

Modern and historic earth buildings: Observations of the 4th September 2010 Darfield earthquake

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ABSTRACT: The New Zealand Earth Building Standards published in 1998 are very comprehensive and gain considerable attention internationally. The Darfield earthquake is the first time that the NZ reinforcing approach has been tested in the field. Ten modern style houses using rammed earth, adobe, pressed earth brick, and poured earth technologies were surveyed in October 2010. Where good reinforcement and design was applied the minor damage was due to differential ground movement, very high walls, or inadequate detailing. Subsequent to the 22nd February 2011 earthquake a further survey identified shaking damage to pressed earth brick houses which require better detailing. Four unreinforced historic, or reconstructed, cob and sod cottages and three historic cob houses were investigated. Two cottages with earth walls from the 1860's were the most severely damaged, reconstruction needs to preserve the original material components.

1 INTRODUCTION

1.1 The earthquake and survey

On 4th September 2010 a magnitude 7.1 earthquake occurred near the town of Darfield approximately 40 km west of Christchurch, at a depth of 10 km as reported in the New Zealand Society of Earthquake Engineering (NZSEE) Bulletin (Cousins and McVerry 2010, Gledhill et al 2010). A survey of earth buildings was undertaken with support from the Earth Building Association of New Zealand EBANZ one month after the earthquake and a summary of all houses surveyed was reported in the Bulletin. (Morris et al. 2010). In 1991 the Christchurch area affected was reported to have 32 earth houses and cottages and around 10 disused sheds or utility earth buildings. (Allen 1991) We located and had permissions to visit 6 of the listed houses and surveyed 8 buildings built since 1991. The damage was consistent with expectations and would have been prevented if the details used were consistent with the New Zealand earth building standards. This paper focuses on three modern adobe houses and one rammed earth house that have damage from the September earthquake that is instructive for the earth building standards. Additional comment is made about pressed earth brick buildings subsequent to the shallow M_m 6.3 February event that generated high local accelerations.

1.2 Earth Building Technologies

Earth buildings use heavy low strength masonry or low strength monolithic walls panels. Buildings in the 2010 survey included a range of earth wall types. These are: Adobe - sun dried brick; Rammed earth - stabilised soil heavily compacted between shutters; Cinva pressed brick - bricks of cement stabilised soil hand pressed with a Cinva Ram or similar mechanical press; Cob - soft soil mixture laid into a wall in layers; Sod - soil blocks cut from the ground and placed directly into the wall; and Poured earth – a cement stabilised semi-liquid soil mixture poured or vibrated into formwork layer by layer. Each of these technologies performed well when properly reinforced. The cob and sod

constructions were unreinforced historic or replica cottages and some suffered major damage.

1.3 Earth Building in New Zealand and around the World

In developing countries over half the world's population live in modest buildings with walls made of earth. Australia has the largest number of larger modern houses, in the 1990's, in Margaret River WA, modern rammed earth houses were around 25% of all new housing with adobe houses continuing to be the preference in the south and west of Australia.(Dobson 2011) Interest in environmentally sustainable construction means a small number of modern earth houses continue to be constructed in the USA and in Canada and there is increasing interest in Europe including commercial and public buildings. In New Zealand approximately 15 earth houses are built each year with about 1/3 constructed by owner builders and 2/3 by commercial contractors with some specialist expertise.

1.4 Typical Unreinforced Seismic Performance

Earth buildings that are unreinforced have a number of typical failure modes as illustrated in Figure 1. These modes of failure were observed in two reconstructed historic cottages. Serious damage to Cotons Cottage in Hororata is shown in Figure 2, the horizontal peak ground acceleration (PGA) measured 0.5g just 350m away. Horizontal accelerations (PGA) through this paper are from GNS data interpolated from the NZSEE bulletin (Gledhill et al. 2010, Cousins and McVerry 2010). It is proposed that this building be reconstructed using the same soils and historic techniques but with steel and polysynthetic geogrid reinforcing within the wall fabric.

