Seismic Retrofit of URM Parapets using Vertical Screw Reinforcing: Experimental Testing and Simplified Design Approach

J.Y. Zhai, E.A. Opabola
University of California, Berkeley, California, USA

F. Galvez, R.J. Hudson
PYTHON Fixings, Auckland, New Zealand

D. Dizhur
DIZHUR Consulting, Auckland, New Zealand

ABSTRACT

Seismic retrofit of unreinforced masonry (URM) parapets can provide enhanced seismic performance and collapse prevention. While widely adopted retrofit methods (e.g. braced systems) have been shown to be effective, they often require trade-offs in the form of high installation and fabrication costs, risk of water ingress due to roof penetrations, and disturbance of historical aesthetic. This paper presents a simple and cost-effective retrofit system consisting of high-strength mechanical fasteners that are drilled and mechanically anchored through the top of the parapet to an effective embedment below the diaphragm-to-wall connection. To demonstrate the effectiveness of this retrofit system, a series of monotonic and cyclic tests were undertaken on as-built and retrofitted URM double-wythe parapet specimens. The results showed that retrofitted parapets had an up to 16x increase in out-of-plane strength and ductility. The ultimate strength and failure mode of retrofitted specimens was influenced by wall aspect ratio, diaphragm connection strength, anchor spacing, and effective anchor embedment. Using the extensive experimental data, a practical retrofit design methodology is developed and presented herein.

1 INTRODUCTION

Unreinforced masonry (URM) parapets are renowned for their susceptibility to out-of-plane collapse under seismic loading (FEMA E-74, 2012). This failure mode has been observed in numerous earthquakes with perhaps the most closely studied in recent history being the 2011 Christchurch, New Zealand earthquake series where comparisons between retrofitted and un-retrofitted URM parapets found retrofitted parapets to have a significantly reduced likelihood of collapse and subsequent reduced risk to life safety (Ingham et al., 2011). Also highlighted in the studies conducted following the 2011 Christchurch, New Zealand earthquake series was the direct risk of URM parapet collapse to life immediately adject to these structures with a country wide URM inventory revealing that 60% of the approx. 600 parapets surveyed in Auckland, New Zealand are street facing (Giaretton, 2016). The location of these parapets, as well as their fundamental susceptibility to earthquake accelerations, makes them a key consideration when assessing a structure, or a societies, susceptibility and risk exposure to seismic events (Aleman et al., 2014, Davey et al., 2010, Dizhur et al., 2015). Subsequently, addressing these elements is a critical part of effective seismic risk reduction.

1.1 Current state of industry

URM parapet retrofits have become industry standard when a building undergoes seismic strengthening. A recommended example by the Ministry of Business, Innovation, & Employment (MBIE) is use of steel bracing to provide horizontal restraint to URM parapets, strengthening them against out-of-plane seismic accelerations, refer Figure 1 (MBIE, 2018). While generally effective when designed and installed following sound engineering and construction practices (Giaretton, 2016), this retrofit does inherently contain a number of significant drawbacks. Primary among these is the inherent (material and labour) costs associated with installing structural steel members to the perimeter of a parapet above the roof level of the structure. Given the propensity for seismic retrofit jobs to be budget constrained, despite the grants available to support building owners in this work (MBIE, 2018), cost is of material impact to the financial viability of these projects. This can impact both how soon a building is retrofitted and if a building owner is financially incentivised to demolish and rebuild in place of retrofitting. These aspects have a societal impact to a community's exposure to seismic risk and the preservation of built heritage respectively. In addition to the cost, steel brace systems generally require penetrations through the roof of a structure for the brace to be connected back to internal structural elements, refer Figure 1 While there are techniques for making these connections waterproof (eg. EPDM rubber boot as specified in Figure 1), these techniques have practical limitations and can result in watering ingress at these locations over time.

