PERFORMANCE OF RESIDENTIAL HOUSES IN THE DARFIELD (CANTERBURY) EARTHQUAKE

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SUMMARY

This paper focuses on the observed seismic performance of residential houses (mainly single-storey and two-storey houses) in the Darfield earthquake on 4 September 2010 and identifies potential research areas for remediation and resilience.

Overall the residential building stock, consisting predominately of light timber frame construction, performed very well, with very little structural damage due to ground shaking. The most significant structural damage to houses was from differential settlement of foundations, induced by soil liquefaction and/or lateral spreading. Many older buildings (more than 20 years old) suffered damage due to falling chimneys. Close to the fault rupture, in areas such as West Melton and Rolleston, there was significant damage to building contents due to strong shaking, and a few broken windows. Away from the fault zone, very few windows were broken in any buildings, indicating limited inter-storey drift.

Research needs were identified associated mainly with the design and repair of houses on liquefaction-prone soils.

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BUILDING STOCK

Most houses in Canterbury are constructed of light timber framing on concrete slab or timber piled foundations, designed and built in accordance with NZS3604:(1999) [1], or earlier documents. A limited number of other structural systems exist including solid timber (Lockwood, Fraemohs or Triboard houses), light steel framing and structural masonry.

Almost all new residential buildings built in the past 20 years have a ground floor concrete slab. These slabs are generally very thin (the NZS3604 minimum of 100 mm) with little or no reinforcing steel, and reinforced thickenings at the perimeter. Most older buildings have a timber floor supported on timber joists and bearers, in turn supported on short timber or concrete piles, with reinforced or unreinforced concrete perimeter foundation walls.

There are several different materials commonly used as exterior cladding to light frame buildings. The most common cladding is timber weatherboards (older buildings), unreinforced brick veneer, or many variations of plastered stucco cladding. Unreinforced brick veneers are usually attached to the timber studs with small steel ties, nailed or screwed to the studs and embedded in the mortar between the bricks.

Most light frame buildings have internal wall and ceiling linings of gypsum plaster board. In most modern buildings, the gypsum plaster linings are relied on to provide some or most of the lateral bracing, in addition to plywood bracing sheets on a few heavily loaded walls, plus diagonal steel straps for construction stability. Older buildings have lath and plaster internal linings. The small number of solid timber houses (Lockwood or Fraemohs style), require no internal lining if the wood is exposed internally.

LIQUIFACTION INDUCED DAMAGE

Soil liquefaction or lateral spreading has resulted in major structural damage to hundreds of houses, many of which will have to be demolished (Tonkin and Taylor Ltd 2010) report [3]). Residential areas that were significantly affected by liquefaction were Avonside, Dallington, Avondale, Bexley, Spencerville, Kaiapoi and Pines Beach. In riverside areas, settlement and lateral spreading, and consequent building damage, increased with proximity to the Avon River. Liquefaction induced damage has been observed in a few other areas, but limited to a smaller number of dwellings.

The amount and uniformity of ground settlement varied greatly from site to site. On sites where the settlement was mainly uniform the structural integrity of the house foundations remained essentially intact but some buildings tilted, causing minor structural damage. On sites where differential settlement or lateral spreading occurred, the buildings became distorted, resulting in cracks in concrete slabs and foundations, brick veneers, and internal linings. On sites where severe lateral spreading occurred, such as Courtenay Drive in Kaiapoi, buildings suffered from extensive structural damage (see Figure 1). Sinking into soft soils appeared to be more severe for buildings with heavy brick cladding and heavy tile roofs.

Concrete slabs and timber floors on short pile foundations were observed to perform very differently on liquefied sites. This was clearly illustrated at an Avondale residence

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consisting of an older (1950s) house, partly built on short concrete pile foundations and newer (1997) extensions built on a concrete slab. The older part of house on piles remained relatively plumb compared to the newer part. The large settlements of the slab foundations caused extensive structural damage at the interface between the old and new structure (see Figure 2). Similar observations were made on sites where a garage or carport on a concrete slab was connected to a house on short pile foundations, giving differential movement between the two foundation types and resulting in damage to the wall and roof structure of the building. In general, for areas where there has been soil liquefaction, short pile foundations performed better than concrete slabs. The better performance of houses on piled foundations may also be a consequence of the timber ground floor which can accommodate differential settlement of the foundation system more easily than a concrete slab.