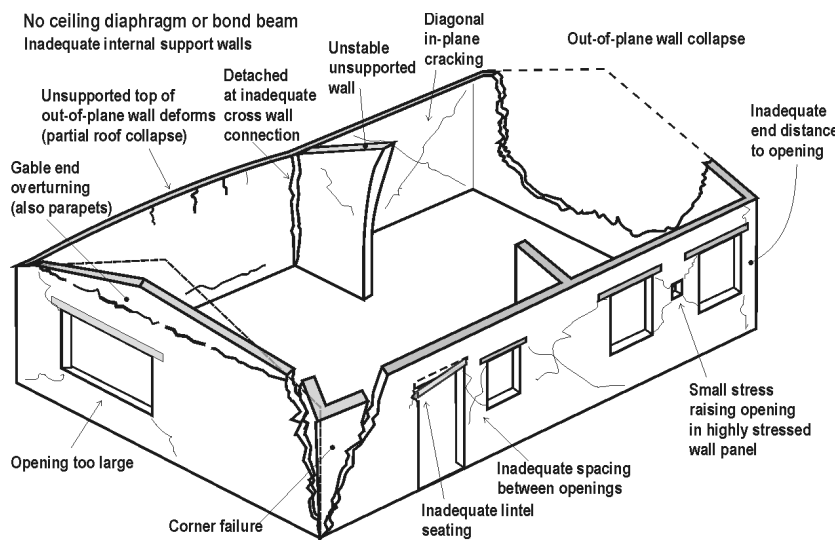


Figure 1 Typical failures of unreinforced earth construction



Figure 2 Cotons cob cottage extensively damaged

2 THE NEW ZEALAND EARTH BUILDING STANDARDS

The New Zealand earth building standards require reinforcement in all buildings in Christchurch and in moderate and severe seismic zones and use limit state design principles for both elastic and limited ductile response. The requirements are specified in a suite of three documents as outlined below. These standards are also used internationally and were cited by ASTM E2392 in 2010 (ASTM 2010).

2.1 NZS 4297 Engineering Design of Earth Buildings

NZS 4297 Engineering Design of Earth Buildings (Standards New Zealand 1998a) specifies design criteria, methodologies and performance aspects for earth wall buildings with wall heights limited to 6.5 m and is intended for use by structural engineers.

In-Plane seismic load resistance is provided by bracing walls in each principal direction of the building. Reinforced earth walls are reinforced vertically and horizontally to provide limited in-plane ductility and to develop full shear strength. Initial failure is in-plane bending with yielding of vertical

end reinforcing with shear failure restrained by the use of well distributed horizontal reinforcing.

Out-of-Plane design of individual wall panels uses ultimate strength reinforced concrete theory as the best approximation. Vertical reinforcing is considered to provide the tensile force for reinforced earth wall panels to work in flexure against out-of-plane face loading. An energy method based on the collapse mechanism when the displacement of the wall moves beyond stability is used for assessing the ultimate limit state seismic out-of-plane resistance for sections of unreinforced walls spanning vertically. This energy approach is based on a method proposed by Priestley for determining earthquake instability criteria to take into account the collapse mechanism in unreinforced masonry. (Priestley 1985) A procedure was published in draft Guidelines for Assessing and Strengthening Earthquake Risk Buildings in 1995 (NZSEE 1995). This procedure was slightly refined and incorporated in NZS4297 for out-of-plane calculations for unreinforced earth brick or adobe walls.

2.2 NZS 4298 Materials and Workmanship for Earth Buildings

NZS 4298 Materials and Workmanship for Earth Buildings (Standards New Zealand 1998b), defines the requirements to produce earth walls which, when designed in accordance with NZS 4297 or NZS 4299, will have the strength and durability to satisfy requirements of the New Zealand Building Code. Requirements are given for all forms of earth construction but more specifically for adobe, rammed earth and pressed brick. Technical detail is available elsewhere (Walker & Morris 1998, Morris 2009).

2.3 NZS 4299 Earth Buildings Not Requiring Specific Design

NZS 4299 Earth Buildings Not Requiring Specific Design (Standards New Zealand, 1998c), provides methods and details for the design and construction of earth walled buildings not requiring specific engineering design. It has comprehensive construction details based on the best practice in New Zealand and Australia, a typical wall detail is shown in Figure 3.

