OBSERVED PERFORMANCE OF RESIDENTIAL MASONRY VENEER CONSTRUCTION IN THE 2010/2011 CANTERBURY EARTHQUAKE SEQUENCE

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Following the 2010/2011 Canterbury earthquakes a detailed campaign of door to door assessments was conducted in a variety of areas of Christchurch to establish the earthquake performance of residential dwellings having masonry veneer as an external cladding attached to a lightweight timber framing system. Specifically, care was taken to include regions of Christchurch which experienced different levels of earthquake shaking in order to allow comparison between the performance of different systems and different shaking intensities. At the time of the inspections the buildings in the Christchurch region had been repeatedly subjected to large earthquakes, presenting an opportunity for insight into the seismic performance of masonry veneer cladding. In total just under 1100 residential dwellings were inspected throughout the wider Christchurch area, of which 24\% were constructed using the older nail-on veneer tie system (prior to 1996) and 76\% were constructed using screw fixed ties to comply with the new 1996 standards revision (post-1996), with 30\% of all inspected houses being of two storey construction. Of the inspected dwellings 27\% had some evidence of liquefaction, ground settlement or lateral spreading. Data such as damage level, damage type, crack widths, level of repair required and other parameters were collected during the survey. A description of the data collection processes and a snapshot of the analysis results are presented within.

\textbf{Keywords:} Residential masonry veneer, Canterbury earthquake, Christchurch earthquake field survey

INTRODUCTION

In the early morning of 4\textsuperscript{th} September 2010 the region of Canterbury, New Zealand, was subjected to a M7.1 earthquake. The epicentre was located near the town of Darfield, located 40 km west of the city of Christchurch. This was the country’s most damaging earthquake since the 1931 Hawke’s Bay earthquake (GeoNET, 2010). Since 4\textsuperscript{th} September 2010 the region has been subjected to thousands of aftershocks, including several more damaging events such as a M6.3 aftershock on 22\textsuperscript{nd} February 2011. Although of a smaller magnitude, the earthquake on 22\textsuperscript{nd} February produced peak ground accelerations in the Christchurch region that were three times greater than those generated in the 4\textsuperscript{th} September earthquake and
in some cases resulted in shaking intensities greater than twice the design level (GeoNET, 2011(a); IPENZ, 2011). The high shaking intensities resulted in structural damage to a variety of building systems, and in particular to unreinforced masonry structures. A post-earthquake field survey was conducted to establish the earthquake performance of residential dwellings having masonry veneer as an external cladding attached to a lightweight timber framing system.

The use of clay brick masonry as an anchored cavity wall veneer was first seen in late 18th century England (Mendygral and Sumnicht, 2011), and today is used in approximately 45% of new residential buildings in New Zealand (Beattie and Thurston, 2011). Clay brick, or other masonry veneer systems, are favoured because of their durability, resistance to fire and moisture, as well as for aesthetic reasons (Okail et al., 2011). However, masonry veneer systems have a history of poor performance in earthquakes.

In the 1989 Newcastle Australia earthquake veneer systems were observed to have behaved poorly, with the ties connecting the veneer commonly pulling out of the wall framing (it was also observed that in some cases the ties were never connected) (Page, 1991). The 1994 Northridge Earthquake also resulted in considerable damage to older brick veneer dwellings, which was due in part to the differential movement between the veneer and the framing, as well as being due to poor anchorage (Okail et al., 2011, Klingner, 2005).

Recent advances in construction techniques were intended to improve the seismic performance of masonry veneer systems (Thurston and Beattie, 2008a). These changes include reduction of the mass of the bricks, by reducing the unit width from 110 mm or 90 mm to 70 mm and by introducing hollow cores. These hollow cores have a double benefit of both reducing the wall mass and allowing mortar to result in formation of a physical key and hence allow a better connectivity between bricks through dowel or shear key action.

The performance of wall ties has also advanced in recent years with the introduction of the requirement for a non-impact connection method to the timber framing, typically being a screw fixing, as tests found that vibrations caused by the nailing of ties resulted in cracking of mortar and de-bonding of ties lower down the masonry stack (Beattie and Thurston, 2011). Modern veneer ties are also capable of transferring stresses and accommodating differential movement.

