STUDY REPORT

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Structural Performance of Houses in the Canterbury Earthquake Series

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Preface

The work contained in this report resulted from a survey of the performance of a sample of houses in Christchurch following the series of earthquakes in the Canterbury area in 2010 and 2011. An extensive survey was undertaken on 314 houses randomly selected throughout Christchurch. Information on the site, the house characteristics and the damage sustained was gathered for each property. An analysis of the gathered data has allowed some correlation of behaviour across a range of parameters, such as house age, house style, cladding and lining materials.

The sample size was relatively small (approximately 0.2% of the total number of houses in Christchurch). Very detailed data was obtained for each property. This meant that multi-variable analysis often resulted in very small sample sizes, which meant that the comparisons were not statistically significant. However, by creating a single value for damage to particular elements for each property, this was able to be assessed against a number of variables.

Acknowledgements

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BRANZ also acknowledges the provision of student resources by Victoria University through the Summer Research Scholarship programme to assist with the analysis of the data, under the leadership of Dr Geoff Thomas. Statistical analysis advice was provided by Victoria University of Wellington’s Statistical Consultant Dr Dalice Sim.

Note

This report is intended for designers, engineers, architects, regulatory bodies and builders.

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Reference

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Abstract

This report describes the collection and analysis of survey data on a group of 314 randomly selected houses in Christchurch following the major earthquakes of the Canterbury earthquake series. The random selection process involved the use of the Statistics New Zealand mesh blocks to select approximately 50 mesh blocks. Six adjacent properties in one corner of each mesh block were surveyed.

The survey collected data on the characteristics of the land at the site, the characteristics of the dwelling and the damage sustained for a range of components of the dwelling. An attempt was made to quantify the extent of damage for the later analysis.

The survey results confirmed the anecdotal evidence that timber-framed dwellings generally performed well in that they satisfied the performance criteria of the New Zealand Building Code. That is, they did not collapse under shaking at least equivalent to the ultimate limit state design event. However, damage was widespread, ranging from very minor to quite major.

A weighting system was used to consolidate the detailed damage data percentages for several levels of damage degree for easier manipulation. Multi-variable analysis was not pursued because the resulting samples were often too small to have statistical significance. However, the damage to two major components of the dwellings' construction – internal linings and veneer cladding – was compared to other variables such as peak ground acceleration, dwelling age, building shape and topography.

The analysis indicated that the move to require all ties to be screw fixed from the mid-1990s had a beneficial effect on the seismic performance of brick veneer claddings. The use of plasterboard as a bracing material in light timber-framed construction since 1980 appeared to be justified. The damage sustained by the linings in these houses was less than that sustained by the linings in older houses. Houses in the hill suburbs sustained greater damage to the veneer cladding and the linings than those on the flat, unless those on the flat had been distorted severely by liquefaction effects. This was thought to be due to the higher-frequency shaking that occurred on the hills and the proximity of the February earthquake epicentre to the hills. Furthermore, with the houses constructed on sloping sites, asymmetric foundations and multiple foundation types are likely to result in greater damage. Eccentric upper-floor bracing layouts, caused by large openings to take advantage of views, are also likely causes of heavier damage.

Contents

1. INTRODUCTION 1
2. SURVEY OPPORTUNITY 1
3. 2011 SURVEY PROCESS 1
   - 3.1 Site selection and occupier notification 1
   - 3.2 Survey form development 2
   - 3.3 Survey work 3
   - 3.4 Survey database 3
4. SURVEY RESULTS 3
   - 4.1 Site information 3
   - 4.2 Building age 3
   - 4.3 Number of storeys 5
   - 4.4 House footprint 5
   - 4.5 Plan shape 6
   - 4.6 Vertical regularity 7
   - 4.7 Foundation style 7
   - 4.8 Subfloor height 8
   - 4.9 House superstructure 9
     - 4.9.1 Structural frame 9
     - 4.9.2 Wall claddings 9
     - 4.9.3 Roof claddings 9
     - 4.9.4 Interior linings 10
5. DATA GATHERED SUBSEQUENT TO THE SURVEY 10
6. ANALYSIS OF DAMAGE RECORDS 10
   - 6.1 Foundations 11
   - 6.2 Wall cladding systems 12
     - 6.2.1 Analysis methodology for veneer cladding damage 13
     - 6.2.2 Comparison of veneer damage with PGA 13
     - 6.2.3 Comparison of veneer damage with house age 14
     - 6.2.4 Comparison of veneer damage with house shape 15
     - 6.2.5 Comparison of veneer damage with site topography 16
   - 6.3 Wall lining systems 17
     - 6.3.1 Analysis methodology for lining damage 17
     - 6.3.2 Comparison of lining damage with PGA 18
     - 6.3.3 Comparison of lining damage with house age 18
     - 6.3.4 Comparison of lining damage with plan shape 19
     - 6.3.5 Comparison of lining damage with topography 20
   - 6.4 Comparison of lining and veneer damage with topography and PGA 20
7. FURTHER ANALYSIS POSSIBLE 22
8. CONCLUSIONS 23

APPENDIX A – REFERENCES 24

APPENDIX B – SURVEY FORM 25

Figures Page

Figure 1. Locations of surveyed houses (CBD = central business district) ... 2
Figure 2. Distribution of site slope characteristics ... 4
Figure 3. Distribution of house age by age band ... 4
Figure 4. Distribution on the basis of number of storeys ... 5
Figure 5. Distribution of house footprint size ... 6
Figure 6. Distribution of plan shape ... 6
Figure 7. Distribution of vertical regularity ... 7
Figure 8. Distribution of foundation styles ... 8
Figure 9. House severely damaged by differential ground settlement and lateral spreading ... 11
Figure 10. Example of reinforced concrete perimeter foundation pulled apart by spreading ground (note reinforcing bar crossing gap in foundation) ... 12
Figure 11. Veneer damage as a function of peak ground acceleration ... 14
Figure 12. Veneer damage as a function of house age (all ground conditions) ... 15
Figure 13. Veneer damage as a function of house age (non-liquefied ground) ... 15
Figure 14. Veneer damage as a function of house shape ... 16
Figure 15. Veneer damage as a function of site topography ... 17
Figure 16. Lining damage as a function of peak ground acceleration ... 18
Figure 17. Comparison of interior lining damage with house age ... 19
Figure 18. Comparison of interior lining damage against plan shape ... 19
Figure 19. Comparison of interior lining damage against topography ... 20
Figure 20. Lining damage as a function of PGA for flat sites ... 21
Figure 21. Lining damage as a function of PGA for hilly sites ... 21
Figure 22. Veneer cladding damage as a function of PGA for flat sites ... 22
Figure 23. Veneer cladding damage as a function of PGA for hilly sites ... 22

Tables Page

Table 1. Percentages of the surveyed houses in the five age bands and breakdown of foundation type for each age band (see Figure 3) ... 8
Table 2. Distribution of wall cladding types on surveyed single-storey and two-storey houses ... 9
Table 3. Numbers of houses with roof cladding type for each age band ... 9
Table 4. Percentage of stucco, masonry and monolithic-clad houses with different types of damage ... 12
Table 5. Summary of the damage categories – veneer ... 13
Table 6. Summary of the damage categories – interior linings ... 17

1. INTRODUCTION

On 4 September 2010, Christchurch was hit by the Richter magnitude 7.1 Darfield earthquake. The quake was centred approximately 40 km west of the Christchurch CBD, at a depth of 10 km. The shaking intensities in Christchurch were in the range of 0.16–0.65 g peak ground acceleration (PGA) in the horizontal direction and 0.05–0.3 g PGA in the vertical direction (Cousins & McVerry 2010). Spectral accelerations were in the order of 0.8 times the design spectral acceleration in the frequency range of typical house structures.

There was a series of aftershocks over the coming months, and on 22 February 2011, a magnitude 6.3 event occurred at a very shallow depth and very close to the Christchurch CBD. The proximity of the earthquake to Christchurch and the timing resulted in severe damage to the building stock and the loss of 185 lives. The range of horizontal PGA recorded in the urban area was 0.2–1.41 g and 0.06–2.21 g in the vertical direction (Bradley & Cubrinovski 2011). Spectral accelerations relevant to typical New Zealand house structures in the February event were of the order of twice the design spectral accelerations in some parts of the city. It is worth noting that only two lives were lost in Christchurch's stock of approximately 150,000 dwellings, and these were the result of a cliff collapse on to the properties.

The severe earthquake motions caused large tracts of sandy soil beneath flat parts of the urban area to liquefy, resulting in a range of severity of ground settlements. The earthquake was centred beneath the Port Hills suburbs between the Christchurch CBD and the port township of Lyttelton. Therefore, houses on the Port Hills were subjected to severe accelerations in both the horizontal and vertical directions. Aftershocks continued for a period of more than a year, mainly small enough that further liquefaction did not occur. However, on 13 June 2011, another significant event (magnitude 6.3) just off the New Brighton beach triggered further liquefaction in some areas and some shaking damage.

2. SURVEY OPPORTUNITY

After the September 2010 event, BRANZ saw an opportunity to study the effects of the earthquake series on typical residential dwellings in greater Christchurch and relate these to site and dwelling characteristics. Subsequent to the survey, other information was obtained that allowed the damage to be related to the peak ground acceleration that occurred at the site. Approximately 100 dwellings were visited in the company of Earthquake Commission (EQC) damage assessors, but this process was not particularly effective. Reliance on the EQC assessors meant that there was a risk of bias in the collection of data depending on the assessors' priorities. Minimal data was also being collected on building damage.

This survey work was still going on at the time of the February 2011 event. It had to cease immediately because of the need to assist the Ministry of Civil Defence and Emergency Management in the safety assessments of houses. It was decided that a different approach was needed for any further survey work.

3. 2011 SURVEY PROCESS

3.1 Site selection and occupier notification

To eliminate as much bias as possible in any future survey process, it was determined that the sampling of houses needed to be as random as possible. Budgetary constraints meant that a manageable sample needed to be obtained while still providing information that was representative of the housing stock. With a population of approximately 150,000 houses, a sample size of 300 houses was settled on (0.2% of the total population).

It was also necessary to efficiently survey the 300 houses. The agreed house selection process involved randomly selecting a little more than 50 mesh blocks from the Statistics New Zealand census database[1]. Mesh blocks are roughly based on numbers of people residing within the block and generally represent an area a little larger than a residential block. Six adjacent houses were selected for surveying at the southeast corner of each mesh block, and the surveyors visited each property. This reduced the amount of travel required between the properties. Figure 1 shows the locations of the mesh blocks where the surveys were undertaken (yellow pins).

Figure 1. Locations of surveyed houses (CBD = central business district)

A letter from the BRANZ CEO was sent to each selected dwelling prior to the visit. This was to inform the occupant of BRANZ's intention to visit them to conduct the survey and to provide assurance that the survey was a bone fide operation. At the time of the survey, the occupant was given a further BRANZ letter introducing the surveyors.

3.2 Survey form development

A comprehensive survey form was created that allowed the surveyor to gather as much information as possible. This included observations about:

- the location of the house
- site hazards (e.g. liquefied soil, susceptible to rock fall)
- construction characteristics (e.g. age, style, shape and size)
- construction materials
- degree of damage sustained by each of the elements of the structure (e.g. foundation, floor, walls and roof).

The form was created in Microsoft Excel because time constraints and database software was not used. The form that had been used in the earlier survey was amended to include more information on the degree of damage observed to allow greater quantification of damage.

A copy of the form is presented in Appendix B – Survey form. Scanned copies of the completed forms have been retained on the BRANZ electronic job file.

[1] www.stats.govt.nz/methods/classifications-and-standards/classification-related-stats-standards/meshblock.aspx

3.3 Survey work

The survey was undertaken in the latter half of 2011. Teams of two BRANZ representatives undertook the survey.

On occasion, an occupant in a mesh block was found not to be home or indicated that they did not want to participate in the survey. A rule was established to go to the next adjacent house and so on to the west of the group to ensure a total of six houses were surveyed in that block.

The surveyors came from different disciplines and included engineers, engineering technicians and building surveyors. All had different previous experience in the collection of data and also different interests. It was often necessary to gather data from the occupants if the evidence of damage had been repaired or access was not possible. Concealed spaces such as subfloors and roof spaces were not always able to be easily checked for damage, and reasonable assumptions about type of structure had to be made. It is possible that damage in these areas was underestimated when it was not apparent from outside. Some more severely damaged houses were not surveyed as they had been demolished by the time the survey took place, which reduced the overall extent of damage recorded in the sample. However, these instances were relatively rare.

3.4 Survey database

All survey records were carefully entered into an Excel spreadsheet for later analysis.

A difficulty using the Excel spreadsheet for data capture was that many columns were required to separate the damage descriptions, and it became unwieldy when attempting to determine trends in the data. Nevertheless, key information on house types and so on was able to be extracted.

