In-Situ Testing of a Post Tensioned Seismically Retrofitted Full Scale Unreinforced Masonry Chimney

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ABSTRACT: Unreinforced masonry (URM) domestic chimneys are highly vulnerable and potentially earthquake prone building elements that represent a hazard to life inside and outside the buildings that they are located on. In addition, past New Zealand earthquakes have resulted in a large number of insurance claims relating to the damage associated with URM chimney failures. As part of ongoing research to establish a database of New Zealand URM chimneys, a statistical survey was conducted in Dunedin and Auckland. Key details and findings are provided from the 910 surveyed chimneys. Currently there is limited experimental research that has been undertaken on cost-effective retrofit techniques that increase the seismic resilience of domestic URM chimneys. In order to increase the pool of knowledge, a post-tensioned (PT) retrofit was experimentally field tested on an old full-scale URM chimney. Findings specific to the tested URM chimney showed a 2.6 times increase in the capacity of the retrofitted URM chimney.

1 INTRODUCTION AND BACKGROUND

An old domestic or commercial unreinforced masonry (URM) chimney is a vertical channel or pipe which vents the smoke and combustion gases up from a fireplace into the external environment. URM chimneys are an ever-present feature in old URM and timber-framed buildings around the world, and in New Zealand they are commonly constructed using solid clay bricks and weak mortar. Due to chimneys typically being a tall and slender element in a building, they experience large amplifications of earthquake ground motion, making them one of the most heavily damaged building elements during an earthquake (FEMA 2010). Damaged URM chimneys that fall through the roof or outward onto an adjacent building or public sidewalk pose significant safety hazards to building occupancy, neighbours and passers-by.

Numerous past earthquakes in New Zealand have reaffirmed and highlighted the hazard that URM chimneys pose. In April 1974 a magnitude 5 earthquake with a shallow epicentre struck Dunedin. Damage was relatively minor and focused around the South Dunedin areas. Considering the low levels of reported earthquake shaking, it is surprising that a large number of insurance claims (approximately 3000 claims, half of which were chimney related, see Figure 1a) were received by the Earthquake and War Damage Commission (Bishop 1974). The 2010-2011 Canterbury earthquakes provided a large and significant amount of data relating to URM chimney damage. One week following the first major earthquake, out of an estimated 50,000 insurance claims, 15,400 claims (31%) were directly related to URM chimney damage. Most cases showed that the chimney was the first (sometimes only) building element to structurally fail due to seismic activity (Dizhur et al. 2011, Giaretton et al. 2016). Two common modes of failure for URM chimneys were: (1) collapse of the chimney onto or through the roof diaphragm, and (2) partial or full collapse outwards towards neighbouring streets and property (Figure 1a, b). Both modes of failure are a serious safety risk to the general public and mitigation of such is notably important. More recently in November 2016, the Kaikoura earthquake resulted in widespread damage to URM chimneys, see Figure 1d, e (Dizhur et al. 2017).
In order to investigate the performance of innovative, cost-effective, and low-aesthetic impact retrofit intervention for old URM chimneys, an in-situ experimental campaign on an existing URM chimney was undertaken to supplement the shake-table testing of as-built and retrofitted chimneys reported in Giaretton et al (2016). Furthermore, chimney stock in Dunedin was surveyed in order to supplement the Auckland survey work reported in Giaretton et al (2016), to provide a framework for a generic chimney case study, and to obtain a basic understanding of expected chimney seismic behaviour. Findings from both the survey and the experimental study are presented herein.

2 CHIMNEY SURVEYING

An inventory of existing old URM chimneys was compiled with the aim to identify the most commonly encountered geometric characteristics, construction details, and conservation state. A dataset of 910 URM chimneys was collected from neighbourhoods across Auckland and Dunedin, New Zealand. Documented URM chimneys were originally built between the end of the 19th century and the beginning of the 20th century using solid clay bricks of a uniform size, bound with mortar that varied considerably in strength. The amalgamated database was organised by typological groupings to include multiple attributes such as cross-section dimensions, height above the roofline, location within the dwelling, whether still in use, weathering and deterioration of the constituent materials, mortar hardness, usage and height of the building, and roof material and slope type.

Data collected on 351 URM chimneys across Auckland was previously reported by Giaretton et al. (2016). Data collected on 559 URM chimneys across Dunedin is reported herein. From the collected Dunedin survey data, the chimney height above roofline ranged between 450 mm and 2700 mm, with the most common height ranging between 1400 mm and 1700 mm. Chimneys were classed by their position on the building: internal chimneys were located inside the building and measured above the roofline.
roofline as opposed to external chimneys that were extruding as a component of the wall of a building (Figure 2d). For external chimneys, the most common height ranged between 4100 mm to 5600 mm.

