

PERFORMANCE OF HOUSES DURING THE CHRISTCHURCH EARTHQUAKE OF 22 FEBRUARY 2011

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SUMMARY

The earthquake on 22 February 2011 was very close to Christchurch city, generating very high level ground excitations that caused severe geotechnical effects and widespread structural damage. This paper outlines the wide range of damage to houses resulting from liquefaction, lateral spreading, rockfall, and horizontal and vertical ground accelerations. The response of typical forms of house construction and structural components are discussed, with many different types of damage described. The majority of houses in the Christchurch region are one or two storey light timber frame buildings. This type of construction has performed extremely well for life safety, but thousands of houses have some degree of structural or non-structural damage. The New Zealand Building Code needs to be reviewed in several areas, especially the requirements for foundations and reinforced concrete floors.

INTRODUCTION

This paper is primarily a review of the performance of houses in the M6.3 Christchurch earthquake on 22 February 2011, which produced severe geotechnical effects and structural damage in the city. Some of the observed damage was as a result of the M7.1 Darfield earthquake on 4 September 2010.

Many thousands of houses were damaged. The Earthquake Commission (EQC) had received over 133,000 claims for the 22 February event by 15 May 2011 [1]. Most of the inspections reported in this paper were carried out by engineers working for "Operation Suburb", managed by EQC and the Civil Defence Controller, during the weeks following the earthquake.

This paper does not report on repairing or re-building of damaged houses. Advice is available in a report from the Engineering Advisory Group of the Department of Building and Housing [2].

SEISMOLOGICAL ASPECTS

The severity of shaking and the types of damage to houses varied considerably throughout the city of Christchurch. Damage due to rockfall was experienced in hillside areas near old sea cliffs or near old quarries, mostly concentrated between Sumner and Lyttelton.

The most extreme ground shaking effects on houses were in the hill suburbs of Huntsbury, Mt Pleasant and the Sumner hills, with some other areas of high accelerations in the

downtown area. Figure 1 shows the areas of most extreme liquefaction, ground acceleration and rockfall. The severity of ground shaking in various areas has been described by others [2 and 3]. A very large number of house foundation problems occurred in the eastern suburbs where there was an unprecedented level of liquefaction and lateral spreading of the underlying soils [4].



Figure 1: Approximate location of the worst types of damage.

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GEOTECHNICAL IMPACTS

Liquefaction Issues

Evidence of liquefaction in Christchurch city was far more widespread in the February 2011 event than it was in the September 2010 earthquake. This caused many houses that had already been affected by liquefaction and spreading in the September event to further subside, in some cases this caused the loss of protection from future flood conditions. In other cases, whole new areas were subjected to liquefaction and lateral spreading.

Rockfall Damage

In areas to the southeast of the city centre including Sumner, Redcliffs, Mount Pleasant and the Heathcote Valley, there were houses damaged due to landslides and boulders that broke free from hillsides during the earthquake. In many cases this type of damage was severe and resulted in large portions of houses being destroyed and rendered uninhabitable, as shown in Figures 2 to 4.



Figure 2: *House damage in Heathcote due to rockfall (Carradine).*



Figure 3: *House damage in Heathcote due to rockfall (Carradine).*



Figure 4: *House destroyed by landslide in Redcliffs (Beattie).*

Hillside Ground Slumping

On a number of occasions, ground slumping was evident behind retaining walls in the hill suburbs, even though the walls did not appear to have failed but rather displaced down the slope or rotated about their bases. It is likely that in these instances a bench had been created to build the house and some of the excavated material had been placed on the downhill side of the site behind the retaining wall. This sometimes caused settlement damage to the house positioned immediately above the retaining wall.

