following the earthquake on 4 September 2010 and after two main aftershocks on 22 February 2011 and 13 June 2011. After the three

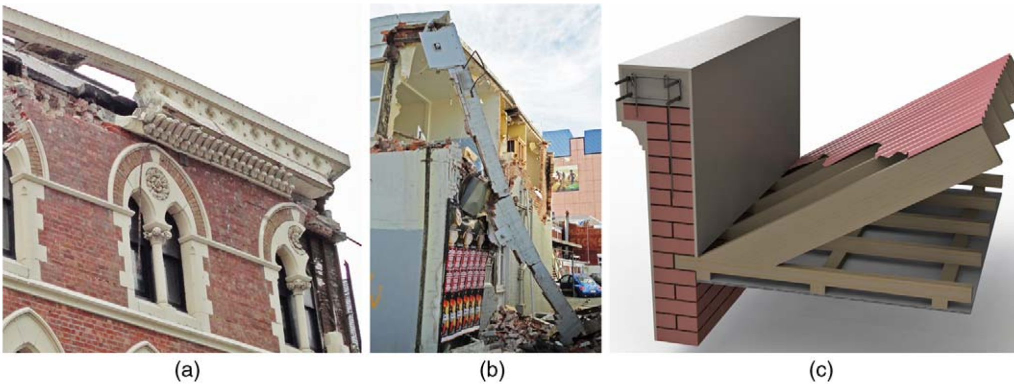


Figure 10. Examples of retrofit with the addition of a concrete bond beam at the top of the parapet: (a) typical concrete bond beam; (b) common failure; (c) design scheme.

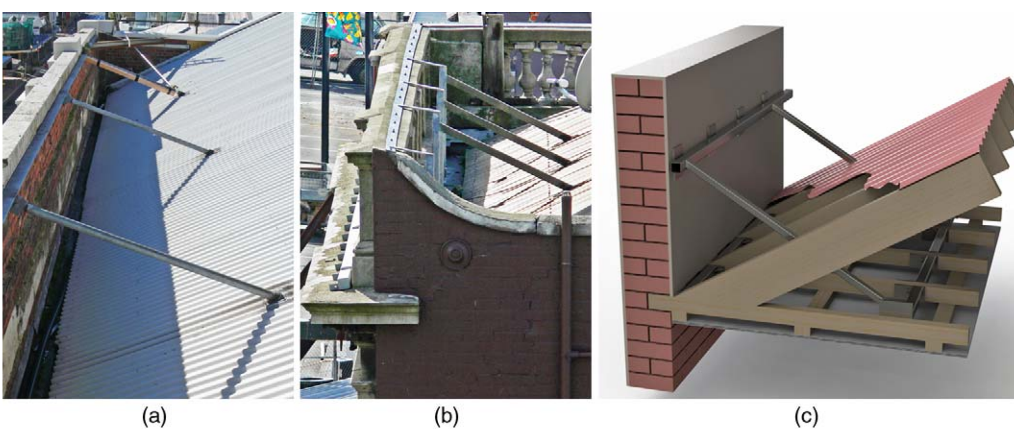


Figure 11. Examples of parapets braced back to structural elements: (a) typical braced parapet; (b) parapet braced back with top connection; (c) design scheme.

seismic events 60% (580) of the documented parapets had collapsed. Table 2 summarizes 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). A level of horizontal PGA was assigned to each of the inspected neighbourhoods, and consequently to each documented URM building, using acceleration records provided by GeoNet (Moon et al. 2014).

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

- Standing parapets, Figure 14, includes: (a) no visible damage, (b) visible horizontal cracking highlighting the initiation of rocking behavior of the parapet, and (c) other visible cracking in the parapet related to in-plane failure of the full facade or pounding effect of nearby structures.

- Collapsed parapets, Figure 15, includes: (a) partial collapse of the parapet, (b) full collapse of the parapet only, or (c) collapse of the parapet and of the top part of the facade.

