OBSERVATIONS OF THE PERFORMANCE OF EARTH BUILDINGS FOLLOWING THE FEBRUARY 2011 CHRISTCHURCH EARTHQUAKE

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SUMMARY

A reconnaissance survey of earth walled buildings in the Christchurch area was carried out following the February 2011 Christchurch Earthquake. Twenty six earth buildings were inspected during the survey including historic earth buildings and recent reinforced earth buildings. Some of these buildings had previously been inspected following the September 2010 Darfield Earthquake.

The February 2011 Earthquake caused comparable patterns of damage to earth buildings as the September 2010 Darfield earthquake except for unreinforced pressed brick buildings which performed particularly badly. Reinforced earth buildings constructed since the 1990's performed well during the February 2011 earthquake provided the overall wall bracing was adequate and detailing of the reinforcement and connections were generally in accordance with the NZ Earth Building Standards. Some older unreinforced rammed earth buildings constructed between 1950 and 1980, all of which had reinforced concrete foundations and bond beams, performed relatively well with only minor cracking. Unreinforced cob and adobe buildings in the area of strong shaking suffered significant damage and will require reconstruction or repair of the walls and strengthening of the upper floor or ceiling diaphragms. The performance of six houses are discussed as case studies that cover the range of buildings observed.

INTRODUCTION

Two significant damaging earthquakes occurred near Christchurch. After the first event in September 2010, the Earth Building Association of New Zealand (EBANZ), organised a reconnaissance survey of earth buildings in October 2010 as reported in the NZSEE Bulletin. (Morris et al. 2010).

After the 22 February 2011 earthquake this second survey was organised by EBANZ and undertaken in March 2011. More details of damage examples from September were also outlined at a conference (Morris et al. 2011). Earth wall terminology used for this investigation can be summarised as Adobe: sun dried bricks, Rammed earth: cement stabilised soil heavily compacted between shutters, Pressed earth brick: cement stabilized bricks compressed in a mechanical press, Cob: soft soil laid in layers and later trimmed, Sod: soil blocks cut from the ground and placed directly into the wall.

Over half the world's population live in earth houses, lessons learnt about performance and effective seismic resisting systems are of significance in New Zealand and worldwide.

Seismological Context

On 22nd February 2011 a shallow magnitude M6.3 earthquake occurred at a depth of 5 km near Lyttleton and approximately 5 km south east of Christchurch causing severe local peak ground accelerations of up to 1.4g horizontal and 2.2g vertical. Modified Mercali intensities (MMI) of up to MMVIII were recorded in the Christchurch area. Further damaging earthquake aftershocks have occurred which have had smaller peak ground accelerations than the February event.

Figure 1 shows the locations of the houses, the approximate location of the fault (no surface trace) and the earthquake epicentre.

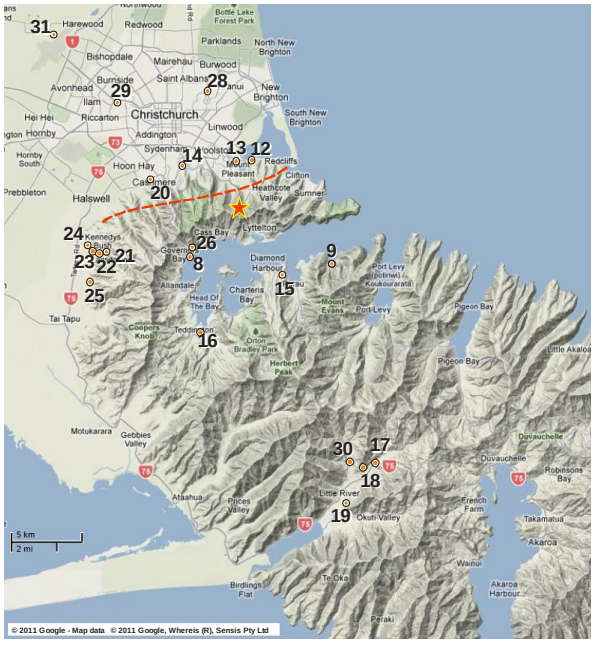

Figure 1: Locations of houses relative to the February epicentre. ***Approximate fault location transcribed from GNS Science.***

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EBANZ RECONNAISSANCE SURVEY

The EBANZ reconnaissance was carried out in March 2011 by three engineers, two experienced in the design and construction supervision of earth buildings, and an engineering academic:

Richard Walker CPEng – Consulting Engineer, Nelson;

Thijs Drupsteen CPEng – Consulting Engineer, Northland;

Hugh Morris – The University of Auckland,

and a very experienced architect of earth buildings:

Graeme North – Ecodesign, Warkworth.