The most commonly encountered cross-sectional dimensions excluding the crown (Figure 2a, b) were $570 \times 570$ mm (23%), while other frequently measured cross-sections were $460 \times 460$ mm (18%), $570 \times 800$ mm (13%), $460 \times 800$ mm (5%), with the remaining 40% being combinations of various dimensions. Aspect ratios were measured as height to width in order to gain an understanding of the slenderness of analysed chimneys. The most common aspect ratio for internal chimneys was between 2.5 and 3.0. Due to external chimneys being located on the outside or part of a wall, the most common aspect ratio was between 8.0 and 11.0.

From the collected field data, it was established that over 70% of the inspected dwellings had two or more chimneys, see Figure 3b. The structural condition of the inspected chimneys was documented, with 48% of chimneys appearing to be in poor condition, see Figure 3c for breakdown.

In the event of an earthquake many factors contribute to the damage and risk associated with URM chimney failure. Three important factors are the height and slenderness of the chimney, the number of chimneys on one house, and what structural condition the chimney is in. The implications from the data results are that if a serious earthquake were to occur in Dunedin, a large number of URM chimneys would topple due to their hazardous characteristics. With a high number of chimneys per house and the majority of chimneys being in moderate to poor structural condition, the risk of damage is very high, see Figure 3b, c.

3 EXPERIMENTAL PROGRAM

The task of finding a full-scale URM chimney that could be tested in-situ was undertaken in collaboration with Auckland Council, via scrutiny of chimney demolition consents submitted by property owners. Once a suitable chimney and willing owners were identified, plans for field testing of the chimney commenced.

Initial meetings were conducted with the property owners and with the builder tasked with the demolition, to ascertain the condition of the chimney, gather further details, and plan a date for testing. A comprehensive testing plan was developed and all parties involved were consulted for approval. Scaffolding was required and arranged for ease of access and safety during site testing.

The selected and tested chimney was an original 1940’s single flu URM chimney with a height of 3700 mm above the roofline (for perspective see Figure 4) and a total height of 8500 mm from ground level to the uppermost point of the chimney. The portion of the chimney above roofline had a square cross-section of $470 \times 470$ mm and was in good un-weathered condition. The chimney was constructed using strong and dense red clay bricks with a strong lime/cement based mortar mix.

3.1 Dwelling and test setup description

Initially the clay smoke cap at the top of the chimney was removed and the flu was checked to ensure
that a clear passage was visible all the way to the fireplace at the bottom, inside the house. Heavy duty rated synthetic strops were attached to the top part of the chimney and to a digital load-cell, which was in turn attached to a 12-volt battery powered winch and anchored to a tree, see Figure 4b. The loading synthetic strops were aligned against the scaffolding in such a way that load was applied horizontally to the chimney, see Figure 4a. This setup enabled easy, controlled load application while having load results immediately available for interpretation. Two Linear Variable Differential Transformers (LVDT) were placed at the top of the chimney at 0.4 m and 1.0 m below the top of the chimney. Snap-back tests were also performed and three accelerometers were placed: one at the upper most part of the chimney, one attached to the chimney near the roofline, and one inside the house attached to the fireplace, see instrumentation locations in Figure 4.

The chimney was first tested in the as-built condition to approximately 1.5% drift level, corresponding to a reduction of ultimate load carrying capacity of approximately 20%. Following the as-built test, a post-tensioned (PT) retrofit was installed inside the URM chimney. The PT system was designed in order to provide ease of installation in a full-scale chimney. Galvanised threaded D16 (Ø16 mm) steel rods in one-meter lengths were inserted down the chimney flu with coupler connections to join individual rods together into a fully functioning single rod that could be post-tensioned (Figure 4d). The dead anchor was located at the base of the chimney underneath the fireplace and consisted of two rectangular 8 mm thick steel plates which were anchored against the four cross sectional sides of the chimney. Similar to the bottom anchorage, at the top of the chimney the live anchor mechanism (Figure 4c) consisted of an 8 mm thick cross plate with the threaded rod centred through a hole and tightened using a washer and a nut. Two tests with different levels of PT were conducted (20 kN and 25 kN of prestress). The prestress was applied to the threaded rod using a hollow hydraulic actuator at the top of the chimney. For all tests, semi-cyclic loading was applied in approximate 0.25 kN increments.

Figure 4: Schematics of chimney loading and instrumentation-setup (a) Top portion of chimney showing loading direction and location. (b) Location of load-cell and load application mechanism. (c) Top portion of chimney showing cruciform anchor plate for PT retrofit. (d) PT threaded steel rod inserted down chimney flu.
4 TEST RESULTS

4.1 Test results

The as-built test provided a benchmark for the subsequent retrofitted chimney tests. A force versus displacement graph was produced using the acquired data, see Figure 5. A maximum lateral force of 1.4 kN at a displacement of 16 mm was achieved for the chimney in the as-built condition. The as-built chimney was loaded until 45 mm displacement with approximately 20% reduction in load. Following the testing, a maximum residual displacement of 8.0 mm was recorded.