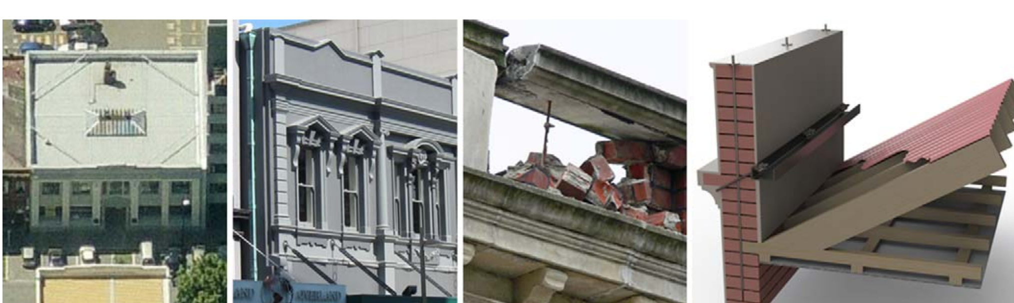
Figure 16 presents an example of progressive parapet damage after different earthquakes.

FREQUENCY OF FAILURE MODE OCCURRENCE

The 2010 Darfield earthquake resulted in less damage to parapets when compared with the subsequent aftershocks, with 75% (327) of the recorded parapet stock exhibiting no 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 0.7 g registered in

(a) (b) (c)

Figure 12. Examples of parapet retrofits utilising the addition of a steel strip on the back of the parapet connected with adhesive anchors: (a) rear view; (b) front view; (c) design scheme.



(a) (b) (c) (d)

Figure 13. Other types of parapet interventions: (a) corner steel bar connection; (b) lightweight polystyrene replica; (c) insertion of vertical steel bars; (d) design scheme of the vertical bars.

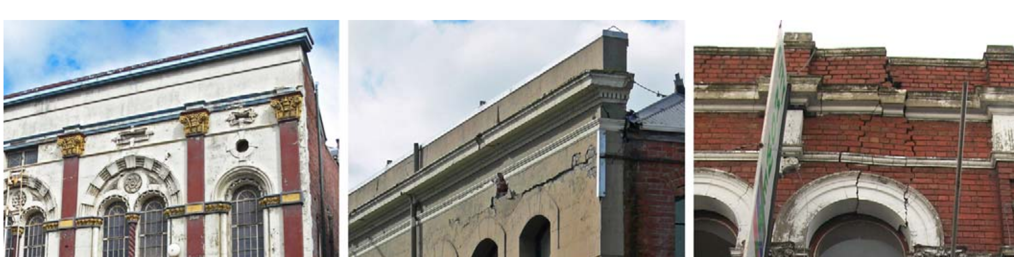
Table 2. Percentage (number in parenthesis) of parapets standing and collapsed after each earthquake with relation to the recorded PGA. Percentages refer to the total number of documented parapets for each earthquake

	4 September 2010 438 URM parapets		22 February 2011 881 URM parapets		13 June 2011 96 URM parapets	
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% (0)	2% (2)
0.76–1.00	n/a	n/a	2% (18)	3% (23)	4% (4)	0% (0)
Total	87% (380)	13% (58)	43% (378)	57% (503)[+]23	35% (34)	65% (62)[+]395

* Data includes no visible damage and all types of cracking
** Data includes partial or full collapse of the parapet or of the parapet and wall below
[+] Number of parapets that had fully collapsed (excluding partial collapse) in previous earthquake(s) and hence were already documented

the Christchurch CBD and 1.0 g registered in Lyttelton, and both vertical and horizontal ground movements were recorded (Bradley and Cubrinovski 2011). The largest number of collapsed parapets (42%, 371) were associated with a recorded PGA value higher than 0.50 g, of which 286 parapets (32%) were as-built and 85 parapets (10%) had been retrofitted. Although the 13 June 2011 earthquake was comparable to the 22 February 2011 earthquake in terms of PGA, location, and depth of the epicenter, the collected data are less than for the previous earthquakes because a large number of parapets (80%, 395) had already collapsed. Most URM buildings were already heavily damaged and during the 13 June 2011 event parapets collapsed at PGA values lower than 0.50 g.