Twenty six earth buildings in the Christchurch area were visited during the survey including several historic and older unreinforced earth buildings, a number of more recent reinforced earth buildings, and buildings with a timber post and beam structure with external pressed earth brick infill walls. A summary of the earthbuildings inspected, including their location, wall material, construction date, estimated Modified Mercali Intensity (MMI) and Damage State are shown in Table 1.

The buildings were assessed with respect to design criteria and details from the NZ Earth Building Standards and the performance and damage criteria of the Modified EERI Methodology. This modified methodology was developed by Webster and Tolles following the 1994 Northridge, California Earthquake (Webster and Tolles, 2000) and further modified by the Morris, Walker and Drupsteen for use in the survey of earthbuildings following the Darfield 2010 Earthquake. The damage states A to E were subdivided further on a scale of 1 to 3 for this reconnaissance survey with 3 being more serious than 1. Details are provided in the earlier paper (Morris et al. 2010).

NEW ZEALAND EARTH BUILDING STANDARDS

Three performance based standards for earth walled buildings were published in 1998. NZS 4297 Engineering Design of Earth Buildings specifies design criteria, methodologies and performance aspects and is intended for use by structural engineers. NZS 4298 Materials and Workmanship defines the the material and workmanship requirements of earthwalls to comply with the requirements of the NZ Building Code. NZS 4299 provides the methods and details for the design and construction of earth walled buildings not requiring specific engineering design. NZS 4299 is the earth wall equivalent of NZS3604 Timber Framed Buildings (Standards New Zealand).

Table 1: Summary of Earth Buildings inspected after the February 2011 Christchurch Earthquake.

No.*	Location and Type**	Earth Wall Material	Construction date	MM*** Intensity	Damage State****
8b	Governors Bay	Reinforced pressed brick	1978	VIII	C2
9	Camp Bay	Rammed earth (RC frame)	1965	VI	B1
12	Ferrymead Cottage	Unreinforced sod &cob	1860/1950	VIII	E
13	Ferrymead Cottage	Unreinforced cob	1982	VIII	C2
14a	Beckenham	Unreinforced rammed earth	1953	VII	B2
14b	Beckenham Garage	Unreinforced rammed earth	1953	VII	B1
15	Diamond Harbour	Reinforced adobe	1995	VII	B3
16	Teddington	Unreinforced rammed earth	1980	VI	B1
17a	Little River	Unreinforced pressed brick infill	1993	VI	D1
17b	Little River	Unreinforced Pressed brick	1993	VI	B1
18	Little River	Reinforced pressed brick	2000	VI	B2
19	Little River	Reinforced rammed earth	1997	V	B1
20	Hoon Hay/Cashmere	Unreinforced adobe	1854	VI	C2
21	Kennedy's Bush	Unreinforced rammed earth	1955	V	A
22	Kennedy's Bush	Unreinforced rammed earth	1956	V	B2
23	Kennedy's Bush	Unreinforced rammed earth	1956	V	B1
24	Kennedy's Bush	Unreinforced rammed earth	1951	V	B1
25	Kennedy's Bush	Unreinforced rammed earth	1959	V	B1
26a	Governors Bay	Reinforced pressed brick	1991 -	VIII	A
26a	Governors Bay	Unreinforced pressed brick internal	1991 -	VIII	E
26b	Governors Bay Garage	Pressed brick infill	1991	VIII	C1
27a	Burwood	Pressed brick veneer	1985	VI	D1
27b	Burwood	Unreinforced Pressed brick infill	1985	VI	D1
28	Fendalton	Unreinforced rammed earth	1960	V	B1
29	Little River	Pressed brick veneer	2002	VI	B1
30	Yaldhurst	Unreinforced cob	1851	V	C3
31	Sockburn	Unreinforced cob	1856	VI	C3

* Numbering consistent with earlier report (Morris et al 2010)

** Houses unless noted

*** Modified Mercalli Intensity mostly based on owner reports

**** ***Damage State*** **A** – None, **B** – Slight, **C** – Moderate with cracking damage throughout the building
D - Extensive crack damage throughout **E**- Very extensive damage with collapse or partial collapse of structure
The digit indicates where in the scale eg B1 low within the B category, B2 mid B category, B3 borderline to C

EARTH BUILDING DAMAGE TYPES

The Standardised Damage Types, as defined by Webster and Tolles (Webster and Tolles, 2000) for earthquake damage to earth buildings are as follows:

Out of Plane Flexural Damage,
Gable Wall Collapse,
Horizontal Upper Wall Damage,
Wall Mid Height Flexural Damage,
Diagonal Crack Damage,
Wall Intersection Separation,
Corner Cracks,
Crack Damage at Openings,
Foundation Movement,
Horizontal Base Wall Damage,
Vertical Cracks,
Moisture Damage.