Following the as-built test, the PT retrofit system was installed and vertically stressed to 20 kN (PT20), and the testing procedure was then repeated (as per section 3.1). Figure 5 shows approximately 2 times (2.9 kN) increase in capacity for the 20PT chimney at a displacement of 46 mm when compared to the as-built condition. The post-peak residual displacement upon unloading was 2.0 mm.

The chimney was further vertically stressed to a total prestress of 25 kN (PT25). The increased prestress resulted in a 2.6 times increase in capacity when compared to the as-built counterpart. As shown in Figure 5, the PT25 test was stopped when the chimney was laterally loaded to 3.7 kN and a displacement of 52 mm was reached. The PT tests showed a continual increase in strength with increasing lateral displacement due to the chimney arching and consequently stressing the steel threaded rod that was centrally positioned within the chimney. The final recorded residual displacement following PT25 test was 3.0 mm.

During and after testing there was no evidence of movement or damage to the anchoring mechanism at the base of the chimney. A horizontal crack in the chimney was observed two brick courses above the roofline, but no evidence of mortar crushing or masonry deterioration following testing was observed at the crack location or anywhere within the chimney.

![Figure 5: Force versus displacement response of as-built and retrofitted chimney](image)

5 DISCUSSION

For the tested URM chimney, the lateral seismic demand was calculated using AS/NZS 1170.5, Section 8: ‘Requirements for Parts and Components’ (NZS 2004) with the section of chimney above the roofline assumed to be supported at the roofline. Key assumptions included the soil type (Soil Type C) and the masonry density being equivalent to 1800 kg/m$^3$. $C_p(T_p)$ in accordance with NZS (2004) was calculated as 0.62g (demand conservatively based on crack/rocking initiation of chimney with a period of less than 0.75sec). The equivalent horizontal force of 3.9 kN applied at the location where test load was applied was calculated as the seismic demand at 100% New Building Standard (NBS) loading (Figure 5). Using simple statics and balance of forces, the capacity of the as-built chimney was calculated as 0.9 kN (Figure
5) at the location where the test load was applied. Hence, for the chimney in the as-built condition the capacity/demand (0.9/3.9) of 23% NBS was calculated. Note that the minimum legislative requirement is 34% NBS (The New Zealand Parliament 2004). Based on the as-built experimental test results, the chimney was able to attain capacity/demand of 36% NBS (1.4/3.9). For PT20 and PT25 tests the chimney was in excess of 74% and 95% NBS respectively (note that the maximum capacity of the retrofitted chimney was not attained as testing stopped at approximately 1.5% drift level).

Although the results showed positive benefits for strengthening URM chimneys against out-of-plane earthquake induced loading, several considerations and factors would need to be addressed before the PT system could effectively be used as a real life retrofit system. Firstly, PT losses experienced by the full system due to creep of connections, settling of the masonry, and initial loosening of live anchorage point would need to be resolved. For the purposes of this study it was assumed that an existing chimney is no longer in use, however for economic and aesthetical reasons it needed to be retained as part of the dwelling. The effects of heat and fire on the PT system have not been investigated or tested and need to be further addressed if the PT system is to be applied in chimneys that are in use. Data gathered from the Dunedin and Auckland chimney surveys showed there is a large number of chimneys that are not in use. More often than not, these chimneys are still considered an aesthetically valuable part of the structure/building and many house owners prefer for the chimney to remain.

6 CONCLUSIONS

From the experimental research undertaken, the following points are concluded:

- URM chimneys without a retrofit system pose serious hazards in an earthquake due to their inherent weakness to destabilise even under shaking generated from minor earthquakes. Due to the heritage value these chimneys often have, it is more appealing to seismically retrofit instead of demolish.
- Survey of existing URM chimneys in Dunedin show that there is a large number of URM chimneys in existence.
- Based on simplified calculations, the tested chimney does not meet current loading requirements in the as-built condition (23% NBS).
- Based on attained test results of as-built chimney, the performance of the as-built URM chimney against the calculated loading demand is 36% NBS.
- The PT system performed as expected by substantially increasing the inherent capacity of the URM chimney and well surpassing the minimum loading requirements of the tested chimney.
- The PT system was simple to install, did not alter the aesthetics of the chimney, and showed significant increase in strength of the chimney.
- With further research, the PT design can be implemented as a cost-effective retrofit and drastically reduce damage caused due to low to high seismic events.

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8 REFERENCES

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