PERFORMANCE OF LIGHT TIMBER FRAMED HOUSES

Overview of Structural Performance

Most houses in the affected area were of light timber frame construction. Extensive investigations have shown that light timber framed houses generally performed very well during the earthquake. In general timber building envelopes and diaphragms succeeded in maintaining the structural integrity of timber framed houses stressed by ground shaking and also by liquefaction settlement. Timber framed houses subjected to lateral ground movement and settlement due to liquefaction were often found to be intact, but damage ranged from minor through to severe. Severe damage was not always a result of structural collapse, but rather due to lack of functionality of doors and windows, and non-structural element damage, as further described below. On occasions when the concrete floor slab had ruptured as a result of land spreading effects, damage to the superstructure framing was evident. However, this was generally confined to the local area of the foundation rupture. There were some cases of soft-storey timber house failures that did not lead to collapse, but rendered buildings unusable as shown in Figure 5.



Figure 5: *Examples of soft storey failures of timber framed houses not resulting in collapse.*



Figure 6: *Roof separation (left) at masonry party wall in St. Martins, and deflection of gable end (right) due to roof bracing failure on same house (Carradine).*



Figure 7: *Superstructure distress caused by foundation failure on sloping ground (Beattie).*

The arrangement and stiffness of bracing walls in new house construction was seen to be important. Excessive damage often occurred in architecturally designed houses built with asymmetric bracing walls to capitalise on available views in one direction.

One example of a framing failure occurred where two roof sections were only minimally braced and not tied together where a masonry wall separated the two halves of a single storey duplex building, allowing each half of the roof to move independently and separate from one another as shown in Figure 6.

Several cases were observed where the timber framing was under considerable distress because of the failure of the foundation system. One such case is shown in Figure 7 where two different foundation systems beneath a house had separated, resulting in the development of a significant opening in the roof structure.

Facades

Building facades and cladding were some of the most highly damaged portions of housing stock. While these types of damage were often limited to exterior cladding, the resulting exposure of the interior structural systems to the weather could lead to durability problems. This will need to be addressed for those buildings that are to be repaired rather than demolished.

Lightweight timber cladding systems such as weatherboards exhibited far less damage than heavier facades such as brick

and masonry. The heavier systems usually failed as a result of poor connections with timber structural components, but also failed due to differential movement between systems having different structural stiffness.

Masonry, bricks and ties

Masonry and brick cladding on timber framed houses generally performed poorly during the earthquake, especially in regions where shaking was more intense, including the city centre and suburbs to the south and east of the city centre. There are many houses where brick and masonry cladding detached from timber framing either partially or completely. In some cases it is clear that the masonry ties intended to restrain the cladding to the framing have been inadequate. In some cases no ties had been installed and in others they had only been placed in the bottom half of the wall.



Figure 8: Collapsed brick veneer (Beattie).



Figure 9. Veneer damage due to lateral spreading and differential settlement (Buchanan) and due to differential settlement (Morris).

One item of particular concern was the apparent failure of the bond between the bricks and the mortar on many occasions, which released the ties from the veneer. Concrete bricks were most badly affected, which may have been caused by excessive suction of water from the mortar by the dry bricks at the time of construction or quick drying of the mortar in the hot Canterbury winds. Furthermore, veneer damage appeared to have been more badly affected on the hills, probably the result of the very high vertical accelerations. Figure 8 shows an example with such poor mortar that the veneer has separated into individual bricks and Figure 9 shows examples of veneer damage due to settlement.

Light weight facades

External Insulation and Finish Systems (EIFS) claddings performed quite well, with cracking occurring in the plaster coating only at the corners of window and door openings (Figure 10). Such behaviour is consistent with previous laboratory testing of such systems at BRANZ [6], and is reasonably simple to repair.



Figure 10: Typical cracking of an EIFS system (Beattie).



Figure 11: Plywood sheet cladding with timber battens (Beattie).

Weatherboard claddings behaved particularly well, generally only experiencing minor cracking of the paint at the intersection of the individual boards as they slipped sideways under lateral building displacements.

Plywood sheet cladding also performed well (Figure 11). If the external plywood was designed as a bracing element it would have been expected to remain well attached to the framing because of the strict fixing requirements.

Older style asbestos cement sheet claddings exhibited brittle behaviour, often cracking badly under the lateral deformations.

Lath and plaster

The use of lath and cement plaster on the exterior of houses was common in the early 1900s for producing a stucco style exterior finish. Naturally the product is very stiff and has no reinforcement to provide any strength. Cases were observed where sheets of the plaster had detached cleanly from the lath (Figure 12). The main diagonal timber bracing for the house can be seen where both the plaster and the lath have broken away from the wall.