A small number of buildings on poor soil sites have driven piles (timber or concrete) several metres long under the concrete slab, but it is not possible to identify these buildings from a visual inspection. There are several verbal accounts of buildings with driven piles performing much better than neighbouring buildings with simple concrete slabs.

Several concrete floor slabs fractured due to uneven liquefaction induced settlements. This occurred mostly in modern buildings, some of which had little or no observable slab reinforcement. NZS3604 does not require any slab reinforcing (except in edge beams) for single storey houses. Structural damage may have been reduced if more reinforcing had been used in the slabs with better detailing, or if a thicker solid slab or thick ribbed slab (Ribraft) had been used.

On all sites with differential settlement, there was significant non-structural damage to the wall linings, windows, doors and fixtures due to cracks in the concrete slab and building envelope. Outside the houses, yards were often covered in ejected soil from liquefaction, and driveways and garages were distorted due to settlement. On most liquefied sites there was no structural damage to houses due to shaking, possibly because the soft soil isolated the structure from the worst ground motion (similar to a base isolation system).

Intuitively, the relative performance different foundation systems is likely to depend on the severity of liquefaction.

Figure 1: ***Lateral spreading of house in Kaiapoi.***

a)

b)

Figure 2: ***Differential settlement of building due to liquefaction (a) cracking in ground floor slab (b) settlement of piles.***

SHAKING INDUCED DAMAGE

Shaking induced structural damage was very minor, in almost all cases. Other than chimney damage, the most severe shaking-induced structural damage was in a small number old buildings constructed of unreinforced structural brickwork.

Compared with Christchurch city, slightly more damage occurred in areas with high proximity to the fault rupture, such as West Melton, where cracking to gypsum board linings and brick veneer was common (see Figure 3). The severity of shaking in West Melton caused some concrete slabs to move or crack.

Markedly different levels of damage were observed surrounding the fault rupture. Areas in-line with the fault trace, such as West Melton, suffered from noticeably more shaking induced damage than areas orthogonal to the fault trace, such as Darfield and Rolleston. Hence, the characteristics of the fault rupture (known as the directivity effect) appeared to significantly influence the seismic demand on buildings.

Shaking induced damage is discussed in five categories: internal linings, masonry veneers, chimneys, damage to contents and structural masonry.

Internal Linings

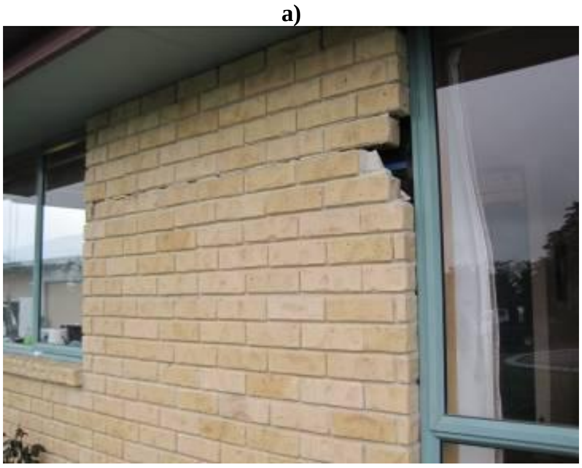
Many houses in Christchurch had zero cracking to internal linings, and others had a few very minor cracks, usually near door or window openings. Due to the limited wall damage, it can be inferred that the gypsum board wall linings worked well to provide most of the bracing to the buildings. Some buildings had additional plywood bracing panels, but it is not possible to visually determine the location of these in an undamaged house. Larger movements and cracks in some older buildings showed that lath and plaster is not as stiff as modern gypsum board as a bracing material. Buildings with heavy roofs tended to have more lining damage than those with light roofs.