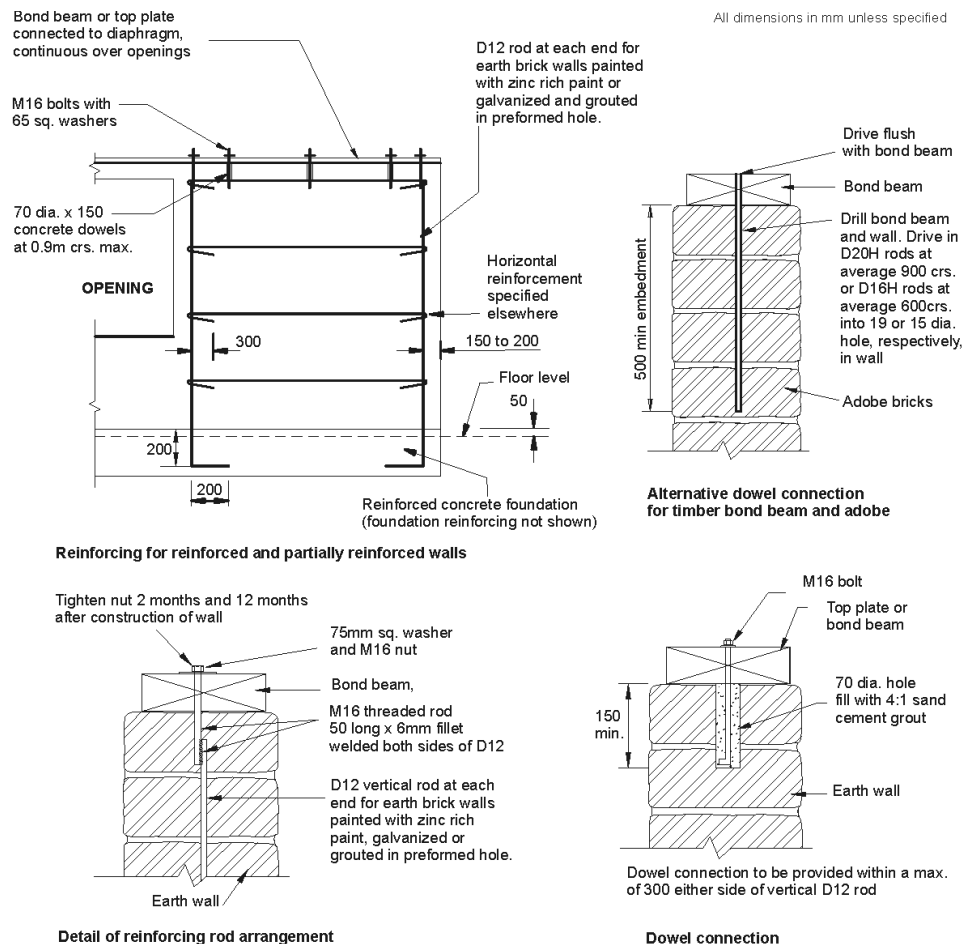


Figure 3 Typical NZS 4299 reinforced wall detail – polypropylene geogrid or steel used horizontally

The document is mainly used for designing houses and users include a range of people in the earth building industry including builders, architects, engineers, and building authority staff.

This standard covers buildings with single storey earth walls and a timber framed roof, or single lower storey earth walls with timber second storey walls and a light timber framed roof. The scope is limited to footings, floor slabs, earth walls, bond beams and structural diaphragms.

Earth buildings covered by this standard resist horizontal wind and earthquake loads by load bearing earth bracing walls that act in-plane in each of the two principal directions of the building. A simple design methodology uses tables in terms of “bracing units” for determining the “bracing demand” required for the building and the “bracing capacity” is provided by the nominated bracing walls. All buildings are required to have substantial concrete or timber bond beams or structural ceiling or roof or first floor diaphragms to transfer out-of-plane loads into transverse earth bracing walls.

The more significant failures observed in the Darfield earthquake would have been avoided if the construction details in the NZS 4299 standards had been followed.

3 OBSERVATIONS OF DAMAGE TO FOUR HOUSES

3.1 Selection of examples

The damaged houses surveyed were those notified to EBANZ as outlined in section 1.1. The four selected for further discussion are those that were subjected to significant earthquake loads and provide the most instructive information for modern reinforced earth construction. One house is rammed earth. The others are reinforced adobe with similar structural detailing to the NZ standards.