4. SURVEY RESULTS

This section presents summaries of the information gathered on the sites, the construction characteristics of the surveyed houses and recorded damage. Correlations were attempted in order to discover any trends in the observations.

4.1 Site information

The sites were classified as either flat, gently sloping, steeply sloping, on a hilltop or on a clifftop. If the property was adjacent to a watercourse, this was also recorded. Figure 2 shows the distribution of site slope characteristics for the sampled properties.

4.2 Building age

The building age was classified to approximately align with changes in standards over the years houses have been built:

- Pre-1930: The first building standard in New Zealand, NZS 35, was published after the 1931 Hawke's Bay earthquake by the New Zealand Standards Institution. However, it wasn't until 1944 that Part IX of this standard, *Light Timber Construction*, was published.
- 1930–1959: From 1930 there was an improvement in house construction standards, culminating in the publication of the 1944 Standard mentioned above.
- 1960–1979: The introduction of NZSS 1900 Chapter 6.1 prescriptive standard.
- 1980–1999: The introduction of NZS 3604:1978, the first engineering-based standard for timber-framed houses.
- Post-2000: The most recent version of NZS 3604 in use at the time of the Canterbury earthquakes, NZS 3604:1999.

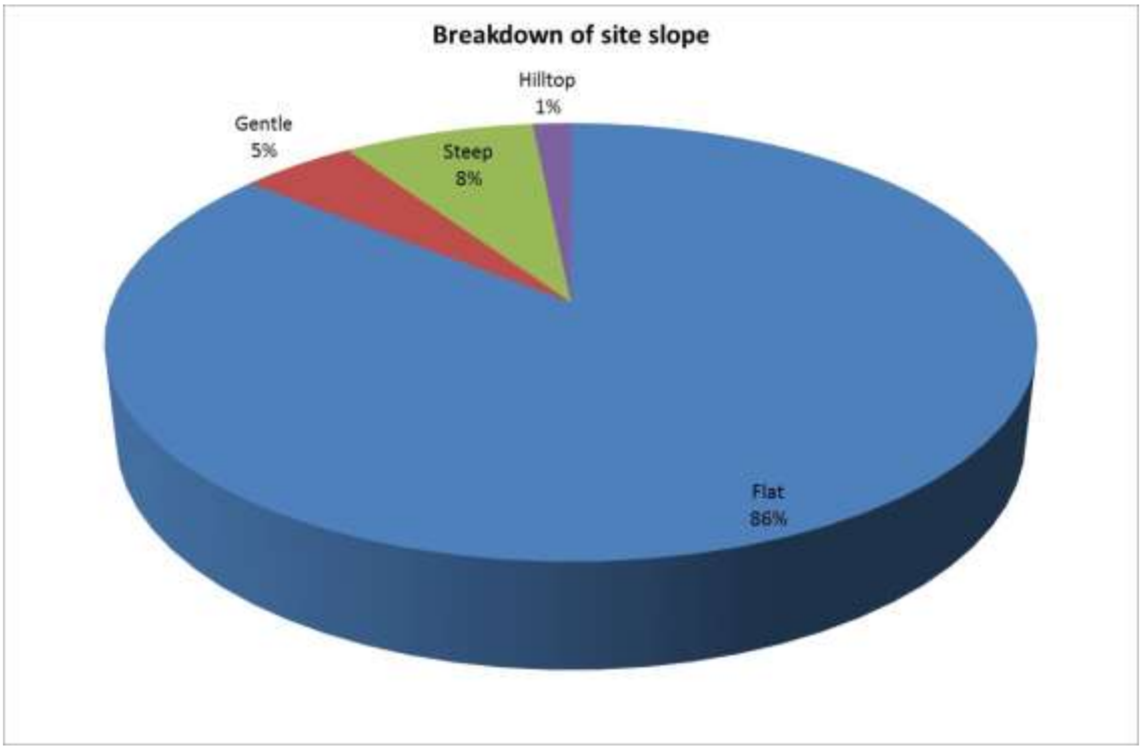

Figure 2. Distribution of site slope characteristics

Figure 3 shows the distribution of houses by age band for the sampled properties. It can be seen from the plot that one-third of the houses were built in the 20-year period 1960–1979. A slightly smaller percentage was built in the 35-year period over which the engineering-based design standard has existed, while 38% of the sample was built prior to 1960.

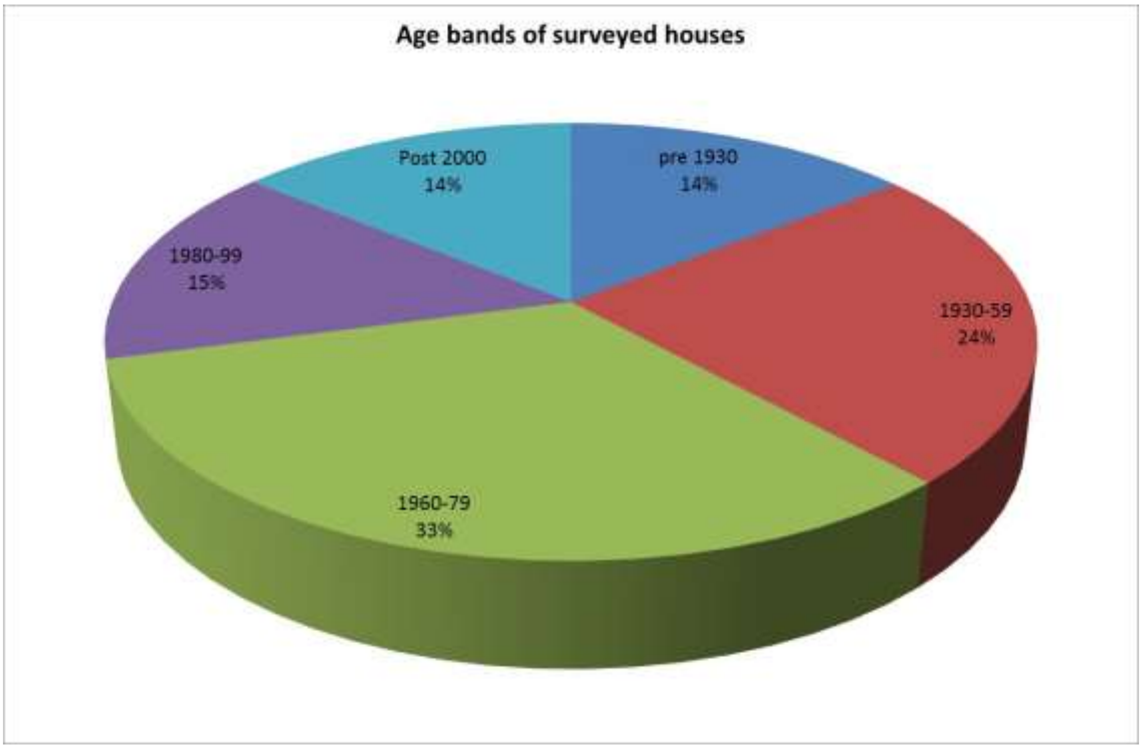

Figure 3. Distribution of house age by age band

4.3 Number of storeys

Three-quarters of the sample was single-storey construction, while the majority of the other quarter was two-storey construction (Figure 4). A small proportion was either three levels or split-level construction.

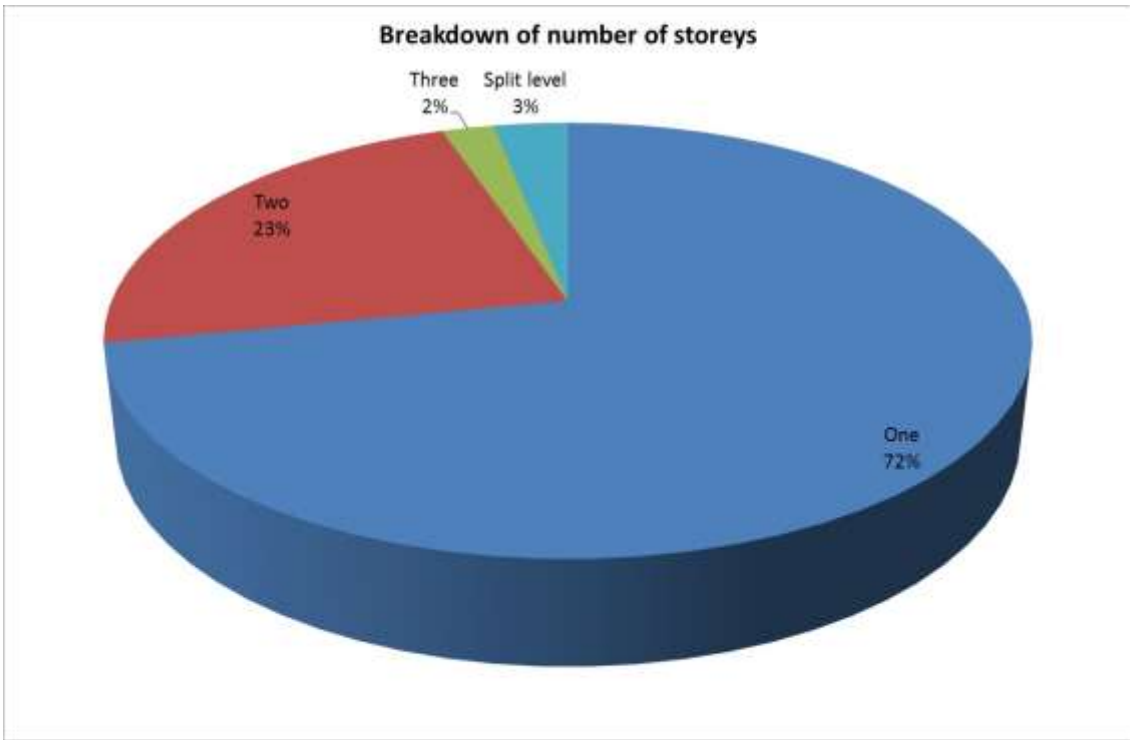

Figure 4. Distribution on the basis of number of storeys

4.4 House footprint

Approximately 20% of the sample of houses had a footprint of 100 square metres or less. Figure 5 shows 42% had a footprint of 101–150 square metres, while the remainder of the sample had a footprint greater than 150 square metres. Typical house floor areas were in the range up to 150 square metres up until about 1992. Since that date, the average floor area size of new houses has increased. Unfortunately, the survey did not differentiate between total floor area and footprint size.

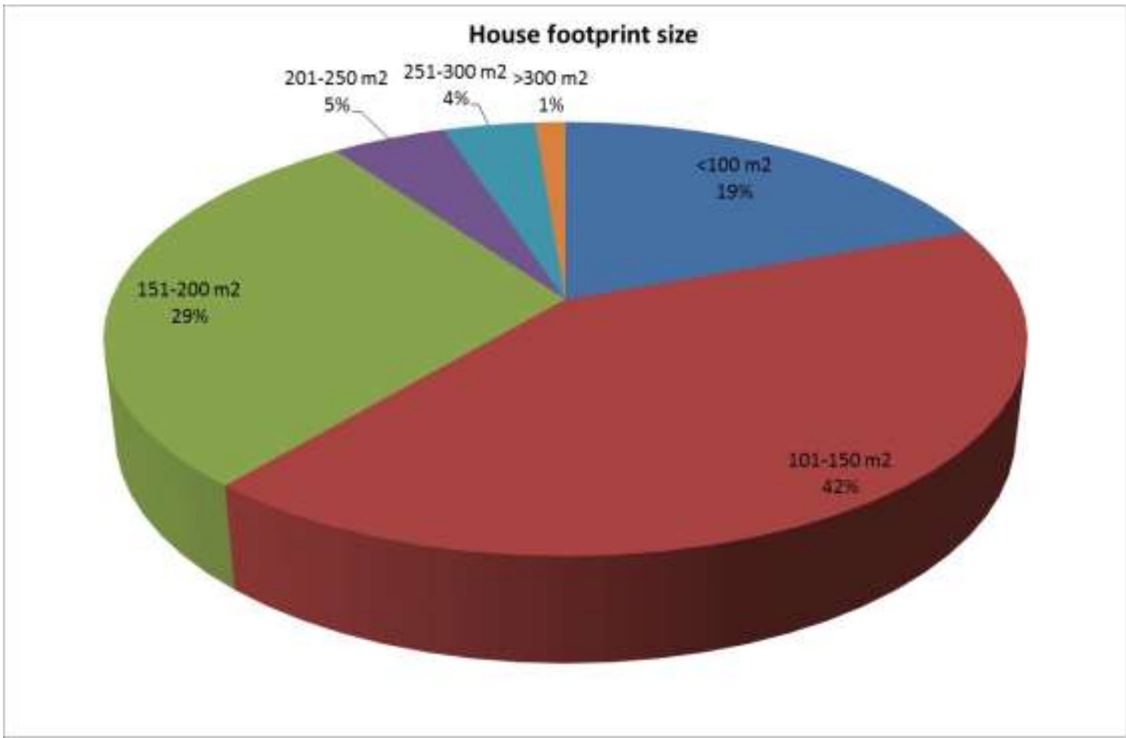

Figure 5. Distribution of house footprint size

4.5 Plan shape

A little over half of the sample had a mostly rectangular plan shape, while the remainder was mainly either L or T shaped (Figure 6). 'Mostly rectangular' is defined as houses that are rectangular or square or with a slight deviation from rectangular. For example, a small extension of a room a few metres outside the otherwise rectangular plan was classified as "mostly rectangular". Approximately 10% had a complex shape.