There was generally very little ceiling damage other than minor cracking at wall-ceiling junctions. The only observations of local ceiling collapse were in a few most severely damaged buildings in liquefaction areas or very near the fault rupture.

a) **b)**

Figure 3: ***Cracking of gypsum board linings .***

a)



b)

Figure 4: ***Two examples of brick veneer cracking.***

Masonry veneers

The vast majority of unreinforced brick veneers suffered very little or no damage. Some had minor cracking in the mortar joints but no lateral displacement of the brickwork. In a small number of cases, mostly close to the epicentre, brick veneers became cracked or partially detached from the framing (see Figure 4). In one particular building (see Figure 5), recycled brick veneer performed very poorly because the bricks had not been properly cleaned, and there was no adhesion of the mortar, reducing mechanical interlock between the new mortar and the old bricks.

Older heavier houses (mainly pre-1970s) with heavy brick veneer or concrete block veneer and concrete tiled roofs, appeared to suffer more structural damage than newer lighter buildings. This can be attributed to the greater mass of the structures. Modern brick veneer construction generally uses thinner bricks and lightweight roof cladding, giving improved seismic performance.

Figure 5: ***Collapse of recycled brick veneer .***

Chimneys

The most common type of damage for older buildings (more than 15 years old) was chimney collapse. This occurred in many thousands of buildings (see Figure 6). Falling chimneys could be interpreted as a violation of the 'life-safety' criterion required by New Zealand Standards (NZS1170.5 2004) [2] for current building seismic design. Falling chimneys resulted in damage or piercing of the surrounding roof structure, damage to neighbouring properties, vehicles but (luckily) no loss of life.

Chimney collapse on to corrugated steel roofing often caused no further damage, depending on the height of the chimney, but some fell through the roof or caused rafter failure. Chimneys falling on to tile roofs (concrete or clay tiles, or slate roofs) more often fell through into the house, sometimes causing further structural damage and potential loss of life.

a)

b)

Figure 6: ***(a) Collapsed chimney on corrugated iron roof ; (b) Damaged chimney being removed.***

Structural masonry

There was extensive damage and partial collapse of old (pre-1930) unreinforced brick masonry houses which do not comply with modern standards. The majority of these buildings consist of double brick structural walls and timber roof trusses, typical of early colonial construction. The Deans Homestead at Homebush is an example (see Figure 7). A number of unreinforced or minimally reinforced concrete block structures (garages and houses) suffered from partial collapse or had very large diagonal cracks. Performance of unreinforced structural masonry buildings is discussed in more detail elsewhere in this bulletin.

Figure 7: ***Collapse of double brick veneer house at Homebush (Lyndon Mechielsen, Source: The Australian).***

Other structural systems

The performance of a limited number of houses with light steel framing or solid timber was observed. There was no evidence of light steel framing performing better or worse than light timber framing. Solid timber houses (Lockwood, Fraemohs or Triboard) performed excellently, exhibiting less shaking induced damage than light timber frame.

DAMAGE DUE TO FAULT RUPTURE

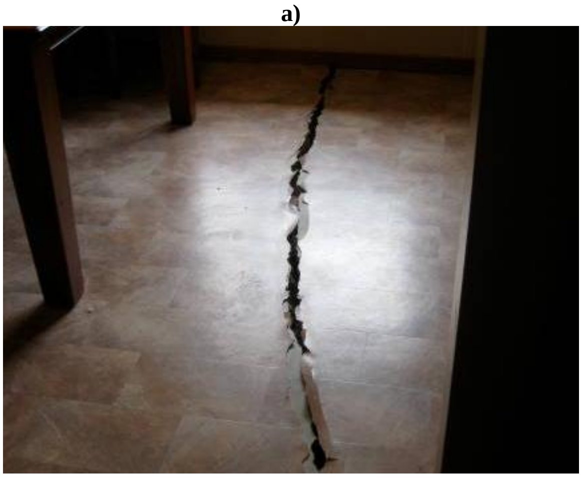
There were limited cases of damage due to differential ground displacement under buildings located on the fault rupture. Concrete slabs and building envelopes were ruptured (see Figure 8). Damage was similar to that seen in buildings that suffered from heavy liquefaction and lateral spreading. The ceiling diaphragm and roof trusses held the structure together, avoiding collapse of the structure.