Figure 12: Detached lath and plaster from an exterior lath and plaster system (Beattie).

INTERNAL LININGS

Plasterboard

The performance of paper-faced gypsum plasterboard linings was dependent on the behaviour of the structural system it was attached to. When damage did occur it was usually at the corners of window and door openings. In most cases damage was limited to cracks, but in some cases there was enough movement to cause the plaster to buckle, as in Figure 13. It is worth noting that in newer houses a significant portion of the lateral load resistance of the building is based on internal linings, which in most cases retained its integrity during the earthquakes. See Winstone Wallboards [7] for a more complete description of earthquake performance of internal linings.



Figure 13: Buckled plasterboard in house in Heathcote Valley (Carradine).

There have been cases of occasional severe damage to the higher grade plasterboard used as an internal bracing material, well fixed at the edges and glue fixed to intermediate timber framing. A case with the board popping off after its lateral load capacity had been exceeded is shown in Figure 14.



Figure 14: Severe failure of high grade plasterboard internal linings (Morris).

NZS 3604 is the comprehensive “Timber Framed Buildings” standard [8] which includes wall bracing systems and bracing ratings. In early versions of NZS 3604 in the late 1970s and 80s one such system included a combination of a plasterboard product fixed at specified centres around the perimeter of the sheets and a light gauge metal brace. Figure 15 shows an example of this system where the plasterboard sheet has detached from the wall framing and the metal braces have buckled under compression loading as the wall has distorted.



Figure 15: Failure of a generic plasterboard/metal brace combination (Beattie).

Fibrous plaster

Fibrous plaster is another type of gypsum plasterboard sheets, made with a mixture of long fibres for reinforcing, but no paper facing. Fibrous plaster sheets were usually joined at the edges of door and window openings, and no reinforcing tape was used at sheet junctions. The product fitted within the description of a generic bracing system in the early versions of NZS 3604 and in the early 1990s bracing ratings were generated from testing at the Forest Research Institute [9] and were therefore expected to act as a bracing element. It was common for these joints to crack and the fixings to “pop” (i.e., pry off the plaster plug from over the fixing head) during the earthquake. Examples were observed of fibrous plaster sheets that had racked in the earthquake (Figure 16).



Figure 16. Cracking of a joint between fibrous plaster wall lining sheets (Beattie).

Plaster on wood lath

Wall linings of trowelled plaster on closely spaced wood lath had considerably more damage than plasterboard sheets. There was a similar concentration of damage around window and door corners, highly dependent on the behaviour of the

structural system to which it was attached. Because it is not a panel system like plasterboard, the pattern of cracks was sometimes more distributed and not localised around seams in panels, as shown in Figure 17.



Figure 17: Damage to plaster on lath lining in Waltham (Carradine).

Softboard and hardboard

Softboard is a low density wood fibreboard, and hardboard is a high density tempered wood fibreboard. These products were commonly used in the middle of the 20th century, with softboard used for lining living areas and bedrooms, and hardboard used for lining utility rooms such as bathrooms, kitchens and laundries. Joints were sometimes expressed (with tapered edges) or otherwise covered with a flat “D” shaped timber trim. Neither product was designed as a bracing material. The fixings for softboard included steel clouts and glue while hardboard was generally fixed with brads. No cases were encountered where the either of these sheet products had torn from the walls of houses, but there were instances where the fixings had worked in the sheets and their locations had become more obvious as a result.

ROOFS

Effect of roof weight on building performance

Houses with heavy roofs tended to suffer much more structural damage than similar houses with light roofs because the mass of the roof is directly related to the inertial forces that a system must resist during an earthquake.

Light weight roofs

It appeared that light weight roofs performed well (Figure 18). These included long run corrugated steel, shorter older style panels of corrugated steel, pressed metal tiles, flexible corrugated products (e.g., bitumen saturated organic fibres), and rubber membrane roofs. The corrugated steel products were particularly resistant to falling chimney components, as were rubber membranes and shingles over plywood substrates (Figure 19).