Considering the damage caused to the parapets by only the 22 February 2011 earthquake, failure was observed to be more prevalent for as-built (URM) parapets while retrofitted



(a) (b) (c)

Figure 14. Examples of failure categories considered in standing parapets: (a) no damage; (b) horizontal cracking; (c) other types of cracking.

Figure 15. Examples of failure categories considered in collapsed parapets: (a) partial parapet collapse; (b) parapet collapse; (c) parapet and wall collapse (braced parapet).

Figure 16. Examples of progressive damage to retrofitted parapet: (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.

parapets presented an increased occurrence of horizontal or other cracking failures (Figure 17). After the 22 February 2011 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 17 shows the improvement in performance of retrofitted parapets when compared with as-built parapets. Note that a large number of parapets (23%, 212) collapsed due to partial collapse of the facade, and hence the adopted retrofit intervention designed only for the parapet was not able to prevent the failure.

Considering the state of the parapets after the three major earthquake events an increase in the level of damage to parapets proportional to the height of the building (number of stories) was observed as expected (Figure 18). In the case of two story buildings, the most frequent category, 27% (153), of parapets collapsed in conjunction with out-of-plane wall failure, 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

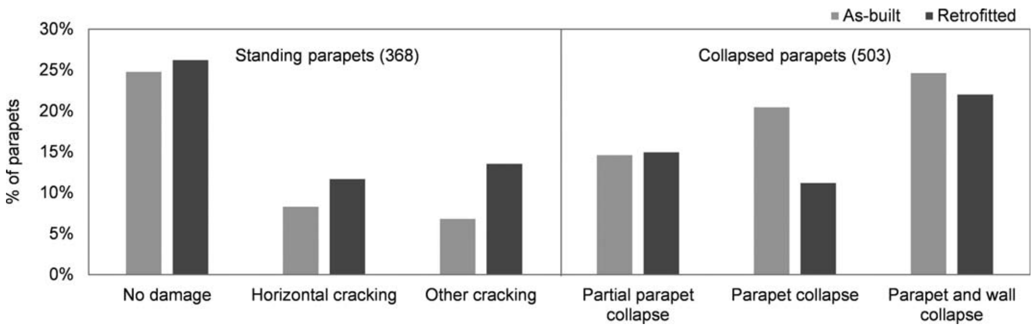


Figure 17. Observed failure categories of as-built and retrofitted URM parapets after the 22 February 2011 Christchurch earthquake.

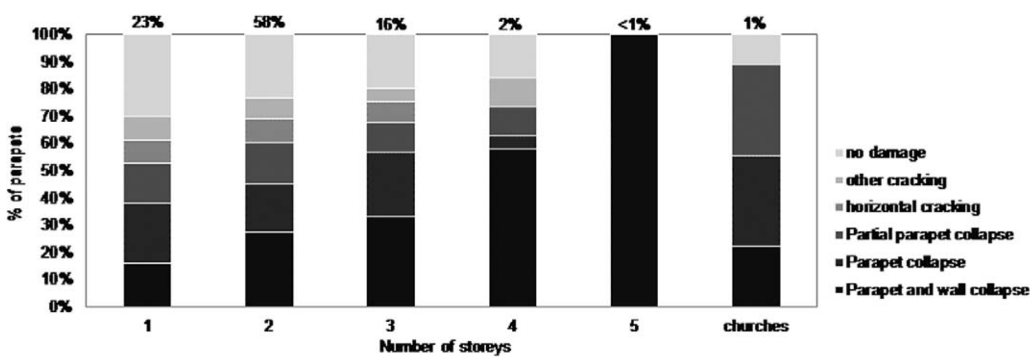


Figure 18. Observed parapet failure categories and proportion in relation to the number of stories of the building.

indicated by horizontal cracking, 8% (43) had other types of cracks and 23% (130) presented no damage.

