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Repair and reinstatement of earthquake damaged houses - Derivation of repair techniques

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Repair and Reinstatement of Earthquake Damaged Houses – Derivation of Repair Techniques

G. J. Beattie

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Note

This report is intended for earthquake damage assessors, the Earthquake Commission and trainers of earthquake damage assessors.

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BRANZ Study Report SR 100 (2001) **G. J. Beattie**

ABSTRACT

This report describes the development of procedures for the repair after earthquake of a selection of structural elements of domestic housing. Systems considered included an exterior wall clad with sheet sheathing, a braced pile foundation system, a brick veneer corner and gypsum plasterboard lined interior walls of a 1960s two-storey duplex housing unit.

Prior to selecting the systems for investigation, earthquake damage records were reviewed, post-earthquake reconnaissance reports were examined and interviews were undertaken with damage assessors, builders and Territorial Authority personnel with experience in damage repair after earthquakes. From these investigations the systems were chosen for testing as being the most in need of guidance to the construction industry.

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1. INTRODUCTION

This study report describes the investigation of repair strategies for elements of houses damaged in earthquakes. The project involved introducing levels of simulated earthquake induced damage to a selection of elements, developing suitable repair strategies, implementing those strategies and evaluating the effectiveness of the repairs. The outputs from this study were provided as inputs for the Earthquake Damage Assessment Catalogue (EDAC) being prepared for use by assessors following an earthquake.

2. EARTHQUAKE DAMAGE ASSESSMENT CATALOGUE

The Earthquake Damage Assessment Catalogue is a reference source being developed and intended to be used by the inspection team when assessing the damage observed in dwellings following earthquakes. Each aspect of damage envisaged to be present within houses is itemised and assigned a unique damage identifier. The damage identifier is then referenced throughout the report to effectively transcribe the damage observed by the inspector during his inspection into a set of reinstatement measures. This approach enables an effective audit trail to ensure consistency of application, quantification of the reinstatement strategy for settlement purposes between the Earthquake Commission (EQC) and the claimant, and the basis of a contract by which the claimant can engage building contractors to undertake reinstatement.

In order to begin creating an earthquake damage assessment catalogue, it was necessary to inspect as many earthquake damage records as could be obtained. Of particular interest were photographs and detailed descriptions of damage observations and proposed repairs.

An industry liaison meeting was convened at BRANZ to help crystallise the format of the catalogue and to agree on potential sources of damage and repair information. It was also agreed at the meeting that probably it would be necessary to divide the damage descriptors into three levels of effect, these being minor, intermediate and severe. With appropriately detailed descriptions, it was thought that this would be the most useful form of document for use by assessors pooled from a wide selection of occupations. Participants at the liaison meeting suggested potential sources of information.

3. SOURCES OF EARTHQUAKE DAMAGE INFORMATION

The Northridge earthquake in 1994 (Richter magnitude 6.7) struck in the heavily populated San Fernando Valley area of Los Angeles. There are many similarities between house construction techniques in New Zealand and the west coast of the USA and reports from New Zealand and US reconnaissance teams were expected to provide valuable damage descriptions. Earthquake reconnaissance reports (Norton et al., 1994) and inspection reports specific to dwellings (NAHB, 1994) were reviewed.

The most recent damaging earthquake in New Zealand history was the Edgecumbe event of 1987 (Richter magnitude 6.3). While the Weber earthquake of 1990 was of similar magnitude (6.7), its epicentre was located in a rural area and damage to house structures was reasonably minor compared to the Edgecumbe event. The most significant difficulty encountered with the long time span since the earthquake, as was discovered during interviews with insurance loss adjusters, was that many of the records had been destroyed because the legal time required to keep the records (10 years) had already elapsed.

A number of potential sources of information were identified. These included the Earthquake Commission (EQC) claim records, BRANZ Edgecumbe photograph files, earthquake reconnaissance reports (Pender et al, 1987, BRANZ, 1987), personal communications with loss adjusters, builders and Territorial Authority staff involved in the recovery after the Edgecumbe earthquake and repositories such as museums and libraries.

3.1 House Damage at Northridge (NAHB,1994 and Norton et al., 1994)

The NAHB report presents the results of a survey of 375 single family detached dwellings that had been damaged in the Northridge earthquake. The stock of houses was built mainly in the 1950s and 1960s and the predominant foundation system (about 2/3 of the total) was timber or concrete piles with concrete or masonry perimeter walls. Stucco was the most common exterior finish and interior linings were mainly plaster or gypsum plasterboard. The report rated damage to six main categories of the structure, these being foundation, connection (bottom plate), walls, roof, exterior finish and interior finish. In general, the damage levels were low for all elements, although those that sustained the most damage were the interior and exterior finishes. It appears from a comparison of responses between Edgecumbe and Northridge, that bottom plate connection failure was only applicable in Northridge. Cripple wall (short jack stud walls between a concrete foundation and the ground floor framing) failure was also only a characteristic of the Northridge experience, with this type of construction being only rare in New Zealand.

A small number of damage photographs were included in the report but, unfortunately, the report does not comment on repair methods used to reinstate the dwellings.

Norton et al. reported that stucco cladding on the exterior of dwellings suffered some cracking at bottom plate level and around window and door openings. The frequency of stucco claddings in the Northridge area is significantly higher than in typical New Zealand urban areas. Nail popping of paper faced plasterboard interior linings was also common, along with joint damage at sheet junctions. On some older dwellings supported on timber piles, the lack of lateral bracing meant that the piles had swayed sideways and in some instances had collapsed.

3.2 Edgecumbe Earthquake Information Sources

Records held by the Earthquake Commission were archived because of the time span since the earthquake occurred. Many boxes of records were made available to the researchers but they were found to be of little use for the project purpose. Most records involved the bases of settlements ascertained by the loss adjuster. Specialist reports were included in some cases but photographic records were sparse in detail. They lacked sufficiently detailed information on the observed damage to be of use in this study and the review of records from this source was abandoned.

The report Edgecumbe Earthquake Reconnaissance Report (Pender et al, 1987) spoke in broad terms about the types of damage experienced, but it did contain descriptive photographs of some damage, which were useful for inclusion in the Earthquake Damage Assessment Catalogue. BRANZ Building Information Bulletin 258 (BRANZ, 1987) highlighted the lessons to be learned for domestic dwellings from the Edgecumbe earthquake. It noted the importance of having a braced subfloor system, the likelihood of damage occurring at junctions between elements of irregular structures and the need to have heavy chimneys adequately reinforced. It also contained a number of photographs of specific detailed damage.

3.2.1 Loss Adjusters, Builders and Territorial Authority Staff (Personal interviews)

Contact was made with some of the loss adjusters and builders that were involved in the assessment and reconstruction after the Edgecumbe event. It became clear early in this process that there were very few documented or photographic records available because of the elapsed time since the earthquake. However, most interviewees had quite vivid memories of the observed damage and repair procedures (Farrell, J. and Howells, P., 1999, Hall, R., 1999, Pullar, J., 1999, Thomlinson, R., 1999, Walker, A., 1999, Wilson, S., 1999, Wood, B., 1999). Recollections did seem to differ quite marketedly, however.

The approach taken with the interviewees was to divide the houses into the following topic areas and ask them to describe the types and levels of damage that they encountered and the repairs undertaken:

- Foundations (piles, slab on ground, concrete/masonry basement)
- exterior cladding (brick veneer, interlocking timber, fibre cement sheet, polystyrene, stucco, weatherboards, corrugated galvanised steel)
- interior linings (painted and wallpapered plasterboard, concrete block, fibrous plaster, interlocking boards)
- ceilings
- roof
- appendages

a) Foundations

Pile problems tended to concentrate on failure through overturning or leaning of short unrestrained piles. Old pumice concrete piles broke off. Repairs ranged from complete replacement to wedging and retying to the bearers. If houses slipped too far sideways on the piles, they punched through the floor with serious repair consequences.

Slab foundation performance was quite variable at Edgecumbe. Minimal damage involved fine cracks which were not noticeable until floor coverings were removed while the most extensive damage involved upward heave of the slabs or slumping. In these instances, complete removal of the slab and repouring were required. Between these two extremes, there were instances of floor slabs sliding on the damp proof membrane and becoming misaligned with the edge foundations. It appeared that the dowel bars connecting the slab to the foundation had sheared off.

Pole house foundations managed to survive the earthquake well except in one instance where the pole failed in shear near to a bearer connection. On some occasions a bearing failure of the soil adjacent to the poles required concrete to be poured into the gap once the poles were realigned.

Concrete block basements were generally not badly damaged. Some shear cracking appeared at and around wall junctions. Structures with unreinforced concrete block infill between reinforced concrete posts and beams tended to lose the unreinforced panels.

b) Exterior Sheathings

Plank materials appeared to perform well in the earthquake because a small amount of slippage was able to be tolerated between planks without causing significant damage. Older asbestos cement sheet claddings were brittle and tended to crack as a result of lateral buckling under in-plane loads or fixings pulled through the edges and corners of the sheets. In these cases the damaged sheets were removed and the wall was reclad with like materials.

Brick veneers received the most damage of exterior sheathings. The recall of the extent of veneer damage varied widely with one loss adjuster suggesting that 80% of the brick veneer houses required a complete re-brick but Territorial Authority records, although incomplete, did not substantiate this observation. One loss adjuster noted that there was evidence of flat ties being badly corroded and staples securing wire ties pulling out under the earthquake motion. In these instances the veneer either fell from the wall or sounded "drummy" when tapped at inspection. In both cases it was necessary to remove the veneer and rebuild it. Damage was often noted around the corners of openings and at changes in direction. In these instances, it was sometimes possible to remove local sections of the wall and rebuild. Achieving a correct match between existing and new veneer was sometimes a problem and a remedy for this sometimes meant sacrificing one wall to provide materials to fix the others; the sacrificial wall being reclad with either another material or with new replacement bricks.

c) Interior Linings

The most common interior lining used was paper-faced gypsum plasterboard. There were few instances of total removal of the sheets. However, there was significant cracking at sheet joints, particularly in a vertical orientation above the corners of windows and doors. On many occasions, no reinforcing tape had been used on the joint when it was first stopped. Repairs appeared to concentrate on gouging out the joint and re-stopping with tape. Tidy-up nailing was sometimes required but there was no established system of repair procedures. Removal of skirting boards and scotia boards was rare and the re-stopping tended to extend only to the board. The integrity of the nailing behind these boards was not often checked. Associated with the re-stopping, was either re-wallpapering or repainting in the affected rooms. In bathrooms where tiles had been glued over backing board, nail popping beneath the tiles had, in some cases, pushed the tiles off.

Plasterboard ceilings fared similarly to the walls. Wadded supports for fibrous plaster ceilings sometimes failed, causing sags. The typical repair involved nailing and re-stopping.

There was some evidence of cracking on the interior surfaces of concrete block walls and those with a plaster coating sometimes lost sections of plaster which debonded from the blockwork. These were repaired with new plaster with netting added as a key.

Damage to proprietary interlocking plank wall systems was minimal and little or no repairs were recalled.

The recall on the extent of glass damage varied considerably from catastrophic to minor damage.

d) Roofs

Corrugated galvanised steel roofs managed to resist the earthquake relatively unscathed. Minor elongation of nail holes occurred on some roofs.

Concrete and clay tiles fared worse, although the damage was still not great. There was some damage observed at the ridge cap where the mortar seating joints failed and the capping tiles slipped from the ridge. Re-mortaring of the capping tiles was all that was necessary. In the body of the roofs, in some instances tiles slipped out of position often because they were not wired to the supporting tile battens. Repairs in these cases were quite straightforward, with the tiles repositioned and wired in place.

e) Appendages

Chimneys were by far the most frequently damaged appendage. Concrete sectioned/precast chimneys often broke off above the roof line and collapsed on to the roof, causing secondary damage to the roofing material. Those that were reinforced showed signs of corrosion of the reinforcing steel, lack of bond of the reinforcing and some bar fractures. There was a common thought that the chimneys should be removed to roof level, even if they had not already failed, and be replaced with lightweight stainless steel flues. Other chimneys fell away from the side of the house in one piece due to uneven ground consolidation beneath their base or lack of an effective tie back at the roof.

Inside the houses, it was common for free-standing wood burners not to be bolted to the floor and these were either thrown or "drifted" some distance from their start position during the earthquake.

Out buildings such as carports and garden sheds did not escape damage. Often these structures were not designed to any standard, but were rather erected by property owners with the materials at hand and with no building knowledge. Unreinforced concrete block masonry walls on inadequate foundations were observed to topple, in one instance leaving the carport roof cantilevering off the end of the house.

3.2.2 Museums and Libraries

Museums and libraries in the local area of Edgecumbe were suggested as a possible source of photographic records of the earthquake. The Whakatane District Museum and Gallery was one such source visited. There were many photographs stored at the museum, but a large number of these were either related to ground movement or infrastructural damage and not so many related to specific structural problems in dwellings. A selection of about 40 relevant photographs was purchased for use in the project.

4. EARTHQUAKE DAMAGE MATRIX

Using the results of the interviews and the reviews of reconnaissance reports, the researchers convened an internal think tank to develop an earthquake damage and likely repair matrix for the various parts of a dwelling. The matrix identified the spatial elements of the structure, the sub-types of the element, the symptoms of the damage and the indicators that may be seen by an inspector.

The matrix is presented in Table 1. Clearly, the listing is very comprehensive and the scope of the project did not allow experimental studies to be undertaken on every case to confirm performance and develop repair procedures. Several critical areas of the structure were chosen for experimental studies (see Section 5).

Table 1 Earthquake damage and repair matrix

ELEMENT	Type	Action	Indicators	Minor	Intermediate	Severe
Subfloor						
	Foundation walls (perimeter)	Settlement	Cracks in walls	Narrow cracks, particularly at changes in section – no repair	Cracks >2mm – epoxy grout and refinish	Cracks >5mm – break out concrete and replace
		Out of plane action	Global misalignment Connection to bearer failure Overall tilting	Minor misalignment <5mm – no repair needed	Moderate tilting <15mm – check and repair bearer connections, refinish	Significant residual out-of-plane distortion – prop, remove existing, recast and refinish
	Piled	In-plane racking – pile failure	Piles no longer vertical (or completely collapsed)	Minor misalignment <10mm – no repair needed	Moderate offset <25mm – check and repair bearer connections, refinish	Significant residual out-of-plane distortion – lift house, remove existing piles, replace and refinish
			Pile fracture or soil failure Above ground Below Ground	Soil bearing failure adjacent to pile – concrete collar at ground level	Some piles fractured (<10%) – temporarily support locally, dig out damaged piles and replace	Piles fractured (often below ground level - – lift house, remove existing piles, replace and refinish
		In-plane racking – Bracing failure	Tension/compression brace fracture or Connection failure to brace	Subfloor misaligned by < 20mm - no repair required.	Subfloor misaligned by 20 - 40 mm - check condition by removing selected bolts and if damage apparent – replace bolts and check others	Subfloor misaligned by >40mm - remove braces, check around bolt for fibre damage, redrill for M16 and replace with new bolt.
			Pile/bearer connection failure	Sign of small <5mm movement – no remedy required	Moderate movement 5-20mm – check services & reattach bearers to piles	Extensive movement >20mm – check connections for damage and replace if necessary.
		Differential settlement	residual vertical misalignment of floors or roof	Misalignment < 20mm - check connections for services but repair generally not needed		Misalignment >30mm - lift house, realign & re-level house over foundations & re-pile if necessary
		Horizontal racking/shear	Joist Rolled over Pile/bearer connection failure Floor plane laterally displaced from seat on bearer.	Misalignment <5mm - no repair required.	Misalignment noticeable, 5-20mm - check for blocking damage and repair if necessary	Misalignment >20mm – check for blocking damage
		Horizontal shear - global misalignment	Torsion/twisting	Misalignment <20mm - check connections for services but no repair likely	Misalignment <50mm - check services & make good visible offset indicators	Lift house, realign & re-level house over foundations & repile if necessary
	Framed	In-plane racking	Frames twisted with residual offset between top & bottom plate & damage to sheathing	Fasteners worked within sheathing but sheets undamaged – no repair needed	Sheets damaged around some fixings - replace damaged sheets and/or re-nail away from original fixings.	Sheets damaged and residual offset >25mm – realign house, replace damaged framing and sheathing
	Poles	In-plane lateral shear	Stiffness incompatibility House twisted with residual offset or fractured poles	Residual offset <40mm – release pole/bearer fixing to relieve strain and reattach	Residual offset >40mm – realign house, release pole/bearer fixing to relieve strain and reattach	Poles broken – prop, remove damaged poles and replace, check other poles for fracture
			Brace connection failure	Remove damaged connections and replace with new	Release brace and reattach or replace.	

Table 1 contd.

ELEMENT	Type	Action	Indicators	Minor	Intermediate	Severe
Floors						
	Timber Strip	Horizontal shear	Differential horizontal movement Coverings ripple or planks twist	Ripples in floor coverings – re-lay coverings	Fastener heads visibly rotating – lift covering, punch fixings flush & re-lay covering	Ripple within flooring as planks lift – lift covering & planks, re-lay and recover
	Sheet flooring panels	Horizontal shear	Shear slip between sheets	No damage	Coverings ripple at sheet joint & fastener heads become visible – lift covering, punch heads flush and re-lay	Coverings tear and sheets lift at local bearing points – lift covering and damaged sheets, replace and re-lay coverings
			Local sheet bearing failure or sheets lifting and/or buckling		Sheet joint slip – lift covering, punch heads flush and re-lay	Joints opening as chord members separate – lift covering and damaged sheets, replace and re-lay coverings
			Joist roll over	No damage likely – check blocking	Movement apparent with fasteners loosened – check blocking and repair if necessary	Significant movement with permanent rotation – straighten joists and re-block
		Differential settlement	Floors slope & doors jamb	Uniform minor slope without ripple effects. – no repair needed	Varying slopes either visible or resulting in secondary effects – pack piles to re-level	Varying slopes either visible or resulting in secondary effects – check for pile damage, otherwise pack piles to re-level
	Slab on grade	Differential settlement	Perimeter crack Visual - Edge Cracking Water Services damaged	Cracks < 1.0mm No repair needed	Cracks 1-2mm - inject epoxy to cracks	Cracks >2mm - cement grout cracks
			Surface cracking Covering misalignment	Cracks < 1mm no step – no repair when carpeted Epoxy grout and relay lino	Cracks 1-2 mm Inject epoxy & replace floor covering	Cracks >2mm or stepped – cut out and re-concrete
		Horizontal shear	Services damaged			Services sheared at junction with slab - replace services connections
			Sliding failure Edge gap	<5mm movement - no repair needed	5-40mm offset - plaster recessed face	>40mm movement - underpin and support from perimeter

Table 1 contd.