Figure 18: Bitumen saturated organic fibre and rubber membrane roofing (Beattie).



Figure 19: Fallen chimney bricks retained on a shingle roof with a solid timber substrate (Beattie).

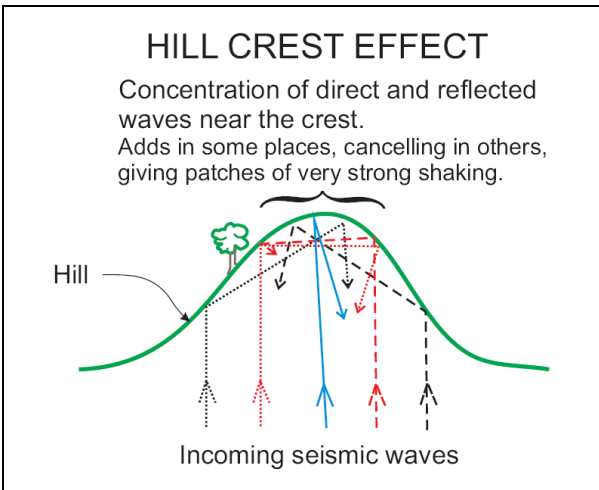


Figure 20: Possible mechanism for amplification of shaking on ridges [3].

Concrete and clay tile roofs

The performance of concrete and clay tile roofs was variable. On the flat land, particularly in the north and west of Christchurch, the damage was relatively minor, with odd cases of ridge and hip tiles dislodging. At the other end of the spectrum, heavy tiles on hillside houses in south-west Christchurch behaved very poorly (Figure 21). Very often, heavy tiles had been laid on battens with no mechanical connection to the battens. While these tiles may be able to resist a reasonable degree of horizontal acceleration before dislodging, the high vertical accelerations experienced on the hills in this earthquake caused widespread rearrangement of these heavy roof tiles. Some have suggested that accelerations appeared to have been higher on ridges than in valleys as shown in Figure 20 [3].

A further aspect of the behaviour of concrete and clay tiles was their inability to support the falling bricks from collapsing chimney stacks (Figure 22).



Figure 21: Dislodged heavy roof tiles on a hillside property (Beattie).



Figure 22: A case where roof tiles were not able to support falling bricks from a collapsing chimney (Beattie)

FOUNDATIONS

This section is a summary of the performance of house foundations in the earthquake. A more detailed description of house foundations in poor soil areas is in other papers [4] and [5].

Concrete slab on grade (reinforced or unreinforced)

Generally, concrete slab-on-grade floors performed well unless they were subjected to liquefaction or lateral spreading of the land beneath the slabs (Figure 23). Most slabs are either unreinforced, or reinforced with a welded wire steel mesh. The forces associated with the land spreading beneath the foundation were often greater than could be resisted by the steel mesh and fracture occurred, which also led to structural damage of houses (Figure 24). There is continuing debate as to whether slab performance was worse for slabs poured on uncompacted tailings used as hardfill, which is a practice commonly used locally in the Christchurch region.



Figure 23: (Left) An unreinforced slab that has been pulled apart because of land spreading beneath (Beattie); (Right) A reinforced slab that has been pulled apart by land spreading beneath (Beattie)



Figure 24: House and reinforced slab damage as a result of ground movement (Buchanan).

Slab-on-grade floors designed to NZS 3604 do not have sufficient stiffness to be able to bridge over severe land deformations beneath the slab, as occurred in areas of significant liquefaction. Slabs sometimes cracked under flexural actions when the ground beneath had differentially settled during the liquefaction process.

Slab to foundation connections

Failure of connections or lack of any connection between concrete floor slabs and their supporting foundation walls or edge thickening occurred quite regularly (Figure 25), as has been observed in other significant NZ earthquakes. NZS 3604 currently allows slabs on good ground to be unreinforced, but the poor behaviour of unreinforced slabs during these earthquakes will very likely lead to the removal of such construction practices from future versions of the Standard.



Figure 25: Example of a floor slab that has slipped sideways on the supporting foundation (Beattie).