Figure 19 shows the results for only the collapsed parapets, where the data is clustered based on height of the parapet and number of stories 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 was applied, in particular in the cases of single or two stories buildings. Similar graphs are presented in Figure 20, where 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 frequency of collapse, in particular at PGA levels lower than 0.50 g.

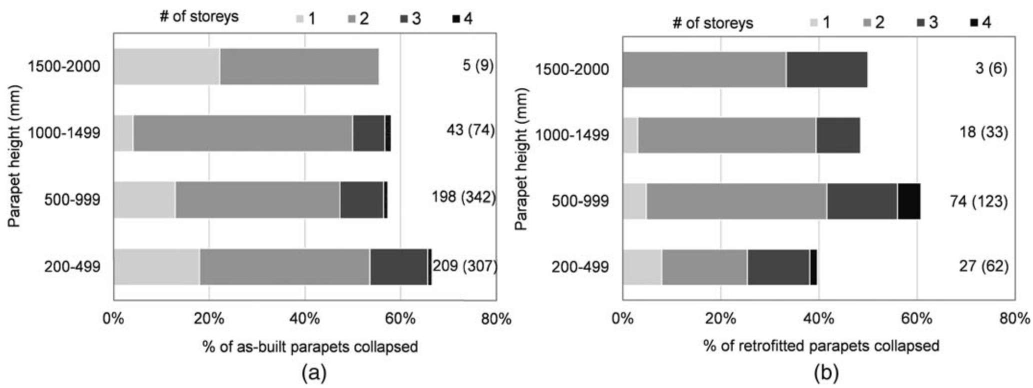


Figure 19. Parapet collapse in relation to parapet height and the number of stories of the building: (a) as-built parapets; (b) retrofitted parapets.

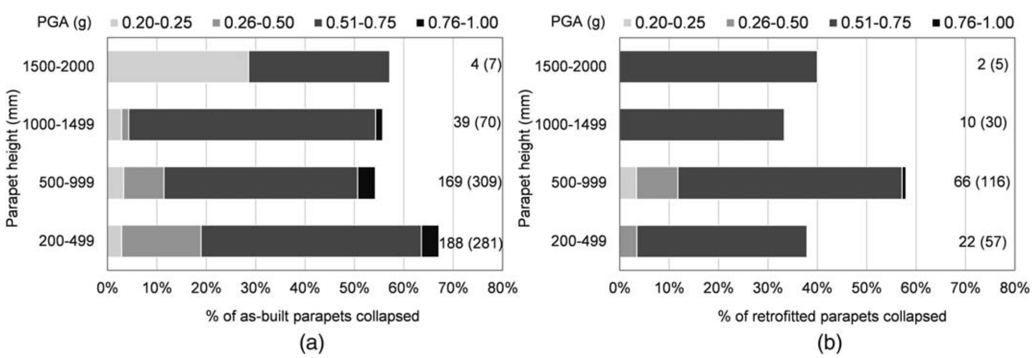


Figure 20. Parapet collapse during the 22 February 2011 Christchurch earthquake in relation to parapet height and the registered PGA: (a) As-built parapets; (b) retrofitted parapets.

EARTHQUAKE PERFORMANCE OF RETROFITTED PARAPETS

In relation to the types of retrofit previously presented, 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 (Table 3).

Due to the increased mass 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 (Figure 21a). The typical failure modes of steel braces mounted behind the parapet were: (1) failure due to short embedment of the ties adopted to fix the beam to the parapet (Figure 21b); (2) horizontal cracking corresponding to the location of the horizontal steel beam, followed by collapse of the remaining un-retrofitted part above (Figure 21d); and (3) horizontal cracking at the base of the parapet. Collapse was typically observed when the parapet was retrofitted using only steel braces locally fixed with

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

	Standing	Collapsed*	Wall and parapet collapse
As-built (100%, 731):	38% (276)	37% (267)	25% (188)
Retrofitted (100%, 228):	45% (102)	26% (59)	29% (67)
Concrete bond beam (39%, 87)	11% (26)	10% (23)	17% (38)
Bracing back to structural element (30%, 68)	17% (39)	6% (14)	7% (15)
Steel strip (24%, 55)	9% (21)	9% (21)	6% (13)
Other (8%, 18)	7% (16)	<1% (1)	<1% (1)