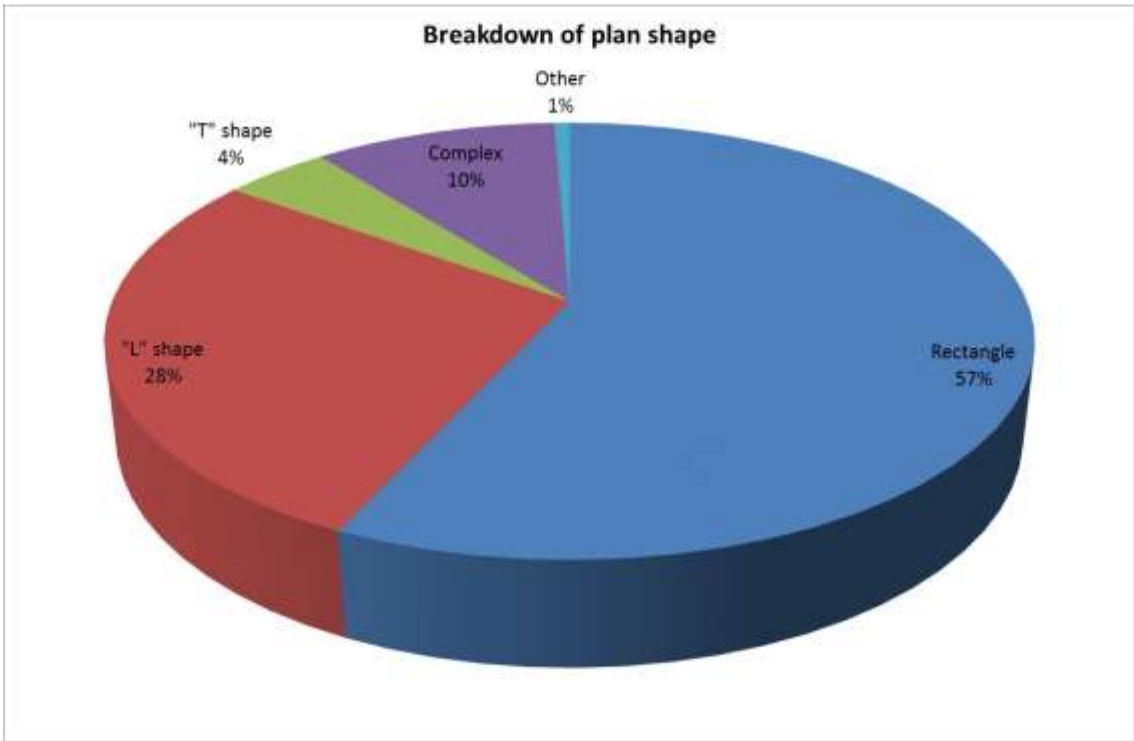

Figure 6. Distribution of plan shape

4.6 Vertical regularity

Approximately three-quarters of the sample had a uniform regularity between floors. Because 72% of the houses were single storey (Figure 4), this means that they automatically had uniform vertical regularity. Therefore, 4% of the total number of surveyed houses had more than one storey and vertical regularity. The remaining 24% had either a stepped subfloor, a stepped upper floor or a reduced upper floor (Figure 7).

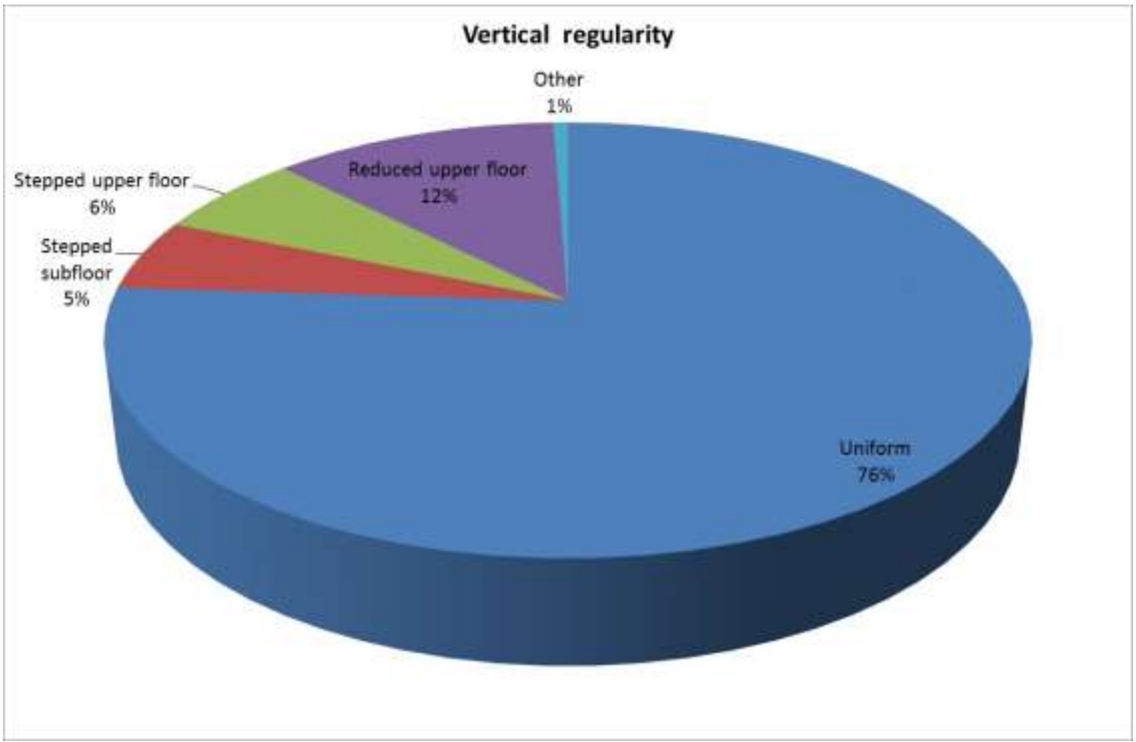

Figure 7. Distribution of vertical regularity

4.7 Foundation style

House foundation styles fall generally into one of three categories – all piles, piles with perimeter concrete foundation and slab on grade. Variations can occur with the perimeter foundation style. Sometimes, the perimeter foundation only supports the veneer, and the timber subfloor framing is not attached to it.

It is also common for houses to have a mix of foundation styles, particularly if they are located on sloping ground. Figure 8 shows 79% of the surveyed houses fitted within one of the three main categories, and 21% were a mixture of styles or an alternative style such as timber poles.

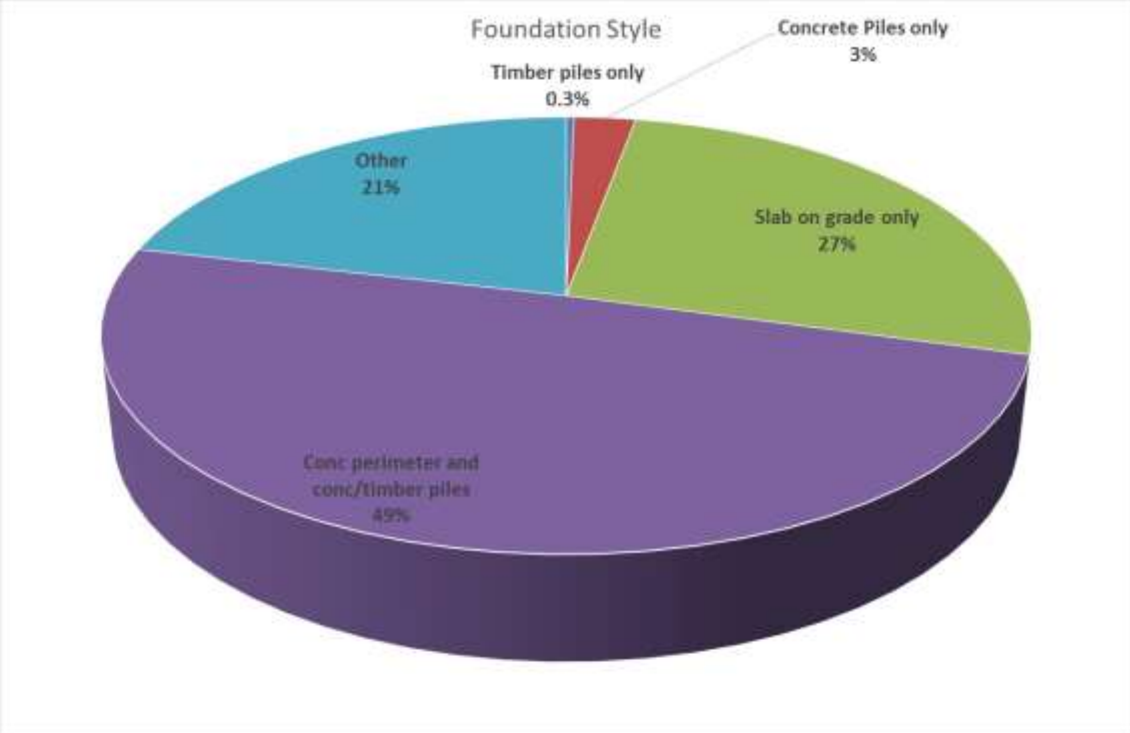

Figure 8. Distribution of foundation styles

The 49% of the sample that had concrete perimeter foundations and piles appears to be well representative of the stock in the city. This style of foundation was popular on the flat land from the early 20th century through until the 1980s when concrete slab-on-grade floors became more popular. In the hillside houses, the floor was often supported on jack studs on short piles

A breakdown of the gathered data, comparing house age against foundation style, also confirmed this observation, as can be seen in Table 1.

Table 1. Percentages of the surveyed houses in the five age bands and breakdown of foundation type for each age band (see Figure 3)

Age band	Percentage of surveyed houses	Percentage of slab-on-grade houses in the age band	Percentage of houses with perimeter foundations in the age band	Percentage of other foundation types in the age band
Pre-1930	14	2	65	33
1930–1959	24	5	87	8
1960–1979	33	21	79	0
1980–1999	15	63	33	4
2000 onwards	14	87	7	6
All ages	**100**	**31**	**63**	**6**

4.8 Subfloor height

The survey captured minimum and maximum heights of the subfloor space for structures that did not have slab-on-grade floors (approximately 230 houses):

- 169 (74%) had subfloor spaces that were not greater than 600 mm high.
- 31 houses had a variable-depth subfloor height ranging from a minimum of less than 600 mm and a maximum that ranged from 600 mm to more than 2.5 m.
- 18 had subfloor spaces that varied between 600 mm and 1 m in height.

- 2 had minimum heights between 600 mm and 1 m and maximum heights greater than 1 m.

4.9 House superstructure

4.9.1 Structural frame

Of the 233 single-storey dwellings surveyed, 228 were framed. It was not possible on most occasions to tell whether the framing was timber or light-gauge steel, because the damage to the dwelling was insufficient to reveal the framing. Light-gauge steel framing is a relatively new construction type in New Zealand, and therefore it is expected that the great majority of the surveyed houses had timber framing.

The other five houses had concrete, concrete masonry or unreinforced brick masonry walls. Of the 74 two-storey dwellings surveyed, 80% had framed bottom storeys, and 20% had concrete or concrete masonry bottom storey walls. In all but one of these cases, the top floor was framed.

4.9.2 Wall claddings

Several cladding systems are common in New Zealand. These include timber weatherboards, brick/block veneer and stucco, although the latter has become uncommon in recent times.

Table 2 shows the distributions of cladding on the surveyed houses. It can be seen that the totals for the lower and upper storeys of the two-storey houses are greater than the 74 two-storey houses surveyed. In both cases, the reason is that some houses had more than one cladding type.

Table 2. Distribution of wall cladding types on surveyed single-storey and two-storey houses

Cladding type	Single-storey houses	Two-storey houses	
		Lower storey	Upper storey
Weatherboards	70 (30%)	28 (29%)	36 (37%)
Brick/block veneer	128 (55%)	29 (31%)	14 (15%)
Stucco	34 (14%)	8 (8%)	7 (7%)
Ply or fibre cement sheets	10 (4%)	9 (9%)	17 (18%)
Exterior insulation and finishing system (EIFS)	7 (3%)	8 (8%)	7 (7%)
Other	8 (3%)	13 (14%)	15 (16%)
Total	**233**	**95**	**96**

4.9.3 Roof claddings

The most common roof claddings in use in New Zealand in the first half of the 20th century were corrugated steel and concrete tiles. In the last 60 years, there has been an increase in the use of pressed metal tiles and clay tiles. However, the use of heavy tiles in general has decreased over the last 30 years. Other systems such as rubber membranes, asphaltic tiles and shingles have rarely been used in New Zealand.