ELEMENT	Type	Action	Indicators	Minor	Intermediate	Severe
Walls Interior						
	Gypsum Plasterboard	In-plane racking	Cracking of Joints, Skirting Architraves	Opening skirtings, architraves – fill joints and refinish	Cracking at corners and around openings & between sheets – re-nail and re-stop	Sheets disengaged from framing & split or torn – remove sheets and replace.
			Fastener pull through	Slight unevenness at fixing positions – punch visible fixings, re-stop & reinstate	Sheets torn at fasteners and often also along joints – either punch fixings flush, repair damage and re-fix or replace	Sheets hanging loose from frame – add temporary brace, remove damaged sheathing, realign walls to vertical, replace sheets, re-stop and re-finish.
			Sheets fail either in bearing or by buckling	Sheet has localized bearing failure – cut out local failure zone, patch damaged area, re-stop and re-finish.	Body of the sheet has cracked – remove damaged sheet, replace, re-stop and re-finish	Sheet is damaged and hangs loose or has fallen from framing - add temporary brace, remove damaged sheathing, realign walls to vertical, replace sheets, re-stop and re-finish
			End hold-down failures of narrow bracing panels <1.8m long	Movements at ends of narrow panels apparent – check that end straps are undamaged – replace if necessary, otherwise no repair needed.	Narrow panels have torn at fixings often with residual offset – check for damaged end straps (& replace as required), patch local fixing damage; realign & re-stop.	Sheet is damaged and hangs loose or has fallen from framing - add temporary brace, remove damaged sheathing, realign walls to vertical, replace end straps, replace sheets, re-stop and refinish
	Plywood Fiber Cement Hardboard	In-plane racking	Joints move and fixings become damaged.	Slight unevenness at fixing positions – punch visible fixings, re-stop & reinstate	Sheets torn at fasteners and often also along joints – either punch fixings flush, repair damage and refix or replace	Sheets hanging loose from frame – add temporary brace, remove damaged lining, realign walls to vertical, replace sheets, re-stop and refinish
			Sheets fail in bearing or by buckling	Sheet has localized bearing failure – cut out local failure zone, patch damaged area, re-stop and refinish.	Body of the sheet has cracked or has buckled often with fixings pulling though the sheet – cut out damaged sheet, replace, restop and refinish	Sheet is hangs loose or has fallen from framing - add temporary brace, remove damaged lining, realign walls to vertical, replace sheets, re-stop and refinish
	T&G planks	In-plane racking	Planks have slid with vertical trims no longer vertical	Surface finishes have cracked following plank sliding - refinish	Planks have slipped and pushed cover boards, trims or doors jambs out of alignment – reinstate to vertical, refinish	Noticeable residual side-sway present & doors/windows jamb or swing open – realign house to vertical, repair damaged joinery, check services, refinish.
	Softboard	In-plane racking	Sheets damaged at fasteners or along joints	Slight unevenness at fixing positions – punch visible fixings, re-stop & reinstate	Sheets torn at fasteners and often also along joints – either punch fixings flush, repair damage and re-fix or replace	Sheets hanging loose from frame – remove damaged lining, realign walls to vertical, replace sheets, re-stop and refinish

Table 1 contd.

ELEMENT	Type	Action	Indicators	Minor	Intermediate	Severe
Walls Interior						
	Lathe & Plaster	Racking or twisting	Cracking of finish or rippled surface coatings	Fine line cracking or crazing is apparent particularly at corners and around openings – refinish with high-build latex paint	Wide cracks and local bearing failures – remove damaged material and replace	Plaster has fallen from support frames and experienced widespread cracking – remove and replace
	Feature walls and fire surrounds (stone; tile, brick)	In-plane rocking	Surfaces crack, crush or tilt.	Minor cracking or crushing visible – probable rocking – check connections with support and repair cracks and damage	Significant cracking or residual tilting – check supports for settlement and/or damage, realign and repair or replace	Units have severe cracks or have fallen away from supports – remove and replace – check supports for damage
		Out-of-plane instability	Walls tilt, lean or become detached from their supports	Gaps appear between units and their supports – realign units and re-attach to supports	Units have residual tilt or lean and have separated from support – either realign or remove and replace	Units have fallen from their supports – remove and replace checking supporting frames for damage
	Concrete masonry	In-plane racking	Cracking	Fine cracks often at penetrations - refinish with high-build latex paint	Wider cracks (up to 2mm) at blocks and mortar joints – where weather may pass – epoxy grout – otherwise cement grout and refinish	Wide cracks (>2mm) and face shells have fallen – check for reinforcing fracture, install fresh face shells and epoxy in place, re-point and refinish
		Out-of-plane	Tilting or twisting	Minor tilting and some gaps noticeable – fill gaps and refinish		Severe tilt or twisting with secondary damage – demolish wall and replace.

Table 1 contd.

ELEMENT	Type	Action	Indicators	Minor	Intermediate	Severe
Walls Exterior						
	Around Penetrations (eg Doors and Windows)	In-plane racking	Weathertight envelope compromised Doors/Windows jambing Broken glass.	Flashings buckled and no longer effective – replace flashings and refinish	Window/door frames distorted – remove joinery item and install with uniform clearances	Window/door frames severely distorted with some broken glass resulting – realign framing to vertical, replace damaged joinery and reglaze broken windows, refinish
	Weatherboard claddings	In-plane racking	Joints opening	Horizontal seams between planks open – re-nail and refinish	Flashing damage around openings – extract and replace flashings	Planks open at corners – replace corner flashings and damaged weatherboards and refinish
	Pressed metal, vinyl or fibre-cement weatherboards		Thin planks buckle & individual sheets fail	Localised damage apparent at plank jointer strips and corner junctions – replace jointers	Local buckling of thin simulated weatherboards often around penetrations – realign framing and replace damaged sheets.	Planks have cracked or been damaged at fixings thereby letting water pass – replace damaged planks and refinish
	Panel products (eg Plywood Fiber Cement Corrugated Iron Hardboard)	In-plane racking	Joints move and fixings become damaged.	Slight unevenness at fixing positions or joints cracked – punch visible fixings, gouge out and re-stop damaged seams, reinstate	Sheets torn at fasteners and often also along joints – either punch fixings flush, repair damage and refix or replace	Sheets hanging loose from frame – add temporary brace, remove damaged sheathing, realign walls to vertical, replace sheets, re-stop and refinish
			Sheets fail by bearing or buckling	Sheet has localized bearing failure – cut out local failure zone, patch damaged area, re-stop and refinish.	Body of the sheet has cracked or has buckled often with fixings pulling though the sheet – remove damaged sheet, replace and refinish	Sheet hangs loose or has fallen from framing - add temporary brace, remove damaged sheathing, realign walls to vertical, replace sheets and refinish
	Solid plank	In-plane racking	Sliding/slipping Corner connection damage	Surface finishes have cracked at joints between planks - refinish	Planks have slipped and pushed cover boards or doors jambs out of alignment – remove cover plates, remove and reinstate windows/doors if needed, refinish	Noticeable residual side-sway present & door/windows jamb or swing open – realign house to vertical, replace cover boards and damaged joinery, check services, refinish.
	Concrete (eg residential precast concrete walls)		Services damage (plumbing/elec. shearing) Corner Damage Connector Damage		Horizontal crack at slab/wall junction – inject with epoxy & reseal	Diagonal cracking within panel – possible spalling of cover concrete.
	Concrete masonry	In-plane racking	Cracking & face shell damage	Fine cracks often at penetrations - refinish with high build latex paint	Wider cracks (up to 2mm) at blocks and mortar joints – epoxy grout – otherwise cement grout and refinish	Wide cracks (>2mm) and face shells have fallen – check for reinforcing fracture, install fresh face shells and epoxy in place, re-point and refinish
		Out-of-plane face loading	Tilting or twisting	Minor tilting and some gaps noticeable – fill gaps and refinish		Severe tilt or twisting with secondary damage – demolish wall and replace.

Table 1 contd.

ELEMENT	Type	Action	Indicators	Minor	Intermediate	Severe
Walls Exterior						
	Veneer (Brick, Clay, Stone)	In-plane racking	Shedding Corner Shear Lintel Damage Sliding Failure	Minor cracking (<0.5mm) within veneer mortar joints adjacent to lintels – no repair needed	Cracking usually at the base or change of section where the panel has rocked – demolish brickwork down to uncracked section and replace with modern ties & matching bricks	Diagonal cracking at corners or corners without damage while significant damage is apparent elsewhere – check the upper ties for damage, demolish damaged brickwork down to uncracked section and replace with modern ties & matching bricks
		Out-of-plane face loading	Shedding Corner Shear Gable Collapse Sliding Failure Stud/plate Failure	Cracks (usually horizontal) are present resulting in the veneer feeling 'drummy' to the touch but no horizontal offset is apparent – check condition of tie connections with borascope - if damaged, locate the stud lines, drill through the mortar joints, screw in helix fixing rod and epoxy veneer to rod	Cracks are apparent and some horizontal offset has occurred across the crack – demolish brickwork down to uncracked section and replace with modern ties & matching bricks	Tie or bond failure has resulted in veneer panels falling from their supporting frames - demolish brickwork down to uncracked section and replace with modern ties & matching bricks
	Stucco (Cement plaster Render)	Twisting and in-plane racking	Shedding plaster Cracking within Walls Cracking/Sliding at base Loosening of Elements	Cracking is limited to the either the bottom plate or adjacent to penetrations – gouge cracks, replace and refinish.	Cracks are apparent over a significant portion of the wall area – epoxy fill cracks and refinish	The stucco has lost its connection to the support framing and either fallen from or is loose on the support framed – demolish and replace
	Polystyrene block	In-plane racking	Corner damage to surface coating	Cracking at corners – patch exterior plaster and refinish	Cracks in ext coating – epoxy fill cracks and refinish	
	EIFS	In-plane racking	Cracking of surface finish Popping of fasteners possible.	Indented fixing heads – re-plaster finish	Minor cracking at insulation sheet joints - gouge and fill with high bond plaster	Sheets become detached - remove and re-fix sheets, re-plaster and refinish.

Table 1 contd.

ELEMENT	Type	Action	Indicators	Minor	Intermediate	Severe
Ceilings						
	Plasterboard & Fibrous plaster	Twisting and in-plane racking	Wall junction damage Tearing of fixings Loss of support	Slight unevenness at fixings along adjacent wall junctions – punch visible fixings, re-stop & reinstate	Sheet damage along junction with wall lining & to joints between sheets - punch visible fixings, re-stop & reinstate	Sheets have become disengaged from their support framing – remove, replace and refinish
	MDF ceilings	Twisting and in-plane racking	Wall junction damage Tearing of fixings Loss of support	Slight unevenness at fixings along adjacent wall junctions – punch visible fixings & reinstate	Sheet joints have cracked and fixings worked proud of the finished surface – punch fixings and re-putty nail heads, make good joints and damage, refinish	Sheets have opened at the joints and/or lost their connections to the support framing - remove, replace and refinish
	Softboard Sheet Softboard Tile	Twisting and in-plane racking	Sheet joint Lining Damaged	Slight unevenness at fixings along adjacent wall junctions – no repair needed unless high quality finish required	Sheet joints have cracked and fixings pulled down below the finished surface – replace fixings, make good joints and damage, refinish	Sheets or tiles have lost their connections to the support framing - remove, replace and refinish
	Lathe & Plaster	Twisting and in-plane racking	Cracking of plaster Localised lathe failures (Sections have fallen to floor)	Slight unevenness at points of support – refinish to flush finish, re-stop & reinstate	Surface rupture has occurred and significant misalignment is apparent – check integrity of supporting lathe (replace if necessary) refinish exposed face to flush, refinish	Ceiling has become disconnected from the support frame – prop, lift and reconnect or replace if ceiling fabric is torn.
	Decorative ceilings	Twisting and in-plane racking	Feature finish has become damaged	Slight unevenness at fixings along adjacent wall junctions – punch visible fixings, re-stop & reinstate	Visual cracking in decoration – fill crack with new plaster and refinish	Ceiling damage is irreparable – remove and replace ceiling
	Ceiling fitments	Twisting and in-plane racking	Sky lights damaged Light fittings collapse	Points of connection with ceiling fitments are damaged – reinstate connections and refinish	Fitments have cracked or become disengaged from the ceiling – repair or replace and reconnect to ceiling.	Fitments have fallen from their mounts within the ceiling – replace and refinish.

Table 1 contd.

ELEMENT	Type	Action	Indicators	Minor	Intermediate	Severe
Roof Systems						
	Clay or Concrete tile, shakes or shingles.	Twisting and in-plane racking	Shedding	Ridge capping units disengaged with some falling – replace lost capping units with new mortar	Individual elements within the body of the roof have moved or become loose – re-fix or replace	The roof plane has distorted and is no longer weathertight – replace the roof cladding.
	Metal tiles	Twisting and in-plane racking	No damage	Edge and ridge flashings have been damaged – replace flashings	Localised buckling is apparent where the roof has pounded walls or penetrations – check batten fixings & replace damaged tiles.	Roof tiles have been damaged by heavy items falling onto them – check support framing & replace damaged tiles.
	Shakes, shingles etc.	Twisting and in-plane racking	Tearing of fasteners, Damage or dislodgement of elements	Edge and/or ridge flashings have been damaged – replace flashings	Individual elements within the body of the roof have moved or become loose – re-fix or replace.	The roof plane has distorted and is no longer weathertight – replace the roof cladding
	Rolled metal sheets	Twisting and in-plane racking	Tearing at fasteners	Nail holes slotted – check weather shedding ability of the cladding	Edge and/or ridge flashings have been damaged – replace flashings	Roof cladding has been damaged by heavy items falling onto it or by tearing around the fasteners. – check support framing; replace damaged sections.
	Membrane (Over Sheet)	Twisting and in-plane racking	Ripple/tearing	Substrate sheets have moved and fastener indentations are visible through the membrane which remains otherwise undamaged – no repair needed	The membrane has become damaged either by movement of the substrate or by items falling onto it – lift membrane and replace.	Substrate sheets have opened at their joints and fixings have worked loose – Lift membrane, repair substrate and replace.

5. EXPERIMENTAL STUDIES

It became clear from the interviews with loss adjusters and others that there were many instances where the level of damage was not clearly obvious from a cursory inspection and that guidance would need to be provided to the assessor on what indicators might be present to be able to specify the likely necessary repair.

Limiting the scope of experimental coverage to foundations and walls, several areas were identified as requiring experimental investigation so that the growth of damage could be tracked and repair procedures could be developed. These included:

1. Plasterboard lined walls with sheet sheathing on the exterior

2. Braced pile systems

3. Brick veneer corners

4. Pre-1978 wall construction

5.1 Plasterboard-lined walls with sheet sheathing on the exterior

These systems rely on bracing being provided by the exterior sheet sheathing and the function of the plasterboard is purely to provide a surface for interior decoration. Because of this, the plasterboard sheets have often been nailed at large centres and sometimes not at all behind skirting boards.

Many dwellings have these types of wall linings and it is important to be able to accurately determine the level of damage and the required repair to reinstate the capacity of the walls. A replica of such a system was constructed in the laboratory and subjected to cyclic in-plane loading. Details of the specimen are presented in Figure 1 and Figure 2.