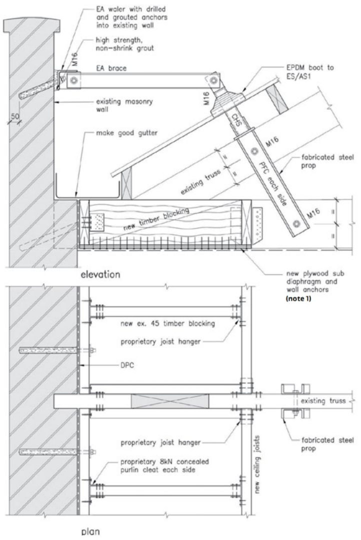

Figure 1 Steel brace parapet retrofit

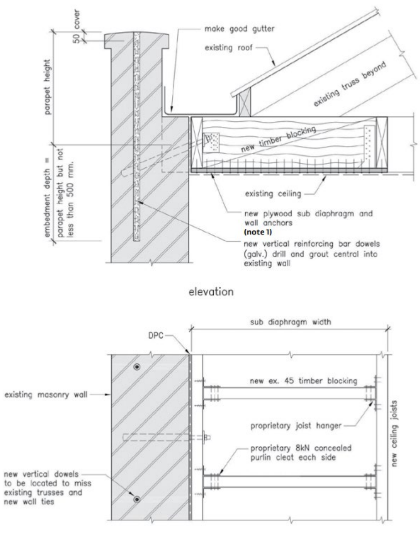

Figure 2 Post installed epoxied or grouted dowls parapet retrofit

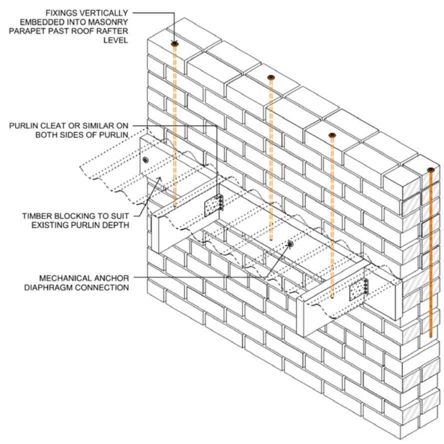

Figure 3 Parapet retrofit with post-installed mechanical anchors (schematic supplied by: PYTHON Fixings)

Vertical dowls are also provided in MBIE documentation as a recommended seismic retrofit for URM parapets, refer Figure 2 (MBIE, 2018). These dowls typically are either epoxied or grouted in and act as post installed vertical reinforcing for the (previously unreinforced) masonry parapet. This vertical reinforcing allows the parapet to behave as a traditionally reinforced element out-of-plane and, similarly to a steel bracing element, provides a horizontal load path to resist seismic out-of-plane accelerations.

This technique has the advantage of being concealed within the boundaries of a parapet. This addresses the waterproofing concerns associated with steel bracing as well as having minimal architectural impact which is generally desirable for building of high heritage value. However, the process of installing these bars requires the use of vertical coring machines. This process requires specialist tools and labour that, particularly in a smaller construction economy such as New Zealand, can make this option impractically expensive for many use cases.

Less common, methods of retrofitting URM parapets include Fiber Reinforced Polymer (FRP), shotcrete, and Fiber Reinforced Cementitious Matrix (FRCM) overlays (Elgawady, 2004), (Borri et al., 2011). FRP and FRCM overlays, while viable, are also typically relatively expensive to implement. Surface treatments with a concrete overlay technique, such as shotcrete, have the additional drawback of adding significant seismic weight which, in turn, increases the seismic inertia forces attracted by this element.

1.2 Post-installed mechanical anchors

The retrofit studied herein consists of the use of mechanical screws anchors installed vertically down through a parapets profile to provide post-installed vertical reinforcing to the (previously unreinforced) masonry parapet, refer Figure 3. The structural mechanics of this retrofit are much the same as the use of post-installed rod shown in Figure 2 and provides the same benefits of being contained within the boundaries of the parapet (no penetration of watertight roof membranes and concealed for heritage preservation). However, through use of an 8mm diameter mechanical screw anchor, this retrofit is able to be installed with a hand drill and general labour rather than a coring machine and specialist labour making this a substantially more cost-effective option.

To validate this technique, and to provide technical basis for design, eleven full scale, single and two leaf wide, parapets were constructed with New Zealand heritage bricks collected from previously demolished buildings and simulated heritage lime mortar. The specimens were then tested under monotonic and cyclic loading in as-built and retrofitted conditions to assess the impact of this retrofit technique in comparison to the as-built rocking strength of URM parapets. Experimental test results provide quantified evidence on the improvement in lateral strength, deformation capacity and ductility of the parapet specimens.

2 EXPERIMENTAL SETUP

2.1 Parapet Specimens

A total of eleven parapet specimens of various geometric designs were constructed using historic bricks collected from demolition sites in New Zealand and simulated historic lime mortar. Each parapet specimen was a 1000 mm wide, single or double leaf wall. Parapet height, anchor spacing, embedment depth, and the inclusion or exclusion of timber strongbacks below the simulated diaphragm were the primary variables investigated. Parapet heights varied from 400 mm to 1010 mm, corresponding to height-to-thickness ratios ranging from 1.7 to 9.2. Timber strongbacks were installed for some tests below the simulated diaphragm connection on the wall's "interior" face to assess the impact of restraining failure modes in this location on lateral strength, stiffness, and failure behaviour. Parapet dimensions can be found in Table 1, 2, 3 while Figure 4 illustrates the specimen and loading configuration.