Table 2: Summary of Damage to Earth Buildings inspected after the Christchurch 22nd February 2011 Earthquake.

No.	Location and Type	Out-of-Plane	Gable Ends	Horizontal Upper wall	Mid Height Flexure	Diagonal Crack Damage	Wall Intersection Separation	Corner Cracks	Crack damage at Openings	Foundation Movement	Horiz Movement at Foundation	Moisture Damage	Vertical Cracks	Estimated MM Intensity	New Damage State*	Pre-Existing Damage State	Subsoil Class**
8a	Governors Bay House No.1 External Walls (250 thick)	1		1		2		1	1	1		1	1	VIII	B2	B	B
8b	Governors Bay House No.1 Internal Walls (100 thick)	3		2		2		2	2	1			2		C2	B	B
9	Camp Bay House					1	1		1				1	VI	B1	B	B
12	Ferrymead Cottage	3	3	3	3	3	3	3	3	2	1	2	3	VIII	E	D	E
13	Ferrymead Cottage	2	1	1			2	1	2			2	2	VII	C2	B	E
14a	Beckenham House			1				1	1	1		2	2	VII	B2	B	D
14b	Beckenham Garage														B1	B	D
15	Diamond Harbour House	2		1	2				2			1	2	VII	B3	B	C
16	Teddington House						1		1					VI	B1	B	C
17a	Little River House No1	3		3	3	3	3	3	3		2	1	3	VI	D1	B	C
17b	Little River Garage No1					1		1					1	VI	B1	B	C
18	Little River House No 2			1		1			1				1	VI	B2	B	C
19	Little River House No 3							1	1			1	1	V	B1	B	C
20a	Cracroft House Hoon Hay Ground					1	1	1	1	1	1	1	1	VI	C2	B	D
20b	Cracroft House – Upper Floor		1	1		1		1	1			1		VI	C1	B	D
21	Kennedys Bush Road								1					V	A	A	C
22	Kennedys Bush Road	1		1	1			1	1				1	V	B2	B	C
23	Kennedys Bush Road					1		1	1			2	1	V	B1	B	B
24	Kennedys Bush Road								1				1	V	B1	A	B
25	Old Tai Tapu Road				1				1				1	V	B1	A	B
26a	Governors Bay House No 2 External Walls 250 thick									2				VIII	A	A	D
26b	Governors Bay House No 2 Internal Walls 100 thick	3		3	3					2			3	VIII	E	C	D
26c	Governors Bay House No 2 Garage 100 thick walls				1	2						2	1	VIII	C1	B	D
27a	Burwood House	3			3	1	2	1	1	1		2	1	VI	D1	B	C
27b	Burwood Garage	3			3	1	1	1	1			1		VI	D1	B	C
28	Fendalton House							1	1			1		V	B1	A	
29	Little River House No 4													VI	B1	B	
30	Yaldhurst Cottage “Tiptree”													V	C3		
31	Sockburn “Chokebore Lodge”	1			1			2				1	2	VI	C3	B	

Note: *New damage state from February event, subdivided with a numeral ** Estimated subsoil class based on AS/NZS1170.5

DAMAGE TO EARTH BUILDINGS INSPECTED

Table 2 provides a summary of the earthquake damage to the earth buildings inspected during the reconnaissance survey after the February 2011 Christchurch Earthquake. Houses 8 to 14 were also inspected in the earlier survey.

All identified earth buildings with access available were inspected. It is estimated that they represent over 60 percent of all known earth walled houses, cottages and garages within the area of significant shaking, greater than MM V, in the Christchurch area. The exact number of earth buildings in the Christchurch area is unknown.

Some similar typical types of seismic damage experienced in unreinforced earth houses are shown in Figure 2.

