The Response of Houses to the Canterbury Earthquake Series 2010-2011

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SUMMARY:
The Response of Houses to the Canterbury Earthquake Series 2010-2011.
This paper describes a series of earthquakes that occurred in the Canterbury region of New Zealand over the period from 4 September 2010 until the end of 2011. It also describes a survey of 314 randomly selected houses that was undertaken by BRANZ , in an effort to identify the range of damage observed, to quantify the damage and to consider appropriate repair strategies. By far the greatest number of houses are constructed with timber framing and plasterboard wall linings but there are a few with unreinforced masonry walls, particularly older houses built adjacent to property boundaries, and some constructed with other materials. The survey showed how the typical New Zealand timber framed houses withstood the extreme shaking action very well, sustaining varying degrees of damage but not collapsing. The paper also describes the development of foundation repair and rebuild solutions for houses affected by liquefaction, and for house superstructures affected by both liquefaction and shaking.

Keywords: Earthquake, houses, damage, repair, liqeufaction

1. INTRODUCTION

At 4:35am local time on 4 September 2010, a magnitude 7.1 earthquake struck the Canterbury region of New Zealand (NZ). The earthquake was centred near the township of Darfield, a small country community approximately 40km west of the city of Christchurch, and its epicentre was at a depth of 10km. The shaking intensities in Christchurch were in the range of 0.16g to 0.65g peak ground acceleration (PGA) in the horizontal direction and 0.05g to 0.3g 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. While the effect on Christchurch houses was generally the loss of unreinforced masonry chimneys and some minor damage to interior linings, several areas were affected by ground liquefaction and associated lateral spreading.

Typically, a series of aftershocks occurred over the following months although none of these events caused further significant damage, until 12:51pm on 22 February 2011 when a 6.3 magnitude event struck beneath the urban area of the city. The epicentre was located 10km southeast of the central business district (CBD) and at a depth of 6km. The range of horizontal PGAs recorded in the urban area ranged from 0.2g to 1.41g and in the vertical direction, 0.06g to 2.21g [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.

Further significant shallow events occurred on 13 June 2011 (magnitude 6.3) and 23 December 2011 (magnitude 6.0) with their epicentres located close to the 22 February epicentre. The events of 4 September 2010, 22 February 2011, 13 June 2011 and 23 December 2011 are referred to in this paper as the main events. The 10,000 odd aftershocks that have occurred over the period between 4 September 2010 and the present time have also served to rattle households.

This paper provides the results of a damage survey of a representative range of Christchurch houses that was undertaken over the period from July to September 2011. The survey therefore does not include the further damage sustained in some areas of the city during the 23 December 2011 event. The paper also draws on the experience of the four BRANZ structural engineers who were involved in the safety assessments of houses in the eastern and southern suburbs following the February 2011 event.

2. SURVEY PROCESS

After the 4 September event, BRANZ attempted to gather information on house performance with minimal disruption to the house occupiers, many of whom were badly traumatised by the event. To achieve this goal the BRANZ surveyors accompanied the Earthquake Commission (EQC) insurance assessors undertaking insurance claim visits. Unfortunately, this gave little control over the properties visited and meant that the sample was badly skewed in favour of the needs of the EQC at the time. This survey did gather data on 120 houses and was almost completed when the 22 February 2011 earthquake struck.

Following the February event, BRANZ undertook another survey, this time of 314 houses, randomly selected from within the boundaries of Christchurch city. The process involved randomly selecting a little more than 50 mesh blocks from the Statistics New Zealand census database [Statistics New Zealand]. Within each mesh block, six adjacent houses were selected for surveying at the southeast corner of each mesh block and the surveyors made cold calls to each property.

Each property was visited by a team of two BRANZ representatives with a comprehensive survey form to gather observations about the site and its hazards (eg liquefied, rock-fall susceptible), house age, house style, construction materials and then estimates were made of the extent of damage sustained by the various elements of the structure. If the occupier of a property was not at home the surveyors moved to the next property adjacent and this was repeated until information was gathered from six houses in the block. The approximate total number of houses in Christchurch city is 150,000 and so approximately 0.2% of the total population was surveyed in this process. This paper presents the results of this second survey.