In contrast to liquefied sites, sites on the fault rupture tended to suffer from more severe shaking. This caused additional damage to structural walls and damage to non-structural components.

DAMAGE TO CONTENTS

Damage to contents varied greatly in different parts of Christchurch. In general, damage increased with increased severity of shaking, especially near the epicentre. Many houses in the city had little or no damage to contents. The most common damage was broken glassware falling from in cupboards, draws and shelves. In areas of the strongest shaking such as West Melton, cabinets, bookshelves, televisions and stereos overturned, and washing machines, refrigerators and freezers moved, sometimes colliding with walls. There were some cases of hot water cylinder brackets breaking and pipes fracturing. Outside the houses, many block fences collapsed and cars were damaged from unrestrained items stored in garages.

a)



b)

Figure 8: ***Damage due to fault rupture: (a) Fault rupture passing through house (c.o. G. A. MacRae) (b) Crack in floor slab of another house***

MITIGATION ISSUES – REMEDIATION AND RESILIENCE

There are several mitigation issues that have arisen from the observed seismic performance of Canterbury houses. These issues include repair of existing damage, and strengthening of damaged and undamaged buildings

Repair of buildings damaged by shaking

Again, the most common form of damage is due to chimney collapse. Repair of damage caused by falling chimneys or other masonry is relatively easy, and in many cases this was done within a few days of the earthquake. However, many houses had damaged or undamaged brick chimneys or brick walls still standing after the earthquake which are major threats to life in future earthquakes. These should be inspected by qualified engineers, and be strengthened or removed as necessary. Most other shaking damage consists of minor damage to linings or cladding which can be repaired in the normal way.

Repair and strengthening of heritage buildings is a complex issue, beyond the scope of this paper, which requires further investigation.

Repair or relocation of damaged buildings on poor soils

Repair of damaged or tilted houses caused by ground liquefaction is very difficult and expensive, and is potentially uneconomical. Repair may not be permitted by the local council or may not be covered by insurance on sites with very poor soils, unless remediation is carried out. This is a geotechnical issue requiring specific advice from geotechnical engineers on a site-by-site basis [3], [4].

Activities such as relocation, or lifting and straightening of damaged or tilted houses will generally be easier and cheaper for houses with timber floors on short pile foundations compared with houses on concrete slabs. Advice must be sought from professional engineers and house-moving experts on a case-by-case basis. Guidance documents for repair and reinstatement are being prepared by EQC, consultants, and the Department of Building and Housing, but these are not yet available at the date of publication of this paper.

Research needs

Based on observations of the damage to residential houses, the following research needs have been identified:

- A full analysis of all Earthquake Commission (EQC) claims, to provide much more specific data on the types of damage described in this report.
- Review of NZS 3604 [1] to address issues of building or repairing houses and foundations on poor soils susceptible to liquefaction and lateral spreading. Potentially, liquefiable sites may require specific design for foundations, outside the scope of NZS 3604.
- Define what is the acceptable damage for a given earthquake event. This will enable more robust performance-based seismic design for houses and foundations.
- Testing and analysis of liquefaction and lateral spreading for typical house construction, and strategies for possible improved behaviour.

- Other aspects of geotechnical earthquake engineering related to house design.
- Strategies for removing or straightening houses on damaged concrete slabs
- Investigation of brick veneer stability including requirements for the use of recycled bricks.

Items not considered

There are many other aspects of earthquake damage to houses which are not covered in this brief report, including:

- Insurance cover for repair, reconstruction or relocation
- Policies of Territorial Authorities for repair, reconstruction or relocation
- Non-structural aspects of buildings being repaired – insulation, weather-tightness etc in relation to current code requirements
- Special conditions for heritage buildings

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