Table 3 provides a distribution of roof cladding types versus the age band of the house for the surveyed houses.

Table 3. Numbers of houses with roof cladding type for each age band

Age band	Heavy tiles	Sheet cladding (e.g. corrugated steel	Metal tiles	Other	Total
Pre-1930	2 (3%) [4%]	37 (20%) [79%]	6 (12%) [13%]	2 (22%) [4%]	47 [100%]
1930-1959	29 (41%) [39%]	32 (17%) [43%]	11 (22%) [15%]	2 (22%) [3%]	74 [100%]
1960-1979	32 (45%) [32%]	57 (31%) [56%]	12 (24%) [12%]	0 (0%) [0%]	101 [100%]
1980-1999	5 (7%) [11%]	32 (17%) [68%]	8 (16%) [17%]	2 (22%) [4%]	47 [100%]
2000 onwards	3 (4%) [7%]	27 (15%) [60%]	12 (24%) [27%]	3 (34%) [6%]	45 [100%]
Total	**71 (100%)**	**185 (100%)**	**49 (100%)**	**9 (100%)**	**314**

4.9.4 Interior linings

Up until the 1940s, lathe and plaster was a common lining system for New Zealand houses. Gypsum-based plasterboard was introduced in the late 1920s and is now the most popular lining material. Fibrous plaster was also popular from the 1950s until the 1980s because it had a very smooth face for accepting wallpapers.

Of the surveyed houses, 79% were lined with plasterboard, 18% with lathe and plaster, 8% with fibrous plaster and 8% with other linings. These percentages total to greater than 100% because some houses had more than one lining type.

Since the first publication of NZS 3604 in 1978, plasterboard linings have fulfilled a bracing role in timber-framed houses. Prior to this, bracing was provided by diagonal timber braces in the wall framing, and the plasterboard was not designed to have a structural function.

5. DATA GATHERED SUBSEQUENT TO THE SURVEY

A series of seismographs scattered throughout Christchurch recorded accelerations during the February 2011 and June 2011 events. Peak ground acceleration (PGA) contour maps were produced using the information gathered at these sites and published on the Canterbury Geotechnical Database. Peak ground acceleration data was interpolated to the nearest 0.1 g from the contours for each site and added to the database following the survey. This allowed comparisons of behaviour to be made against experienced ground accelerations.

6. ANALYSIS OF DAMAGE RECORDS

Of the 314 houses surveyed, 167 were damaged in the September 2010 event, 237 in the February 2011 event and 136 in the June 2011 event. It is not known when 20 of the houses were damaged. Only 10% of the houses surveyed had sustained no damage. In many houses, damage was limited to joint cracks in plasterboard linings or cracking in fibrous plaster or plaster and lathe.

Much of the damage to houses on the flat was due to differential ground settlement and lateral spreading associated with liquefaction and varied from quite minor to major (Figure 9).

In houses not affected by ground liquefaction, the most obvious signs of house damage viewed from outside were failed unreinforced masonry chimneys on older houses and the loss of portions of veneer.

In the hill suburbs, the shaking was more severe, resulting in substantial damage to brick veneer claddings, heavy tile roofs and interior linings.

Figure 9. House severely damaged by differential ground settlement and lateral spreading

6.1 Foundations

Slab-on-grade foundations generally performed well under earthquake shaking. Sometimes, severe distortion of a concrete slab was a result of ground deformation beneath the slab. This was caused by liquefaction settlement or lateral ground spreading on the flat or ground slumping in the hill suburbs.

Of the surveyed properties, 81 had some evidence of liquefaction on the site – 18 were slab-on-grade foundations, and 14 were classified as undamaged (78% of the slab-on-grade sample). Of those with cracking, it was identified as minor (<5 mm wide) in the slab-on-grade sample on liquefied ground.

Of the slabs in properties that did not experience liquefaction, 91% were undamaged. The number of properties with slab damage was a smaller percentage of the total than for slabs on liquefied sites, but the damage was more pronounced in the slabs of these properties. Significant rupture was reported in two properties and significant misalignment reported in four properties. Only one of these was situated on a steep hillside, where slumping might have occurred, so the reason for the significant damage in stable ground is uncertain.

The common perimeter concrete foundation in combination with internal piles also fared well under ground shaking but was affected by varying degrees by the ground movement. It was usual for these perimeter foundations to be unreinforced in the early to mid-20th century houses, but most foundations constructed after this contained at least one 12 mm diameter bar, often plain. Whether reinforced in this way or not, these foundations were unable to resist the ground deformations associated with lateral spreading and severe liquefaction, and they fractured (Figure 10).

Figure 10. Example of reinforced concrete perimeter foundation pulled apart by spreading ground (note reinforcing bar crossing gap in foundation)

If not attached to the subfloor framing, they were sometimes observed to pull away from the framing, carrying the veneer cladding with them. Fifty seven of the surveyed properties with perimeter foundations were located where the ground had liquefied, and 24 (42%) of these were undamaged. Of those that were damaged, the majority had up to 10 cracks that were up to 5 mm wide, although more than two-thirds of this number had fewer than five cracks. Six houses at liquefied sites had ruptured perimeter foundations. Of the 140 perimeter foundations on land that had not liquefied, 90 (64%) were undamaged. When cracked, these foundations tended to have small numbers of narrow cracks that probably pre-existed and resulted from shrinkage and ground consolidation prior to the earthquakes. Two perimeter foundations had ruptured, and both were on steep sites where slumping was likely to have occurred.

6.2 Wall cladding systems

Table 4 shows the extent of damage for different wall cladding systems – 72% of houses with brick/block veneer claddings, 76% with stucco claddings and 67% with monolithic claddings sustained damage. About a quarter of all veneer-clad houses surveyed had a significant proportion where cladding fell off or was detached or unstable. Almost all veneer-clad buildings with more than 10% of cladding fallen, detached or unstable were in the hill suburbs. The balance were mostly houses with separate unattached foundations for the brick veneer and the framing. Veneers constructed after the mid-1990s performed much better than earlier construction because of improvements in the tie fixing systems to the framing that were introduced at that time.

Table 4. Percentage of stucco, masonry and monolithic-clad houses with different types of damage

	% cracked			% fallen, detached, unstable			% with cracks over substrate joints		
Area of wall affected	**>50%**	**10–49%**	**<10%**	**>50%**	**10–49%**	**<10%**	**>50%**	**10–49%**	**<10%**
Stucco	10	26	38	0	0	0	-	-	-
Veneer	12	18	41	11	6	8	-	-	-
Monolithic (plastered sheet materials, EIFS)	0	5	10	0	0	0	2	24	38

The majority of houses surveyed with monolithic cladding suffered from some sort of cracking, but only 21 houses of this type were surveyed. Most of the cracking was from the corners of windows, and experimental studies conducted at BRANZ some years earlier (Beattie 2006) had indicated that such damage was relatively easy to repair. The damage to weatherboard claddings was not specifically recorded because it was generally observed to be very low.

6.2.1 Analysis methodology for veneer cladding damage

As can be seen from Table 2, veneer was a predominant cladding for single-storey houses and also popular for two-storey houses. For the veneer systems, the survey recorded whether there was no damage to the veneer or whether it was cracked or detached/unstable or had fallen from the house. For each house, the surveyor estimated the percentage of each type of damage and recorded this in one of six ranges (<10%, 10–24%, 25–49%, 50–79%, 80–89% and 90–100%). A single value for overall damage was necessary for statistical analysis, so these levels of damage were assigned values of 0–6 respectively, where 0 represented no damage. Based on the level of damage observed in laboratory tests of veneer claddings on the extent of damage, a decision was made to assign a four-fold increase in values. The integer value for detached/unstable is therefore multiplied by 4 and by 16 for fallen panels. The three values are added together to give an overall weighted value score that covered the damage condition of the whole of the veneer, which can vary from 1 to 126. For example, if the surveyor noted that 10–24% of the veneer was cracked, 50–79% was detached and 25-49% had fallen from the house, the score would be (2 x 1) + (4 x 4) + (3 x 16) = 66. The set of final scores was analysed and cut-off points for the damage levels given as shown in Table 5. As most of the sample had limited damage, the cut-off points are biased towards the bottom end of the scale to give similar numbers in each group.

With a single value for damage, the overall damage could be assessed against a number of variables.

Table 5. Summary of the damage categories – veneer

Category	Veneer damage
Undamaged	0
Minimal	1
Minor	2
Moderate	3–10
Major	11–126

6.2.2 Comparison of veneer damage with PGA

To facilitate easier manipulation of the data, the information was copied into the commercial statistical software package SPSS, licensed to Victoria University of Wellington, so that quantitative statistical analysis could be undertaken.

It was intended that the damage to claddings be compared against the highest peak ground acceleration (PGA) from either the February 2011 or the June 20111 event. However, from the PGA contour maps, none of the houses surveyed underwent a higher PGA in June than February, so only February values were used for comparison. Figure 11 compares PGA against damage to veneer claddings. The expected result would be that damage would generally increase with increased PGA for claddings, which would show up as higher percentages for the lower PGA for undamaged and minimal damage observations. As the PGA increased, higher percentages would be expected for the major damage observations. This expectation was met, which gives confidence in the accuracy of the survey, but there were some anomalies. There was a slightly lower proportion of houses subjected to a PGA of 0.2 and 0.3 in the undamaged category than those subjected to a PGA of 0.4. There were more in this category subjected to a PGA of 0.6 than a PGA of 0.5. There is some variation due to statistical variation, but an obvious explanation for this discrepancy is the effect of liquefaction on damage to houses on sites that experienced a lower PGA.

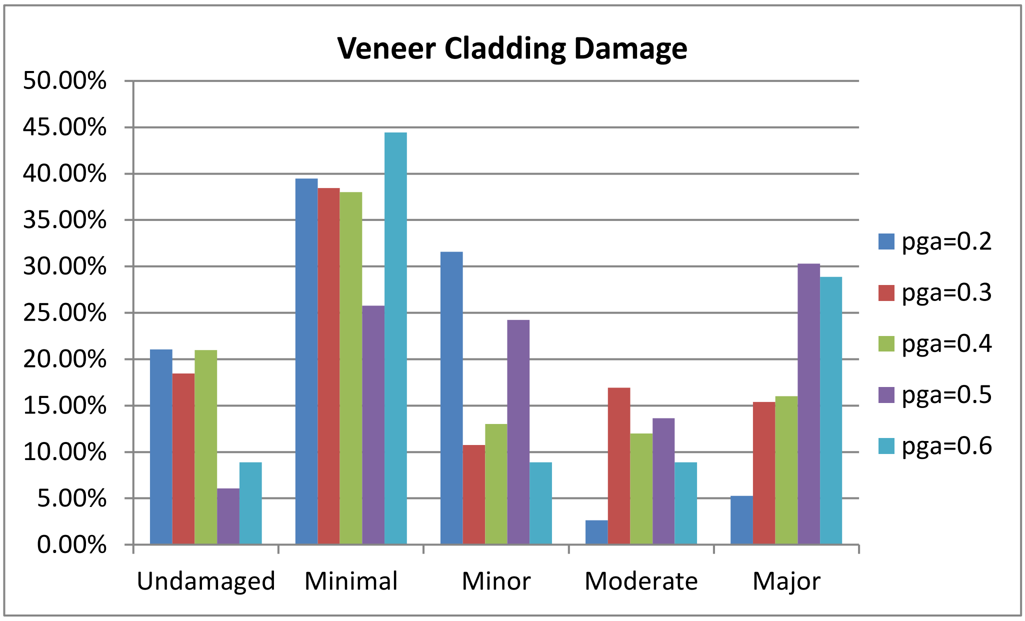

Figure 11. Veneer damage as a function of peak ground acceleration

6.2.3 Comparison of veneer damage with house age

House age was divided into pre-1980 and post-1980. This corresponds with the introduction of NZS 3604 *Code of practice for light timber frame buildings not requiring specific design* in 1978, with some allowance for uptake of the new standard. Figure 12 shows a comparison of veneer cladding damage against house age for all houses where veneer was present.

The percentage of post-1980 houses with damage was always significantly less than the pre-1980 house sample, across the range of damage levels. In the mid-1990s, changes were made to the standardised requirements for tying brick veneers to the framing. It was therefore expected that the performance of these veneers would be significantly better than veneers installed earlier. However, observations immediately after the earthquakes (Buchanan et al. 2011) indicated there were often bond issues between the mortar and the bricks in relatively new construction, leading to collapse of the veneer.