(a) Test setup – view from diaphragm side *(b) Custom, 860mm long, PYTHON MT* *(c) Test setup – side view and schematic*

Figure 4.URM parapet test configuration

Loading was applied in the out-of-plane direction at the top of the parapet using a hydraulic ram and horizontal timber member to distribute the load simulating a uniformly distributed load across the parapet. The loading protocol applied was either monotonic in the "push" or "pull" directions, with reference to the reaction frame, or cyclic quasi-static.

A simulated timber diaphragm was provided to a) represent the stereotypical construction typology found in URM construction across New Zealand and b) to provide out-of-plane restraint for the parapet to react against. The diaphragm was connected to the parapet / wall with equally spaced port-installed mechanical anchors. This detail is based on best practice seismic retrofit procedure and is assumed by the authors to be a precondition of implementing post installed vertical screw anchor reinforcing to a parapet as a retrofit technique.

A timber reaction frame, anchored to the concrete foundation below, provided the reaction point for loading of parapet specimens with the hydraulic ram. Additionally, timber members were bolted to the concrete foundation each side of the parapet + wall specimens base to supress horizontal sliding failure along the concrete foundation which would not be representative of conditions in practice.

The 8mm diameter mechanical anchors were installed vertically using an off the shelf and readily available drill and impact driver into an 8mm diameter pilot hole pre-drilled using a hand drill approx. 50mm deeper than the intended anchor embedment. Due to the large embedment depth, a vacuum was used to remove dust from the pilot hole to reduce installation resistance during installation of the anchors. All installation of vertical mechanical screw anchors was done into brick sections; vertical mortar head joints were avoided in all tests. Refer to Figure 4 for test setup, load cell and displacement gauge set out. Refer to Table 1, 2, 3 and Figure 4 for specimen dimensions.

Table 1: Group 1 (0.4 MPa mortar) specimen overview and geometry

Test ID	Parapet Name	Leaf's	Height (h) [mm]	Num. Anchors	Anchor Spacing s_a[mm]	Anchor Embedment ($l_{emb,a}$) [mm]	Loading Protocol	Strong-backs
G1-1	#PL1-S2	2	500	2	480	360	M-Push	No
G1-2	#PL1-S3	2	500	2	480	360	M-Push	Yes

Table 2: Group 2 (4.6 MPa mortar) specimen overview and geometry

Test ID	Parapet Name	Leaf's	Height (h) [mm]	Num. Anchors	Anchor Spacing s_a[mm]	Anchor Embedment ($l_{emb,a}$) [mm]	Loading Protocol	Strong-backs
G2-1	#PM1-S2	1	500	2	480	360	M-Push	No
G2-2	#PM1-S3	1	500	2	480	360	M-Push	Yes
G2-3	#PM2-S2	2	500	2	480	360	M-Push	No
G2-4	#PM2-S3	2	500	2	480	360	M-Push	Yes
G2-5	#PM3-S2	1	1010	2	470	25 (into concrete)	M-Push	--
G2-6	#PM3-S3	1	1010	2	470	80 (into concrete)	M-Push	--

Table 3: Group 3 (9.7 MPa mortar) specimen overview and geometry

Test ID	Parapet Name	Leaf's	Height (h) [mm]	Num. Anchors	Anchor Spacing s_a[mm]	Anchor Embedment ($l_{emb,a}$) [mm]	Loading Protocol	Strong-backs
G3-1	#PH1-S4	2	650	2	500	350	M-Push*	Yes
G3-2	#PH2-S2	2	650	3	250	350	M-Push*	Yes
G3-3	#PH2.1-S1	2	650	1	--	350	Cyclic	Yes
G3-4	#PH2.2-S2	2	400	1	--	600	Cyclic	Yes
G3-5	#PH3-S2	2	650	2	500	350	Cyclic	Yes