* Excluding collapsed parapets that presented also the collapse of the top part of the facade

adhesive anchors or plates, without the presence of a horizontal steel beam, as shown in the building in Figure 22, where both systems were adopted. The use of horizontal steel strips fixed to the parapet with adhesive anchors resulted in the collapse of the parapet due to the absence of connection to a primary structural element (Figure 21c). Horizontal cracking at the

Figure 21. Typical examples of observed failure mode for adopted retrofit interventions: (a) collapsed concrete beam; (b) bracing back to structural element – short embedment of the adhesive anchors; (c) steel strip; (d) bracing back to structural element – cracking above the horizontal steel strip (highlighted in black); (e) steel strip – cracking above the horizontal steel strip.

Figure 22. Performance comparison between parapets braced back to a structural element with and without a horizontal steel strip: (a) with a horizontal steel strip; (b) without a horizontal steel strip.

location of the steel strip was observed when the steel strip was applied to all the perimeter parapets as a ring beam (Figure 21e). In some cases, it was recognized that the horizontal steel strip had occasional vertical steel struts connected to the roof structure, typically having insufficient capacity to support the parapet when subjected to earthquake loads.

A critical analysis of the observed earthquake performance of retrofitted parapets suggests that the steel bracing type of retrofit performed better than others types. It is noted that waterproof detailing of penetrations through the roof membrane needs to be carefully considered for such type of bracing in order to satisfy long-term durability aspects. Construction recommendations on braced parapets are available in (FEMA E-74 2011). Other intervention such as corner connections, lightweight replica, and vertical steel bars inserted into the parapet, performed also well. Nevertheless, the limited number of parapets (17) retrofitted with such techniques suggests that further studies are required to better understand the behavior.

LEVEL OF DAMAGE AND FRAGILITY CURVES

The level of damage observed to masonry parapets following the Canterbury earthquakes was recorded and categorized in accordance with the European macroseismic scale, EMS 98 (Grunthal et al. 1998), as below:

- D0 – None visible
- D1 – Insignificant (<10%) – visible hairline cracks in the mortar joints
- D2 – Minor (11–30%) – visible and significant cracks
- D3 – Moderate (31–50%) – initiation of out-of-plane failure
- D4 – Severe (51–80%) – partial out-of-plane collapse
- D5 – Extreme (81–100%) – full collapse of masonry parapet

The data were used to produce a scenario-based study for parapets as a function of peak ground acceleration (PGA) registered during the 22 February 2011 Christchurch earthquake. Two-parameter (median and log-standard deviation) log-normal distribution functions were used to represent the fragility curves utilizing the maximum likelihood procedure, as suggested in (Shinozuka et al. 2000). Figure 23a presents the results in terms of damage

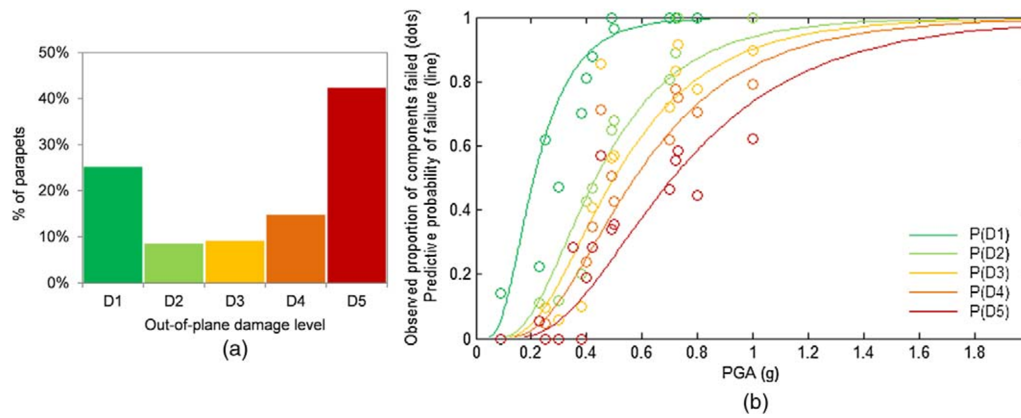


Figure 23. Damage level observed for unreinforced masonry parapets following the Canterbury earthquakes: (a) breakdown of damage levels; (b) fragility curves.