The seismic performance of masonry veneer systems attached to light timber framing has been experimentally investigated in both New Zealand and the US (Thurston and Beattie, 2008a, 2008b, 2008c, 2009, Okail et al., 2011). Simulated seismic testing of timber framed walls with masonry veneer was conducted using both quasi-static and dynamic conditions, on one and two storey systems, and with different masonry types and veneer ties. It has been found that clay brick veneer can carry a considerable amount of its own seismic load, act as an energy dissipater, and assist in maintaining building deflections to within acceptable limits due to its self-weight and added stiffness reducing internal damage. Generally with clay brick veneer, sliding was only seen along existing cracks or those cracks formed by rocking, except in two storey veneer tests where some sliding was associated with the shearing off of mortar shear keys (Thurston & Beattie, 2009).
Masonry veneer tends to act as large, rigid bodies, rather than individual bricks. This behaviour has been observed not only with the dowel action associated with modern clay brick masonry, but in older masonry as well, at least before significant cracking had developed. Tests have shown that masonry veneer exhibits good out-of-plane performance. Before cracking the veneer tends to act as large elements, rotating around its base, while after cracking the masonry spans vertically and horizontally between wall ties, rotating around the cracks. In-plane performance also typically exhibits rigid body behaviour, such as rocking panels and corner sections moving as blocks. The older, solid forms of masonry tend to crack at much lower deflections than do modern, hollow bricks with dowel action.

Tests were also conducted by Thurston & Beattie (2008c) using solid, concrete brick veneers. Although these veneer systems also performed well they lacked the dowel action of the hollow core clay brick veneers. Thus, while these veneer systems were observed to perform well at lower shaking levels, at higher shaking levels sliding was observed along the mortar joints, causing the masonry to break into individual components (Thurston & Beattie, 2008c).

It should be noted that Beattie (2004) found that it is difficult to determine the integrity of veneer ties after an earthquake without using invasive techniques. However, with the many large, damaging aftershocks in Christchurch, veneer ties which developed hidden weaknesses in early earthquakes were expected to show symptoms in later events.

CURRENT CONSTRUCTION PRACTICE IN NEW ZEALAND

The focus of the post-earthquake survey was on the performance during the 2010/2011 Christchurch earthquake sequence of modern masonry veneer cladding systems used in timber framed dwellings. Current veneer systems consist of 70 mm hollow core bricks (see Figure 1(a)) with a veneer cavity of 40-60 mm. The veneer is connected to the structural timber framing using regularly spaced screw-on steel ties placed in the mortar joints, as shown in Figure 1(b). Figure 1(c) illustrates a typical example of a residential single storey timber framed dwelling with a brick veneer cladding system, under construction. Current construction using the masonry veneer cladding must adhere to the following standards: NZS 3604 (1999), NZS 4229 (1999), NZS 4210 (2001), BRANZ Appraisal No 690 (2010).

![Figure 1: Typical current construction practice](image-url)
INSPECTIONS
Areas and suburbs selected for inspections were chosen based on the areas of recent development in Christchurch and the recent population increases from the 2006 statistic census of the Christchurch Metropolitan Area (Statistics New Zealand, 2011). An area-based survey was conducted, and depending on the dwelling density typically included every second veneer dwelling. Detailed door to door assessments of brick veneer dwellings were conducted in a variety of areas of Christchurch, with areas being chosen to include different levels of earthquake shaking in order to allow comparison between the performance of different systems and different shaking intensities.

The assessed residential dwellings were required to have at least 50% of the veneer cladding visible and accessible for inspection. When the dwelling residents were available, information on the internal damage, further details about any damage to veneer cladding and other additional information was collected, and in these cases typically 100% of the veneer was inspected. Veneers or remains of veneers were closely inspected to determine the type of cracking and the failure patterns.

During the inspection and data collection period a number of significant aftershocks occurred. Following major aftershock activity, for example on 13th June, 2011 (GeoNET, 2011(b)), indicative veneer dwellings were re-inspected for signs of any obvious increase in damage and it was intended that if major changes were noted then re-inspections were to be undertaken. No major damage increase was observed during inspections of indicative dwellings and therefore no re-inspections of previously inspected dwellings were conducted.

The survey was divided in order to include residential dwellings constructed prior to the introduction of the new 1996 standards revision, with a greater focus on newer post-1996 construction techniques. A major focus of the survey was on two storey post-1996 veneer construction, with an initial aim for at least 40% of houses surveyed to be of two storey construction. The survey was divided so that approximately 70% of the survey focused on post-1996 construction with the remainder focusing on pre-1996 construction. The survey was also arranged to ensure the inclusion of locations with varying shaking intensities, different types of ground conditions as well as being distributed geographically to accommodate as many relevant suburbs of Christchurch as feasible.