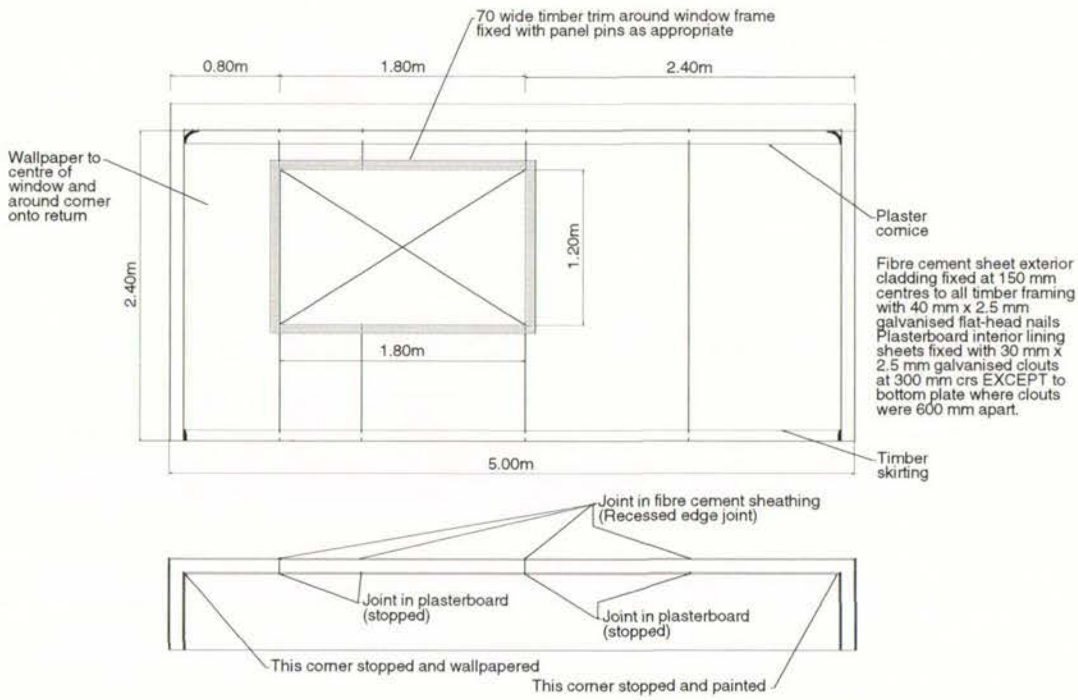

Figure 1: Details of the exterior wall specimen

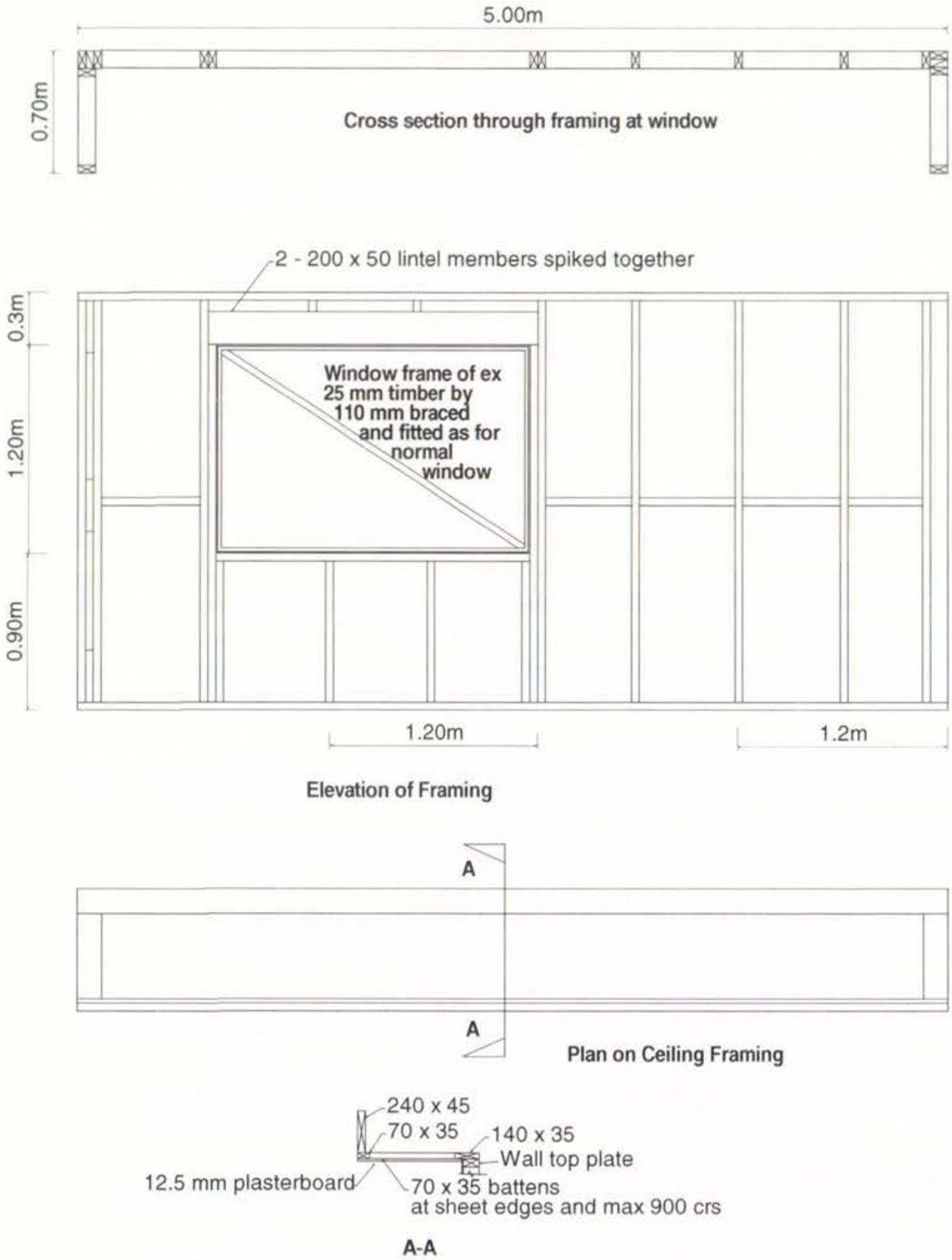

Figure 2: Details of the exterior wall specimen (cont'd)

The specimen was built on a simulated concrete foundation system (Figure 3) and a section of plasterboard ceiling, complete with cornice, was included to model the junction between the walls and the ceiling (Figure 4). One end of the interior face was painted while the other was wallpapered to investigate the differences in observed damage formation. On the exterior face, the fibre cement board was nailed in accordance with the manufacturer's literature. The tapered edge joints between the sheets were filled with joint filler 2[i] (Figure 5). No texture coating was applied to the surface of the fibre cement board. While it is not recommended by the manufacturers, the sheets of both the plasterboard and fibre cement board were joined at the edge of the window to represent what has been common practice by the construction industry.

[i] See Appendix A for description

Figure 3: Simulation of concrete foundation (bottom plate coach screwed to foundation beam and flooring beneath skirting board)

Figure 4: Section of ceiling and walls complete with cornice in place

Figure 5 Filled joint between fibre cement sheets

To model the dead weight of the roof structure, 100 kg masses were hung from the strongback at each end of the specimen. The racking load was applied by the structures laboratory servo-controlled actuator to the top plate of the long wall.

Initial cycles were applied up to a ±5 mm top plate deflection and an inspection of the damage was made.

Cracks had appeared in the painted plasterboard joints below the window corners during these cycles. The repair method selected was based on what was done at Edgecumbe after the 1989 earthquake. This procedure involved V-ing out the joint. In doing this the tape was cut and the paper edges of the sheets were also cut. The joint was filled with normal first coat stopping compound. The compound shrank on drying and did not bond well to the sides of the V. There was no apparent damage where the wallpaper was present. If there were cracks in the plasterboard joints, these were hidden behind the wallpaper.

A small crack had formed up to about 1 mm wide on the fibre cement sheet joints, extending from the bottom corners of the windows to the bottom plate. These cracks were filled with joint filler 1. Overcoating with a new textured coating would have been necessary to hide the repair to the satisfaction of a building owner.

The specimen was then re-cycled to ±5 mm and the strength and stiffness compared. A plot of the before and after repair cycles is presented in Figure 6. The repaired strength in one direction matched the initial strength but only reached about 65% of the initial strength in the other. There was no clear reason for this asymmetric behaviour.

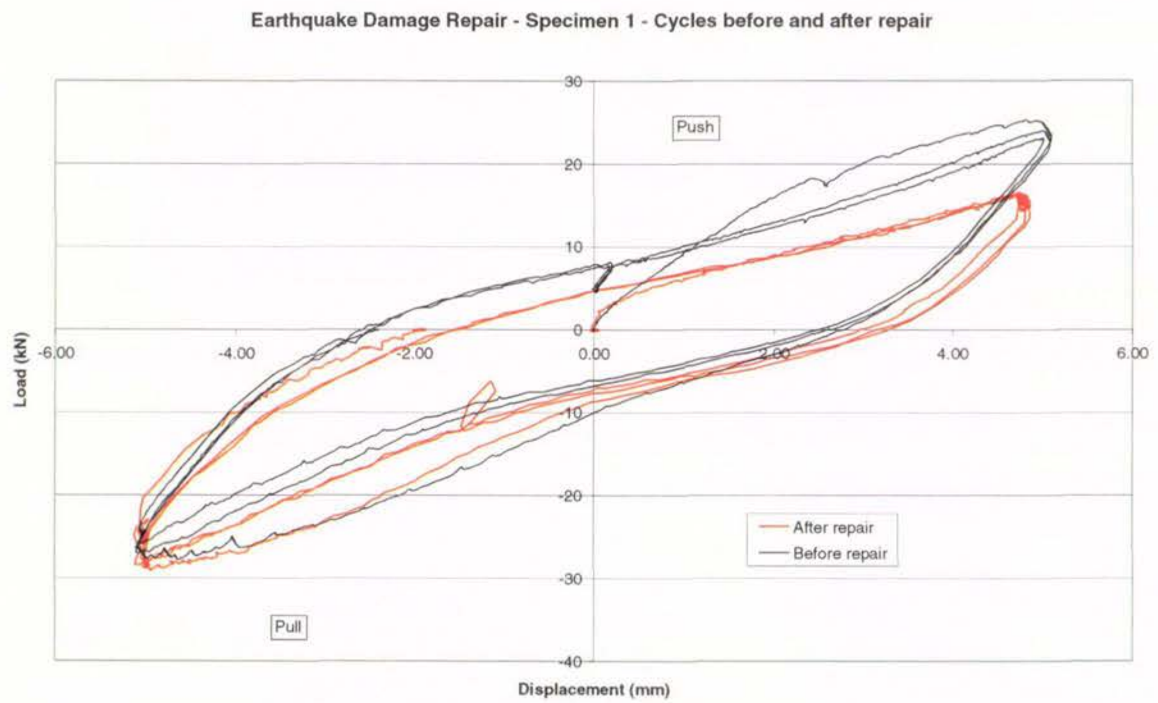

Figure 6: Comparison of performance before and after the first repair work

For such a wall in normal practice only the 2.4 m length of fibre cement sheet could be included as a bracing element and the short length on the opposite side of the window could only have been included if hold-down straps had been installed. No contribution from the gypsum plasterboard could be included because the nailing was insufficient for it to achieve a bracing rating. Therefore, the design strength of the wall was about 11 kN and this was still able to be achieved after the repair had been undertaken with little displacement.

Cycling continued to ±10 mm and ±15 mm (3 cycles each). During these cycles the gypsum plasterboard joint adjacent to the window opening on the painted side sheared up to 11 mm and the remaining tape at the bottom of the joint tore. On the opposite side the wallpaper sheared with the joint and repair would require removal of the wallpaper and re-stopping. In accordance with the manufacturer's advice, the plaster surface was scraped back to the paper tape and the tape removed (Figure 7). Then the plaster beneath the tape was slightly V-ed without damaging the paper surface of the board. The joint was then stopped in the normal manner. Extra nails were installed along the edge of the sheets (Figure 7) at the joint adjacent to the damaged ones and the bottom edge of the plasterboard sheets was nailed at 300 mm centres once the skirting board had been removed.

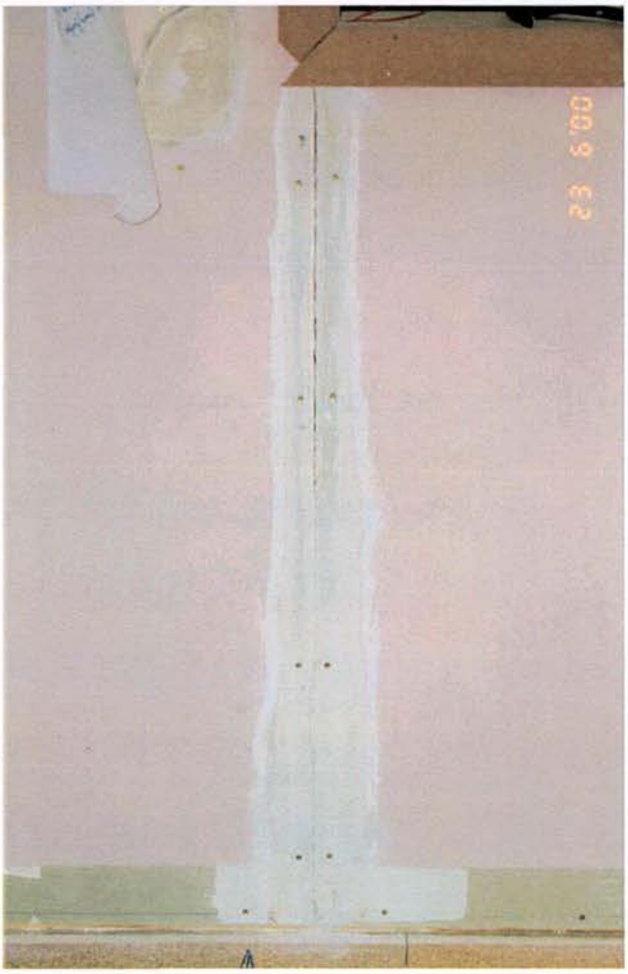

Figure 7: Painted gypsum plasterboard joint prepared for stopping after 15 mm displacement cycles

Manufacturer's advice was also followed for the treatment of the damaged joints in the fibre cement board. Each joint on either side of the window opening was treated differently.

The right side joint was ground out with an angle grinder, to form a V between the sheets. This was then filled with joint filler 2 and over-coated with joint filler 1. No further primer was added.

The left side joint was ground back to original sheet face and the joint V-ed out. The repair involved the application of a water-based primer and then filling with joint filler 3 (Figure 8).

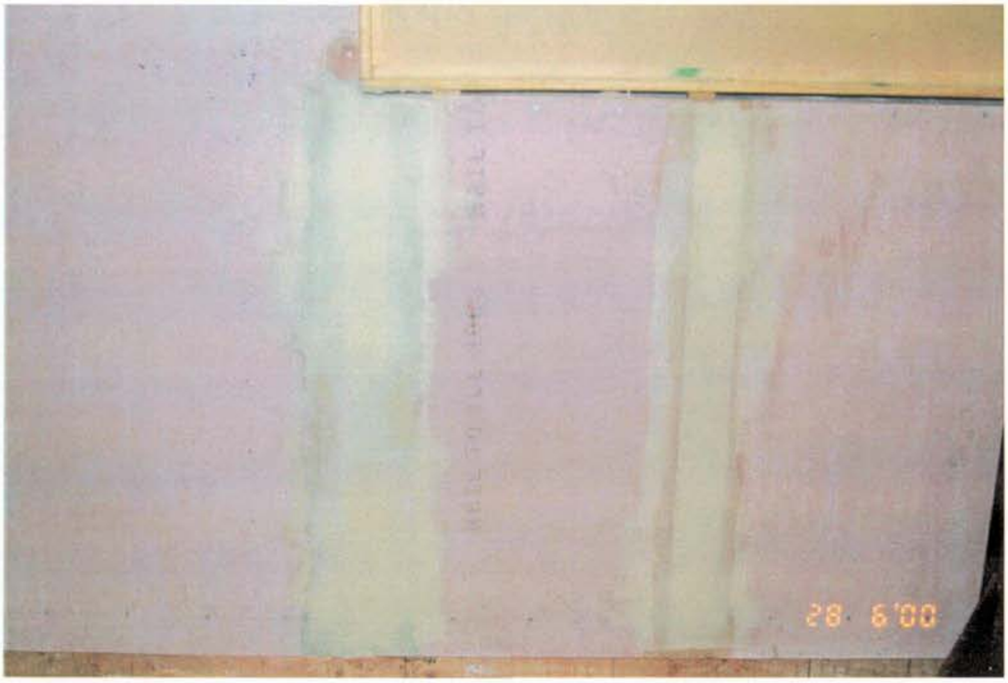

Figure 8: Repaired fibre cement board joints on left side

When the old filler was removed nails were added to the sheet at the joint. An extra nail was added at each gap between the existing nails. Also, the top and bottom corners of the 2.4m long "bracing panel" were nailed to the plates with an extra nail between each of the first four nails in the horizontal row (Figure 9).

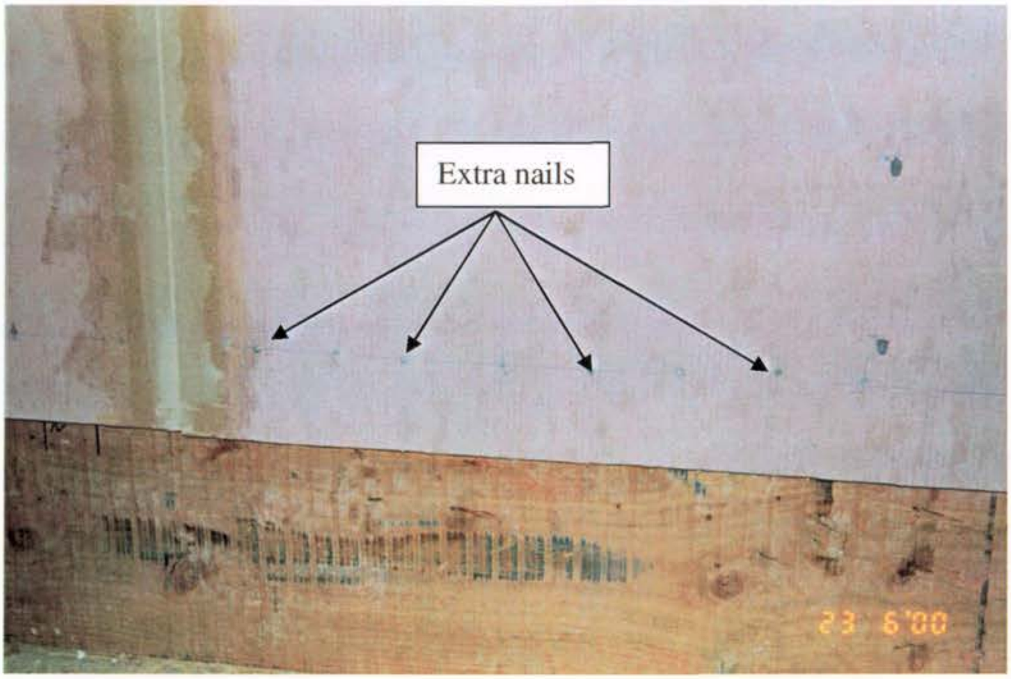

Figure 9: Extra nails added at bottom plate

Some over-coating cosmetic work would be required to hide the appearance of the new nail heads in service.

The specimen was then cycled again to the same displacement levels to compare the performance. Plots of the two sets of cycles are presented in Figure 10.

In one direction the after-repair plots closely matched the before-repair plots but in the other direction there was a significant mismatch until the 15 mm displacement. The reason for the asymmetry is uncertain but because the load levels were almost recovered and well above the design load the wall was still effective as a bracing element.

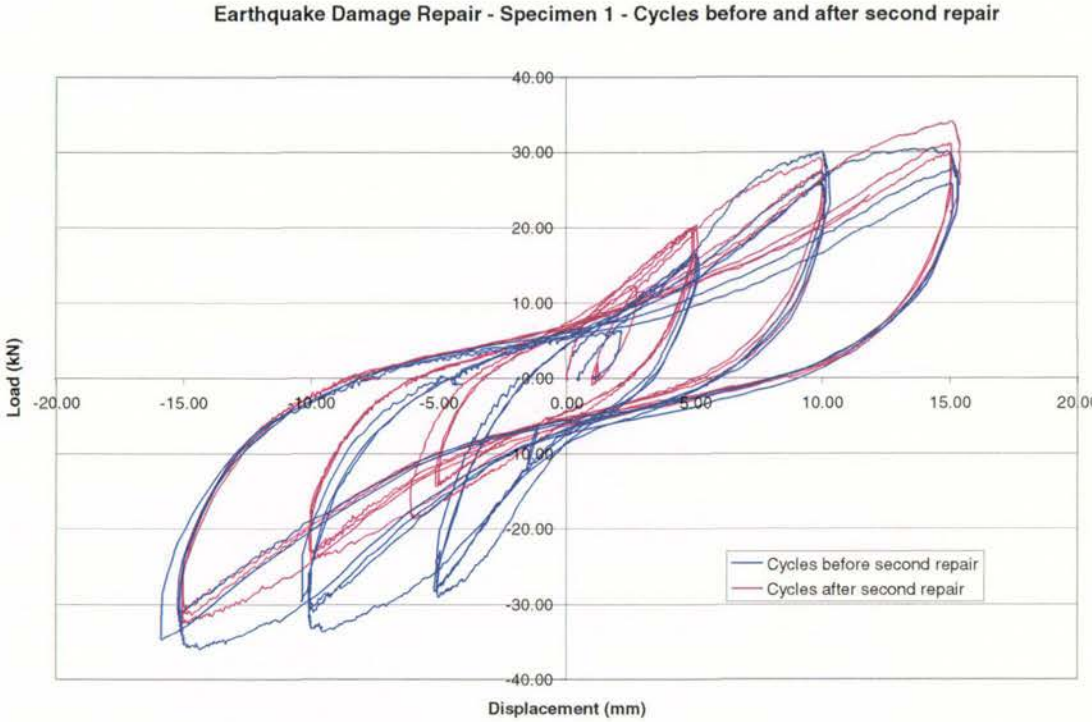

Figure 10: Comparison of the load deflection behaviour before and after the second repair

The specimen was then cycled to displacements in excess of ±15 mm. During these cycles the gypsum plasterboard joints began to open again, as they had done before the repair was undertaken. The connection to the bottom plate was lost as the nails pulled completely through the bottom edge of the sheet.