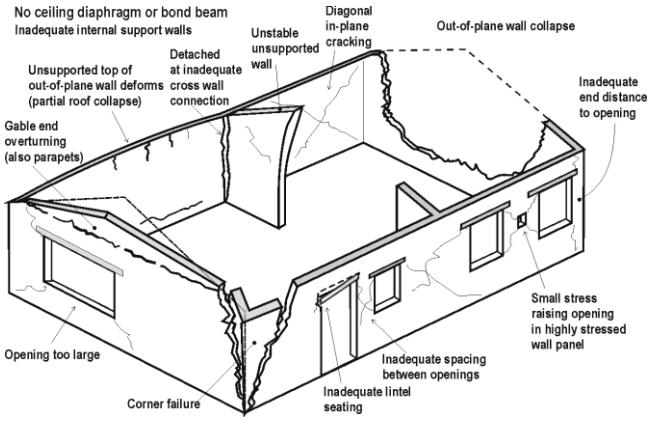

Figure 2: Typical earthquake damage in unreinforced houses. *© Morris*

TYPICAL DAMAGE FOR DIFFERENT TYPES OF EARTHWALL CONSTRUCTION

Unreinforced cob and adobe buildings

Historic unreinforced cob and adobe buildings in the area of strong shaking suffered significant damage and will require reconstruction or repair of the walls and strengthening of the upper floor or ceiling diaphragms. One historic adobe house constructed in 1854 with 500 mm thick 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.

Unreinforced rammed earth buildings

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 between 150 and 250 mm thick. These walls do not comply with the thickness or reinforcement requirements of the current NZ earth building standards but performed relatively well, most with only minor cracking.

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. 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.

In two other pressed brick houses which experienced very strong MM VIII 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 unreinforced wall construction does not comply with the New Zealand Earth Building Standards.

Reinforced adobe buildings

One reinforced adobe house constructed near Diamond Harbour in 1995 was inspected. This house has adobe walls on the ground floor and a timber second storey and experienced moderately strong shaking with estimated Modified Mercalli intensity of MM VII. The earth walls have both vertical and horizontal reinforcement similar to the details in the NZ earth building standards. There was some minor cracking particularly adjacent to openings but no significant structural damage. There were no other known reinforced adobe houses in the area of strong shaking.

Reinforced rammed earth buildings

One reinforced rammed earth house constructed on the Banks Peninsula in 1997 was inspected. This house has rammed earth walls on the ground floor and a timber second storey and experienced moderate shaking with estimated Modified Mercalli intensity of MM V. Only very minor cracking at some locations was evident, otherwise the rammed earth walls performed well. There were no other known reinforced rammed earth houses in the area of strong shaking

Reinforced pressed earth brick buildings

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 MM VIII). 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 on the Banks Peninsula with pressed brick walls constructed in 2000 experienced strong shaking (estimated MMI VI). The earth walls are reinforced both vertically and horizontally and are generally in accordance with details in the NZ Earth Building Standards. The house has a timber second storey with pressed brick veneer walls. The house performed well with only very minor cracking mainly near openings and with some cracking of some of the veneer bricks but no significant structural damage.

CASE STUDIES

Unreinforced adobe building- Cracroft House 20

Cracroft House is an historic 1851 adobe building in Hoon Hay that has been subject to a number of alterations. This has included a conventional brick rear section and a 1990 timber structure that is largely seismically independent at the rear.