It is estimated that there are 134,000 residential private dwellings of all construction types located in the wider Christchurch area, and the survey population consisted of a total of 1084 dwellings. Therefore, the surveyed sample corresponded to just less than 1% of the total residential dwelling population in Christchurch (Statistics New Zealand, 2011).

DATA COLLECTION
General information such as the address (dwelling number, street name and suburb) of the dwelling and the number of storeys was recorded. Also, it was noted whether the veneer was applied solely to the bottom storey, to both storeys of the dwelling, or to the upper storey only.
Types of veneer

The types of recorded masonry veneers were divided into four categories:

- Traditional clay brick – this type of veneer unit typically measures 230 mm long and 76 mm high. The bricks are smooth, patterned or textured and are of varying colour, for example in Figure 2(a);
- Larger veneer units - this type of veneer unit typically measures approximately 230 mm long and 150 mm high and is made from clay or concrete. The bricks are smooth, patterned or textured and are of varying colour, for example in Figure 2(b);
- Long veneer units – these units are typical in the older type of veneer construction and are typically made of concrete (or Summerhill stone in older dwellings), and are approximately 350 mm long and 100 mm high. A typical example of this category is illustrated in Figure 2(c);
- Other – other veneer types that do not fit into any of the above categories, such as varying size and shape natural stone veneer and cut Oamaru stone (sandstone) veneer.

A range of unit thickness was recorded during the survey, and where possible, it was noted whether the veneer units were hollow cored or solid.

Ground settlement and lateral spreading

The observed level of ground damage evident on the day of the inspection was recorded for each property. This damage included liquefaction (silt ejections), which could potentially cause foundation subsidence depending on the level of severity, and any differential settlement or lateral spreading. The levels of severity for liquefaction and ground settlement/lateral spreading were categorised into the following: none visible, very minor, minor, moderate, severe, and extreme. Ground conditions were categorised based on the observations made on site on the day of the inspections. Some sites had been re-worked and evidence of liquefaction removed. Therefore, the observations did not necessarily correspond to the actual severity of the ground conditions immediately following the earthquakes.

Types of ties

One of the most important criteria associated with the performance of masonry veneer is the method used to connect the veneer to the structural timber framing. Where possible, such as in cases of partial or full collapse, or through discussions with the dwelling owner, the type of veneer ties used in each dwelling was established and recorded. For the purpose of the survey the type of ties was divided into five main categories:
 Unknown type of ties – this category is present due to uncertainty of the type of ties that were used in the construction of a dwelling;

Screw-fixed ties – this category refers to ties that are “flat” metal ties, and have one end fixed to the non-rigid members (eg. timber studs) using screws, as shown in Figure 3(a), and the other end encapsulated in the mortar joint. These types of ties (and the fixing method in particular) were introduced in about 1996;

Nail-on ties – this category refers to ties that are “flat” metal ties, and have one end fixed to the non-rigid members (eg. timber studs) using nails as illustrated in Figure 3(b). The other end of the tie is encapsulated in the mortar joint. These types of ties were used prior to 1996;

Wire ties – these types of ties were generally used in older veneer type construction and consist of a twisted flexible steel wire that is attached to the side of wall framing using nails or staples, as shown in Figure 3(c);

Other type – this category included veneer ties that are not part of any of the above categories.

(a) Screw-fixed ties  (b) Nail-on tie  (c) Wire ties

Figure 3: Types of ties

Internal damage
The level of internal damage was typically unknown, but when possible the internal parts of the house were inspected or information was verbally communicated by the dwelling tenants. The level of internal damage was recorded as either: unknown, none visible, very minor, minor, moderate, severe and extreme.

Level of veneer damage
The level of damage to the veneer was recorded on the survey forms in the following categories: none visible, very minor, minor, moderate, severe and extreme. Examples are shown in Figure 4. Due to the timing of the survey, which was performed approximately three months after the 22nd February 2011 earthquake, a number of dwellings had already had their unstable veneer removed and replaced with temporary lightweight cladding. The removal of veneer was recorded on the survey forms as partial.
The types of cracks (and average crack widths) observed were recorded for each dwelling inspected. Crack types were identified as being either through the mortar only, or through both the mortar and the veneer units. Observed failure patterns were divided into three main categories:

- **In-plane failure** – this category was selected when the dominant failure pattern observed was in the plane of the veneer, and included all types of in-plane failures including rocking, diagonal shear, and sliding, as illustrated in Figure 5(a);
- **Out-of-plane failure pattern** – this category was selected when the dominant failure pattern observed was in the veneer out-of-plane direction, as illustrated in Figure 5(b);
- **Mixed failure pattern** – this category was selected when both in-plane and out-of-plane failure patterns were observed.