The interior lining was not intended to have any bracing function in this test because the fibre cement exterior sheathing was the designated bracing system. Removal of the plasterboard sheets was not necessary after these cycles as they were intact. Only the joints between the sheets required repair and perhaps the odd nail head in the in-field of the sheet would need to be punched and stopped. Nail head popping under the wallpaper would not be noticed, although would be expected to be present.

There was no damage to the plasterboard at its intersection with the scotia between the wall and the ceiling that required any sort of repair.

At the completion of the cycles to <u>±30 mm and ±40 mm</u> the individual fibre cement sheets were still in good condition but the nailing along the bottom plate was in a bad condition. The nail heads had pulled through the sheet and it was hanging proud of the bottom plate.

The sheets could be re-nailed to the bottom plate but with a textured coating in place it may be difficult to find the original nail positions for re-nailing, unless they can be felt from underneath. A plot of the load-displacement cycles up to ±40 mm is presented in Figure 11.

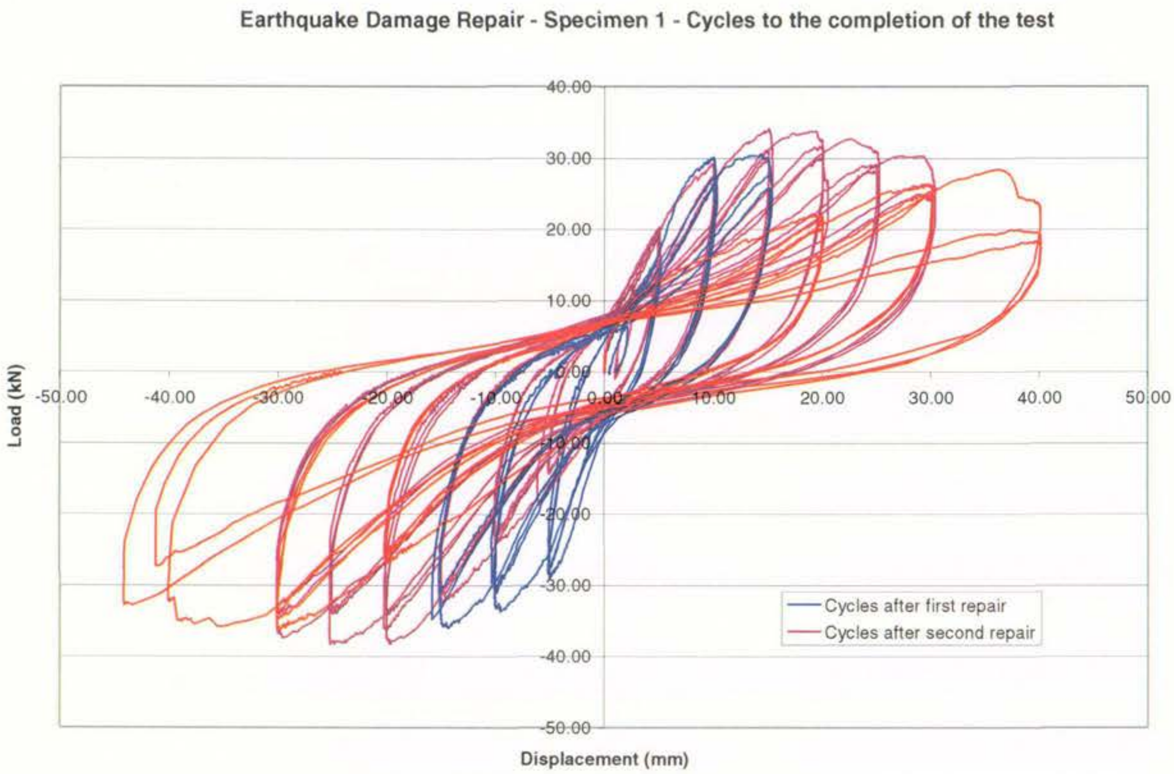

Figure 11: Load displacement history

5.1.1 Conclusion on testing on exterior sheet sheathing and plasterboard lining

The results of the testing on this system indicated that it would not generally be necessary to remove the exterior sheet sheathing or the plasterboard lining after earthquakes causing in-plane deflections of the top plate of up to 40 mm in both directions. In these combinations of wall claddings in older houses, the interior lining is not expected to perform any bracing function, and it is therefore not necessary to reinstate any bracing capacity. Re-nailing of the sheet material and re-stopping plasterboard joints and popped nails, depending on the level of damage, followed by redecoration, would be necessary on plasterboard linings. The exterior sheet cladding is likely to partially detach from the framing in a severe event but can be re-nailed and the joints refilled with appropriate filler materials. The re-nailing will need to be done carefully so that the bracing capacity of the cladding is re-established. Any nailing repairs to the sheet cladding will generally result in the need to reinstate the texture coating.

5.2 Braced Pile Systems

A specimen which included four piles and three diagonal braces was constructed to determine the repair procedure for various levels of damage that may occur in an earthquake. The pile members were 125 mm by 125 mm in cross section and the brace members were 100 mm by 75 mm. Dimensional details are presented in Figure 12. Construction of the braced piles replicated the requirements of NZS 3604 (SNZ 1999). All bolted connections were M12 galvanised bolts through close fitting holes in the timber. A 50 mm x 50 mm x 3 mm flat washer was installed beneath each bolt head and under each nut. The bolts were tightened firmly with an adjustable spanner, as would be expected to occur in practice. To simulate the "pinned" support from the ground, the bases of the piles were restrained against movement along the line of the piles 500 mm below the bottom brace connection, but were allowed to rotate.

As can be seen in Figure 12, the pile system had a floor and wall simulation attached to the bearer. This was used for another research project being undertaken at the same time, but provided a source of gravity load for the pile system under investigation in this project. Load was applied to the top plate of the wall and the floor at the same time with a pinned linking beam so that the load was distributed according to the stiffnesses of the two systems.

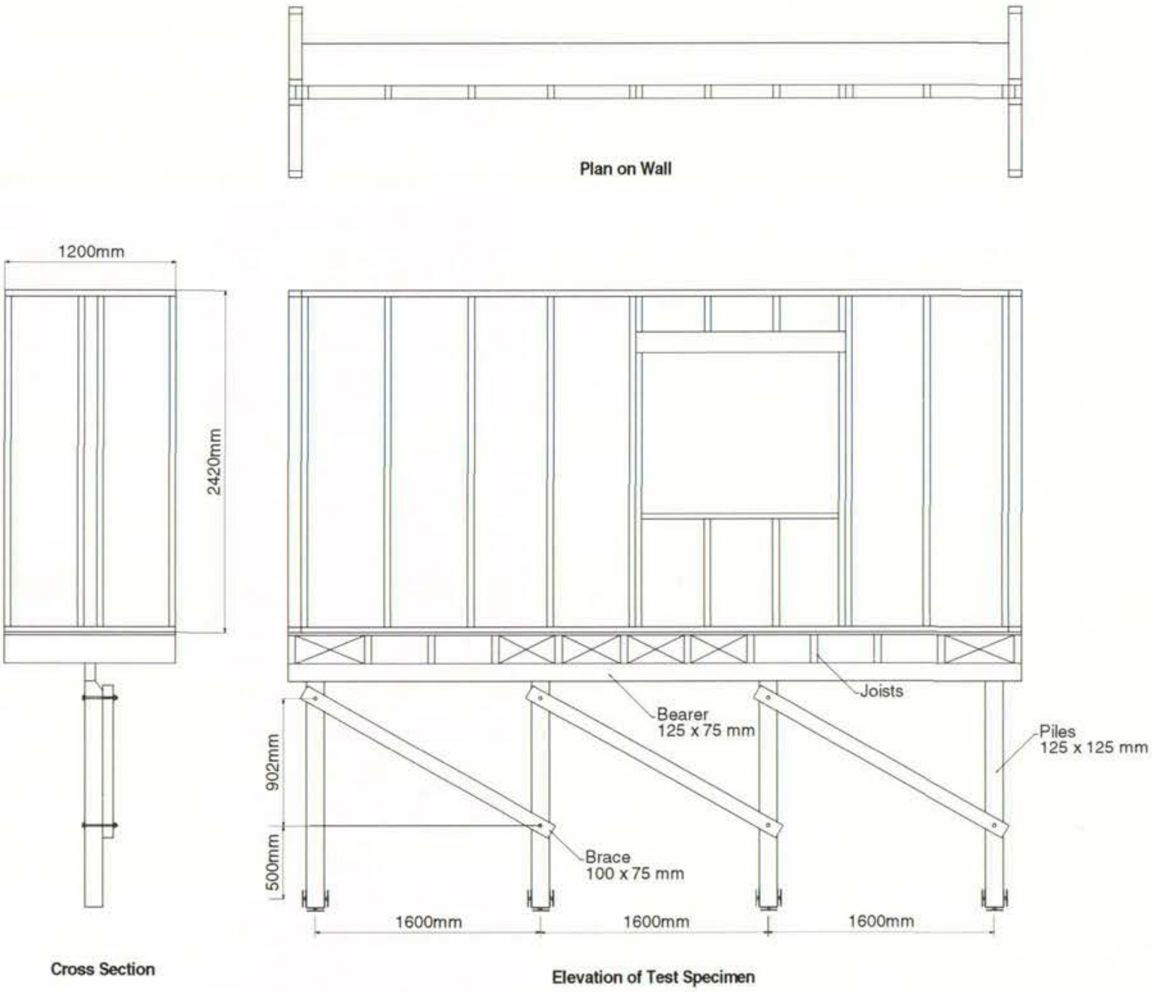

Figure 12: Details of the braced pile specimen

The system was first racked through increasing levels of loading to provide an as-built cyclic response to an expected earthquake, using the structures laboratory 100 kN servo-controlled actuator. A plot of the load-displacement behaviour is included in Figure 13.

As cycling progressed, it was difficult to tell what damage was occurring in the joints between the piles and the braces because there was nothing visible happening, except that tell-tale lines on the members at the joints indicated clear movement between them.

A major difficulty for an inspector after an earthquake will be that he/she will not have tell-tale lines to refer to, to judge how much movement has occurred. Also, because the damage is hidden, it won't be possible to determine the extent of it without removing a brace and checking the state of the bolt and the timber around it.

When the bolts were finally removed, there was a large slot in the timber of both members (particularly the brace) and the bolt was significantly bent (Figure 14).

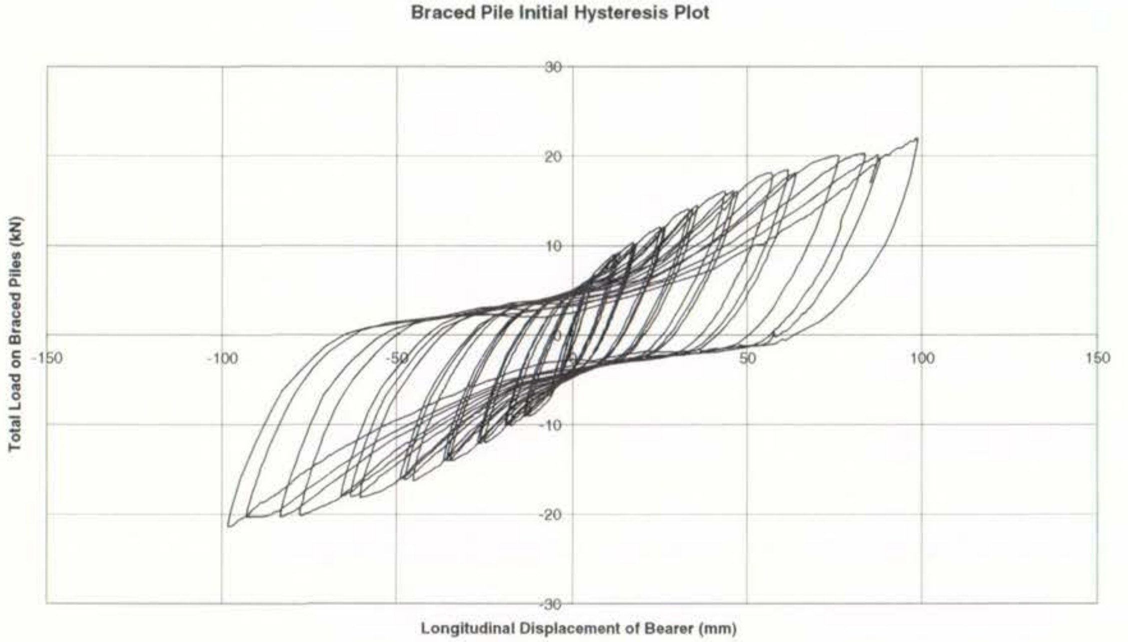

Figure 13: Longitudinal displacement of bearer against load

Figure 14: Pile brace after removal showing bent bolt and slot in brace

5.2.1 Repair Procedures Attempted

Two repair procedures were attempted for the damaged bolted joints. The first of these involved filling the holes with builders' fill, available off the shelf at most hardware stores and redrilling them once the fill had hardened. The bolts were also replaced with new straight bolts. The second involved removal of the bolts and enlarging the holes for M16 bolts.

1. Builders' Fill

When the specimen was cycled after the repair the service stiffness was of the order of 50-60% of the stiffness in the initial cycling (Figure 15). As the displacement increased, the difference between the two plots remained relatively constant so that at 100 mm displacement the difference was about 10-15%.

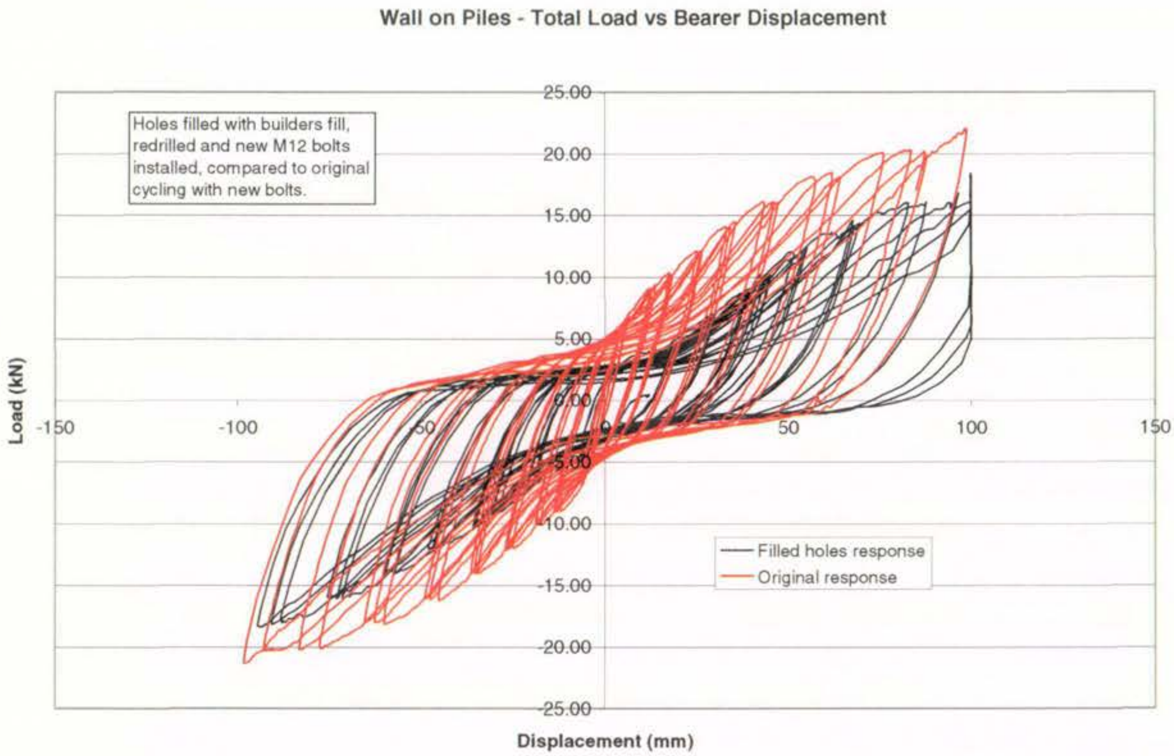

Figure 15: Comparison of performance before and after holes repaired with builders' fill

The bracing rating in NZS 3604 for a single braced pile is 120 bracing units which translates to 6 kN. Therefore, the design load for the specimen is 18 kN. To achieve this load with a system that had never been subjected to earthquake loading before, the displacement of the bearer was between 60 and 70 mm. After the repair, the system displaced to 100 mm in one direction and further in the other before the design load could be achieved (note that the right side plot in Figure 15 does not extend beyond 100 mm because the deflection gauge had reached the end of its stroke).

When the joints were reopened it was clear that the builders filler was not able to cope with the high bearing stresses placed on it and it crumbled badly and fell from the joints in small pieces. Because it was not sufficiently strong, the filler provided no support for the bolts and they bent as they had done in the virgin specimen.

2. Larger Bolts

For this alternative, the braces were removed from the piles and turned over so that the hole adjacent to the pile was not damaged. The holes were then drilled out to accept the M16 bolts and these were installed complete with flat square washers beneath the bolt heads and nuts.

The initial stiffness of the repaired specimen was not quite as good as that of the virgin specimen but was likely to be sufficient to provide resistance to movements under service loads after an earthquake. As cycling continued, the strength gain was faster than in the original specimen (Figure 16). Once the displacements had reached approximately 40 mm the strength of the repaired structure was greater than the original and this continued up to displacements of ±100 mm, when the testing was terminated.