3.2 Hororata Rammed Earth House

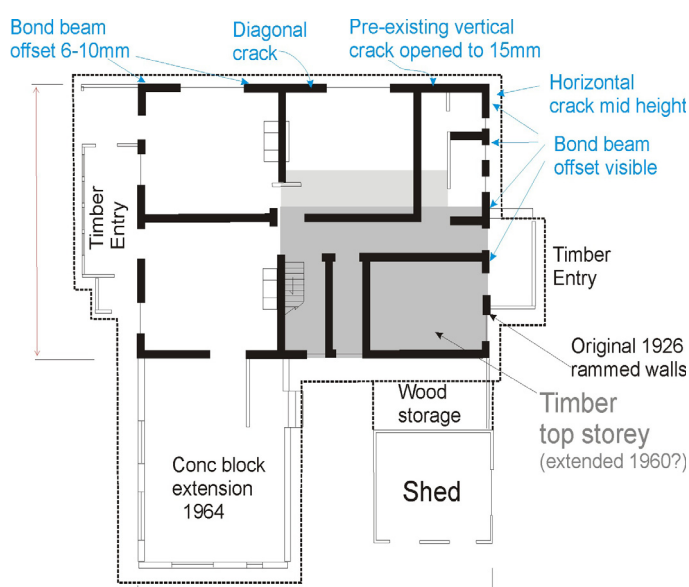


Figure 4 Hororata rammed earth house plan, rammed earth walls are heavy lines, showing damage locations.

The Hororata house was a rectangular plan with rammed earth walls 450mm thick and 2.1m high with no reinforcement in the wall matrix. It was competently built in 1925 and has a reinforced concrete bond beam that was poured on top of the rammed earth wall,



Figure 5 Hororata house, rammed earth on lower right

the reinforcement details are not known but there was no apparent key to the wall. As shown in Figure 4 and Figure 5 the house had a small upper level above the east entry at the time of construction, this was extended in the 1960's and a reinforced concrete block extension added. The slip of the bond beam relative to the north wall can be seen in Figure 6 and in Figure 7 some cracks are shown at the base of that wall

The house needs maintenance for moisture protection, the rammed walls had some pre-existing cracks due to earlier shrinkage, earthquakes or foundation settlement. One of these opened from about 10mm

pre-existing to 15mm.

The house is located 14km from the Epicentre in the highest horizontal ground acceleration zone directly between two strong motion seismographs and would have been subjected to 0.65g horizontal PGA and 120cm/s peak velocity. The brick chimneys collapsed and furniture was overturned but the walls performed well. The major disrupting feature was the bond beam that shifted to the North West by 6-10mm. The most significant earthquake damage was at a point where part of a wall panel adjacent to a window remained attached to the bond beam noted as a diagonal crack on figure 4.

Most of the damage to this house would have been prevented if there was a positive connection from the wall to the bond beam. The wall thickness is greater than would be required by the earth building standards which would require vertical reinforcement at the ends of each panel as a minimum in moderate or high seismic zones.



Figure 6 Hororata house showing offset of the bond beam outside and inside and a related wall crack

3.3 Charing Cross Adobe House

The adobe house illustrated in Figure 8 and 9 was built in 1997, 4km from the epicentre. It was 800m from the fault trace towards the epicentre and 6km from the Greendale seismometer so is likely to have experienced 0.7g to 0.8g horizontal PGA. The walls are 275 mm thick and 2.7m high and are horizontally and vertically reinforced. Vertical reinforcing is continuous to the top plate which is additionally anchored to both the wall and the ceiling diaphragm. The most significant damage was a cracked floor slab evident from a 2-3mm crack in the floor