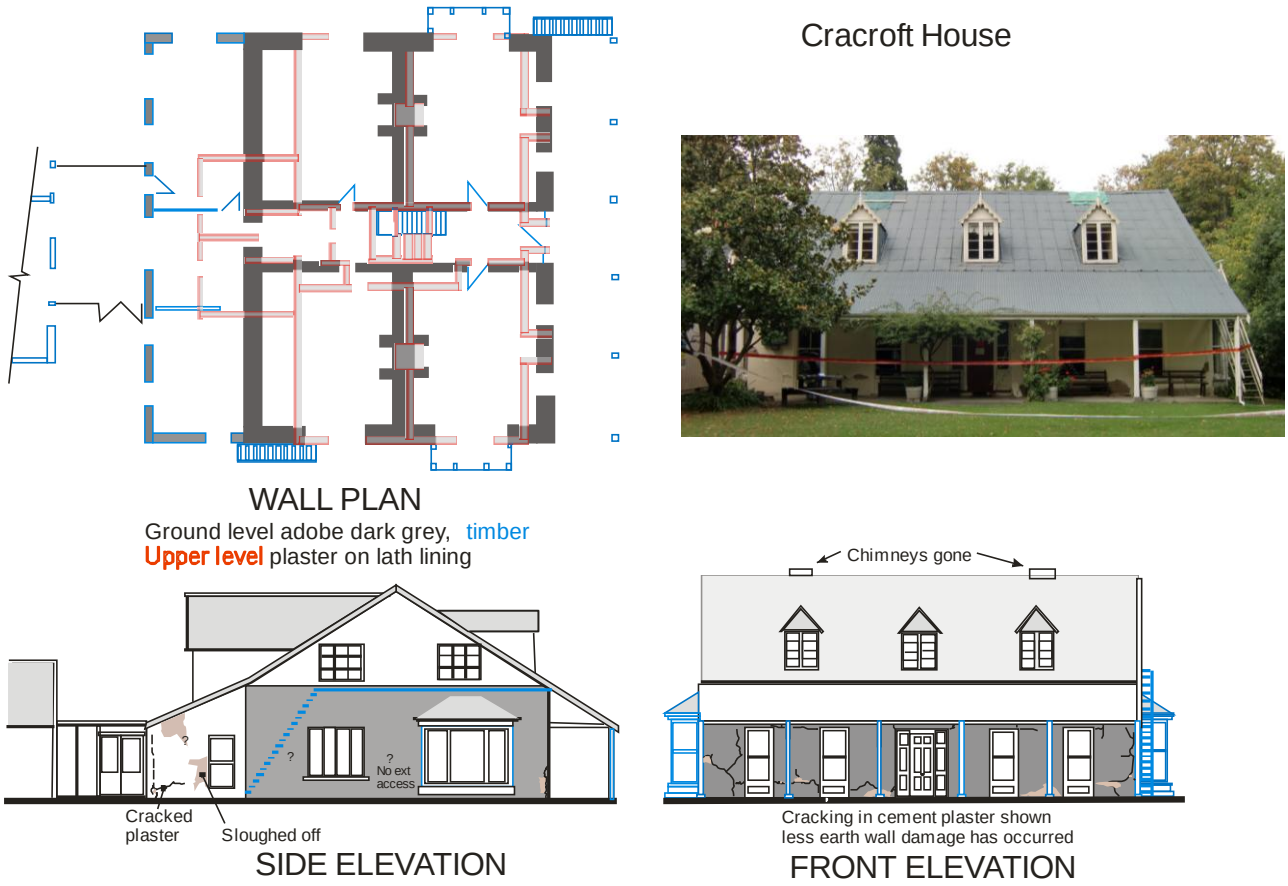

Figure 3: Cracroft House drawings illustrating the visible exterior damage, photograph of front at top right. *(Photo G North)*

Some of the adobe structure has been repaired with burnt brick and plastered with a cement plaster. The cracking in the plaster indicated significant deformation while the underlying adobe has suffered significant fracture it appeared to be to a lesser extent than the plaster. Figure 3 illustrates the overall house and crack damage, in particular on the front wall.

Figure 3 also shows the very symmetrical plan configuration of the original adobe. It provides a good basis for restoration and provision of a floor diaphragm if this is economic.

Figure 4: Cracroft House front corner with plaster cracks. The small plaster drop out revealed burnt brick repairs.

Figures 4 and 5 show detail of the front wall damage. Where the walls were visible inside the structure, significant movement was evident as shown in figure 6.

Figure 5: Cracroft House front wall plaster cracks and minor lateral spreading damage to the concrete porch.

Figure 6: Cracroft House interior plaster with significant damage, underlying adobe wall showing less damage.

The upper level was light construction with mud plaster on lath for both walls and ceilings. This suffered significant damage as shown in Figure 7.

Figure 7: Cracroft House damage to upper level walls of plaster and lath.

Unreinforced rammed earth building – Kennedys Bush Road House 23

A number of cement stabilized rammed earth houses were constructed in the late 1950s based on the research work of P.J.Alley at Canterbury University. (Alley, 1952) These houses were high quality unreinforced rammed earth and had a continuous reinforced concrete bond beam. Five of these houses remain in Kennedy's Bush Road and even with thin walls only suffered minor damage.

Figure 8: Unreinforced Rammed Earth Kennedy's Bush Road (Building 23) showing overall layout. New conventional addition to left front.

Figure 9: Unreinforced Rammed Earth Kennedy's Bush Road (House 23) showing a minor vertical crack.

Figure 10: Unreinforced Rammed Earth Kennedy's Bush Road (House 23) showing damage at the bond beam interface over a lintel. *(Photo Drupsteen)*

House 23 had only suffered moderate shaking of about MM V. Some internal walls were less than 150 mm thickness and additional restraint should be considered.