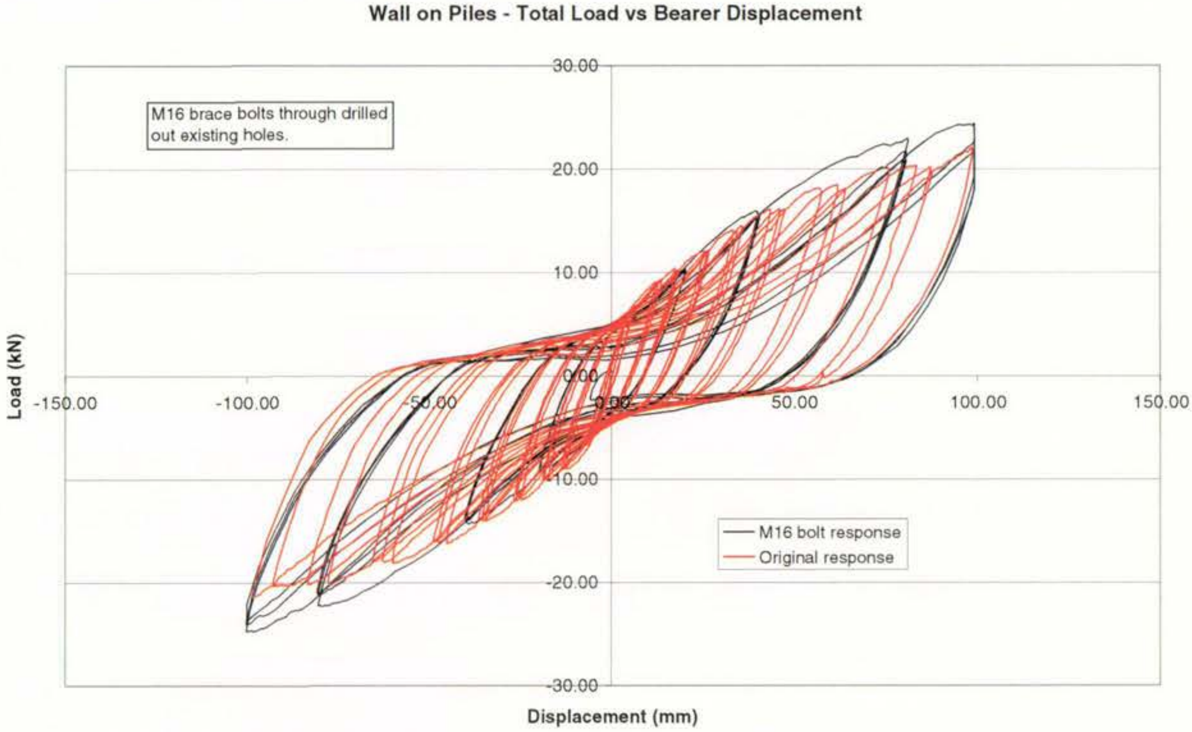

Figure 16: Comparison of performance before and after holes drilled out and m16 bolts installed

5.2.2 Conclusions on braced pile testing

With braced piles, it appears that it will probably be necessary to remove at least one brace after a severe earthquake to check for internal damage. A decision can be made at that point about whether it will be sufficient to retighten the existing bolts (thus mobilising greater friction between the two timber surfaces and stiffening the joint) or whether the holes should be drilled out and M16 bolts installed.

5.3 Brick Veneer Corner

Corners of brick veneers have often been areas of damage in previous earthquakes. This is caused by the rigid nature of the veneer and the conflicting displacement requirements of the face loaded section and the in-plane loaded section.

A section of wall was built for this study with a 2.6 m length of veneer parallel to the direction of loading and a 1.4 m return. The height of the veneer was 2.32 m and it was attached to a light timber framed wall with flat commercially available ties, nail-fixed to replicate construction prior to 1990. The tie spacing was 600 mm centres horizontally to match the stud spacing and 350 mm vertically. The first tie was at the top of the fourth course of bricks. The inside face of the timber framing was lined with gypsum plasterboard and was not expected to behave as a bracing element. A section of ceiling and gypsum plasterboard ceiling lining was included, along with a plaster cornice and a timber skirting board. Details of the test specimen are given in Figure 17 and Figure 18.

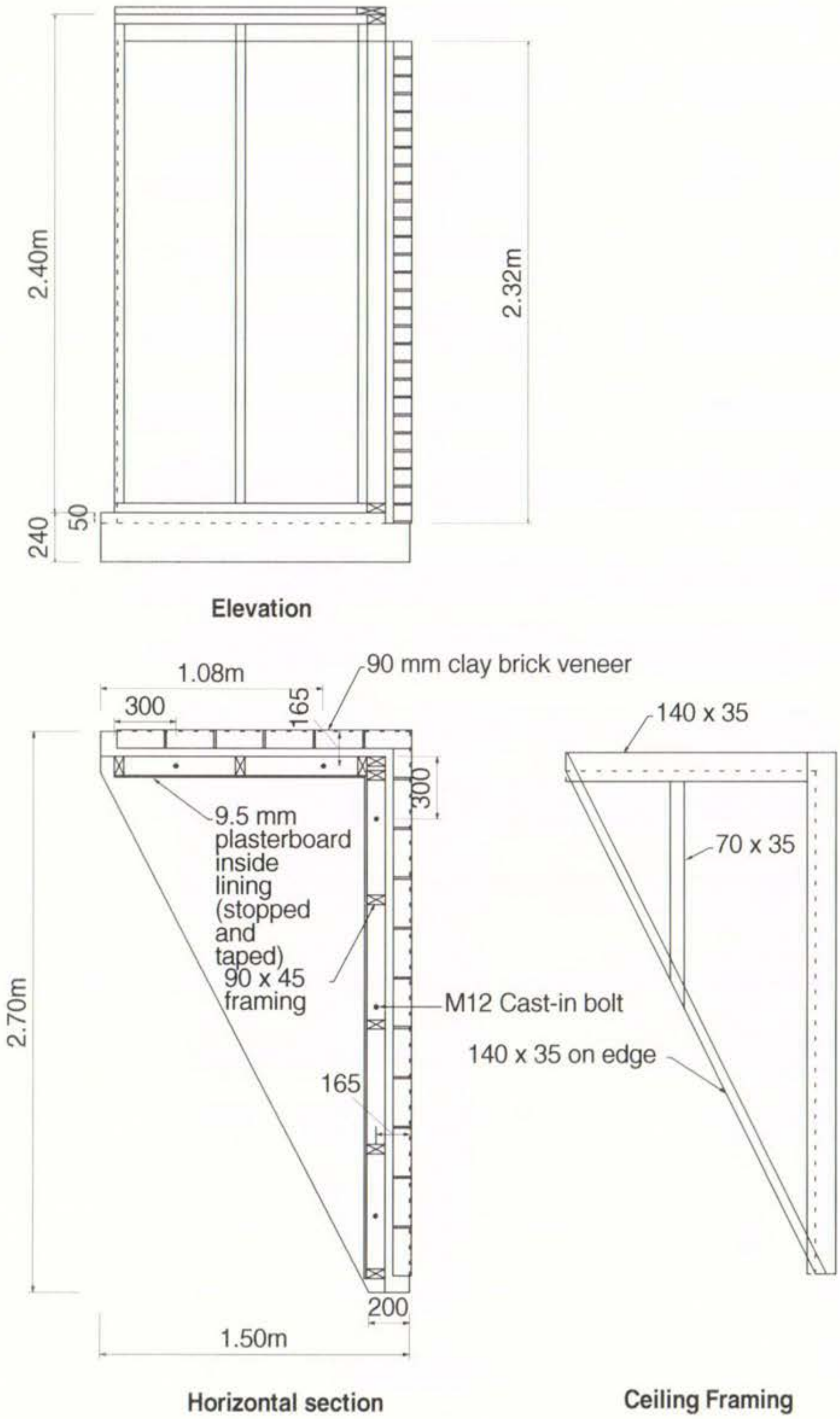

Figure 17: Details of the brick veneer corner specimen

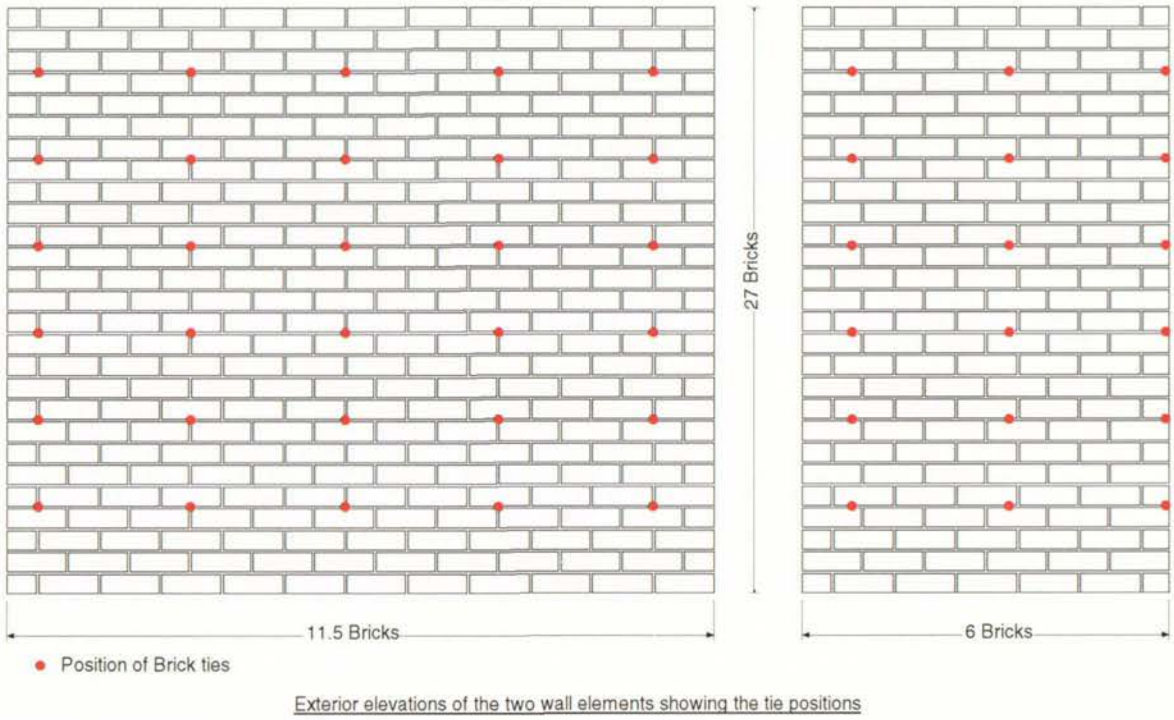

Figure 18: Wall elevations showing the positions of the veneer ties

Photographs of the exterior and interior views of the test specimen are included in Figure 19 and Figure 20. The small square holes in the interior lining were cut to provide access to the adjacent veneer ties to monitor their performance during the cycling. Cyclic loading was applied to the top plate of the long wall with the laboratory's 100 kN servo-controlled actuator.

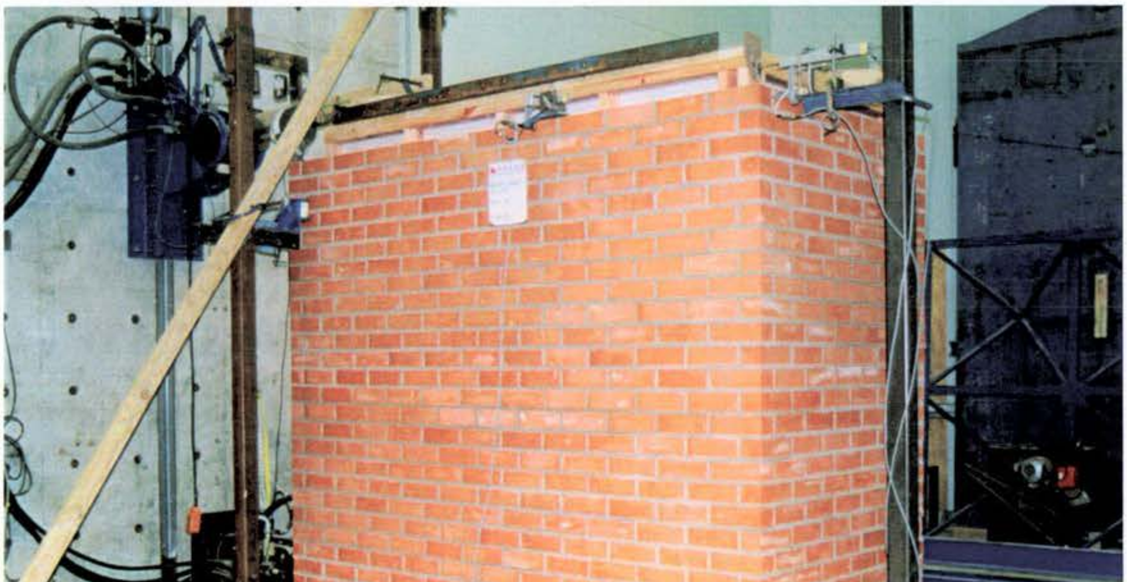

Figure 19: Exterior view of the brick veneer test specimen

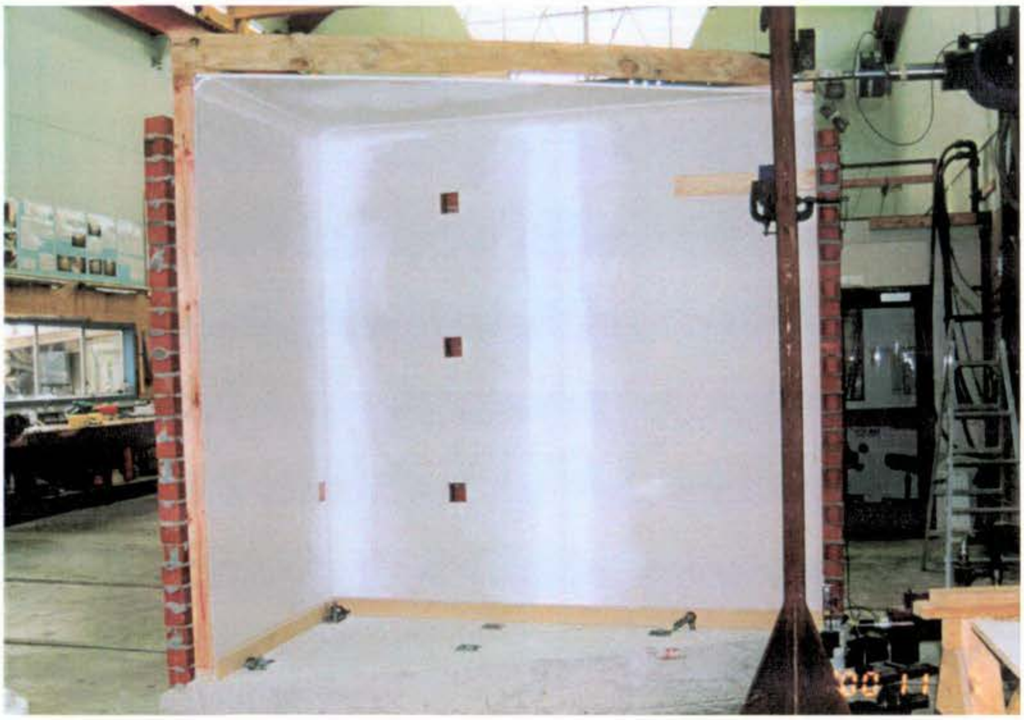

Figure 20: Interior view of the brick veneer test specimen

Three initial slow cyclic (approx. 60 seconds per cycle) racking cycles were applied to a target load level of 5 kN. The top displacement of the timber framing was about ±2 mm while that of the veneer was approximately 0.5 mm. Thus the veneer ties were being subjected to 1.5 mm differential lateral shear. The ties near the top of the return wall were simultaneously subjected to ±1 mm axial shortening.

The second set of cycles repeated the 5 kN cycles from the initial series and then went on to cycles targeting 10 kN. When approximately 9 kN was reached, the end of the veneer under the actuator began to lift from the slab during the push cycles. For this direction, a target displacement of 6 mm was set so that 3 complete cycles could be achieved to 10 kN in the pull direction. Once again, there was differential movement between the veneer and the framing, in the order of 4 mm at the peak load (Figure 21).

A vertical restraint was installed over the end of the veneer beneath the actuator and the third set of cycles was commenced. A target load of 10 kN was achieved in both directions and an attempt was made to continue on with cycles to 15 kN. In the pull direction, at a load of about 14 kN, the remote end of the long veneer and the attached return veneer began to lift off the foundation slab. Testing continued to achieve three complete cycles but the displacement in the pull half cycles was limited to approximately 13 mm (Figure 22).

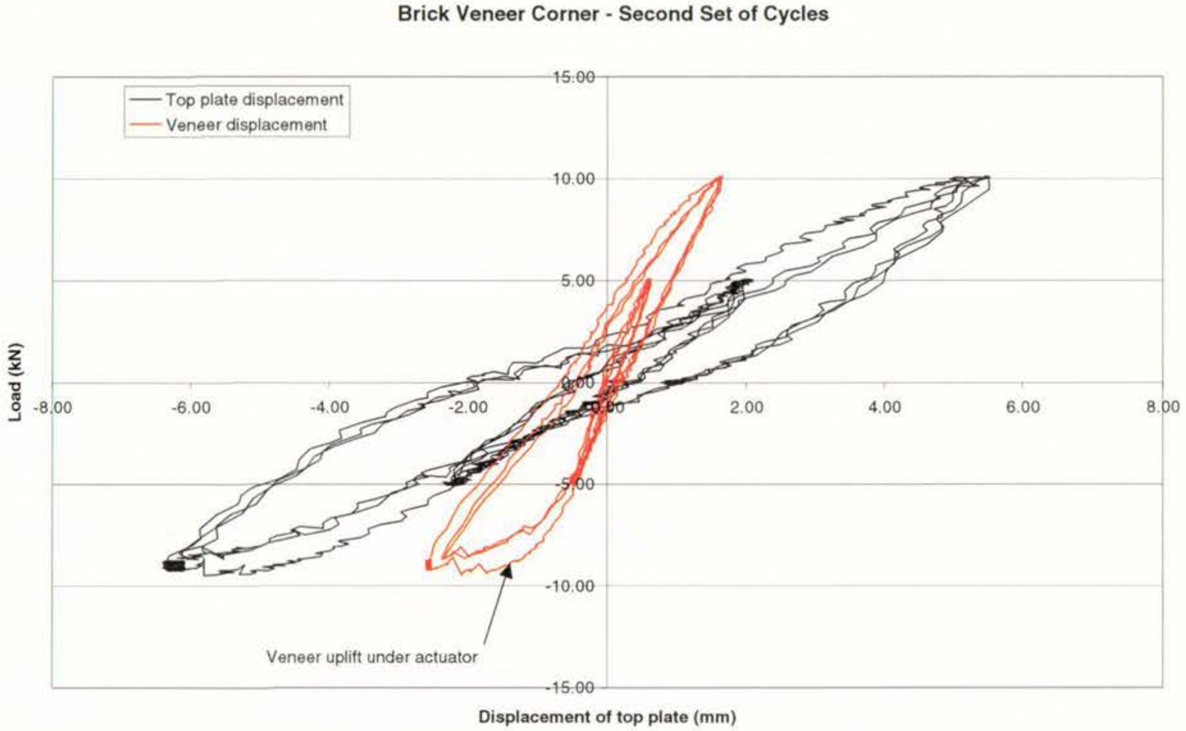

Figure 21: Comparison of top plate displacement and veneer displacement against load – cycles to 10 kN.