(a) Example of in-plane veneer failure  
(b) Example of out-of-plane veneer failure

**Figure 5: Examples of observed failure patterns**
Observed pier and spandrel behaviour

The observed pier behaviour was recorded in the following categories: none, shear, rocking, both shear and rocking, and sliding. The observed spandrel behaviour, including crack types, was also recorded in the survey forms. Spandrel behaviour was divided into the categories of: none observed, shear, rocking, and shear or rocking; and the respective crack patterns recorded as: diagonal, vertical, or both. A typical example of spandrel rocking occurred in a single storey dwelling directly above lintels and resulted in vertical cracks at the corners of the openings. Brick crushing is typically common at building corners and at locations of pier rocking, and any occurrences of brick crushing were recorded.

Corner separation

Corner separation, if any, was recorded as part of the survey. Different types of corner separation observed are presented in Figure 6.

(a) Corner mortar cracking  (b) Corner separation through bricks and mortar  (c) Dislodgement of veneer units at a corner

Figure 6: Examples of corner separation

ANALYSIS AND DATA INTERPRETATION

In total 1084 residential dwellings were inspected throughout the wider Christchurch area, with 24% being pre-1996 construction and 76% being post-1996 construction. Of all inspected dwellings 30% had two storeys, and 69% of all two storey dwellings had the veneer extending up both storeys, while 9% of the two storey dwellings had veneer on the top storey only. As per the aim of this survey, the majority (69%) of the dwellings that were inspected were constructed in the 2000s, with 5-7% of the dwellings being placed in each of the other decade categories, except for the 1940s and 1950s where the number of dwellings inspected was low.

The majority (61%) of the inspected dwellings were constructed with traditional clay brick type veneer, while the second most popular type of veneer observed was the large veneer units (27%). It should be noted that a larger number (17 dwellings, 1.6% of the total population) of Oamaru stone (sandstone) veneer was observed than initially anticipated. Sandstone is much weaker than many of the local (volcanic) natural stones, so a separate category, Oamaru stone, was added during data processing. In some cases where the veneer had already been fully removed it was not possible to determine what type of masonry units had been used, so these cases were classified as unknown. The most commonly occurring veneer thickness was 70 mm, which was used in 76% of total dwellings inspected.
Foundation and ground conditions
82% of the inspected dwellings were identified as having been constructed using a concrete slab-on-grade type foundation and 18% of dwellings were constructed using a concrete ring foundation, which was predominantly used in older construction types. Also, 27% of inspected dwellings had some evidence of liquefaction, ground settlement or lateral spreading. Figure 7 shows that in areas that had some form of liquefaction or ground movement occurring the cause of damage for 40% of the dwellings was attributed to ground movement only and 28% of dwellings had damage that was attributed to shaking damage only. It should be noted that at the time of inspection the exact cause of veneer damage was often difficult to identify, and therefore these results may potentially lack accuracy. Also, there was no strong trend to suggest that older construction was primarily damaged by a different cause than was newer construction.

![Figure 7: Cause of damage, in areas with observed liquefaction, lateral spreading or ground movement](image)

Damage Distribution
To facilitate the interpretation of the results, individual dwellings were grouped into clusters based on location. The clusters are presented as pie charts showing the proportion of dwellings in each of the damage categories at each location. From the map in Figure 8 it can be observed that the severe and extreme damage to the veneer dwellings was concentrated in the Port Hills and foothills suburbs (13% of inspected dwellings). This concentration of damage may have been due to proximity to the 22nd February earthquake epicentre as well as the typography amplification (Rahimian et al. 2007). It is also evident that the majority of severe and moderate damage was concentrated close to the river banks, mainly due to substantial liquefaction and lateral spreading. Generally, the masonry veneer type dwellings that were located in areas away from the hills and were not affected by liquefaction sustained only minor damage or had no visible damage to the veneer.
Figure 8: Geographical distribution of damage

The acceleration records for 22nd February earthquake were analysed for the Christchurch area (GeoNET, 2011(a)) and in order to facilitate data interpretation the level of ground shaking was categorised as shown in Table 1. It is evident that 49% of dwellings experienced horizontal acceleration levels equivalent to a very strong shaking level (0.28 - 0.62g).