Unreinforced pressed brick building –Little River House 17

Little River was over 20 km from the epicentre where moderate shaking of approximately MM VI experienced. This house was timber post and beam construction with unreinforced pressed earth brick double skin infill panels on the lower floor. It suffered major damage and the overall structure lost most of its lateral strength expected from the infill panels (see Figure 10).

Figure 10: Little River House 17 post and beam construction supporting upper storey, detail view showing ties pulled out of mortar.

Figure 11: Little River House 17 showing major damage to outer skin of pressed earth brick and significant damage to the inner skin.

Figure 12: Little River House 17 showing overall house, some minor in-plane cracking and out-of plane failure of the inner and outer skin. (G North)

Figure 13: Little River House 17 showing detail of the distorted masonry tie that has failed due to mortar bond. On the right in plane rupture showing mortar failure and crushing of the pressed earth masonry. (G North)

Reinforced adobe building – Diamond Harbour House 15

This reinforced adobe house used detailing and reinforcement that is similar to the New Zealand Standards (see Figure 15).

Figure 15: Diamond Harbour reinforced adobe house overall view.

Figure 16: Diamond Harbour reinforced adobe house showing detachment of inadequately reinforced concrete chimney and crack damage at south window.

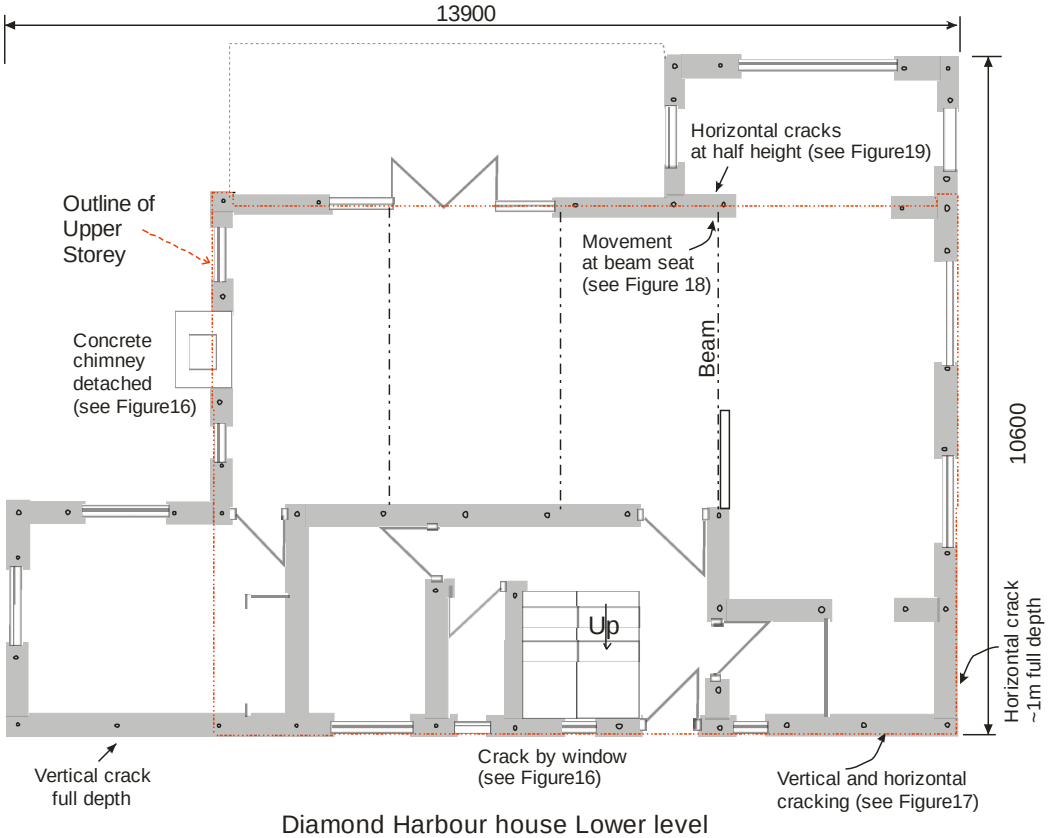

Figure 14: Diamond Harbour adobe house plan showing location of damage observed and vertical reinforcement.

This adobe house experienced MM VII shaking. The most significant damage was to the concrete chimney (Figure 16) which had been reinforced only part height. There was considerable minor cracking that spalled small plaster fragments, cracked window corners (Figure 16 right), and hairline cracks in the adobe brickwork as visible in Figure 17.