3. SURVEY RESULTS

This section presents information gathered on the sites and the construction characteristics of the surveyed houses.

3.1 The site

The majority of Christchurch city is situated on the flat Canterbury plains, but there has also been urban development on the Port Hills to the south of the CBD over the entire life of the city, with the hillside development making up approximately 10% of the total housing stock. The survey proportions of flat land and hillside houses match this ratio relatively well (Figure 1).

3.1.1. Liquefaction occurrence

Of the 270 properties surveyed on the flat, 81 sites (30% of the flat land properties) had experienced ground liquefaction in either one or more of the first three main earthquakes. All of these properties liquefied in February 2011, 31% of these also liquefied in September 2010 and 42% also liquefied in June 2011. Seventeen of these properties liquefied in all three events.

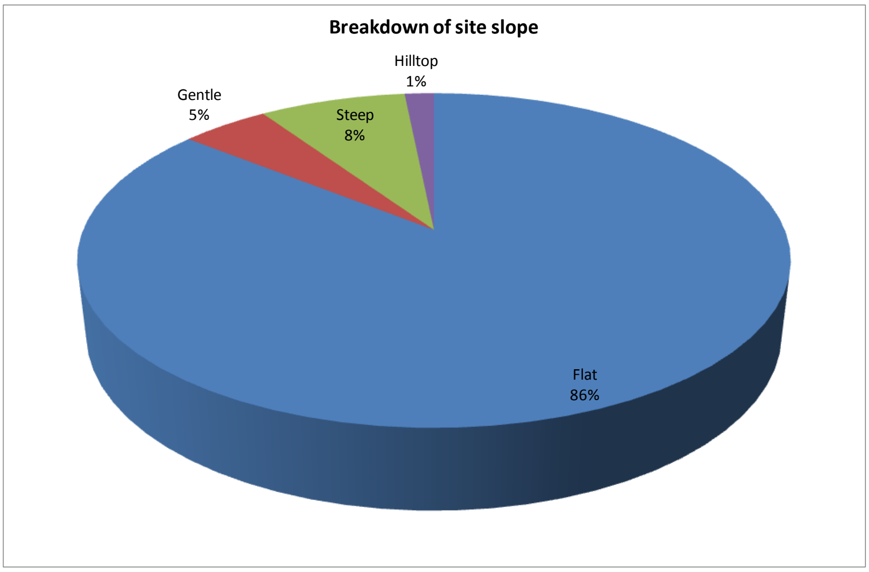

Figure 1. Breakdown of the surveyed houses with respect to the slope of the site

3.2 House Age and Style

The Christchurch housing stock comprises dwellings constructed from the latter part of the 19th century through to the present day. Five age bands were selected into which each house was placed. The bands were pre-1930, 1930 to 1959, 1960 to 1979, 1980 to 1999 and 2000 onwards. These age bands were chosen to represent distinct periods of development of standards for house construction in New Zealand. Prior to 1930 there were no standards. In the early 1930s the first regulatory standards were produced. These were largely prescriptive and based on typical construction styles in the USA. They were not always adopted by the local jurisdictions either. In the 1960s the timber framing standards were developed further in a series of model building bylaws. These were in use until 1978 when the first engineering based light timber framing standard (SANZ 1978) was published. A significant review and republication of this standard occurred in 1999. The percentages of house surveyed from each of these five bands are given in Table 1.

New Zealand houses are generally one or two storeys, but on hillsides it is common for there to be more than two storeys. Houses built to the NZ non-specific design standard, NZS 3604:2011 (SNZ 2011) and its predecessors are limited in height to a maximum of 10m and two and a half storeys, the half storey being in the roof space. Houses built outside of these (and other) requirements must be specifically designed.