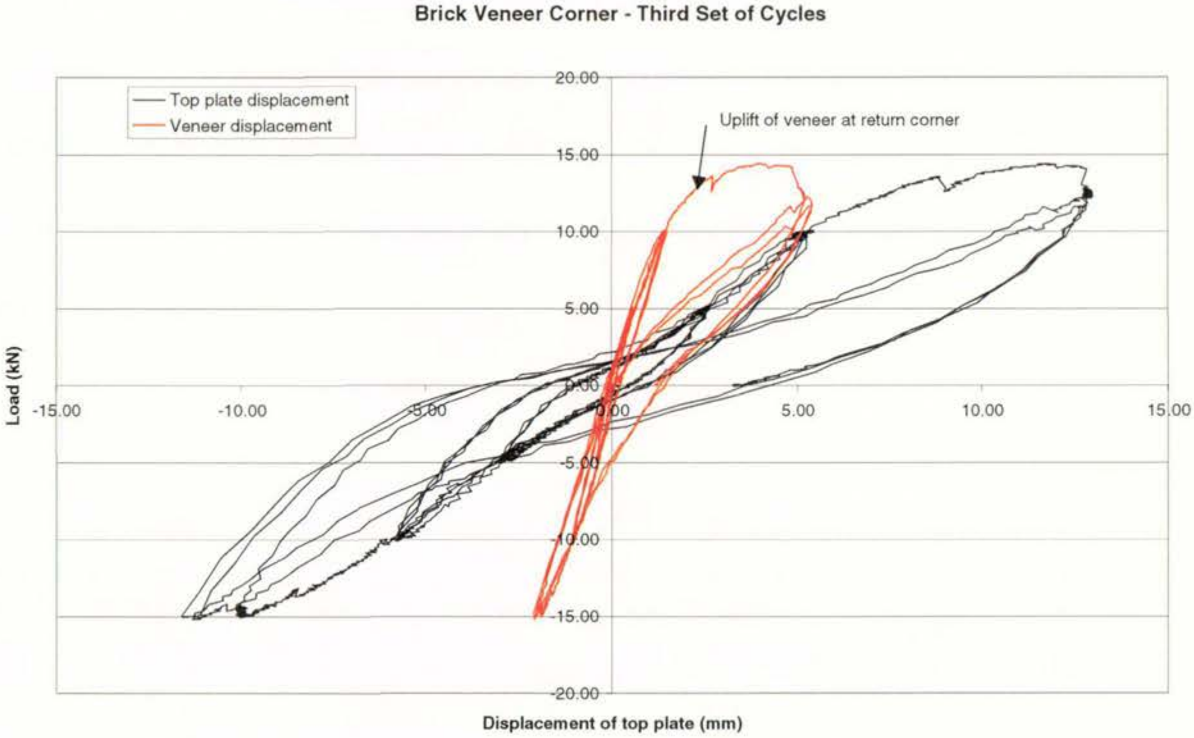

Figure 22: Comparison of top plate displacement and veneer displacement against load – cycles to 15 kN.

A second vertical restraint was added at the remote end of the return wall so that the corner could lift but the two free ends were fully restrained against uplift.

The specimen was then cycled so that the peak loads for the two directions and failure mechanisms could be established. In the push direction 20 kN was achieved at about 22 mm of top plate displacement, while in the pull direction the load did reach 20 kN momentarily at a displacement of about 23 mm. While the two ends remained tied down, the corner of the veneer lifted appreciably (up to 14 mm). Considerable in-plane differential movement between the wall framing and the veneer occurred, particularly at the top of the wall where the differential displacements were up to 25 mm. The differential displacement between the return veneer and the framing was up to 20 mm of opening as the ties straightened and the nails pulled from the studs.

A close inspection of the outside face of the veneer showed no signs of distress at this stage. Fine cracks expected to be present in the mortar joints because of the torsion being applied to the veneer were not visible. No disconnection from the timber framing could be detected by tapping on the outer surface of the veneer and listening for any change in tone.

At this time the gypsum plasterboard lining, while still behaving as a single item with no cracking along joints, was discovered to have lost its nail connection to the framing over large areas. This was easily detected by tapping on the wall and noting its sound. When detached from the framing, a "drummy" sound was apparent when tapped.

A set of six cycles was done at a reasonably fast manual control in an attempt to introduce dynamic behaviour but this still caused no detectable damage to the veneer. However, the plasterboard continued to detach from the framing.

It was clear that the slow cyclic loading was not providing a sufficient enough simulation of earthquake loading to cause damage similar to that observed after real earthquakes.

An attempt was then made to dynamically cycle the specimen. This was in an effort to introduce an element of shock loading to the specimen, partially commensurate with real earthquake loading, bearing in mind that the base of the specimen was not able to be excited. Six cycles were applied sinusoidally at 1 Hz at a displacement target of $\pm$30mm. There was some evidence of damage to the veneer at this point although only slight. The top tie on the face loaded veneer nearest the corner bent under compression loading and both securing nails were pulled out of the frame (Figure 23). The tie at the same level and on the adjacent stud of the face loaded wall appeared to push the mortar through the joint and a small section of brick fell off the outside face (Figure 24). The nails in this top row of ties pulled part way out of the studs and the top row of ties on the in-plane loaded frame were rotating significantly on the nailed connections to the studs as the studs bent about their weak axis. The veneer continued to remain intact.

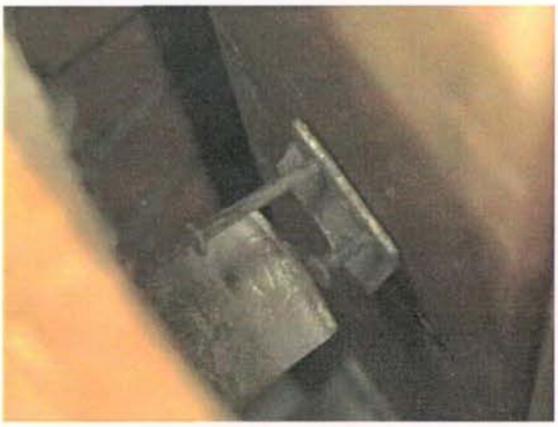

Figure 23: Nails pulled from frame and tie broken

Figure 24: Section of punched brick

Two sets of six cycles to ±30 mm at 2 Hz were applied to the wall followed by a set of six cycles with a target displacement of ±40 mm at 2 Hz. At the completion of these cycles, the second tie down on the corner stud of the face loaded wall had pushed the mortar slightly out of the joint (Figure 25) and a similar situation had appeared at the top tie at the free end of the face loaded wall. The plasterboard had detached from the studs over most of the height of the specimen and there was some damage at the intersection of the two walls. The damage was considered to be repairable with re-nailing and new tape and stopping.

Figure 25: Section of mortar punched out by tie

The plasterboard was re-nailed to the studs at positions 50 mm away from the original nail positions and the tape was replaced at the corner junction. The wall was re-stopped.

A triangular displacement signal was applied to the wall in an attempt to cause impulse forces on the specimen at the changes in displacement direction. Accelerometers were added to the specimen in the following positions:

1. Top plate adjacent to the loading angle
2. Top of veneer parallel to direction of loading
3. Top of veneer perpendicular to the direction of loading

A series of 10 triangular displacement cycles at 2 Hz, targeting ±30 mm top plate displacement, was input to the specimen and the outputs from the actuator displacement transducer and the three accelerometers were recorded using computer-based software. This scanned at a rate of 100 Hz while all other instruments continued to be recorded at an 8 Hz scanning rate on another datalogging system.

The top plate recorded acceleration was about 1.5 g (g = gravitational acceleration, 9.81 m/s^2), caused mainly by the quick change in direction at the end of the triangular displacement stroke. Veneer accelerations were similarly in the order of 1.5 g.

The nails securing the plasterboard worked hard during these cycles and loosened significantly in the plasterboard at the bottom plate and for some distance up the studs. The new plaster popped from the heads of the nails, making their presence obvious. There was no further visible damage to the brick veneer.

This was followed by a second series with the same input signal parameters. There was no significant increase in the amount of damage.

Then a series of triangular displacement signals targeting ±30 mm was applied at a frequency of 4 Hz. After 8 cycles, the actuator shut down because it was unable to follow the command signal. The top plate acceleration was in the order of 2 to 3 g and the parallel veneer 1.5 g. The face loaded veneer had an acceleration of about 2 to 2.5 g.

Again, there was no significant change to the condition of the plasterboard wall and the veneer did not degrade any further. The top tie securing the face loaded veneer to the framing at the corner had broken in half and a number of the ties at the top of the long veneer parallel to the loading direction had twisted sufficiently to shear off the securing nails.

The difficulty with this in the field would be identifying the amount of damage because it is hidden in the wall cavity. No amount of tapping on the outside surface of the veneer appeared to divulge where the ties had failed. A borascope could be used to pick up where the ties have failed after an earthquake but the process of checking scores of houses with such an instrument after an earthquake would be very slow.

5.3.1 Conclusions from veneer corner testing

Testing of the brick veneer corner by the application of essentially static loads to the top plate of the specimen has not proved to be a successful means of replicating a real earthquake. . While the testing has shown that damage to the associated interior linings can be expected and will need to be repaired in much the same manner as described in section 5.1, the type of damage observed on veneers after historic earthquakes was not able to be reproduced. It is thought that this is because the inertial mass of the veneer has not been mobilised as it would be in a real earthquake.

The veneer corner specimen has been retained for further investigation on the laboratory shaking table.

5.4 Pre-1978 Wall Construction

The focus of this assessment was the performance of interior walls of an existing 1960s house. The test walls were located in a two storey duplex housing unit with a concrete block wall separating the two dwellings. The house was constructed in 1964 for the Housing Corporation of New Zealand (now Housing New Zealand). The plan dimensions of each unit were 7.85 m by 6.55 m. The roof was corrugated galvanised steel over 75 mm x 50 mm purlins supported by 100 mm x 50 mm rafters at 900 mm centres. The roof was framed rather than trussed.

The exterior cladding was bevel back weatherboards over the upper storey and asbestos cement sheets over the bottom storey. Ceiling linings in both the upper and lower storeys were fibrous plaster, while the wall linings were gypsum plasterboard. Both the upper and lower storey floors had nominal 80 mm wide tongue and groove floor boards over 200 x 50 floor joists at 450 mm centres on the top floor and 125 mm x 50 mm joists at 450 mm centres on the lower floor. Wall framing was generally 100 mm x 50 mm at 450 mm centres on both storeys. The top and bottom plates of the lower storey were 100 mm x 75 mm. A photograph view of the back wall of the unit is given in Figure 26. Floor plans are presented in Figure 27. Though the drawing shows 6" x 1" braces cut into the first floor joists, these were not present in the house.

Figure 26: Back view of test house

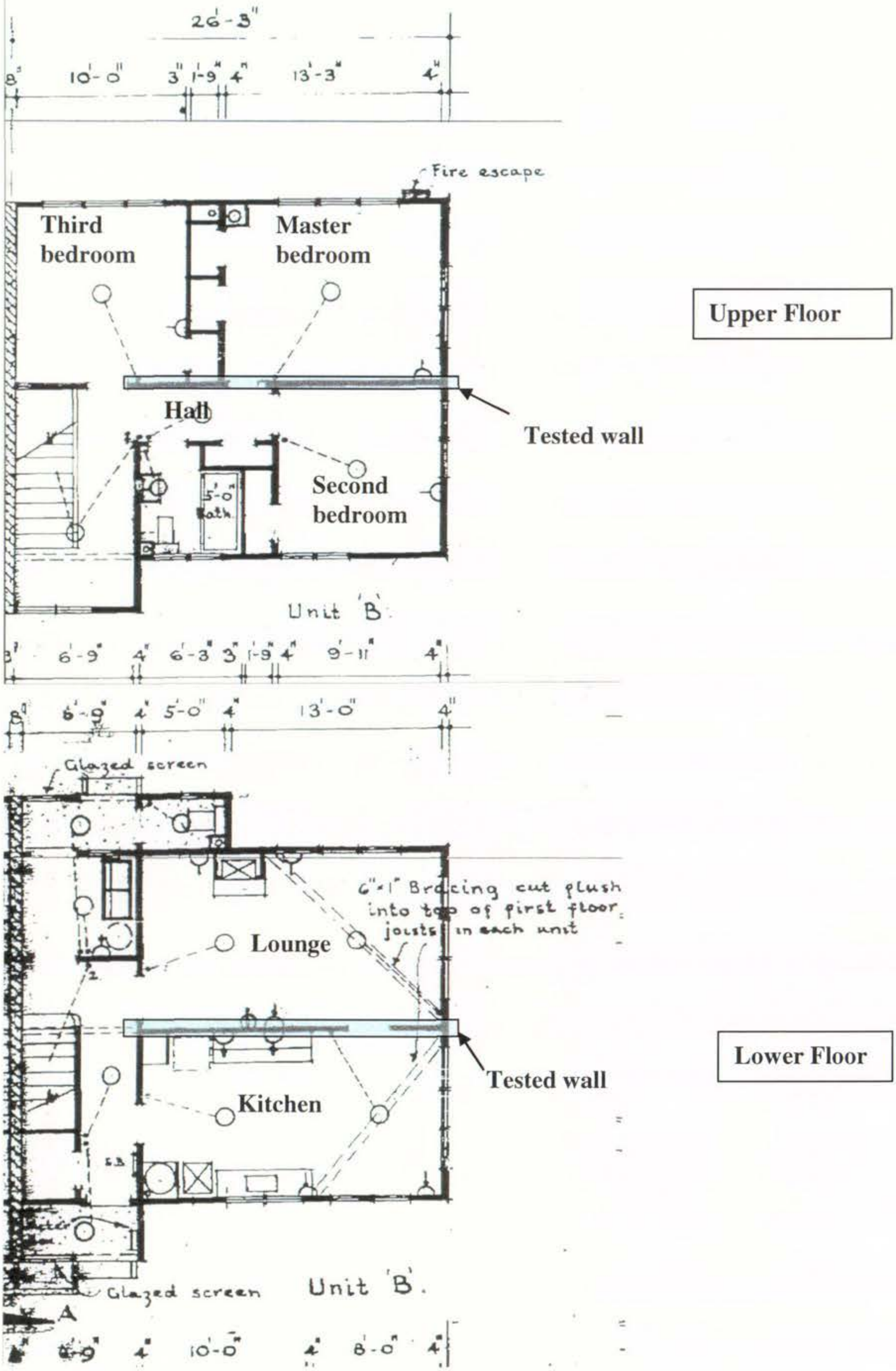

Figure 27: Floor plans of the tested unit

5.4.1 Upper storey testing

Testing began on the top floor of the unit. The aim of the test was to rack the central wall between the hallway and the bedrooms (Figure 27) to create damage expected to be caused by an earthquake, to repair the damage and retest the wall. An elevation of the test wall is presented in Figure 28.

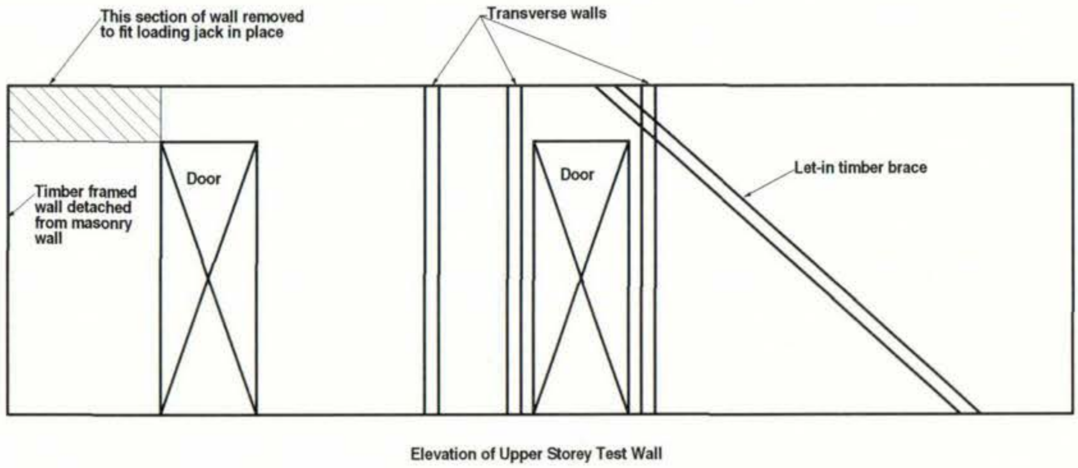

Figure 28: Upper storey test wall

Load was applied to the top plate of the wall. Diagonal steel struts were installed to transfer the reaction force to the first floor, using the concrete block masonry inter-tenancy wall as the vertical leg of the force triangle (Figure 29).