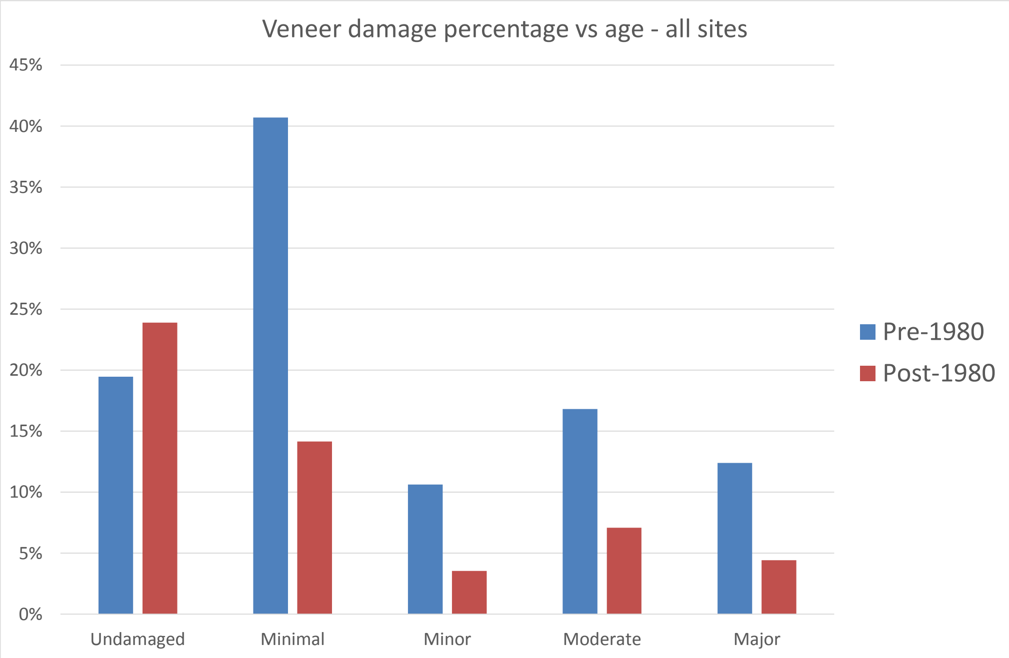

Figure 12. Veneer damage as a function of house age (all ground conditions)

Approximately 80% of the surveyed houses with veneers were on sites where no liquefaction had occurred. Shaking was therefore the major cause of any damage to the veneer. Figure 13 presents similar data to Figure 12 for these houses. There is no major difference between the trends except that the proportion of veneers with moderate damage has lessened for both age groups. The reason for this difference is not obvious.

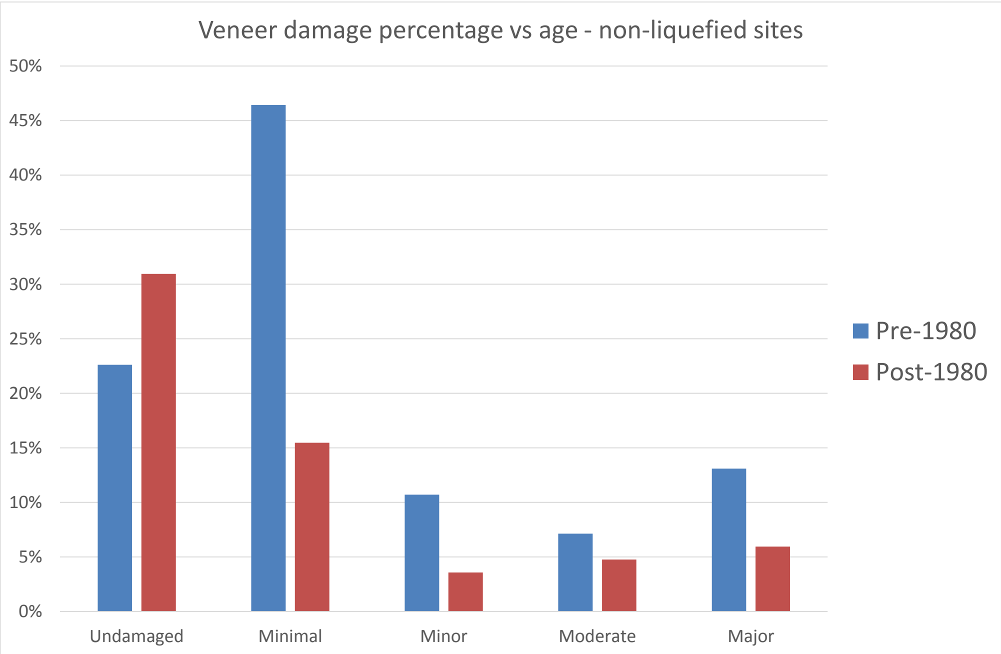

Figure 13. Veneer damage as a function of house age (non-liquefied ground)

6.2.4 Comparison of veneer damage with house shape

Of the houses in the sample, 57% were mostly rectangular (see section 4.5 for a definition). Non-rectangular (complex) houses had more damage overall to claddings (Figure 14). Mostly rectangular houses are more likely to be in the undamaged or minimal categories for veneer damage, and this is confirmed by Figure 14. Close to 35% of the rectangular houses had no veneer damage compared to less than 25% of the non-rectangular houses. When damage did occur, with the exception of the major damage band, the non-rectangular houses had greater percentages of the sample. There is likely to be significant differential movement between two planes of cladding meeting at a re-entrant corner with confinement by the other plane of cladding and wall framing limiting differential movement. Therefore the cladding can generally only crack, displace or fall off, which could explain some of the additional damage.

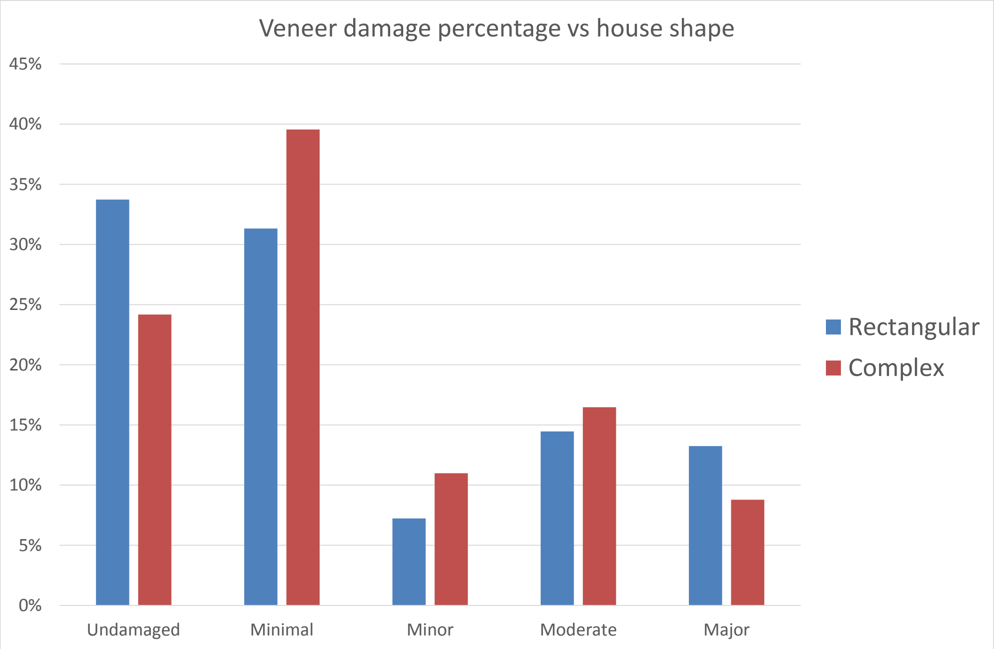

Figure 14. Veneer damage as a function of house shape

6.2.5 Comparison of veneer damage with site topography

The effect of topography on damage is marked. Figure 15 shows that a large proportion of houses on hilly (sloping or hilltop) sites had some veneer cladding damage. Although the percentage of the sample reduces as the damage level increases, there is a marked jump at the major damage level to 46%. In comparison, 70% of the houses on the flat had either minimal damage or were undamaged and had a very low proportion of major damage. This finding aligns with the fact that the level of shaking was higher in hill suburbs, with some particularly high vertical accelerations recorded.

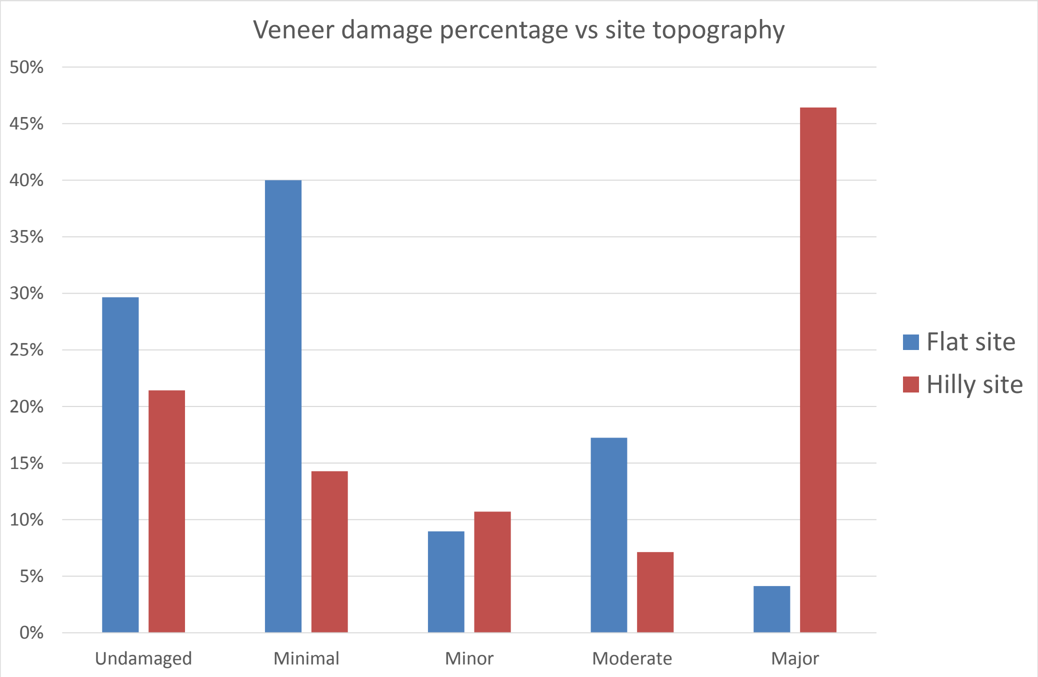

Figure 15. Veneer damage as a function of site topography

6.3 Wall lining systems

As noted in section 4.9.4, a large number of the surveyed houses were lined with plasterboard. It has greater stiffness than the diagonal braces used for bracing before plasterboard became acceptable as a bracing material, so it tends to sustain cracking damage early, particularly at sheet junctions. The concentration of analysis effort was therefore focused on the damage to the plasterboard against several other parameters.

6.3.1 Analysis methodology for lining damage

The methodology for the analysis of lining damage was similar to that for the consideration of veneer damage (section 6.2.1). The survey recorded joint cracking, diagonal cracks or detached sheets. For each house, the surveyor estimated the percentage of each type of damage and recorded this in one of six ranges (<10%, 10–24%, 25–49%, 50–79%, 80–89% and 90–100%). As with veneer cladding, a single value for overall damage was necessary for statistical analysis, so these levels of damage were assigned values of 0–6 respectively, where 0 represented no damage. Based on the level of damage observed in laboratory tests of wall linings on the extent of damage, a decision was made to assign a four-fold increase in values. The integer value for diagonal cracking is therefore multiplied by 4 and by 16 for fallen sheets. The three values are added together to give an overall value score, which can vary from 1 to 126. The set of final scores was analysed and cut-off points for the damage levels given as shown in Table 6. As most of the sample had limited damage, the cut-off points are biased towards the bottom end of the scale to give similar numbers in each group.

Table 6. Summary of the damage categories – interior linings

Category	Interior lining damage
Undamaged	0
Minimal	1
Minor	2
Moderate	3–6
Major	7–126

6.3.2 Comparison of lining damage with PGA

As reported above, 79% of the houses were lined with plasterboard. Figure 16 gives a plot of damage to all linings versus peak ground acceleration (PGA) . Of the 57 properties that had major damage recorded, one-third had linings that were other than plasterboard, a figure disproportionate to the material proportions in the sample. However, this skewing is to be expected because the majority of non-plasterboard linings were either lathe and plaster or fibrous plaster. The first of these is very brittle and the second cracks easily, resulting in high damage levels.

It is worth noting that quite a high proportion of the sample (approximately 55%) sustained no damage, regardless of the PGA. While not so clear for the minor and moderate damage categories, the trend to fewer instances of minimal damage and more instances of major damage as the PGA increases is obvious.