G3-6	#PH3.1-S1	2	400	2	500	600	Cyclic	Yes
G3-7a	#PH4-S2	2	650	2	700	350	Cyclic	No
G3-7b	#PH4-S3	2	650	2	700	350	Cyclic	Yes
G3-8	#PH4.1-S1	2	400	2	700	600	Cyclic	Yes
G3-9a	#PH5-S2	2	900	2	500	300	Cyclic	No
G3-9b	#PH5-S3	2	900	2	500	300	Cyclic	Yes
G3-10	#PH5.1-S1	2	650	2	500	550	Cyclic	Yes
G3-11a	#PH6-S2	2	400	2	500	600	Cyclic	No
G3-11b	#PH6-S3	2	400	2	500	600	Cyclic	Yes
G3-12	#PH7-S2	2	650	1	--	80 (into concrete)	Cyclic	--
G3-13	#PH7-S3	2	650	2	500	80 (into concrete)	Cyclic	--

*Monotonic Load Protocol, loading in the "push" direction.

2.2 Materials

The heritage bricks used in this test program were reclaimed from demolished historic buildings in New Zealand. Historic lime mortar was recreated to mimic stereotypical site conditions of existing URM structures in New Zealand. Their properties were as follows:

Material	Average Compression Strength (MPa)	CoV (%)
Historic Brick	17.8	40
Group 1 mortar	0.4	--
Group 2 mortar	4.6	20
Group 3 mortar	9.7	30

The high strength steel mechanical anchors used for this program were 8mm diameter with custom length of 1300mm, 1000mm, or 860mm, refer to Figure 4b,c. These anchors are threaded along the full length of their shank providing continuous mechanical engagement with the full height of the parapet and anchor embedment depth below the diaphragm.

3 RESULTS

To simulate the cracked and weathered condition commonly observed in existing URM buildings, parapet specimens were loaded either monotonically or cyclically in their as-built condition to induce horizontal cracks in the mortar bed joints above the simulated diaphragm connection. The out-of-plane rocking strength was then measured and recorded as the specimens as-built capacity. The load-displacement behaviour of the 11 parapet specimens tested are provided below in Figure 5, 6, 7, 8 and a summary of the results in Table 4.

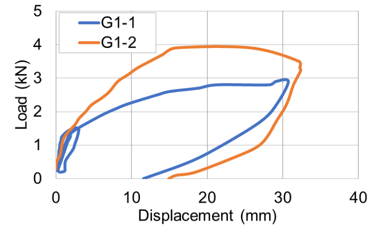

Figure 5: Load displacement results for G1 tests.

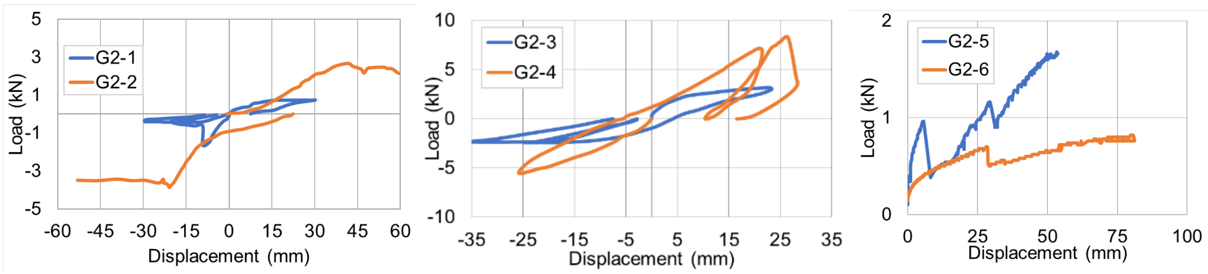

Figure 6: Load displacement results for G2 tests.