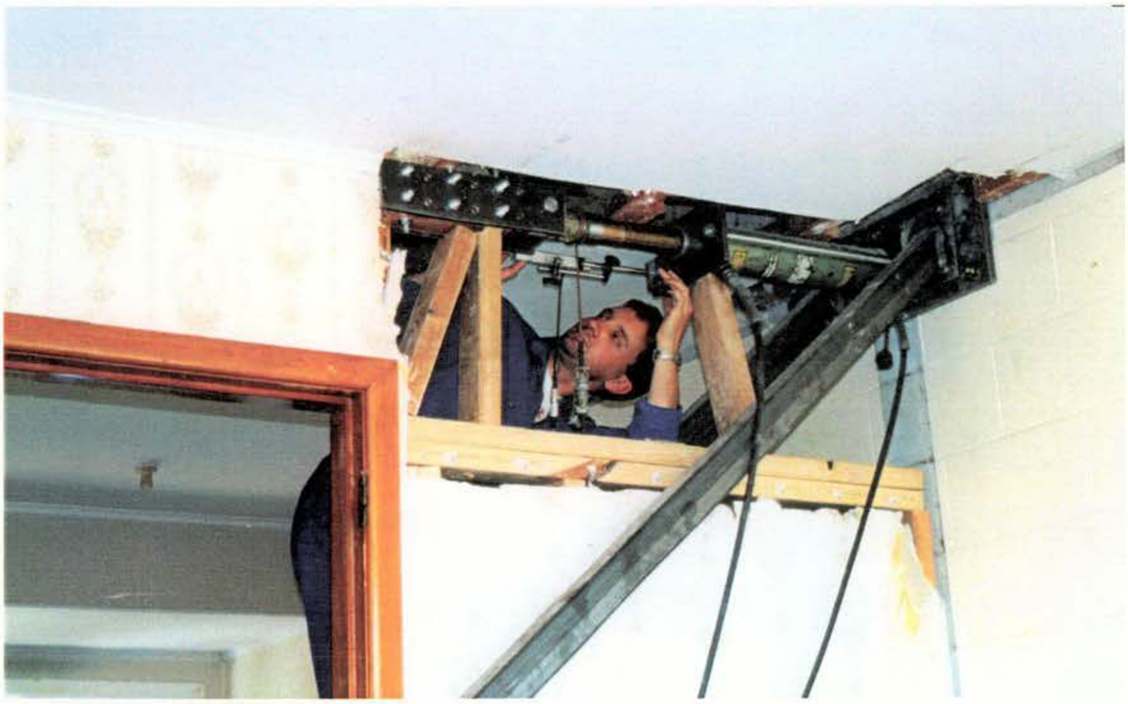

Figure 29: Reaction frame and loading ram at top floor ceiling level

Initially, the ceiling linings of the upper floor were left intact. The wall was cycled three times to increasing levels of load in the push direction and up to 75 kN (the pull capacity of the ram) in the pull direction. During the cycles to 125 kN of push the ceiling adjacent to the outer walls was observed to have moved away from the wall by up to 4 mm, indicating some rotation of the ceiling lining in the horizontal plane. There was further evidence of translational movement of the ceiling lining in line with the loading in that the painted joint between the ceiling and the scotia on the transverse walls between the two bedrooms and adjacent to the bathroom had opened up.

In the hallway, cracking was evident in the ceiling lining adjacent to the manhole to the roof space, where a stress concentration was occurring (Figure 30). The loaded wall was showing signs of minor distress. The wallpaper was concertinaing on vertical lines above the top corners of doorways (Figure 31) where joints in the lining were forcing together and the skirting boards were lifting (Figure 32) and slipping horizontally along the floor a small amount. When the loading direction was reversed, the concertinaed wallpaper straightened out and then tore under tension load as the lining joint opened. The skirting board also returned to its original position in contact with the floor boards. A hole was cut in the lining near to the bottom plate at the ends of the two wall panels so that the state of the nails securing the bottom plate to the floor could be established. It was discovered that the nails had remained firmly embedded in the bottom plate and were being extracted and then re-driven into the flooring as the cycling progressed.

Figure 30: Upper storey ceiling damage at the edge of the roof space access hole

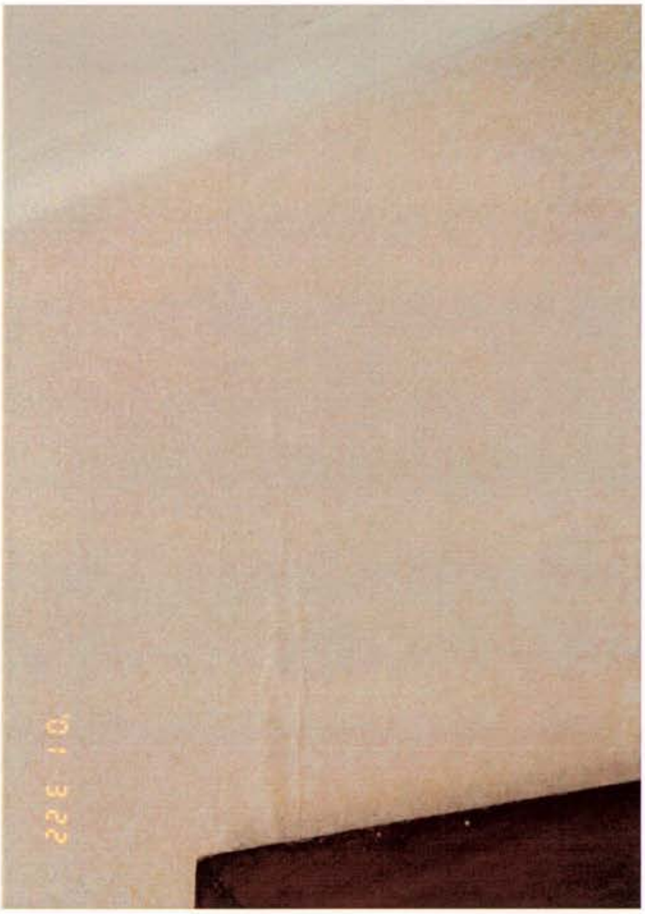

Figure 31: Wallpaper concertinaing under racking load

Figure 32: Upper floor skirting board lifting

The damage to the wall elements appeared to be mainly cosmetic. There was a 100 mm x 25 mm diagonal brace in the larger of the two elements and this appeared to have sufficient strength to resist the applied load. Because the damage was cosmetic, simple repairs were undertaken. The damaged joints between the gypsum plasterboard sheets were V-ed out, the edges of the sheets were re-nailed with 30 mm x 2.5 mm galvanised clouts at 150 mm centres (Figure 33) and then the joint was re-stopped with paper tape reinforcement included.

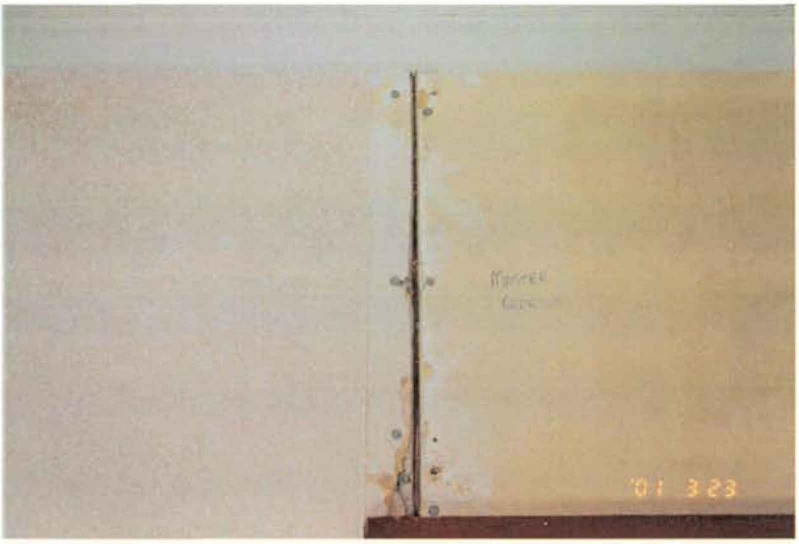

Figure 33: Prepared gypsum plasterboard joint ready for re-stopping

There was insufficient damage at the scotias and skirting boards to warrant any repairs. The re-stopping operation at the sheet joints would have necessitated a re-wallpapering in a papered room and re-painting a room with painted walls.

At the intersection of the ceiling with the concrete block inter-tenancy wall, the scotia had been removed to set up the hydraulic ram. Quite significant separation of the ceiling from the wall was visible at the peak loads and the nails securing the ceiling lining to the stringer were pulling through the edge of the sheet. A repair in this area required a re-nail of the sheet to the stringer and would have required a reinstatement of the scotia.

After carrying out the repairs the wall was again racked to increasing load levels to compare the strength and stiffness with the previous series. A plot showing a comparison of the backbone curve of the load-displacement hysteresis loops is presented in Figure 34. The top plate failed in tension during the last cycle at about mid length of the section of wall between the hallway and the third bedroom.

At this point the ceiling lining was cut through its full thickness along a line half way between the wall under test and the outer wall on the master bedroom side and on a line running along the hallway side of the bathroom in an attempt to discontinue the diaphragm action to the outer walls. The linings were also removed on the section of wall adjacent to the hallway and splices were added to reintroduce the load to the top plate. The testing then focused on the wall between the master bedroom and the second bedroom.

This section of wall was cycled to compare the strength and stiffness of the wall element with its strength and stiffness before the ceiling was cut. Top plate displacement was set as the controlling parameter for these cycles. Three cycles to ± 5 mm were completed before the top plate failed again, this time in compression at a knot. The backbone curve covering these cycles is also plotted in Figure 34. As expected, the strength was less because of the discontinuity introduced in the ceiling and because then only one wall element was resisting the load.

Testing was abandoned on the top storey at this point.

Figure 34: Comparison of the wall strength and stiffness before and after the re-nailing and re-stopping and after ceiling diaphragm interrupted

At no time during the testing did the joints between lining sheets in the region of the diagonal brace open or shear, despite there being no tape in place. The reason for this was that the wall element containing the brace behaved as a rigid element, rotating and lifting the bottom plate as load was applied. There was therefore insignificant stress on the joints between the sheets.

5.4.2 Lower storey testing

The loading rig was moved to the lower floor and installed so that the racking load was introduced to the underside of the upper floor joists approximately 350 mm out from the top plate of the wall under test (Figure 27). This was done so that the integrity of the connection between the floor joists and the top plate could be investigated during the testing. A general view of the test wall is given in Figure 35 and the method of application of the load is given in Figure 36. From statics, approximately 90% of the applied load was expected to be transferred to the internal wall.

To isolate the test wall from the parallel exterior walls, a cut was made in the ceiling lining in both the kitchen and the lounge approximately 1 metre out from the wall. On the upper floor, a saw cut was also made along one tongue and groove floor board directly above the cut in the ceiling. At the transverse wall between the lounge/kitchen and the hallway, the cuts in the ceiling were not continuous through the top plate.

Loading was applied under displacement control in the push direction but the previously mentioned pull limitations of the jack meant that when in the pull cycle the load was applied to the limit of the jack capacity (approx. 70 kN) if the target displacement was not able to be achieved.

Displacement measurements were made of the ceiling at the lounge side loading beam and the top plate adjacent to this point. Bottom plate slip and vertical movement of the wall at the hallway end and at the slider opening, with respect to the floor, were also recorded.

Figure 35: General view of the test wall between the lounge and the kitchen (note that the load application is through the doorway at the right end of the photograph)

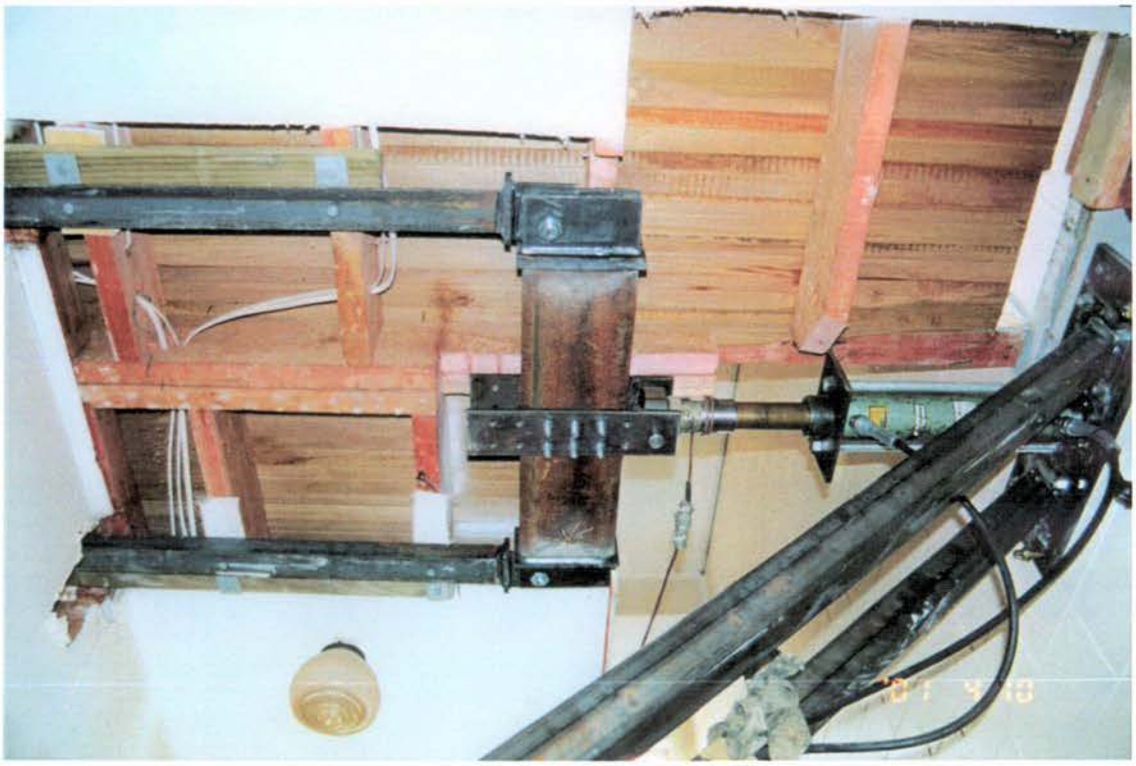

Figure 36: Details of the load application rig (load was applied via the spreader beam in the centre of the photograph to the two beams fixed to the underside of the joists)

The initial set of cycles was made to ± 1 mm, ± 2 mm and ± 4 mm of the top plate (3 cycles to each displacement level). Plots of the load-displacement hysteresis loops are provided in Figure 37. It can be seen from the plot that the displacement of the ceiling was about 25% more than that of the top plate. This was caused mainly by weak axis bending of the top plate but partially by slippage at the joint between the wall and the ceiling. The loads achieved were very high, reaching 72 kN at 4 mm of top plate displacement.

During these cycles a definite misalignment had occurred across the saw cut made in both the lounge and the kitchen ceilings and a stopped joint adjacent to the transverse hallway wall was beginning to open (Figure 38). Bottom plate uplifts and horizontal slippage were negligible.

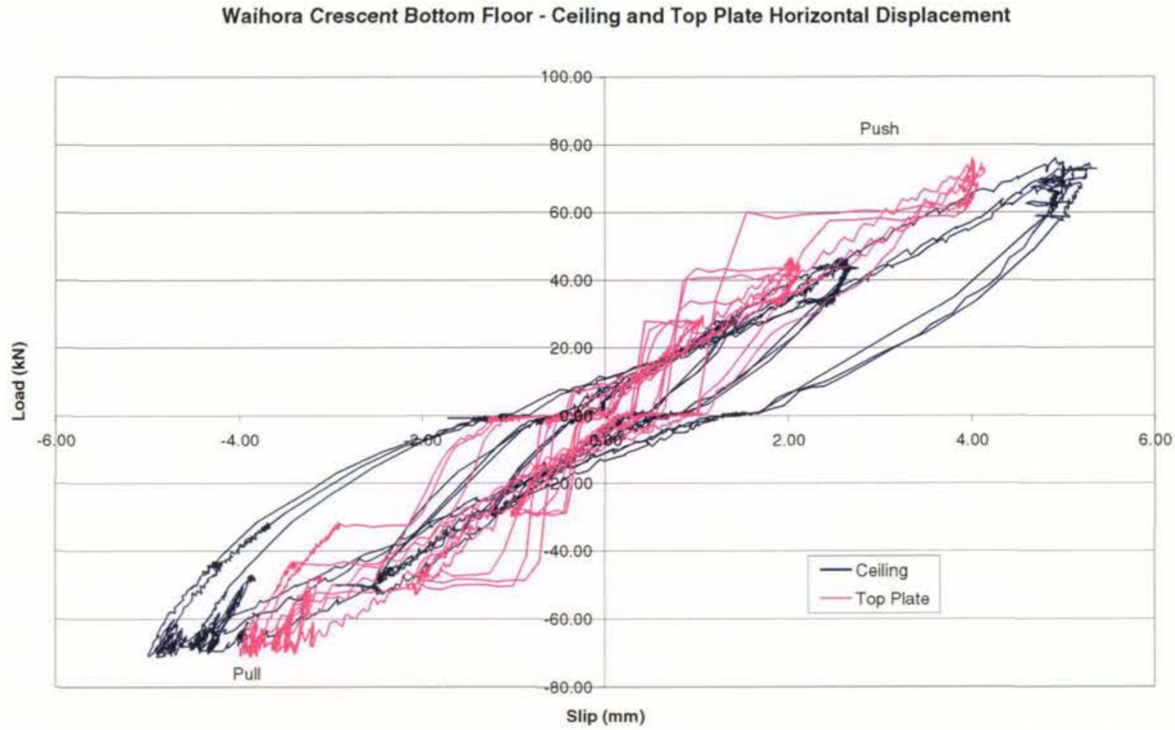

Figure 37: Load-displacement cycles up to ± 4 mm of the top plate

Figure 38: Ceiling misalignment and joint opening

It was decided to lift a series of four adjacent floor boards in the upper storey at the previously made saw cuts in an effort to reduce the diaphragm action that appeared to be occurring in the floor. Loading cycles were repeated to 4 mm for comparison with the previous set and then continued on to 6 mm and 8 mm. Backbone curves for the first cycle peak loads have been plotted in Figure 39. It can be seen from the curves that there was some small drop off in stiffness after the floor boards were removed. At the peak loads of these cycles there was no perceptible movement across the openings that had been created by removing the floor boards, nor was there any obvious slippage between the boards that remained. Uplifts of up to 0.5 mm occurred at the two ends of the test wall.