levels, while Figure 23b reports the simulated fragility curves for each level of damage, demonstrating that the median fragility values increase with increasing damage level. The estimated median fragility values are: $P(D1) = 0.21\,g$; $P(D2) = 0.43\,g$; $P(D3) = 0.50\,g$; $P(D4) = 0.57\,g$; and $P(D5) = 0.71\,g$.

PARAPET PERFORMANCE VERSUS EARTHQUAKE DIRECTION

A final comparison was undertaken to consider the orientation of the parapets versus the direction of the earthquake with 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), northwest (NW), and northeast (NE). The angle between the epicenter and each building was calculated using GPS coordinates. The resulting angles were then clustered into four groups: (1) "0 degrees" that includes the angles from 337.5° to 22.5° and the opposite 154.5° to 202.5°; (2) "45 degrees" between 22.5° to 67.5° and 202.5° to 247.5°; (3) "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° (Figure 24). 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 the most populated and effected areas of the CBD (6–12 km from the epicenter) and Lyttelton (5–6 km from the epicenter), all the parapets oriented NE are perpendicular (⊥), parapets oriented NW are parallel (//), and parapets oriented NS and WE are considered diagonal (∠). Figure 24 summarizes the results using pie charts divided into sectors representing each angle group. The pie charts present standing (blue portion) and collapsed (red portion) parapets considering their orientation as perpendicular, parallel or diagonal. In the CBD ("−45 degrees" group) where most of the parapets were located, the urban pattern was mainly oriented NS and EW and as a consequence a large number of parapets (650, 83%) were oriented diagonally to the direction of the earthquake and hence it was not possible to clearly observe a predominant response for the perpendicular and parallel oriented parapets. The majority of the parapets (408, 52%) that were located in the CBD and oriented diagonally