Ribbed concrete slabs

Ribbed concrete floor systems performed better than NZS 3604 designed slab systems. Such proprietary systems utilise ductile reinforcing bars running in two orthogonal directions in the tops and bottoms of the ribs as well as mesh in the slab. The presence of the ribs stiffens the slab but not sufficiently to resist all deformations of the ground beneath and examples have been observed where the ribbed floor has hogged under the differential loads imposed by the exterior walls and the interior space.

Concrete slabs on driven piles

A number of houses on poor soil sites in Christchurch have reinforced concrete slabs cast on driven piles, which have been driven several metres into the ground. From a small number of observations, houses on slabs on driven piles performed better than simple slabs on grade [5].

Short concrete piles and perimeter concrete walls

Before the advent of slab-on-grade construction, the most common system of foundation construction in Christchurch was a concrete perimeter foundation. The ground floor of the house is a light timber floor system, most often with tongue and groove timber flooring on timber joists and bearers, supported by short concrete piles which are based on isolated concrete pads. The short piles are sometimes made from timber, in which case they may be called jack-studs. In some instances the house framing is supported entirely on the pile system within the perimeter walls and the veneer cladding is supported on the concrete foundation wall. Generally, most of these systems have performed very well because the continuous concrete foundation wall (especially if it is reinforced) has provided good bearing capacity and has held the whole house together, while the relatively stiff floor plate has transferred lateral forces to the perimeter foundation.



Figure 27: (Left) Failed unreinforced concrete wall foundation and (Right) jack studs (Beattie).

When lateral spreading has occurred beneath such houses, foundation walls have been observed to pull away from the timber framed floor system (Figure 26). Some of the foundation walls are unreinforced and some of these have failed as the tensile stresses caused by the spreading have increased beyond the tensile strength of the concrete.



Figure 26: Example of a foundation wall that has pulled clear of the floor framing. Note how the veneer and foundation have pulled away from the framing at the corner (Beattie).

Unreinforced concrete foundation walls in hill suburbs

In the hill suburbs, it appeared to be common for houses built in the 1960s and earlier to have similar concrete foundation wall and pile systems to those in the flat regions. The sloping ground necessitated the incorporation of taller walls at the lower end of the slope and short concrete piles with jack studs at the higher end of the slope. Several cases were observed of failed unreinforced concrete foundation walls which will need to be re-built with reinforced replacements to re-instate their resilience (Figure 27).



Figure 28: (Left) Bottom plate anchors that have torn out of the unreinforced concrete foundation wall; (Right) No apparent connection between the plate and the concrete slab (Beattie).



Figure 29: Houses sliding on foundations (Left, Buchanan, Right, Morris).



Figure 30: Failed diagonal brace between poles of a pole framed house (Left, Beattie) and lateral movement of house on pole foundations (Right, Buchanan).

Foundation-superstructure connections

Several cases of failures of connections between concrete foundations and the superstructure were observed in houses constructed until the 1960s. In some cases, hooked starter bars for bottom plate connections tore from the unreinforced concrete foundation (Figure 28, left). In other cases, it was difficult to find any obvious connection between the timber bottom plate and the floor slab (Figure 28, right).

Houses sliding on foundations

Several houses with insufficient attachment to the foundations slid up to 300 mm as a rigid body over the foundations, as shown in Figure 29. This is a clear result of insufficient anchorage between the perimeter foundation and the bottom plate of the light timber framing.

Pole houses

In general, pole houses appeared to perform well. Cases were observed where connections between unbraced pole structures and adjacent stiff concrete or concrete block foundations had failed because of the stiffness incompatibility between the two systems. Diagonal braces between poles performed well on most occasions but occasional failures were observed (Figure 30). Figure 30 (left) shows a failure initiated at the bolted end connection.



Figure 31: Evidence of impact of the house superstructure on the supporting pole structure (Beattie).



Fresh evidence was observed of vertical impact from a house superstructure on a pole frame foundation, confirming that the vertical component of the earthquake may have been sufficient to lift the superstructure and drop it back onto its supporting structure (Figure 31).