Figure 17: Diamond Harbour house showing cracks on south wall adjacent to entry. *(G North)*

The main item of structural interest was the stub wall supporting a beam which fractured at about half height as shown in figures 18 and 19.

Figure 18: Diamond Harbour house showing beam landing on the stub wall.

Figure 19: Diamond Harbour house showing the stub wall mid height horizontal cracks due to out-of-plane flexure.

Rammed earth building – Little River House 19

At Little River, House 19 had 2.4 m high and 400 mm thick rammed external earth walls and 300 mm internal walls (Figure 20) that formed part of the lower storey. A 400 mm architectural feature wall stands alone as shown in figures 21 and 22. The walls had a strong timber well fastened bond beam. The house was greater than 22 km from the February epicentre with a reported intensity of MM V and although the walls supported a light timber frame upper level the only damage was hairline cracks that extended less than 500 mm.

Figure 20: Little River rammed earth house 19 overview showing exterior rammed walls.

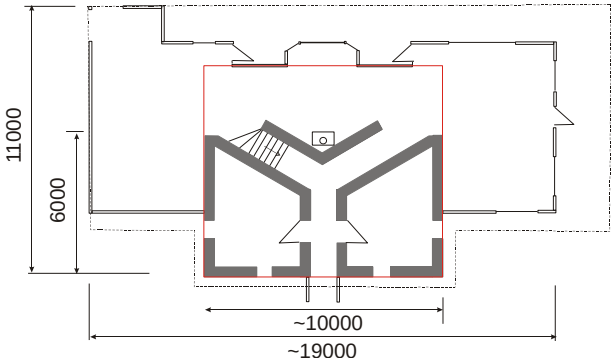

Figure 21: Little River rammed earth House 19 ground floor plan showing rammed walls and outline of upper storey.

Figure 22: Little River rammed earth House 19 internal feature wall and stairway. *(Photo G North)*