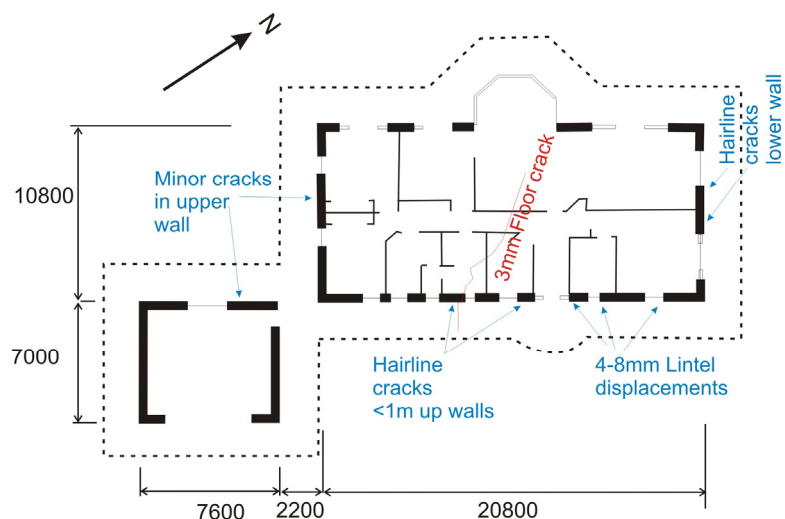


Figure 8 Charing Cross adobe house plan showing adobe walls and minor damage locations

tiles. This crack continued as a 1mm crack through the concrete foundation beam reinforced with a D16 (deformed 16mm rod) top and bottom (two D16 reinforcing rods top and bottom are specified in NZS4299). There were also hairline cracks at foundation level as shown in Figure 8. It appears that there was some differential movement at the west corner where settlement and movement of the verandah posts embedded in the concrete path caused cracking in the upper south wall (Figure 10). Lateral movement had caused movement or minor pounding of the lintels leaving gaps of 4-6mm at ends of the lintels (Figure 11).

The Charing Cross house incorporated many details that are included in the earth building standards but with a slightly weaker diaphragm and no rigid cross walls. The primary damage was due to differential ground movement and while the cracking indicated that the building had suffered significant shaking the limited amount of damage in this significant event provides some evidence for the effectiveness of the building system.



Figure 9 Charing Cross adobe house, 4km South East of the epicentre



Figure 10 Crack in wall near the west corner



Figure 11 Opening at edge of lintel beam

3.4 Leeston Adobe House

An adobe house built in 1999 with wall thickness of 275mm and wall height of 2.25m, a feature wall along the apex of the East West wing is 4.1m high and has 430mm wall thickness. The walls were vertically and horizontally reinforced and fixed to timber ceiling diaphragms. The soil on site is soft and deep with surface evidence of liquefaction with sandy soil ejected in the driveway. The likely horizontal PGA at 30km from the epicentre is 0.2g and Modified Mercalli intensities of MMVI to MMVII were reported in the area.

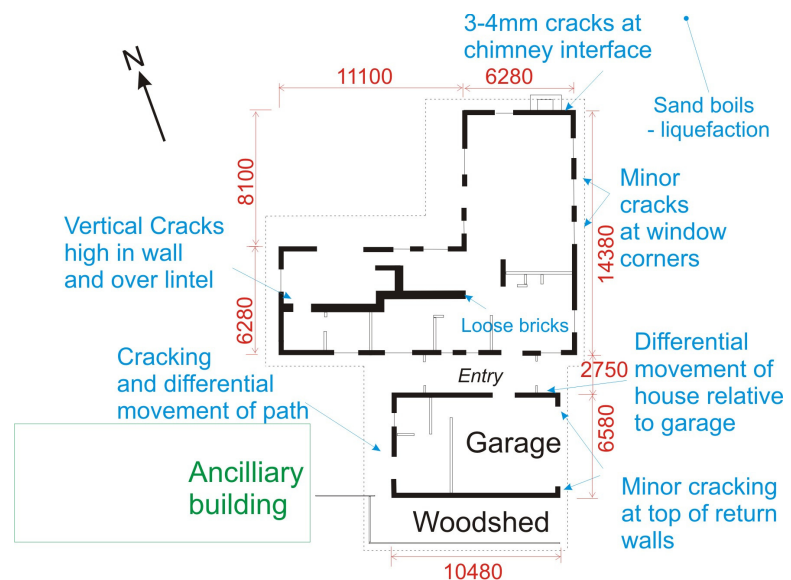


Figure 12 Leeston adobe house plan showing locations of damage

Most of the damage is shown in Figure 12, it was clear that differential ground movement had separated the garage from the house. The return walls at the garage entry were too short and there was some dislocation of upper level bricks. The most obvious damage was due to the differential movement of the chimney (Figure 13). This is not structurally significant but will require a difficult repair. There were minor cracks that extended for several brick depths below several windows as shown in Figure 14. The high wall had several bricks at the top that were insufficiently anchored into the top beam and cracked with some becoming loose.