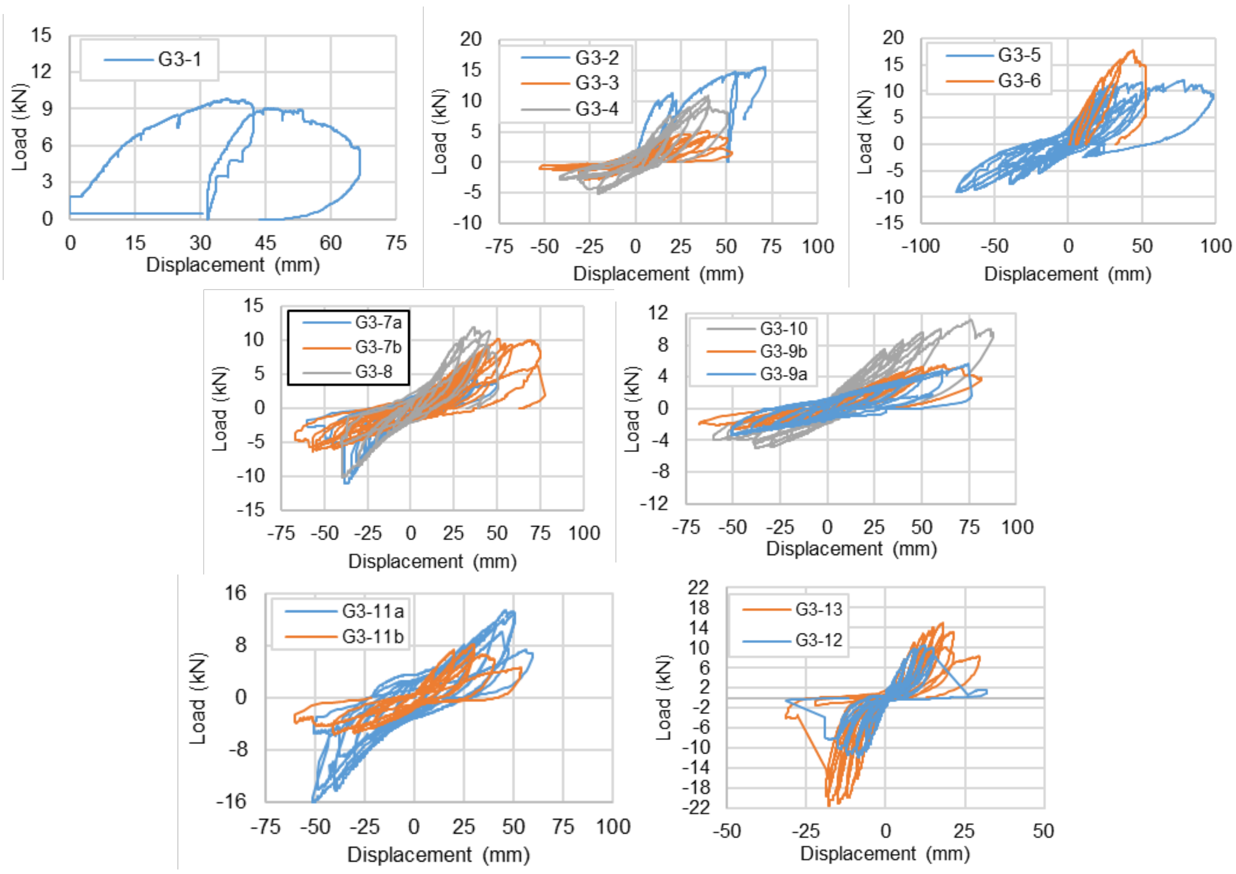

Figure 7 Load displacement results for G3 tests

Table 4: Summary of results

Parapet height above diaphragm (mm)	Parapet thickness (mm) (# of wythe)	As-built rocking capacity (g)	Capacity when retrofitted with 2 vertical screws (g)	Capacity when retrofitted with 2 vertical screws and strong-backs capacity (g)
1010 (80 mm into concrete)	110 (1)	0.11	0.96 (G2)	(Installed into concrete)
500	110 (1)	0.23	1.85 (G2)	4.52 (G2)
400	230 (2)	0.58	11.80 (G3)	6.01 (G3)
500	230 (2)	0.38	1.68 (G1) / 1.85 (G2)	2.26 (G1) / 4.81 (G2)
650	230 (2)	0.39	2.41 (G3)	4.77 (G3)
900	230 (2)	0.19	1.80 (G3)	1.77 (G3)