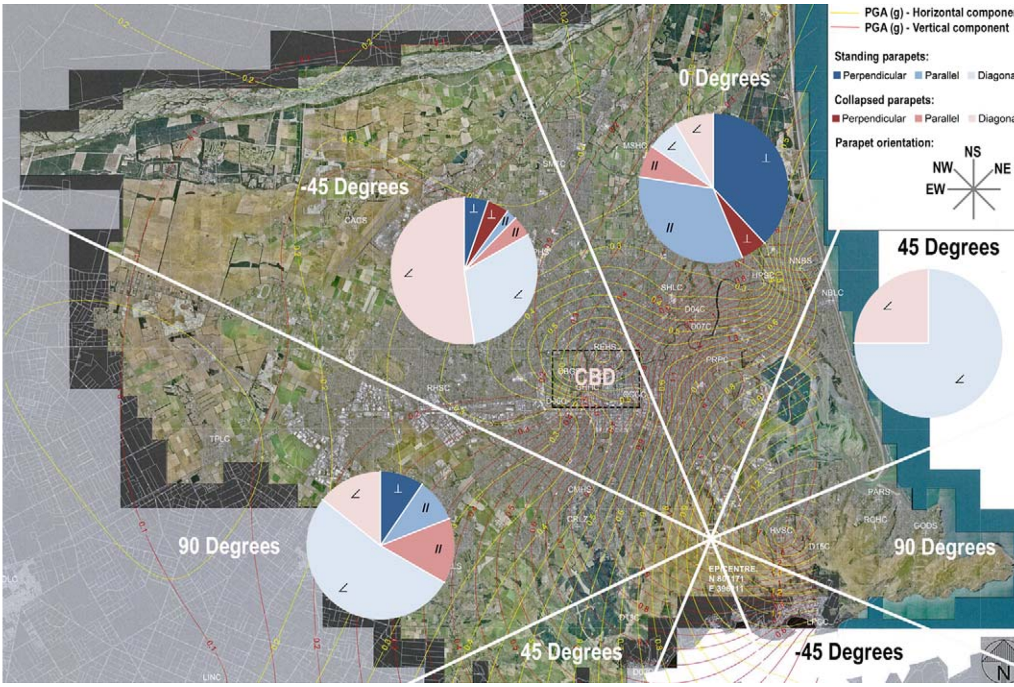


Figure 24. Map showing the epicenter and PGA contours (Source: Christchurch City Council) and for each considered angle group a pie chart showing standing and collapsed parapets for each orientation.

collapsed. Parapets were predominantly oriented perpendicular and parallel to the earthquake direction in the area referred to as "0 degrees," where only 71 URM parapets were identified. Nevertheless, in the "0 degrees" quadrant a large number of parapets remained standing and it was not possible to assess the influence of the directivity effect because of the distance from the epicenter, being 32 km and 22 km, respectively, for Rangiora and Kaiapoi, where in both cases the recorded PGA was lower than 0.20 g. Table 4 presents the results and the number of parapets considered for each group.

Table 4. Orientation and state of parapets with respect to the angle between the building and the epicenter of the 22 February 2011 Christchurch earthquake. Percentages refer to the total number of parapets for each group

Angle (refer to Figure 24)	Perpendicular		Parallel		Diagonal		Total
	Standing	Collapsed	Standing	Collapsed	Standing	Collapsed	
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

CONCLUSIONS

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

- **Prevalence:** A large number of parapets were located in two story buildings, being approximately 5.8 m to 6.6 m above ground level. The typical height of the parapet from the roof line was estimated to be between 500 to 1,000 mm (48%, 456), being typically two-leaf thickness. Three types of cross section arrangements were identified: (1) continuous wall type (solid or cavity wall); (2) solid or cavity wall parapet with RC beam at roof level or cornice; (3) solid wall parapet over cavity wall.
- **As-built performance:** Different extents of out-of-plane failure were observed in the documented parapets, including initiation of rocking behavior with horizontal cracking at the base, partial or full collapse, and other damage modes related to failure of the facade.
    - Building height, recorded PGA, and parapet height (hence slenderness) were the primary factors that influenced parapet collapse. The worst scenario was recorded during the 22 February 2011 earthquake, with 40% (269) of the as-built parapets standing and 60% (403) collapsed.
    - During the 22 February 2011 the largest stock of collapsed parapets was correlated to PGA values higher than 0.50 g while in the 13 June 2011 event, when buildings were already heavily damaged, PGA values lower than 0.50 g were sufficient to cause collapse of the parapets.
- **Retrofit performance:** 23% (224) of the documented parapets had been retrofitted prior to the 2010/2011 earthquakes, significantly reducing their likelihood of collapse.
    - The retrofit techniques adopted included a concrete bond beam at the top of the parapet, a steel brace fixed to a structural element, a steel strip fixed with adhesive anchors or struts at the edge, and other solutions, 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.
    - Steel bracing exhibited better performance than other retrofit interventions with the percentage of collapsed steel-braced parapets reduced to 25%, and hence is considered the most suitable retrofit intervention when applied with carefully engineered steel strips and diaphragm anchors.

ACKNOWLEDGMENTS

The original data collection following the 2010/2011 Canterbury earthquakes was funded by the Natural Hazards Research Platform. Christchurch City Council kindly provided records and access to property files. Lisa Moon is thanked for her efforts during the data and photo collection and inspection of damaged URM buildings. Mèlanie Brisacque and Dr. Matthew Cutfield are thanked for their assistance with data analysis.

REFERENCES

Bradley, B., and Cubrinovski, M., 2011. Near-source strong ground motions observed in the 22 February 2011 Christchurch earthquake, *Seismological Research Letters* **82**, 853–865.