In the survey population, 233 houses (74%) were single storey structures, 74 (24%) were two storey structures and 7 (2%) were three storey dwellings. Of the single storey dwellings, 58% were a simple rectangular shape, 31% were "L" shaped, 3% were "T" shaped and 8% were complex shapes. Of the 74 two storey dwellings surveyed, 55% were a simple rectangular shape, 23% were "L" shaped, 5% were "T" shaped and 17% had a complex shape.

3.3 House Foundation Types

There are two major foundation types in use for house construction in Christchurch. Slab on grade floors have been the predominant construction style over the last 30 or so years for houses on the flat and also for some properties on the hills. This is confirmed from the survey of randomly chosen houses (Table 1). Over the early to mid 20th century, the preferred foundation style was a concrete perimeter foundation wall with concrete piles inside the perimeter. Such a style was typical on both the flat and the hills. Figure 2 shows the percentages of the foundation types. In the hillside structures the floor was often supported on jack studs on short piles (Figure 3). Very occasionally houses were built entirely on timber piles in the early part of the 20th century.

Table 1. Percentages of the surveyed houses in the five age bands and breakdown of foundation type for each age band

Age band	Percentage of surveyed houses	Percentage of slab on grade houses in the age band	Percentage of perimeter foundation houses 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

3.4 House Superstructure

3.4.1 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. However, light gauge steel framing is a relatively new construction type in NZ and therefore it is expected that the great majority of the surveyed houses had timber framing. The other five houses had either concrete, concrete masonry or unreinforced brick masonry walls. Of the 74 two storey dwellings surveyed, 80% had framed bottom storeys and 20% had either concrete or concrete masonry bottom storey walls. In all but one of these cases the top floor was framed.

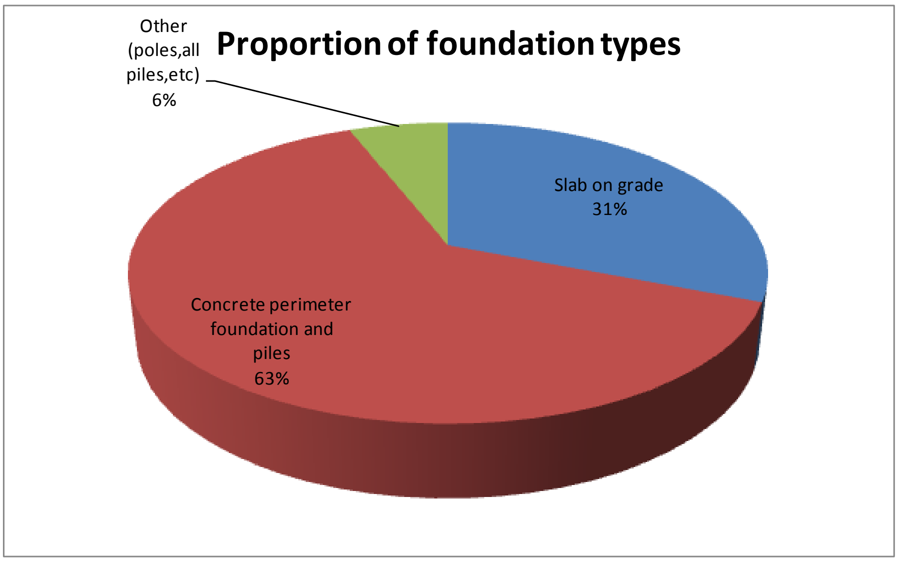

Figure 2. Proportions of foundation types in surveyed structures

3.4.2 Wall Claddings

Several cladding systems are common in NZ. These include timber weatherboards, brick/block veneer and stucco, although the latter is much less common nowadays. 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 on occasions there was more than one cladding type on a house.