* Anchor spacing min: 2 anchors per meter

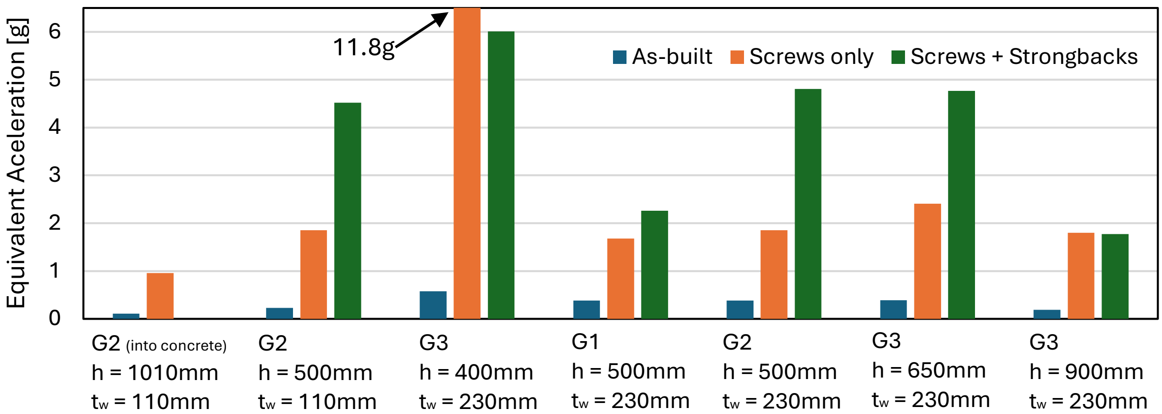

Figure 8 Summary of results

In general, four failure modes were observed to govern failure of the retrofitted parapet specimens.

a) Flexural mortar bed cracking below termination point of the post-installed mechanical anchors.
b) Yielding and subsequent failure of the anchor under flexural tension.
c) Brick crushing under flexural compression.
d) Splitting pullout failure of the anchor from the brick, initiating from below the diaphragm.

(a) Flexural mortar cracking below anchors *(b) Splitting/pullout of anchors above diaphragm* *(c) Crushing of brick and mortar in the push phase of the cycle*

Figure 9: Failure mode observations

4 CONCLUSIONS

A total of 11 full scale sub-assembly tests were performed to validate the use of vertically installed mechanical screw anchor as a seismic retrofit technique for existing URM parapets. This technique provides the industry with an opportunity for a more cost effective, heritage sensitive, and reliably watertight retrofit method to address the fundamental seismic vulnerability, and significant seismic risk to our communities, that URM parapets pose.

The key findings of this study were:

- Use of mechanical screw anchors as post-installed vertical reinforcing improved the out-of-plane capacity of URM parapets by an average of 9 times the cracked as-built rocking capacity.
- Where there was concrete below the URM parapet (eg. A bond beam), use of this retrofit improved the out-of-plane capacity of URM parapets by up to 20 times the cracked as-built rocking capacity.
- Increasing the number of post-installed mechanical screw anchors improved the performance of this retrofit technique. Parapet G3-1, G3-2 and G3-3 reached an improvement ratio from the as-built capacity of 7, 16 and 21 times respectively.
- The addition of an internal retrofit to the wall below (timber strongbacks), significantly improved the out-of-plane capacity of the retrofitted parapet by an average of 13.6 times. The use of timber strongbacks could theoretically be substituted for other strengthening techniques that supress cracking in the URM wall below the termination of the post-installed mechanical anchors (e.g. Shotcrete).
- Three critical failure modes were identified: horizontal flexure cracking in URM parapet regions, masonry crushing and compression failure, and anchor pullout.

5 ACKNOWLEDGEMENTS

The authors thank the collaborative efforts of PYTHON® Fixings in generously sponsoring this research and granting access to their products and laboratory facilities. Sandeep Sadhu and Selin Tonnerre are acknowledged for their invaluable assistance during testing.

6 REFERENCES

J. Aleman., et al. Out-of-plane shake table testing of URM walls with parapets and wood diaphragms. 2nd Eur. conf. earthq. eng. seismol. Istanbul, Turkey: 1-11. 2014.

A. Borri, G. Castori and M. Corradi, "Shear behavior of masonry panels strenghtened by high strength steel cords," Construction and Buildling Materials, vol. 25, no. 2, pp. 494-503, Feburary 2011.

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.

D. Dizhur., et al. Performance of as-built and retrofitted URM parapets during the 2010/2011 Canterbury earthquakes. 10th Pacific Conference on Earthquake Engineering. Sydney, Australia. 2015

M. Elgawady, , "Seismic In-Plane Behavior of URM Walls Upgraded with Composites," Cairo University, Cairo, Egypt, 2004.

FEMA E-74, "Reducing the Risks of Non structural Earthquake Damage - A Practical Guide," Federal Emergency Management Agency, Washington, D.C., 2012.

M. Giaretton, D. Dizhur, F. Porto and J. M. Ingham, "Post-Earthquake Reconnaissance of Unreinforced and Retrofitted Masonry Parapets," Earthquake Spectra, vol. 32, no. 4, pp. 1951-2585, 2016.

J. Ingham and M. Griffith, "Performance of Unreinforced Masonry Buildings During the 2010 Darfield (Christchurch, Nz) Earthquake," Australian Journal of Structural Engineering, vol. 11, no. 3, pp. 1-18, 2011.

MBIE, "Securing parapets and facades on unreinforced masonry buildings," Ministry of Business and Employment, Wellington, NZ, 2018