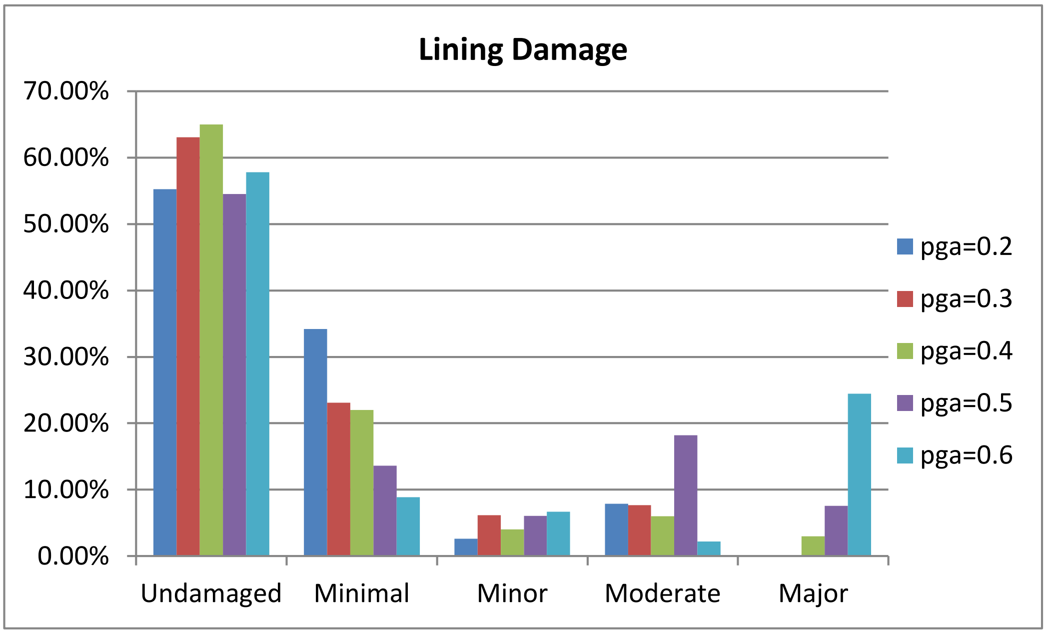

Figure 16. Lining damage as a function of peak ground acceleration

6.3.3 Comparison of lining damage with house age

With the introduction of NZS 3604 in 1978, an engineered approach to the provision of bracing in light timber-frame houses was introduced. By that time, lathe and plaster and fibrous plaster were also no longer used as wall linings. Therefore, a comparison of lining performance against house age should show an improvement in performance after 1980.

Figure 17 presents a plot of recorded lining damage against age. Although older and newer houses had a similar proportion in the moderate category, overall, the older houses performed slightly worse, with more in the minor and major category. Pre-1980s houses had slightly fewer openings. More importantly, the location of openings around the houses, as measured by the relative proportions of windows recorded in the survey on each side, is more even. It can be inferred that improvement in bracing performance with NZS 3604 has been largely countered by a trend for dominant openings on one or two adjacent sides of a house. An increase in the overall amount of openings has contributed to a lesser extent.

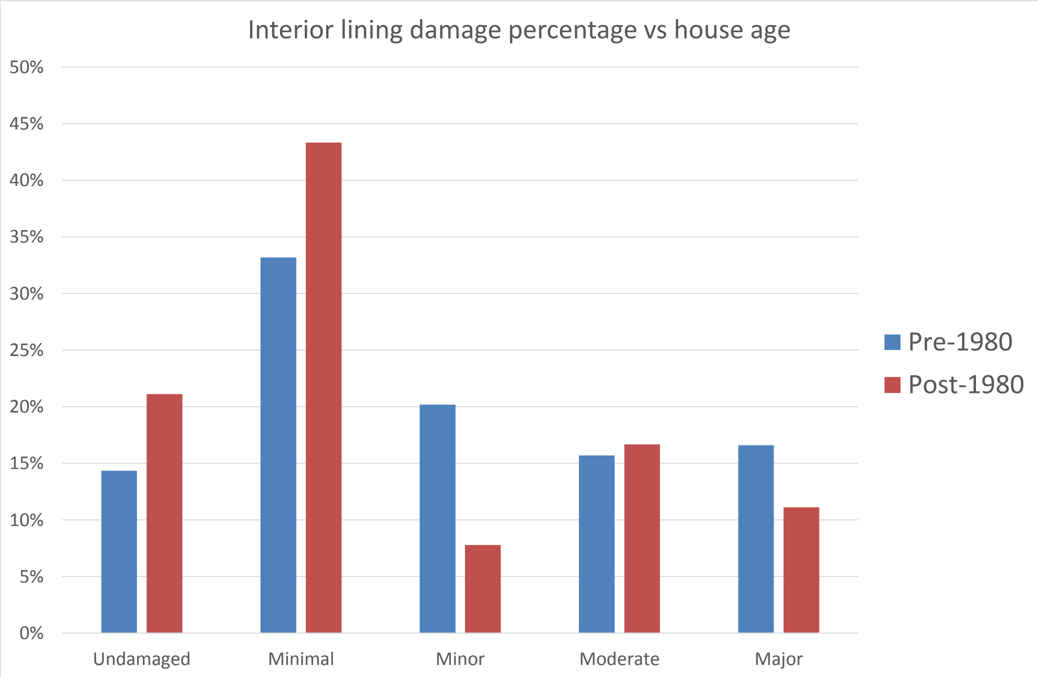

Figure 17. Comparison of interior lining damage with house age

6.3.4 Comparison of lining damage with plan shape

A complex plan shape is expected to result in more damage to interior linings because of potential movement at junctions between the various parts of the building. Figure 18 presents a comparison between the damage sustained by the two shapes (57% of the houses in the sample were rectangular). The expectation is largely justified – a greater proportion of the complex properties experienced minor and moderate damage whereas a greater proportion of the rectangular houses had either no or minimal damage.

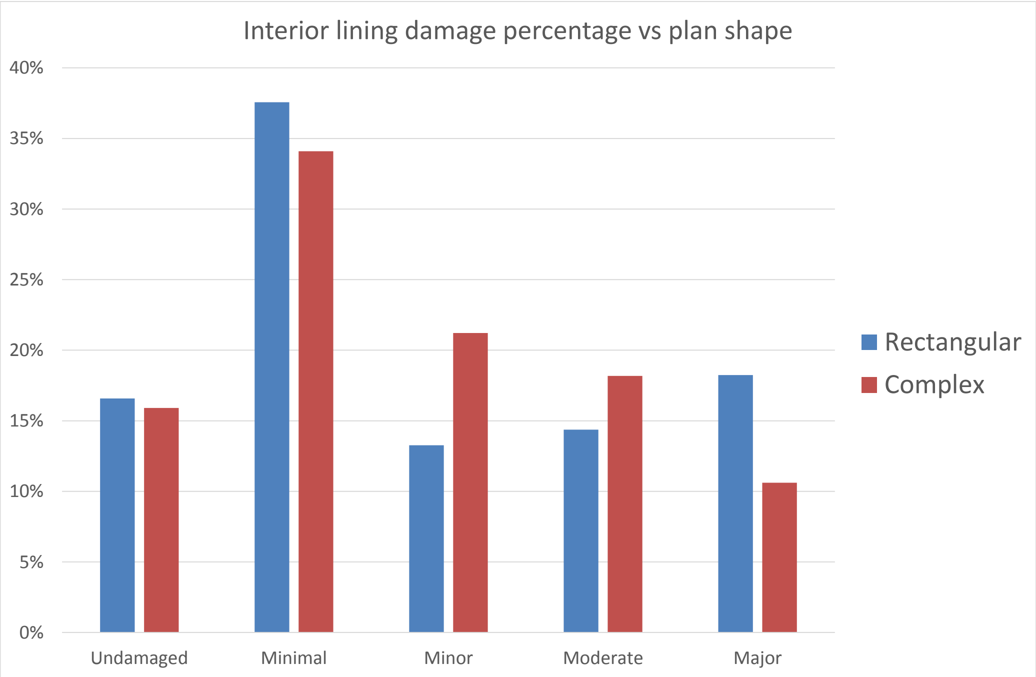

Figure 18. Comparison of interior lining damage against plan shape

The exception was the major damage category where the rectangular-shaped dwellings fared worse than the complex ones. A visual inspection of the survey records did not identify any particular reason for this anomaly. One possible reason for the greater damage may have been related to the combination of shape and age. Rectangular houses tend to be of an older vintage. It is possible that the major damage was associated with failure of relatively sparse fixings compared to more modern construction with plasterboard wall linings fixed more regularly. Further interrogation of the records revealed that 29 of the 33 houses with rectangular shape and major damage were built before 1980.

6.3.5 Comparison of lining damage with topography

Figure 19 presents a plot of lining damage with topography. The effect of topography on damage is marked. All houses on hilly (sloping or hilltop) sites had some lining damage. In the minimal and minor categories, a higher proportion of houses were on the flat, but 66% of the houses on hilly sites had moderate or major damage to linings. This should be compared to only 25% of the houses on the flat with moderate or major damage. This observation appears to confirm that, unless houses were badly damaged by liquefaction settlement on the flat, the performance of their linings was significantly better than those in houses on the hills.

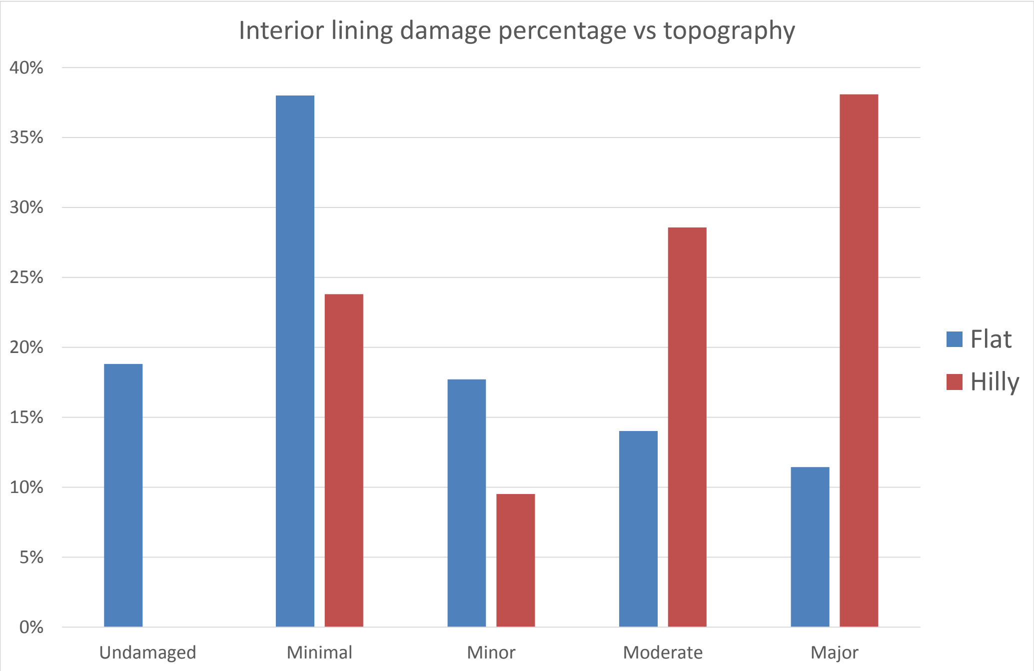

Figure 19. Comparison of interior lining damage against topography

6.4 Comparison of lining and veneer damage with topography and PGA

Figure 20 and Figure 21 provide a breakdown of the damage to linings on flat and hilly sites respectively, versus peak ground acceleration (PGA). Figure 21 shows that all houses on hilly (sloping or hilltop) sites had some lining damage. Although in the minimal and minor categories a higher proportion of houses were on the flat, over 50% of houses on hilly sites had major damage to linings. The same trend, although less marked, is apparent for veneer damage, with over 30% of the houses on hilly sites having major damage to veneer claddings. This finding is complicated by the fact that the level of shaking was higher in hill suburbs.

The results for veneer claddings have been separated for flat and hilly sites compared with PGA in Figure 22 and Figure 23.