Figure 3. Jack studs beneath a hillside dwelling (tilt due to superstructure lateral displacement)

Table 2. Distribution of cladding types on surveyed single 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 insulating finishing system (EIFS)	7 (3%)	8 (8%)	7 (7%)
Other	8 (3%)	13 (14%)	15 (16%)
Total	233	95	96

3.4.2 Roof Claddings

The commonest roof claddings in use in NZ 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, although 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 been rarely used in NZ. 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 (eg corrugated steel)	Metal tiles	Other
Pre-1930	2	37	6	2
1930-1959	29	32	11	2
1960-1979	32	57	12	0
1980-1999	5	32	8	2
2000 onwards	3	27	12	3
Total	71	185	49	9

3.4.3 Interior linings

In the early 20th century and before, lathe and plaster was a common lining system for houses. This system continued to be used through until the 1940s. Gypsum based plasterboard was introduced in the late 1920s and has gone on to be the most popular lining material at the present time. 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 on occasions there was more than one lining type present in a single dwelling. 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 had a non-structural function.

3.5 Recorded Damage

Along with gathering information on the characteristics of the properties, estimates were made of the levels of damage sustained by the various components of the dwellings in order to derive damage ratios for the houses which could be applied to the remainder of the un-surveyed dwellings in the city. Analysis of the gathered damage data is still going on at the time of writing. It is notable that no timber framed houses collapsed in any of the earthquakes unless affected by ground movement such as cliff collapses above or adjacent to houses or rolling rock impacts. It is also important to remember that the performance expectation in the NZ Building Code (DBH 1992) is that buildings should not collapse when subjected to what is referred to in the NZ loading standards as the ultimate limit state loading condition. However, damage is expected to occur to buildings in an event of this size. This condition was exceeded in many areas of the city, particularly in the February 2011 event.

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

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 4). The most obvious signs of house damage viewed from the outside were failed unreinforced masonry chimneys on older houses and the loss of portions of veneer.

Figure 4. Severely damaged house from differential ground settlement and lateral spreading

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

3.5.1 Foundations

Slab on grade foundations performed well under earthquake shaking. However, ground deformations beneath these slabs, caused either by liquefaction settlement or lateral ground spreading on the flat or ground slumping in the hill suburbs, resulted in sometimes severe distortions of the concrete slabs. The common perimeter concrete foundation with internal piles also fared well under ground shaking but was affected by varying degrees by the ground movement. It was common 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 12mm diameter bar, often plain. Whether reinforced in this way or not, these foundations were unable to resist the ground deformations and fractured (Figure 5).

Figure 5. Example of reinforced concrete perimeter foundation pulled apart by spreading ground

3.5.2 Wall cladding systems

Seventy two percent of the brick/block veneer claddings on the surveyed houses sustained damage, 76% of houses with stucco claddings and 67% of houses with monolithic claddings (eg plastered sheet materials and EIFS) (Table 4). About a quarter of veneer clad houses 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, with the balance mostly being houses with separate unattached foundations for the brick veneer and the framing. Veneers constructed after the mid 1990's 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 monolithically clad houses with different types of damage

	% cracked			% fallen, detached or 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	0	5	10	0	0	0	5	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.

3.5.3 Roof claddings

Damage to sheet roof claddings and metal tiles was confined mainly to damage sustained from falling chimneys and tended to be minor. Concrete and clay tile roofs also sustained damage from falling chimneys but those in the hill suburbs often suffered from dislodgement of the tiles from the supporting battens (Figure 6). It was common for such tiles not to be tied to the framing or for the ties (if they were present) to have corroded. Very high vertical peak ground accelerations (>1g) were recorded in February 2011 in the hill suburbs and this is sure to have contributed to the tile dislodgement.

Figure 6. Dislodged concrete roof tiles

3.5.4 Interior linings

Eighty five percent of the surveyed houses had damage to wall linings and 73% had damage in the ceiling linings. Joint cracks were the most common form of damage, with 72% of houses suffering from them. Wall linings rarely became detached. Diagonal cracks were rare in houses that only had plasterboard linings. Most of the diagonal cracking that did occur in plasterboard appeared to be at the corners of openings, and some was observed in houses that suffered from severe sagging and hogging in the foundations due to ground movement.