The most significant damage was a vertical crack in the high wall above the lintel beam, the 2m of wall above the opening had moved out-of-plane during the earthquake (Figure 15). This unusual feature would require more specific reinforcement detailing if it were to be formally designed.

The majority of damage to the house was minor and differential movement of the chimney and garage was clearly made worse by the poor foundation conditions. The tall wall did satisfy the height to thickness requirements of the NZS 4297 Engineering Design standard but is well outside the scope of NZS4299 and is not recommended in high seismic zones.



Figure 13 Leeston adobe house showing chimney



Figure 14 Typical cracks adjacent to window



Figure 15 High wall above lintel (vertical crack not visible)

3.5 Staveley Adobe House

This house has lower storey adobe walls with a thickness of 280mm and 2.4m high, it was built in 2008. It is 60km from the epicentre on shallow soil and subjected to about 0.15g-0.2g horizontal PGA and MMVI. It has a timber upper storey and had some design input to comply with aspects of the Standards but does not comply with NZS 4299 in terms of cross walls and had very short return walls as shown in Figure 16 and Figure 17.

The house was maintained to a high standard but the lateral movement during strong wind was reported by the owners to be significant at the NW end of the house. Cracks were identified through the full wall thickness following the moderate to strong shaking (Figure 18). Preliminary evaluation indicated that the bond of the brickwork had failed in the very short return walls, because there were no other internal return walls and the reinforcement was discontinuous and only tied with wire ties. If the details in the Non-Specific Design standards had been followed this would not have occurred.

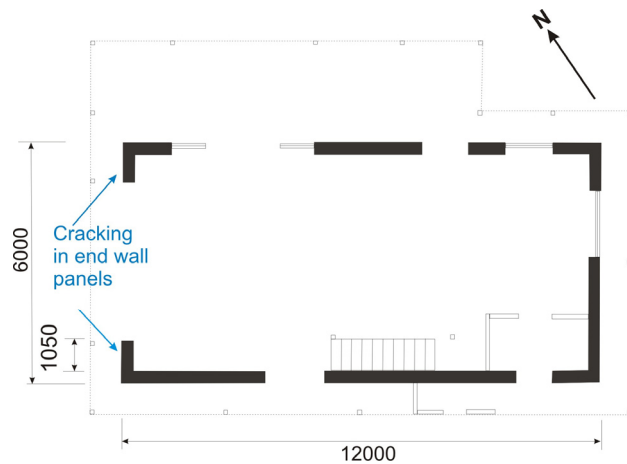


Figure 16 Staveley adobe house – lower level plan



Figure 17 Staveley house lower walls adobe



Figure 18 Cracking through plaster showing fractures at mortar joints

4 HOUSE DAMAGE IN THE FEBRUARY EARTHQUAKE

4.1 February 22 earthquake and second survey

After the earlier part of this paper was completed a $M_w 6.3$ earthquake 5km deep occurred 5-10km east of Christchurch on 22 February 2011 causing severe local PGA's as high as 2.2g. Fifteen houses and three garages and two cottages, in addition to those visited in October 2010 following the Darfield Earthquake, were inspected. These included buildings located from the national inventory survey undertaken by Miles Allen in 1990 (Allen 1991). Over 70 percent of all known earth wall houses, cottages and sheds within the area of significant shaking (greater than MM V) near Christchurch and west of Christchurch were inspected in the surveys of October 2010 and March 2011. In the March survey building owners were asked specific questions to confirm the estimated MM intensity.

4.2 Unreinforced cob, adobe and rammed earth buildings

The March survey indicated that historic unreinforced cob buildings in the zone of strong shaking on 22 February 2011 suffered significant damage and will require reconstruction or repair of the walls and strengthening of the upper floor or ceiling diaphragms. One historic building with 500 mm thick adobe walls on the ground floor and earth walls with timber framing on the upper floor appeared worse initially due to the cracking of incompatible stiff cement plaster. However cracking within the actual adobe wall, where visible, appeared to be relatively minor and repairable.