Reinforced pressed brick building – Little River House 18

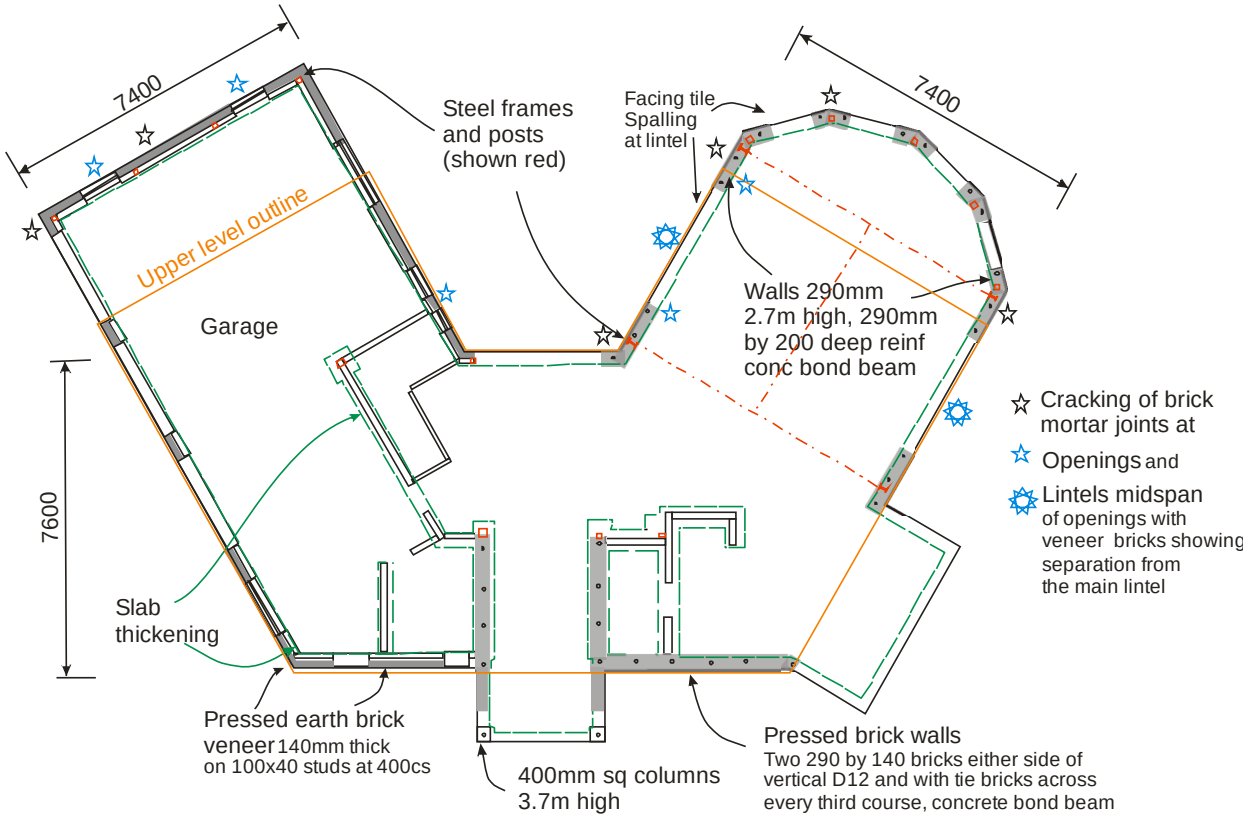

Figure 23: Little River pressed earth House 18 ground floor plan showing foundation thickening, lower level reinforced double skin and single skin veneer walls. Upper level outline shown orange.

The Little River pressed earth brick house shown in Figures 23-25 had double skin reinforced pressed brick lower storey and performed well under the moderate shaking and significant lateral seismic loads generated by the large second floor and roof and large span beams, and was basically in good shape. Most cracking was reported to have been initiated in the September 2010 earthquake or earlier. No vertical control joints provided for the pressed brick walls, if these were provided there may have been less cracking.

There was no damage to the foundations or to the upper level, the west side of house had 100 by 40 mm studs at 400 mm crs with 140 mm thick pressed brick veneer.

Figure 24: Little River pressed earth house 18 overview of north facing walls.

Figure 25: Little River pressed earth house 18 side view showing garages with insufficient adjacent bracing walls. *(G North)*

Figures 26 and 27 show the types of cracking adjacent to openings at the locations highlighted in Figure 23.

Figure 26: Little River pressed earth house 18 showing cracking of the pressed brick veneer.

Figure 27: Little River pressed earth house 18 showing cracking of veneer.

MAIN CONCLUSIONS FROM THE SURVEY

The February 2011 Earthquake caused comparable patterns of damage to the September 2010 Darfield Earthquake except for unreinforced pressed earth brick buildings which performed particularly badly.

Reinforced earth buildings constructed since the 1990s and inspected during the survey generally performed well during the February 2011 Christchurch Earthquake provided the overall wall bracing was adequate and the detailing of reinforcement and connections were in accordance with the NZ Earth Building Standards.

Some limited minor cracking can be expected in most earth buildings during major earthquake events, particularly adjacent to windows and door openings. This cracking is generally of no structural significance if the buildings are provided with vertical and horizontal reinforcing and the overall wall bracing provided in the building is adequate and in accordance with the requirements of the NZ Earth Building Standards. The requirement of the standards for continuous vertical reinforcement from foundation to top plate provides integrity that has been evident.

Cracking is likely to be greater and more widespread in older unreinforced earth buildings with greater structural significance.

Some older unreinforced cob and adobe earthbuildings constructed before 1900 suffered significant structural damage during the February 2011 Christchurch Earthquake and will require reconstruction or substantial repair work.

Unreinforced rammed earth buildings constructed between 1950 and 1980 with reinforced concrete foundations and bond beams and lintels performed well. Most were subjected to moderate shaking during the February 2011 Christchurch Earthquake with generally only minor cracking.

Unreinforced pressed brick buildings including those with double skin and a cavity performed badly and the walls will require dismantling and reconstruction.

REVIEW OF THE PERFORMANCE OF EARTH BUILDINGS IN RELATION TO THE NZ STANDARDS AND RECOMMENDATIONS

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. Double skin cavity construction is not covered by the Standards but should be specifically excluded.

Unreinforced earth walls of any existing NZ houses in high seismic zones thinner than 200 mm and without any lateral support from timber framing are also not covered by the NZ Standards and should also be specifically excluded.

These unreinforced thin earthwalls and double skin earth masonry walls with a cavity should be dismantled or strengthened by providing additional lateral support to the walls.

Second storeys of earth in all high seismic risk zones should be discouraged. A review of the provision for second storeys in NZS 4299 is recommended. Some apparent poor designs indicate the need to check the competency requirements for designers of second storeys under NZS 4297.

A number of earth walls had weakened earth wall material due to weather damage that may have contributed to failures. Weather protection of earth walls in accordance with the provisions of NZS 4299 remains very important and some of these weather protection details should be made mandatory for earth walled houses specifically designed by a structural engineer.

ACKNOWLEDGEMENTS

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