As with wall linings, joint cracks were the most common form of damage in ceiling linings, with 49% of houses suffering from them. Diagonal cracks were not common in plasterboard ceilings but far more common (27%) in fibrous plaster ceilings. It is believed that because the fixing of the fibrous plaster ceilings is often more rigid than the plasterboard products (eg wadded connection to the framing), distortion of the supporting framing causes the diagonal cracks to occur. It was rare for whole sheets to fall from the ceiling or the walls, but popping of fixings occurred in about 10% of the surveyed houses.

Diagonal cracks were more common in wall linings than in ceiling linings. This is likely to be due to there being openings causing stress concentrations. NZ plasterboard manufacturers recommend fitting sheets around the corners of openings to provide a better finish performance during normal seasonal changes in the timber framing, which does make the sheets more susceptible to diagonal cracking than linings with joints coincident with the edge of the opening, as the walls rack in an earthquake.

4. REPAIR AND REBUILD STRATEGIES

The author was a member of a group formed by the Department of Building and Housing (the Engineering Advisory Group (EAG)) to develop repair and rebuild strategies for houses that were affected by the earthquakes. A document was produced in November 2011 (DBH 2011) which superseded a similar document that was published by the Department in December 2010 but which had been made obsolete by the February 2011 earthquake. The liquefaction severity in the February event forced the division of the urban area of Christchurch into Red zones and Green zones. In the Red zones, it was considered that there were too many factors to allow the economic rebuild of the area and that it would be necessary to retreat from the area. Such reasons included a very high likelihood that significant liquefaction could occur again in low shaking levels and severe settlement of the land had created a potential flooding problem.

While the Green zone was considered to be good enough to allow repairs and rebuilds to go ahead, there was quite a range of expected future land performance. Because of this, the Green zone was sub-divided into Technical Categories (TC) 1, 2 and 3.

In TC1 the risk of liquefaction in the future was considered to be very low and foundation structures constructed in accordance with the current NZS 3604 were considered to be satisfactory with the inclusion of ductile reinforcing steel in the floor slab. In TC2, low levels of liquefaction settlement and lateral spreading are expected and the aim of the new foundation solutions for this TC was to provide a stiff platform that could be re-levelled by packing in the case of piles and jacking of slabs and perimeter foundations, should differential settlement occur. Stiff platforms include thick solid concrete slabs, gridded slabs, waffle slabs and reinforced compacted gravel rafts. Any repairs to house foundations in this TC were considered to be satisfactory provided shallow geotechnical investigations confirmed the bearing capacity of the soil. Further damage in a future event could be expected but this would be manageable with minimum disruption to the home owner. In TC3 significant liquefaction settlement and lateral spreading are expected and a range of new foundation solutions and concepts (requiring professional engineering design involvement) has been developed. These include suspended slabs supported on deep columns, ground improvement options including soil densification, crust stabilisation/strengthening, deep soil mixing, stone columns and low mobility grout columns. Several stiff surface structures and laterally strong surface structures have also been developed. The choice of option will be made by the professional engineer, having established the details of the likely ground movement at the site. For example, deep piles are not considered to be suitable in situations where significant global lateral movement of the crust is expected because they will be locked in the bearing stratum beneath the liquefied layer and could potentially fail in bending.

Repair procedures for the superstructure elements (mainly the linings and claddings) have also been developed. These are applicable for dwellings in all of the TCs.

5. CONCLUSIONS

This paper has provided a brief description of the earthquakes that occurred in the Canterbury region over the period from 4 September 2010 until December 2011. It also discusses the types and proportions of house construction present in the city of Christchurch and then goes on to describe the results of a survey of 314 randomly selected houses over the period following the June 2011 earthquake.

The survey has shown that the performance of timber framed houses under the intense shaking has been good in terms of the performance expectations of the NZ Building Code. No collapses occurred directly from the shaking. However, damage was sustained by many of the houses, the majority of it reparable, but in some cases affected by significant liquefaction re-building will be necessary.

A number of repair and rebuild options for houses have been developed covering a range of potential ground movement from liquefaction, both vertical and horizontal.

ACKNOWLEDGEMENT

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