CASE STUDIES OF APARTMENT BUILDING COLLAPSES

Case Study 1

We are only aware of shake damage causing collapse of three light timber framed buildings. Two residential examples are covered in the following case studies. Case Study 1 is a multi-family residential unit. Figure 32 (left) shows the apartment building prior to the 22 February earthquake and Figure 32 (right) shows the collapse of the entire lower storey of the building after the earthquake. The images show that there was considerable lateral movement of the upper portion of the structure and site observations indicate that there was inadequate lower storey bracing in the collapse direction. Note that this building is outside the scope of NZS 3604 in that it has three timber storeys and NZS 3604 limits its scope to two storeys with a part storey in the roof space.

Case Study 2

Case study 2 is a three and a half storey apartment block which also suffered a soft storey collapse as shown in Figure 33. This building also is outside the scope of NZS 3604. This building had a lateral displacement of about 500 mm immediately after the earthquake as shown in Figure 34, but suffered a soft-storey collapse due to wind a few days later.



Figure 32: (Left) Google Street View image of the Case Study 1 apartment prior to 22 February, and (Right) Soft storey collapse in 22 February earthquake (Turner).



500 mm displacement, immediately after the earthquake (Structex).



Same building after collapse, several days later (Buchanan).

Figure 33: *Soft storey collapse of Case Study 2.*



Figure 34: *(Left) Interior lining damage to steel framed house, and (Right) Exterior cladding damage to steel framed house (Carradine).*

PERFORMANCE OF LIGHT STEEL FRAMED HOUSES

Although there is limited information currently available on light steel framed houses, the available data suggests that they performed quite well in cases of shaking and in general damage was limited to cracks of internal linings and exterior cladding (Figure 34). In one house with significant damage to linings, the plasterboard linings were only glued to the steel studs, with no screws or other mechanical fasteners (Figure 35). As with other types of houses, in cases of severe ground movement it was not possible for these structures to accommodate the movement without significant damage.



Figure 35: *Damage to plasterboard bracing sheet glued to steel studs with no screws.*



Figure 36: *Examples of partial collapse of double brick houses (Carradine).*



Figure 37: *Failure of brick fire wall near city centre (Carradine).*

DOUBLE BRICK HOUSES

Double brick houses generally performed very poorly during the earthquake and many were observed to have partially collapsed as shown in Figure 36. Roof and floor diaphragms and internal timber framed walls were in many cases able to maintain integrity even in houses with failed double brick exterior walls. There were also many instances where double brick fire walls collapsed, leaving the remaining timber framed house relatively intact (Figure 37).



Figure 38: *UngROUTED cells with reinforcing steel in place (Beattie).*



Figure 39: (Left) Collapse of unreinforced masonry exterior wall (Carradine), and (Right) Collapse of unreinforced masonry exterior wall (Morris).



Figure 40: Soft storey collapse of unreinforced masonry structure (Carradine). Performance of Solid Masonry and Concrete Houses

REINFORCED MASONRY HOUSES

Generally, fully reinforced and grouted concrete block masonry houses performed very well. Current standards for reinforced masonry houses allow the use of either partial filling or complete filling of the cells in the blocks with grout. In the partially filled case, only the reinforced cells are filled with grout. It was observed that on many occasions the grouting process for the partially reinforced walls was not completed well, leaving reinforcing steel dangling in unfilled cavities (Figure 38).

UNREINFORCED MASONRY HOUSES

As would be expected, unreinforced masonry houses did not perform well during the earthquake and numerous examples have been found showing examples of exterior structural wall failure (Figure 39). There were also some cases of full collapses, as shown by the soft storey collapse of the lower level in Figure 40, where the horizontal movement of the upper storey was over 2 m.



Figure 41: Compression failure of tilt-panel concrete house (Carradine).



Figure 42: Failure of a concrete sandwich panel wall system (Beattie).

TILT-PANEL CONCRETE HOUSES

Damage to tilt-panel reinforced concrete houses showed a mix of damage levels from minimal to severe and in some cases within a close proximity, it is clear that detailing of these buildings is a key factor in determining earthquake resistance. Some of the observed damage included compression failures at regions of high stresses, as shown in Figure 41, and failures of welded steel clips that connect the panels and the concrete around the clips.