Nine cement-stabilised unreinforced rammed earth houses constructed between 1950 and 1980 were inspected. Each house had reinforced concrete foundations and reinforced concrete bond beams and well constructed rammed earth walls 150 to 250 mm thick. These do not have the reinforcement or thickness required by the NZ standards but performed relatively well, most with only minor cracking.

4.3 Unreinforced pressed earth brick buildings

Two houses had a light timber post and beam structure with infill pressed earth (Cinva) brick walls and experienced strong shaking (estimated MM VI). The walls comprised double skin 100 mm thick pressed bricks laid on their edge with a 50 mm cavity with metal ties across the cavity as shown in figure 19. Major failures of the walls occurred for both these houses with significant collapse of the outer skin and some drop outs of bricks from the inner skin. The timber structure in both cases remained intact and the houses did not collapse. However the overall wall bracing in both houses was compromised by the collapse of these walls and both houses will require substantial repairs and strengthening.



Figure 19 Little River post and beam house with pressed brick infill walls. Lower storey shows a post and damaged exterior double skin cavity walls with some remaining pulled out ties between wythes indicated.

The damage to the second single storey post and beam pressed brick house is shown in figures 20 and 21 showing double skin pressed earth walls that were significantly damaged and in danger of collapse.

In two other pressed brick houses which experienced very strong MMI 8 shaking, the internal non load bearing walls comprised 100 mm thick pressed bricks laid on their edge without any form of reinforcement or additional support or concrete bond beam. Most of the longer 100 mm thick walls in both these houses suffered complete or partial collapse. Shorter walls with support from timber posts each end of the wall generally remained intact. Collapse of the thin internal walls in both these houses posed a serious hazard to the inhabitants. This type of thin unreinforced single skin wall construction and double skin cavity construction are not covered by the New Zealand earth building standards and should be specifically excluded.



Figure 20 Burwood single storey post and beam house with pressed brick walls showing upper level damage



Figure 21 Burwood house internal infill double skin cavity wall showing major damage.

4.4 Reinforced pressed earth brick houses

Two pressed brick houses with external double skin pressed brick walls and a 50 mm thick reinforced concrete core and total wall thickness of 250 mm experienced very strong shaking (estimated MMI 8). The external walls in one of the houses appeared to suffer no damage while the external walls in the other suffered limited damage.

A large house which experienced strong shaking (estimated MMI 6) with reinforced pressed brick walls constructed in 2000 generally in accordance with details similar to the NZ Earth Building Standards and with a timber second storey with pressed brick veneer walls performed well with only very minor cracking mainly near openings.

5 CONCLUSIONS

In October a detailed survey was undertaken of 14 earth wall buildings reported to have damage following the Darfield earthquake. Several historic and replica unreinforced buildings suffered major damage that is typical of earthquake damage to such structures. Work is ongoing to determine the best repair methodologies to maintain the historic components and incorporate reinforcing that maximizes preservation of the historic value.

The September event was the first major earthquake where modern reinforced earth buildings have been tested. Damage was minor in most of the modern buildings surveyed and able to be understood in all cases with most of the more serious damage to modern buildings due to differential ground movement. The specific examples considered in this paper were a rammed earth building with thick

unreinforced walls that suffered moderate damage that would have been significantly reduced if the reinforced concrete bond beam been properly attached to the unreinforced walls. The three adobe buildings all used modern detailing and where properly applied confirmed the requirements of the New Zealand earth building standards as detailed in NZS 4299. Full height continuous vertical reinforcement is critical, timber ceiling diaphragms work well, and a minimum length of return walls and stiff cross walls need to be provided.

The February earthquake caused comparable patterns of damage to the September event except for pressed earth brick buildings. Unreinforced earth walls thinner than 200mm, without any lateral support from timber framing, should be dismantled or strengthened by providing additional lateral support to the walls, this should also apply to existing NZ houses in higher seismic zones. The same recommendation applies to unreinforced double skin earth masonry walls with a cavity. Although none of the damaged pressed brick walls complied with the New Zealand earth buildings standards, modification to the pressed earth brick section of the standards will be required.

6 ACKNOWLEDGEMENTS

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