Bruneau, M., 1995. Performance of masonry structures during the 1994 Northridge (Los Angeles) Earthquake, *Canadian Journal of Civil Engineering* **22**, 378–402.

Canterbury Earthquakes Royal Commission, 2012. *Final Report. Volume 4: Earthquake-Prone Buildings*, Vol. 4, New Zealand.

Davey, R. A., and Blaikie, E. L., 2010. Predicted and observed performance of masonry parapets in the 2007 Gisborne earthquake, in *New Zealand Society for Earthquake Engineering Conference – NZSEE*, Wellington, New Zealand.

Dicksee, B. J., 1906. *The London Building Acts 1894 to 1905: (57 & 58 Victoria, Cap. CCXIII; 61 & 62 Victoria, Cap. CXXXVII. 5 Edwardus VII. Cap CCIX.)*, E. Stanford, London.

Dizhur, D., Jiang, X., Chengliang, Q., Almesfer, N., and Ingham, J., 2015. Historical development and observed earthquake performance of unreinforced clay brick masonry cavity-walls, *SESOC Journal* **28**, 55–67.

FEMA 547. 2006. *Techniques for the Seismic Rehabilitation of Existing Buildings*. Prepared by R&C Consulting Engineers and NIST. Federal Emergency Management Agency (USA).

Federal Emergency Management Agency (FEMA E-74), 2011. *Reducing the Risks of Nonstructural Earthquake Damage – A Practical Guide*, Prepared by ATC, Washington, D.C.

Federal Emergency Management Agency (FEMA P-58/BD-3.9.8), 2010. *Fragility of Masonry Parapets*, ATC-43 Project, Washington, D.C.

Filiatrault, A., Uang, C-M., Folz, B., Chrstopoulos, C., and Gatto, K., 2001. *Reconnaissance Report of the February 28, 2001 Nisqually (Seattle-Olympia) Earthquake*, Report SSRP–2001/02, University of California, San Diego.

Giaretton, M., Dizhur, D., da Porto, F., and Ingham, J., 2015. Constituent material properties of New Zealand unreinforced stone masonry buildings, *Journal of Building Engineering* **4**, 75–85.

Grunthal, G., Musson, R. M. W., Schwarz, J., and Stucchi, M., 1998. *European Macroseismic Scale 1998 (EMS-98)*, Centre Europèen de Géodynamique et de Séismologie, Luxembourg.

Johnston, D., Standring, S., Ronan, K., Lindell, M., Wilson, T., Cousins, J., Aldridge, E., et al. 2014. The 2010/2011 Canterbury earthquakes: Context and cause of injury, *Natural Hazards* **73**, 627–37.

Lumantarna, R., Biggs, D. T., and Ingham, J. M., 2014. Compressive, flexural bond, and shear bond strengths of in situ New Zealand unreinforced clay brick masonry constructed using lime mortar between the 1880s and 1940s, *Journal of Materials in Civil Engineering* **26**, 559–66.

Moon, L., Dizhur, D., Senaldi, I., Derakhshan, H., Griffith, M., Magenes, G., and Ingham, J., 2014. The demise of the URM building stock in Christchurch during the 2010–2011 Canterbury earthquake sequence, *Earthquake Spectra* **30**, 253–76.

New Zealand Society for Earthquake Engineering (NZSEE), 2006. *Assessment and Improvement of the Structural Performance of Buildings in Earthquakes*, New Zealand.

Shinozuka, M., Feng, M. Q., Lee, J., and Naganuma, T., 2000. Statistical analysis of fragility curves, *Journal of Engineering Mechanics* **126**, 1224–1231.

Walsh, K. Q., Dizhur, D. Y., Almesfer, N., Cummuskey, P. A., Cousins, J., Derakhshan, H., Griffith, M. C., and Ingham, J. M., 2014. Geometric characterisation and out-of-plane seismic stability of low-rise unreinforced brick masonry buildings in Auckland, New Zealand, *Bulletin of New Zealand Society for Earthquake Engineering* **47**, 139–156.

(Received 17 December 2015; accepted 10 May 2016)