<table>
<thead>
<tr>
<th>Acceleration level</th>
<th>PGA (%g)</th>
<th>Percentage of dwellings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>12.6 - 27.9</td>
<td>11</td>
</tr>
<tr>
<td>Very strong</td>
<td>28.0 - 61.9</td>
<td>49</td>
</tr>
<tr>
<td>Severe</td>
<td>62.0 - 130</td>
<td>27</td>
</tr>
<tr>
<td>Extreme</td>
<td>&gt; 130</td>
<td>13</td>
</tr>
</tbody>
</table>

An acceleration level was assigned to each suburb and for suburbs where acceleration records were not available linear interpolation was used in conjunction with the shaking map to estimate the severity of the accelerations. Figure 9 graphically presents the level of veneer damage observed for each of the shaking intensities. As can be seen from Figure 9(a), and as expected, the level of damage increased with an increasing level of acceleration. It is evident that severe and extreme damage only occurred to veneers in areas of severe (0.62 – 1.3 g) or extreme (>1.3 g) shaking. From Figure 9(b) it is evident that the level of damage was more critical for sites where the peak ground acceleration (PGA) values were between 0.62 to 1.3g and that damage levels were predominantly severe and extreme with PGA values of >1.3g. From Figure 9 it can be seen that generally dwellings performed well in areas having less than
0.62g PGA, that dwellings performed satisfactorily in areas where the PGA was between 0.62 to 1.3g, and that dwellings performed poorly with extensive damage in areas having a PGA greater than 1.3g.

(a) Veneer damage level compared to PGA  
(b) Damage level for decade of construction

Figure 9: Masonry veneer damage level

Figure 9(b) shows the distribution of damage levels for each decade of construction. Although there are no distinctive trends, generally dwellings constructed since the 1990s tended to suffer lower levels of damage than those built earlier. There is, however, another spike in extreme damage levels corresponding to houses built since 2010. It should be noted that the post-2010 grouping contains a small sample only, and that the percentage of dwellings that exhibited extreme damage does not necessarily indicate a trend.

From the data survey it is evident that overall screw-fixed ties performed better than the other types of ties, with the majority of dwellings having screw-fixed ties showing no visible or minor damage only. It is apparent that dwellings with nail-on ties feature more predominantly in the moderate to extreme damage categories, and it appears that wire ties performed the worst as a higher proportion of inspected dwellings that had wire type veneer ties sustained severe to extreme damage.

60% of all inspected damaged dwellings sustained in-plane damage only. Also, dwellings constructed prior to 1996 were more likely to sustain out-of-plane damage in comparison to dwellings constructed post-1996. Of all the inspected dwellings which sustained some damage, 33% of these dwellings had problems with corner separation.

CONCLUSIONS
Detailed door to door assessments of residential brick veneer dwellings were conducted in a variety of areas of Christchurch, and specifically in areas with different levels of earthquake shaking, in order to allow comparison between different system performances and different shaking intensities.

It can be concluded that the severe and extreme damage to veneer clad dwellings was concentrated in the Port Hills and foothills suburbs (13% of inspected dwellings), due in part to the proximity to the epicentre as well as topography amplification. Also, it is evident that
the majority of cases of severe and moderate damage were concentrated close to the river banks, mainly due to substantial liquefaction and lateral spreading.

As expected, the level of damage increased with an increasing level of acceleration. Strong shaking mainly resulted in no visible damage, but did generate some minor damage and a little moderate damage. Very strong shaking mainly resulted in no visible damage, but did generate some minor damage and a little moderate damage. Severe shaking showed no visible damage in about 60% of cases, but damage up to extreme was seen for this shaking level. Extreme shaking led to damage ranging from none-visible right up to extreme. Alternatively, it is evident that severe and extreme damage only occurred to veneers in areas of severe (0.62 – 1.3 g) or extreme (>1.3 g) shaking.

It is evident that overall screw-fixed ties performed better than other types of ties, with the majority of dwellings that had this type of fixing exhibiting no visible or minor damage only. It is apparent that damaged dwellings with nail-on ties featured more predominantly in the moderate to extreme damage categories, and it appears that wire ties performed the worst as a higher proportion of inspected dwellings that had wire type veneer ties sustained severe to extreme damage.

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REFERENCES