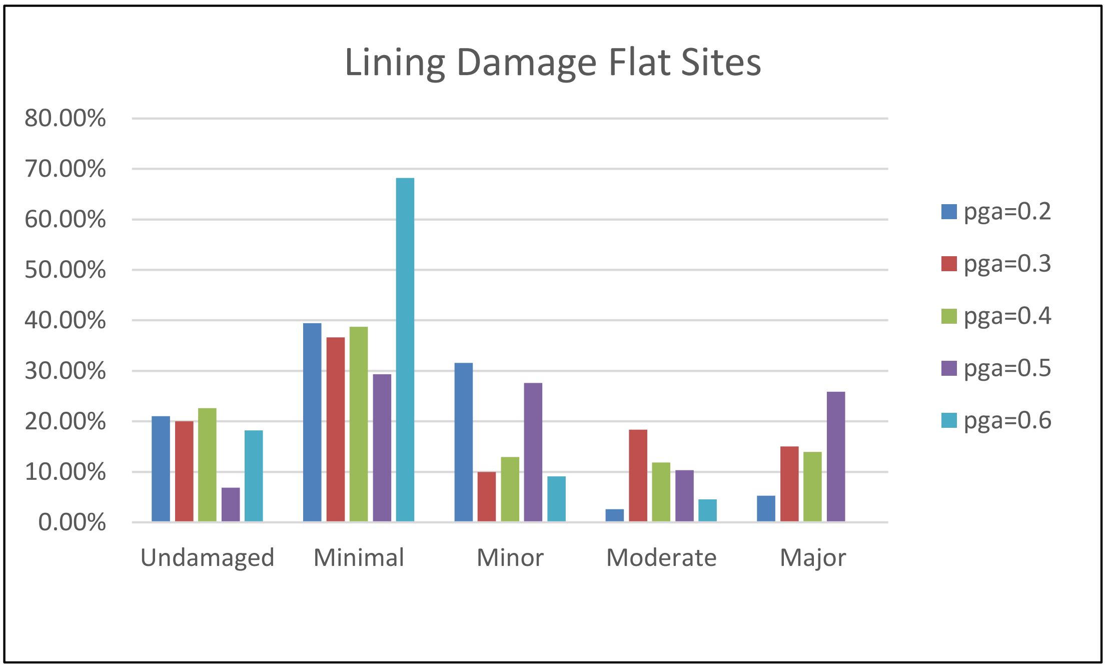

Figure 20. Lining damage as a function of PGA for flat sites

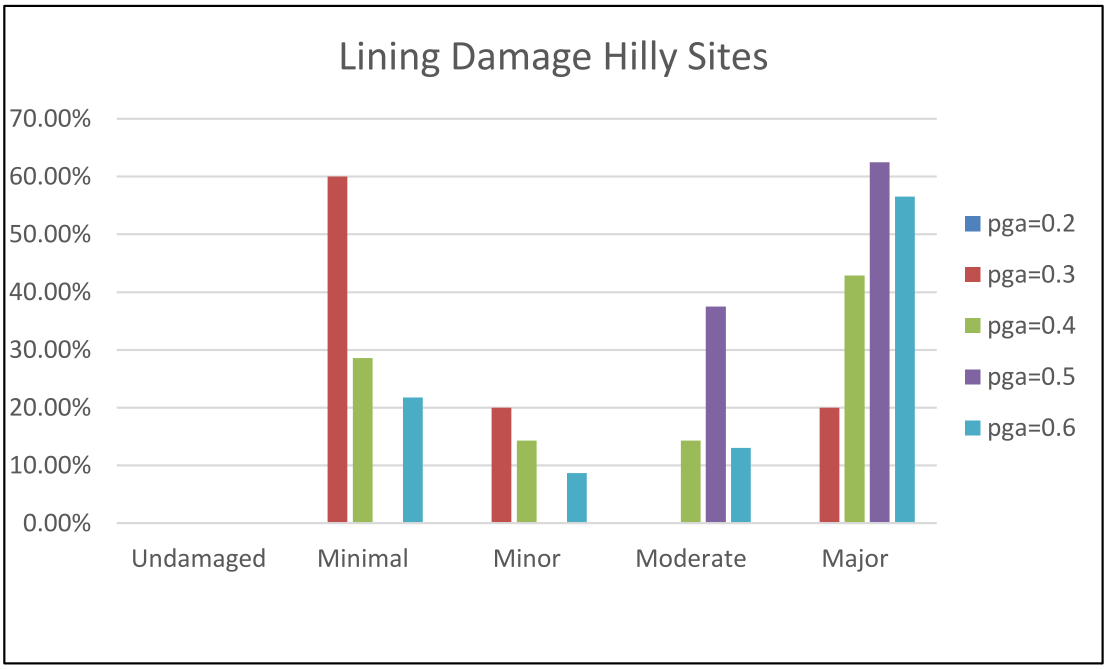

Figure 21. Lining damage as a function of PGA for hilly sites

It is difficult to draw general conclusions from the middle of the range of lining damage, but at the extremes, findings are more obvious. No houses on hilly sites had linings that were undamaged, regardless of the PGA, but on flat sites, about 17% were undamaged. In the major category, there are a much higher proportion of houses, regardless of PGA, on hilly sites.

For cladding damage, because of the smaller sample size for both hilly and flat sites, there is more scatter in the data. However, there appears to be some evidence of a trend of more damage in hilly sites regardless of PGA. The effect of site topography on shaking damage would likely be more marked if the properties with liquefaction effects were removed from the sample.

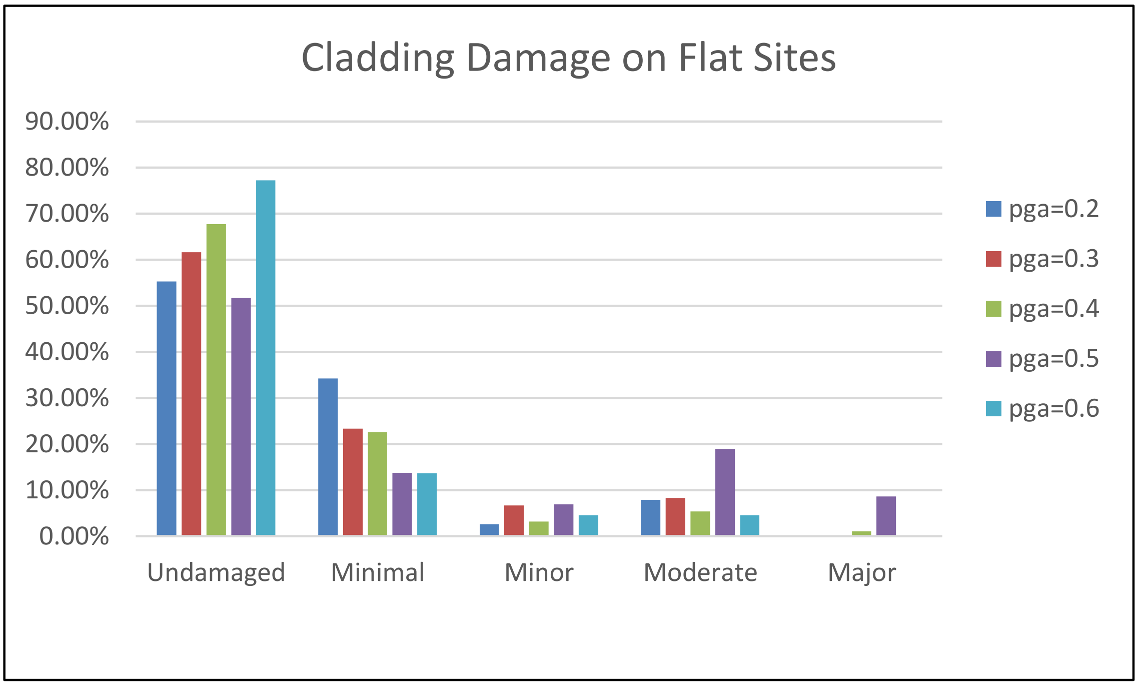

Figure 22. Veneer cladding damage as a function of PGA for flat sites

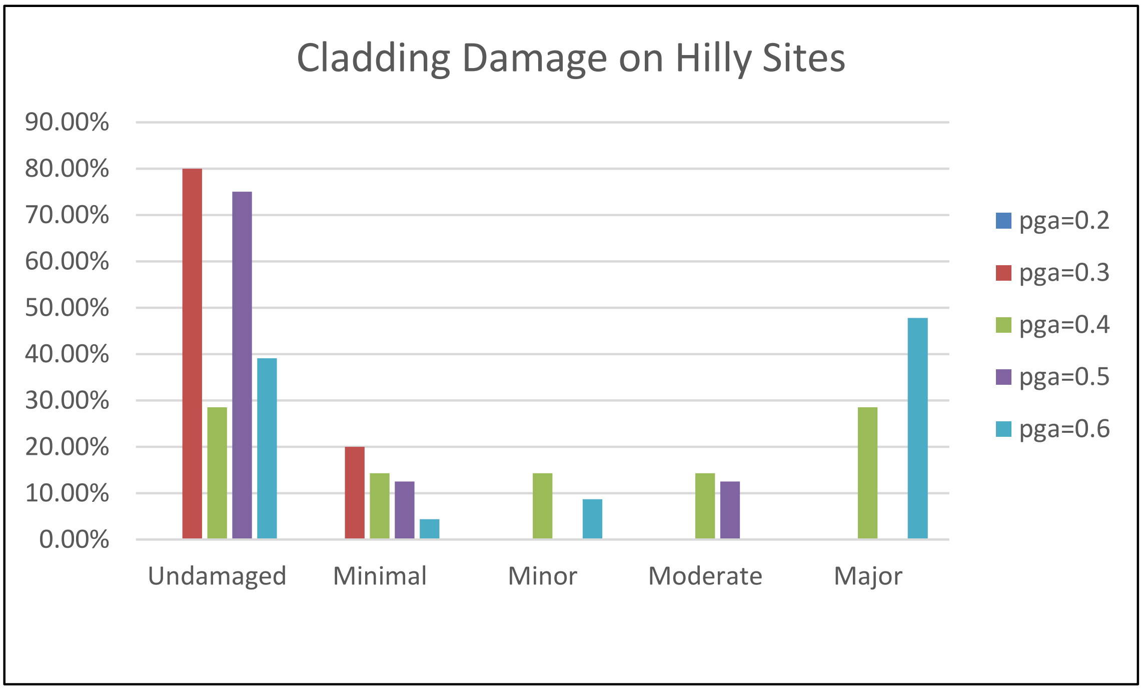

Figure 23. Veneer cladding damage as a function of PGA for hilly sites

7. FURTHER ANALYSIS POSSIBLE

Analysis of the categories with large populations has been undertaken in this project. These have included brick veneer cladding and plasterboard wall linings. There is further opportunity to delve more deeply into the multi-variable relationships. However, this would need to be treated with care because of the small group populations, and small populations will be less statistically significant.

8. CONCLUSIONS

The Canterbury earthquake series over 2010 and 2011 provided an ideal opportunity to study the impact of the Canterbury earthquake series on the housing stock. BRANZ was able to gain a detailed understanding of the performance of a typical sample of the New Zealand housing stock when subjected to a major earthquake. In some areas, this was greater than the design level event.

A survey of 314 houses was conducted in the latter half of 2011, after all of the major earthquake events that made up the series had occurred. Data was gathered about the site characteristics, the dwelling characteristics and the damage sustained to all parts of the structure. This included foundations, exterior claddings, interior linings and roof. With further information sourced after the earthquakes on ground shaking intensity over the city, it was possible to also compare damage against the peak ground acceleration.

The survey results confirmed the anecdotal evidence that timber-framed dwellings generally performed well in that they satisfied the performance criteria of the New Zealand Building Code. They did not collapse under shaking at least equivalent to the ultimate limit state design event. However, damage was widespread, ranging from very minor to quite major.

Brick veneer cladding has been a popular form of construction for many years because of the low-maintenance aspect. However, there have been improvements made over this time to the manner in which the veneer is tied to the timber frame. A particular improvement is the switch to requiring all veneer ties to be screw-fixed to the frame from the mid-1990s. It was therefore of particular interest to determine the effect of these changes on the seismic performance. Comparisons were made between houses built before and after 1980, so some houses with older fixings would have been included in the post-1980 sample. Nevertheless, the percentage of post-1980 houses with damage was always significantly less than the pre-1980 house sample, across the range of damage levels. Clearly, the move to require all ties to be screw fixed has had a beneficial effect on the seismic performance of veneers.

Since 1978, plasterboard linings have been extensively used as bracing in light timber-framed structures. Prior to this, bracing was provided by diagonal timber braces in the framing. While not totally convincing, the analysis showed that the modern bracing methods resulted in less damage to the plasterboard lining than the older methods. This may be partially due to the older linings being fixed to the framing at greater centres and therefore more easily detached from the framing.

It has been commonly thought that the shape of a dwelling will affect its propensity for being damaged in an earthquake. Houses with wings and blocks, split levels and irregular plans were expected to fare worse in an earthquake. This study did not show convincingly that this was the case, with a larger proportion of the rectangular houses having major damage than those with complex plans. However, it is likely that the rectangular houses were older, and the issue with detached linings may have been the reason.

For both veneer cladding and plasterboard lining, the proportion of the sample that sustained major damage was far greater for the dwellings on hilly sites than on flat sites. This is to be expected because the 22 February earthquake, which had the most effect on the housing stock, was centred under the hill suburbs. The spectral ground accelerations at these sites were larger in the frequency range of the houses than they were on the flat land. With this more severe shaking, greater damage would be expected. The analysis also showed that houses in the hill suburbs sustained greater levels of damage regardless of the peak ground acceleration experienced. Obvious reasons for this are asymmetry in foundations, multiple foundation types and eccentric upper floor bracing layouts due to large openings facing views on sloping sites.