CONCRETE SANDWICH PANEL HOUSES

At least two examples of concrete sandwich panel houses were observed where failure of the connection between the inner and the outer skins had occurred. In one case it appeared that the only connections between the skins were plastic ties which had failed in either tension or shearing (Figure 42).

PERFORMANCE OF SOLID WOOD HOUSES

Although numbers are limited, some solid wood houses in and around Christchurch are made from stacked and interlocking courses of timber rather than having traditional timber framing. A major difference between these and other wooden house constructions is that in solid wood houses the wall system often serves as a structural wall including interior and

exterior finishes, so there is no separate cladding or interior wall lining. These types of houses performed well during the 2010 and 2011 seismic events.

Lockwood Houses

Lockwood Group Ltd provided information on the performance of Lockwood Houses from the 4 September 2010 and 22 February 2011 earthquakes in a report by Parker [10]. In general the performance of these buildings was very good during both events and damage where more than minimal was limited to ground movement and liquefaction. According to the report, none of the houses inspected were uninhabitable and the majority experienced no additional damage beyond what occurred during the September 2010 event. Also of note was that in some cases the undamaged Lockwood homes were located in areas where the majority of surrounding houses were moderately to severely damaged.

Fraemohs Houses

Fraemohs Homes Ltd also provided a report on the performance of their buildings during the earthquakes [11]. While these buildings were reported to have moved significantly during the earthquake, the damage observed after the event was minimal, even in cases where significant ground settlement (up to 200 mm) was observed. It was noted that for Fraemohs houses built using 63mm thick (2 and 3 laminates) walls, there were some cases where small portions of the timber sections had sheared off near the bottoms of walls, as shown in Figure 43. This was reported to be the most severe damage to any of the inspected Fraemohs homes and it was noted that the failures occurred in places where the laminates were half notched, therefore having a smaller cross-section. No damage was observed in Fraemohs homes made using 93 mm thick, 3 ply laminates.

A Fraemohs house located in the Avondale area of Christchurch was found to have only minimal separation of some of the log/timber courses even though the house suffered differential settlements up to 100 mm, cracking of the concrete floor slab, and severe liquefaction resulting in several tonnes of silt needing to be removed from inside the house and from the surrounding yard (Figure 44)



Figure 43: Examples of damage to Fraemohs home located near Dyers pass (Love).



Figure 44: Minor damage to interior of Fraemohs house despite serious liquefaction and differential settlement (Buchanan).

CONCLUSIONS

Summary

Many thousands of houses were damaged with the worst damage occurring in the eastern suburbs due to liquefaction and lateral spreading. Very high levels of lateral and vertical shaking were the main causes of damage in the hill suburbs. Light timber framed buildings provided excellent life safety, and prevented walls and roofs collapsing when subjected to high levels of seismic shaking and severe ground deformations. Gypsum plasterboard linings generally provided excellent earthquake resistance, provided that design and installation had been carried out correctly. When lives were at serious risk due to rockfall, the resilience of light timber frame construction was evident with houses still standing after large sections of walls were destroyed.

While light framed houses performed well for life safety there are a number of opportunities to improve current practice and performance, as outlined in the Recommendations below.

Recommendations for Urgent Research and Possible Changes to Standards

As a result of the observations described in this paper, it is recommended that the following steps be taken:

- Review NZS 3604 requirements for reinforcing in concrete slab-on-grade, for sites on good ground, and especially for sites prone to liquefaction and lateral spreading
- Review the widespread local practice of using uncompacted tailings as hardfill under slab-on-grade floors.
- Find a way to require builders to sign off on placement of veneer ties when masonry veneer cladding is used.
- Review the structural design and detailing for those few modern multi-storey houses which suffered a soft-storey collapse.
- Require a higher quality of construction and supervision for structural reinforced masonry houses, especially if only the reinforced cores are filled with grout.
- Reconsider the distribution and stiffness of bracing walls in new house construction, especially for architecturally designed houses outside the scope of NZS 3604.

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