APPENDIX A – REFERENCES

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Important notice

Figure 11 and Figure 16 of this report were produced from maps and/or data extracted from the Canterbury Geotechnical Database (https://canterburygeotechnicaldatabase.projectorbit.com), which were prepared and/or compiled for the Earthquake Commission (EQC) to assist in preparing claims made under the Earthquake Commission Act 1993 and/or for the Canterbury Earthquake Recovery Authority (CERA). The source maps and data were not intended for any other purpose. EQC, CERA, their data suppliers and engineers, Tonkin &Taylor, have no liability for any use of the maps and data or for the consequence of any person relying on them in any way. This important notice must be reproduced wherever these figures (or derivatives) are reproduced.

APPENDIX B – SURVEY FORM

BRANZ

BRANZ Canterbury Earthquake House Inspection Survey Record **SR0956**

Address	House ID
	Date
Owner name	Inspectors
Contact details	Geo ref

[Upper storey on next sheet] [Tick all relevant boxes - use multiple choices if required]

Site	Slope		Flat	Gentle	Steep	Hilltop	Cliff top
	Adjacent to watercourse		Yes	No		Upslope	Downslope
Building general	Age band		pre 1930	1930-59	1960-79	1980-99	Post 2000
	Stories		1	2	3	>3	Split level
	Structure of building? (esp. subfloor)		Gen'ly 3604	Approx footprint area	<100 m²	151-200 m²	251-300 m²
			Mostly SED		101-150 m²	201-250 m²	>300 m²
	Plan shape		Rectangle	"L" shape	"T" shape	Complex	Other
	Vertical irregularity		Uniform	Stepped subfloor	Stepped upper floor	Reduced upper floor	Other
Floor system	Sub-floor structure		None (slab)	Conc perimeter	Poles	Conc ret. wall	Timber ret. wall
			Concrete piles	Sq. timber piles	Driven timber piles		Other
	Ground floor height	max	<600 mm	600 - 1 m	1 - 2.5 m	>2.5 m	
		min	<600 mm	600 - 1 m	1 - 2.5 m	>2.5 m	
	Ground floor		Concrete slab	Suspended timber	Sheet flooring	Timber strip floor	
Ground floor walls (upper floor is on next sheet)	Wall structure		Framed	URM	Concrete	Stone	Other
			Panelised	RCM	Earth		
	Ext cladding		Weather-board	Clay brk. veneer	Nat. stone veneer	Ply sheet	EIFS
			Stucco	Conc blk. veneer	Cut stone veneer	FC sheet	Other
	Int. lining		Plaster-board	Fibrous plaster	Lath and plaster	Timber	Other
	Windows		Wood	Metal	PVC		
	External doors		Wood	Metal			
	% openings (ext. walls)	N	<25%	25 - 50%	50 - 75%	75 - 100%	
		E	<25%	25 - 50%	50 - 75%	75 - 100%	
		S	<25%	25 - 50%	50 - 75%	75 - 100%	
		W	<25%	25 - 50%	50 - 75%	75 - 100%	
Roof	Roof structure		Truss	Framed	Skillion	Other	
	Roof shape		Hip	Gable	Monopitch	Mansard	Other
	Roof slope		<10 deg	11 - 20 deg	15 - 25 deg	> 25 deg	
	Cladding		Heavy tiles	Sheet	Metal tiles	Shingles	Other
Appendages	Garage		Separate	Attached	Under house	Over house	Other
	Chimney(s)		Internal	External	Precast	Brick	Metal
	Attachments		Deck/ balcony	Steps attached	Steps freestanding	Concrete terrace	Other
	Garden features		Retaining wall	Heavy wall	Light fence	Pond/pool	Other
Services	Water heating		Internal HWC (elec)	External (gas)	Inst electric	Solar	Header tank
	Space heating		Heat pump	Gas ducted	Gas portable	Elect port.	Solid fuel

Canterbury Earthquakes House Inspection Survey Form

BRANZ Canterbury earthquake House inspection survey record **SR0956**

(sheet 2. Use for 2 stories)

[Tick all relevant boxes -use multiple choices if required]

	Upper floor		Concrete ☐	Suspended timber ☐	Sheet flooring ☐	Timber strip floor ☐	
Upper floor walls	Wall structure		Framed ☐	URM ☐	Concrete ☐	Stone ☐	Other ☐
			Panelised ☐	RCM ☐	Earth ☐		
	Ext cladding		Weather-board ☐	Clay brk. veneer ☐	Nat. stone veneer ☐	Ply sheet ☐	EIFS ☐
			Stucco ☐	Conc blk. veneer ☐	Cut stone veneer ☐	FC sheet ☐	Other ☐
	Int. lining		Plaster-board ☐	Fibrous plaster ☐	Lath and plaster ☐	Timber ☐	Other ☐
	Windows		Wood ☐	Metal ☐	PVC ☐		
	External doors		Wood ☐	Metal ☐			
	% openings (ext. walls)	N	<25% ☐	25 - 50% ☐	50 - 75% ☐	75 - 100% ☐	
		E	<25% ☐	25 - 50% ☐	50 - 75% ☐	75 - 100% ☐	
		S	<25% ☐	25 - 50% ☐	50 - 75% ☐	75 - 100% ☐	
		W	<25% ☐	25 - 50% ☐	50 - 75% ☐	75 - 100% ☐	

Damage descriptions (sht 1)

(ignore pre-existing damage) (tick all relevant boxes)

General Property/site

(describe any damage not covered by tick boxes)

House Undamaged ☐

	Sept	Feb	June	Not known
Damaged but occupied	☐	☐	☐	☐

Unoccupied (reason):

No services	☐
Unsecure	☐
Red placarded	☐
Abandoned	☐
Under repair	☐

Liquefaction None ☐

	Sept	Feb	June	Not known
On property	☐	☐	☐	☐
Under house	☐	☐	☐	☐

Lateral spread None ☐

	Sept	Feb	June	Not known
On property	☐	☐	☐	☐
Under house	☐	☐	☐	☐

Boulder/rock fall hazard

Yes ☐

No ☐

Services

(describe any damage not covered by tick boxes)

Service supply (Immediately after Feb earthquake)

	No supply	Supply	Not known
Power	☐	☐	☐
Sewer	☐	☐	☐
Water	☐	☐	☐
Gas	☐	☐	☐
No gas	☐		

HWC

Undamaged	☐
Moved	☐
Leaking	☐
Unusable	☐

Header tank

None ☐

Undamaged	☐
Moved	☐
Leaking	☐
Unusable	☐

Damage descriptions (sht 2)

(ignore pre-existing damage)

(tick all relevant boxes - irespective of event)

Foundation/ground floor

(describe any damage not covered by tick boxes)

General

Floor stretched overall by:	
<10 mm	☐
10 - 50 mm	☐
>50 mm	☐

Overall shape misalignment	
None	☐
Tilt	☐
Hog	☐
Sag	☐
Twist	☐

Slab

Undamaged ☐

Unable to check ☐

Approx. extent (linear metres)	Cracked <5mm	Ruptured (incl reinf)	Mis-aligned
0 - 10 m	☐	☐	☐
10 - 20 m	☐	☐	☐
20 - 30 m	☐	☐	☐
30 - 40 m	☐	☐	☐

Perimeter foundation

Undamaged ☐

Floor detached from perimeter found. ☐

(no of cracks)	Cracks <5mm	Ruptured (incl reinf)	Mis-aligned
1 - 5	☐	☐	☐
6 - 10	☐	☐	☐
11 - 15	☐	☐	☐
16 - 20	☐	☐	☐

Piles

None ☐

Piles undamaged ☐

Extent (%)	Leaning	Mis-aligned	Defective fixings
90-100	☐	☐	☐
80-89	☐	☐	☐
50-79	☐	☐	☐
25-49	☐	☐	☐
10-24	☐	☐	☐
<10	☐	☐	☐

Jackstuds

None ☐

Jackstuds undamaged ☐

Extent (%)	Leaning	Mis-aligned	Defective fixings
90-100	☐	☐	☐
80-89	☐	☐	☐
50-79	☐	☐	☐
25-49	☐	☐	☐
10-24	☐	☐	☐
<10	☐	☐	☐

Damage descriptions (sht 3) (ignore pre-existing damage)

(tick all relevant boxes - irespective of event)

External and internal walls
(describe any damage not covered by tick boxes)

Masonry (veneer or structural)

Extent (%)	Cracked	Detached/unstable	Fallen
None	☐	Undamaged	☐
90-100	☐	☐	☐
80-89	☐	☐	☐
50-79	☐	☐	☐
25-49	☐	☐	☐
10-24	☐	☐	☐
<10	☐	☐	☐

Stucco

None ☐ Undamaged ☐

Extent (%)	Cracked	Fallen
90-100	☐	☐
80-89	☐	☐
50-79	☐	☐
25-49	☐	☐
10-24	☐	☐
<10	☐	☐

Monolithic cladding cladding

None ☐ Undamaged ☐

Extent (%)	Joint cracks	Diag cracks
90-100	☐	☐
80-89	☐	☐
50-79	☐	☐
25-49	☐	☐
10-24	☐	☐
<10	☐	☐

Windows

Extent (%)	No damage	Jammed	Broken
90-100	☐	☐	☐
80-89	☐	☐	☐
50-79	☐	☐	☐
25-49	☐	☐	☐
10-24	☐	☐	☐
<10	☐	☐	☐

Doors

Extent (%)	No damage	Jammed	Broken
90-100	☐	☐	☐
80-89	☐	☐	☐
50-79	☐	☐	☐
25-49	☐	☐	☐
10-24	☐	☐	☐
<10	☐	☐	☐

Internal wall linings

Undamaged ☐

Extent (%)	Joint cracks	Diag cracks	Detached
90-100	☐	☐	☐
80-89	☐	☐	☐
50-79	☐	☐	☐
25-49	☐	☐	☐
10-24	☐	☐	☐
<10	☐	☐	☐

Damage descriptions (sht 4) (ignore pre-existing damage)

(tick all relevant boxes - irrespective of event)

Roof, ceilings etc

(describe any damage not covered by tick boxes)

Roof Undamaged ☐

Extent (%)	Mis-aligned	Split	Damage by chimney	
90-100	☐	☐	☐	☐
80-89	☐	☐	☐	☐
50-79	☐	☐	☐	☐
25-49	☐	☐	☐	☐
10-24	☐	☐	☐	☐
<10	☐	☐	☐	☐

Chimney(s)	Undamaged	Cracked	Removed	Fallen
No. 1	☐	☐	☐	☐
2	☐	☐	☐	☐
3	☐	☐	☐	☐
4	☐	☐	☐	☐
5	☐	☐	☐	☐
6	☐	☐	☐	☐

Roof tiles Undamaged ☐

Extent (%)	Hips loose	Tiles dislodged	Tiles fallen	
90-100	☐	☐	☐	☐
80-89	☐	☐	☐	☐
50-79	☐	☐	☐	☐
25-49	☐	☐	☐	☐
10-24	☐	☐	☐	☐
<10	☐	☐	☐	☐

Plasterboard Undamaged ☐

Extent (%)	Fixings popped	Joint cracks	Diag cracks	Sheets fallen
90-100	☐	☐	☐	☐
80-89	☐	☐	☐	☐
50-79	☐	☐	☐	☐
25-49	☐	☐	☐	☐
10-24	☐	☐	☐	☐
<10	☐	☐	☐	☐

Fib. plaster Undamaged ☐

Extent (%)	Fixings popped	Joint cracks	Diag cracks	Sheets fallen
90-100	☐	☐	☐	☐
80-89	☐	☐	☐	☐
50-79	☐	☐	☐	☐
25-49	☐	☐	☐	☐
10-24	☐	☐	☐	☐
<10	☐	☐	☐	☐

Damage descriptions (sht 5) (ignore pre-existing damage)

(tick all relevant boxes - irrespective of event)

Appendages
(describe any damage not covered by tick boxes)

Decks/ balconies

Undamaged ☐

Extent (%)	Separated	Collapsed	
90-100	☐	☐	☐
80-89	☐	☐	☐
50-79	☐	☐	☐
25-49	☐	☐	☐
10-24	☐	☐	☐
<10	☐	☐	☐

Steps

Undamaged ☐

No.	Cracked	Separated	Settled
1	☐	☐	☐
2	☐	☐	☐
3	☐	☐	☐
4	☐	☐	☐
5	☐	☐	☐
6	☐	☐	☐

Boundary fences/ garden walls

Undamaged ☐

Extent (%)	Leaning	Ruptured	Fallen
90-100	☐	☐	☐
80-89	☐	☐	☐
50-79	☐	☐	☐
25-49	☐	☐	☐
10-24	☐	☐	☐
<10	☐	☐	☐

Retaining wall(s)

Undamaged ☐

Extent (%)	Leaning	Ruptured	Collapsed
90-100	☐	☐	☐
80-89	☐	☐	☐
50-79	☐	☐	☐
25-49	☐	☐	☐
10-24	☐	☐	☐
<10	☐	☐	☐