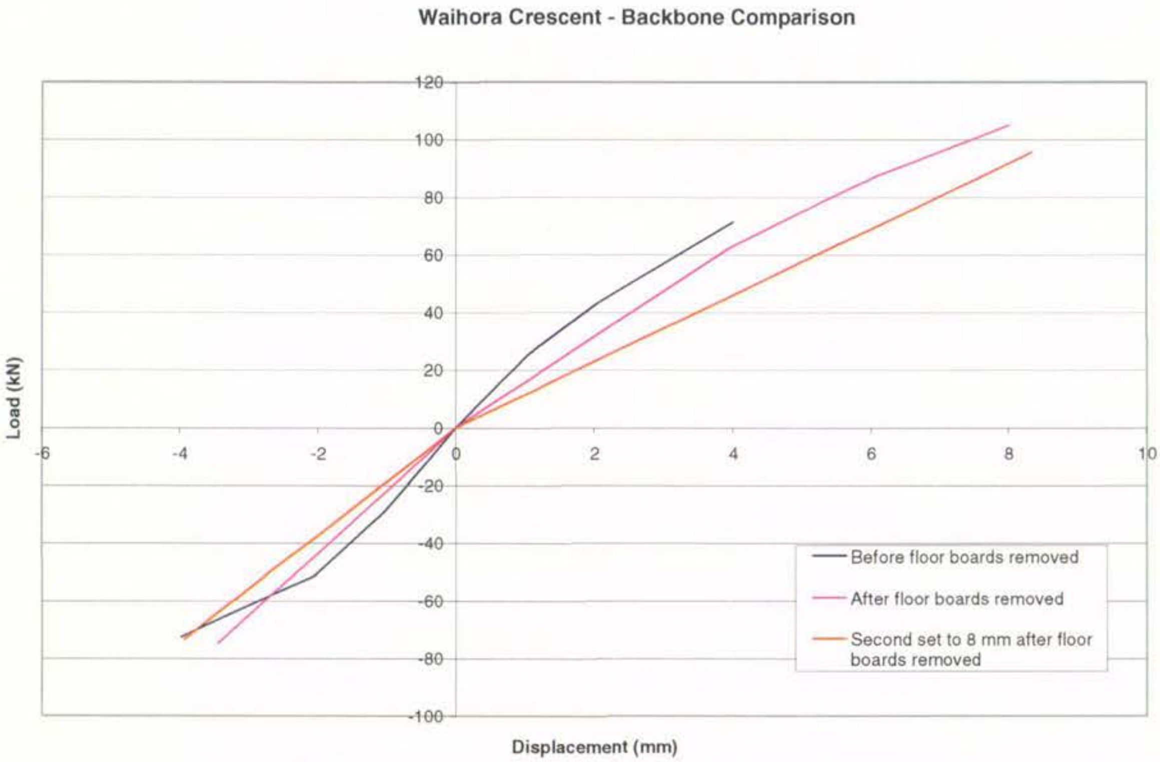

Figure 39: Comparison of the backbone curves of first cycle peak loads before and after the floor boards were removed

During this set of cycles the wall linings in the lounge began to move with respect to each other. Above the sliding door opening to the kitchen, a joint in line with the edge of the door frame compressed and pulled apart during the cycles sufficient to cause the wallpaper to tear. At the doorway into the hall the lining on the test wall was lifting vertically up to about 6 mm with respect to the door frame (Figure 40). The uplift measuring gauge at this end of the wall had been attached to the door frame in anticipation of the two moving together. However, the transverse wall and the bottom plate of the test wall did not lift, indicating that the linings on the test wall were lifting off the plate and the nails would have been ripping out of the edge of the sheets behind the skirting board. Fine cracks appeared in the body of the fibrous plaster ceiling and nail heads were popping the stopping compound.

The top plates of the transverse wall adjacent to the slots cut in the ceiling lining were then cut through so that there was no continuity for force transfer along the transverse wall (Figure 41). The wall was then cycled to 8 mm, then 12 mm before all the linings were removed from the wall between the hall and the laundry to prevent any load-resisting contribution from it.

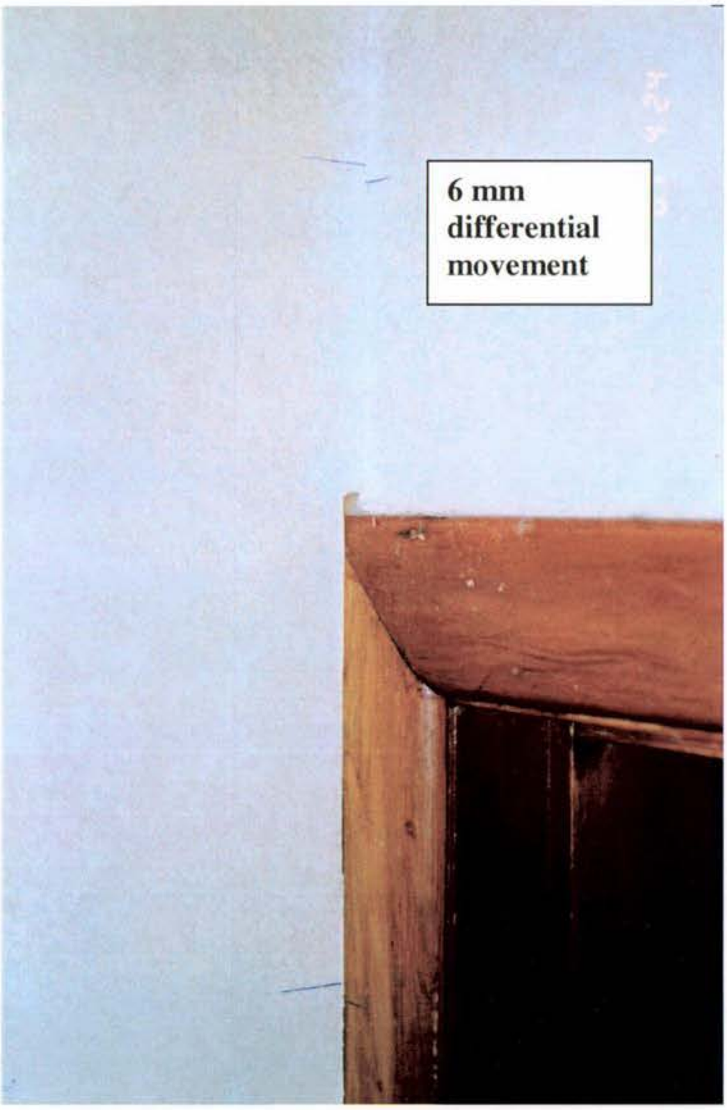

Figure 40: Differential movement between the test wall and the transverse hall wall

Figure 41: Photographs of the kitchen (left side) and the lounge (right side) showing the cut through the top plate

A comparison of the top plate displacement and the ceiling displacement showed that the top plate was still displacing to about 80% of the ceiling. At the hallway end of the test wall the uplifts were peaking at about 8 mm but at the sliding door opening they were still little more than 1 mm. The reason for this difference is discussed later in the report.

The linings were then removed from the upper storey test wall and the tongue and groove flooring was separated from the concrete block masonry wall over the full width of the house rather than the width to the removed floor boards. Plots of the backbone curves for the first cycle peak loads are presented in Figure 42. It can be seen from the plot that the removal of the laundry wall linings had a significant effect on the load resistance but the wall above was offering little resistance.

Figure 42: Comparison of backbone curves as potential load transferring elements successively removed

An increase in the displacement increments followed to 16 mm, 20 mm, 24 mm, 30 mm, 36 mm and 42 mm.

During these cycles the hallway end of the test wall was uplifting to greater than 20 mm (deflection gauge ran out of travel), but at the sliding door the uplift was still only 1.5 mm. Bottom plate slip peaked at 3.2 mm in one direction and 1 mm in the other. Inspection of the lining on the lounge side of the of the wall clearly showed that there was shear slippage occurring on the vertical joint between lining sheets just to the hallway side of the sliding door (Figure 43). All the movement at this joint accounted for the lack of uplift at the sliding door. Other vertical joints along the wall were not showing any signs of differential movement. The reason for this behaviour was that a let-in 150 mm by 25 mm diagonal brace on the kitchen side of the wall was maintaining that part of the wall in a rectangular shape and it was rotating under the applied loads (Figure 44).

Sheet damage was limited to around the perimeter of the individual sheets and could be repaired by removal of the skirting boards and scotias and re-nailing and re-stopping. Replacement of the sheets would not be necessary.

Figure 43: Shear slippage between lining sheets in lounge

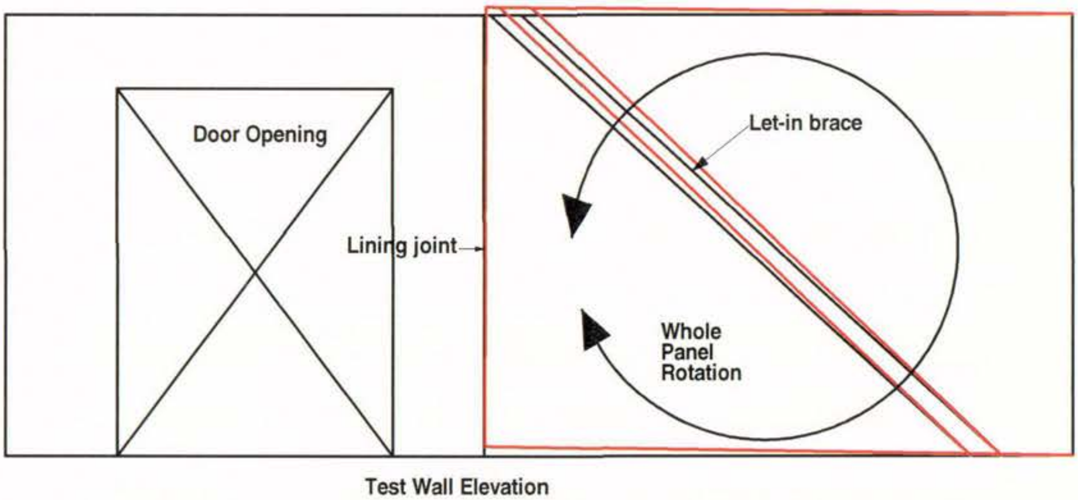

Figure 44: Diagrammatic representation of wall panel rotation during the test

Finally, the diagonal brace in the test wall was cut between each stud crossing so that it would no longer be able to function as a brace and the wall was loaded once again until 60 mm top plate displacement was reached. A comparison of the backbone curves before and after the brace was cut is shown in Figure 45. There was a clear reduction in stiffness up to 40 mm but the load continued to climb until the test was terminated. The maximum uplift reached at the hallway end of the test wall was 24 mm. The bottom plate slip remained at about 3 mm in one direction and 1 mm in the other.

With there being essentially no bracing resistance left in the test wall but with the applied load as high as it was, it is very likely that the tongue and groove floor was transferring the force to the external walls of the house. There were no obvious signs of any distortion of the exterior walls.

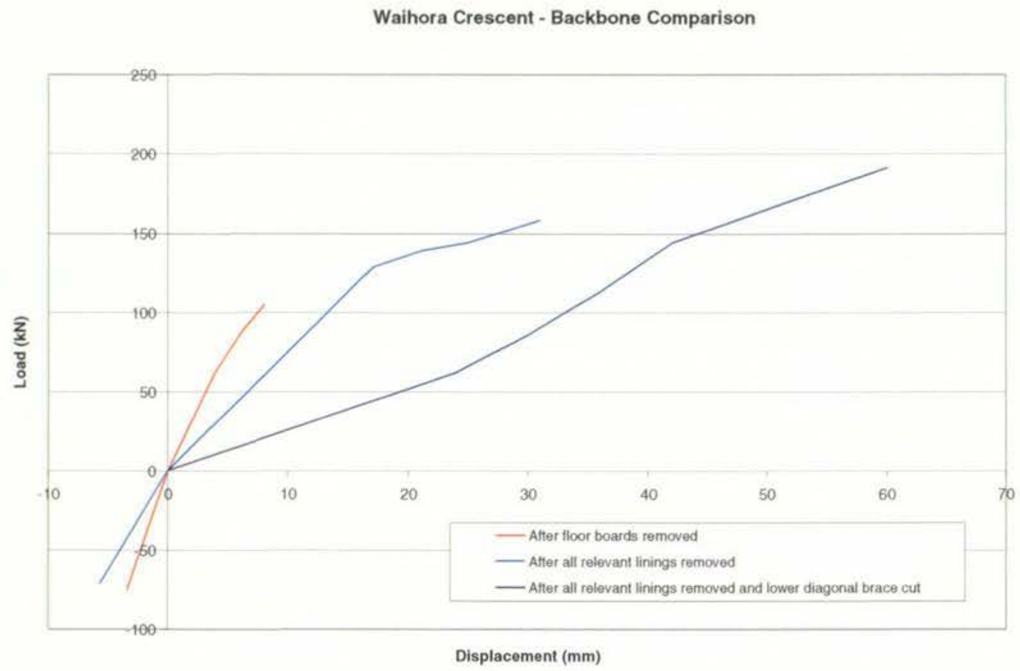

Figure 45: Comparison of the backbone curves before and after the diagonal brace was cut in the test wall

5.4.3 Conclusions from the testing of the pre-1978 wall construction

In conducting the racking tests on the 1960s duplex unit, it was determined that it is hard to isolate individual bracing elements in a real house because of the complex relationships present. For example, the load introduced at the top plate of the interior wall was resisted by the interior wall itself and also by the parallel exterior walls. While not normally allowed for in the design of force transferring systems, the in-plane strength of ceilings and plank floors that are not designed as diaphragm elements is significant.

The structure of the house was cellular, thus providing a great deal of resistance to lateral load by the numerous walls, even though these were not designated bracing walls. The walls that included let-in timber diagonal braces provided large lateral load resistance and the panel of wall containing the brace tended to behave as a rigid body, rotating about its base. It is expected that such cellular style houses would behave well in severe earthquakes.

6. SUMMARY OF REPAIR TECHNIQUES DERIVED

The aim of the experimental work was to derive repair techniques for a selection of wall and foundation bracing systems. Repair procedures have been derived and are presented in **Table 2**.

Table 2: Repair procedures for the investigated constructions

System	Damage Sustained	Repair Procedure	Other Considerations
Fibre cement cladding	Minor cracks in sheet joints (<0.3 mm)	Paint over crack to reseal against weather	
Fibre cement sheet cladding	Cracks in sheet joints >0.3 mm but <1.0 mm	Fill cracks with joint filler 1, reinstate architectural texture coating and repaint surface	
Fibre cement sheet cladding	Cracks in sheet joints >1.0 mm but < 3.0 mm. Nail heads showing through surface	Grind V at the joint and fill with joint filler 2 , over-coated with joint filler 1. Punch nail heads and patch. Reinstate texture coating and repaint.	In newer houses (built since 1980) some fibre cement panels are likely to be designated bracing panels. Nail spacing around the perimeter of these sheets will be at a maximum of 150 mm. Extra nails will need to be added between existing nails.
Fibre cement sheet cladding	Sheets partially detached from framing	Re-nail the sheets to the framing and reinstate texture coating and repaint.	If the sheets have been damaged other than at fixings it may be necessary to replace the sheets, reinstate the texture coating and repaint. Check also for plumbness of the wall.
Gypsum plasterboard interior lining	Minor (<0.3 mm) cracks in joints of painted surfaces	Skim coat with stopping compound and repaint	
Gypsum plasterboard interior lining	Cracks in joints >0.3 mm but <2.0 mm in painted surfaces	V out the joint to the full depth of the sheets and re-stop and paint	If the joint has been previously taped, scrape away the stopping compound to the tape, remove the tape, V the joint and re-stop with new tape

System	Damage Sustained	Repair Procedure	Other Considerations
Gypsum plasterboard interior lining	Cracks beneath wallpaper – wallpaper not torn	If the damage is not obvious do nothing, otherwise replace wallpaper	
Gypsum plasterboard interior lining	Cracks beneath wallpaper – wallpaper torn or wrinkled	Remove wallpaper, skim coat the joint area and re-wallpaper	Evidence of tapered slippage between the lining and the skirting board but no damage to vertical joints over a length of at least 2.4 m suggests that a diagonal brace is present in the wall and this is likely to be still performing satisfactorily
Gypsum plasterboard interior lining	Joint cracks >2 mm but <5.0 mm on painted and wallpapered surfaces, nail heads have popped and nail tearing is evident through sheet edges	V out the joints, re-fix the sheets with fixings between existing fixings and re-stop with new tape. Reinstate the paint or wallpaper.	Some sheets may be designated bracing panels, particularly in houses built since 1978, and the nails/screws are likely to have large heads or washers beneath the heads and be spaced at a maximum of 150 mm centres. In these cases re-fix the sheets with similar fixings, check and refix the in-field area of the sheets if necessary
Braced piles	No obvious damage	Check that bolts are tight and re-tighten if loose	
Braced piles	Piles have some inclination from vertical	Remove a brace to confirm that damage to the bolted joint has occurred. Jack the house sideways until the piles are vertical and temporarily brace. Remove pile braces, drill the bolt	

System	Damage Sustained	Repair Procedure	Other Considerations
		holes to 16 mm and replace the M12 bolts with M16 bolts	
Brick Veneer Corners	No obvious damage	Check for any "drumminess" of the veneer by striking with a rubber mallet over the outer surface. Any "drumminess" may mean a lack of tie connection to the framing.	Further survey using a borascope is recommended, particularly around the upper ties if the wall feels "drummy". Proprietary helical ties will need to be installed from the outside of the veneer if a lack of connection is detected.
Brick Veneer Corners	Obvious cracking and/or lost bricks or evidence of tie punching through the veneer	Carefully remove all loose bricks and inspect the integrity of remaining ties. Rebuild that section of veneer with recovered or matching bricks, installing new ties to the requirements of NZS 4210	If the surrounding veneer still has cracks that are only visible on close inspection (ie <0.2 mm) and the veneer is not "drummy", no further repair is likely to be necessary.

7. SUMMARY

Various sources of information on behaviour of houses in earthquakes were reviewed. These included Earthquake Commission claim records, Edgecumbe earthquake reconnaissance reports, house damage records from the Northridge earthquake, earthquake damage assessors, builders and Territorial Authority personnel interviews, museums and libraries. From this review four systems were selected as being areas where there was a need to formulate repair techniques for increasing levels of earthquake damage. These included a modern exterior wall clad with fibre cement sheet bracing and lined with plasterboard, a row of braced piles constructed to NZS 3604, a corner section of brick veneer cladding and an interior wall of a 1960s (pre-NZS 3604) house.

In the laboratory tests, while every effort has been made to model the expected construction details, and the observed behaviour is expected to be representative of an actual element in practice, BRANZ cannot be held liable for subsequent earthquake damage to elements repaired by the suggested procedures. The performance will be influenced by the strength of the subsequent event, the correct identification of the damage sustained and by the quality of the repair carried out, over all of which BRANZ has no control. Repairs must be undertaken by recognised tradespeople.

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APPENDIX A

Proprietary Products Used in Tests

Proprietary products used for the experimental work reported here were as follows:

Builder's Fill: CRC Builders' Fill

Fibre cement sheet: James Hardie Building Products 7.5 mm thick Harditex™

Plasterboard: Winstone Wallboards Ltd 9.5 mm Standard Gib® Plasterboard

Plaster cornice: Winstone Wallboards Ltd Gib® Cove

Joint Filler 1: Fosroc Ltd Taping Paste

Joint Filler 2: Fosroc Ltd Flexipaste

Joint filler 3: Fosroc Polyclad Plaster

Water-based primer: Fosroc Primer #2W

Note: The use of these products in the particular circumstances described in this study report cannot be inferred as a guide to their likely performance in general.

research

by Graeme Beattie, a BRANZ Senior Research Engineer, who is running the project

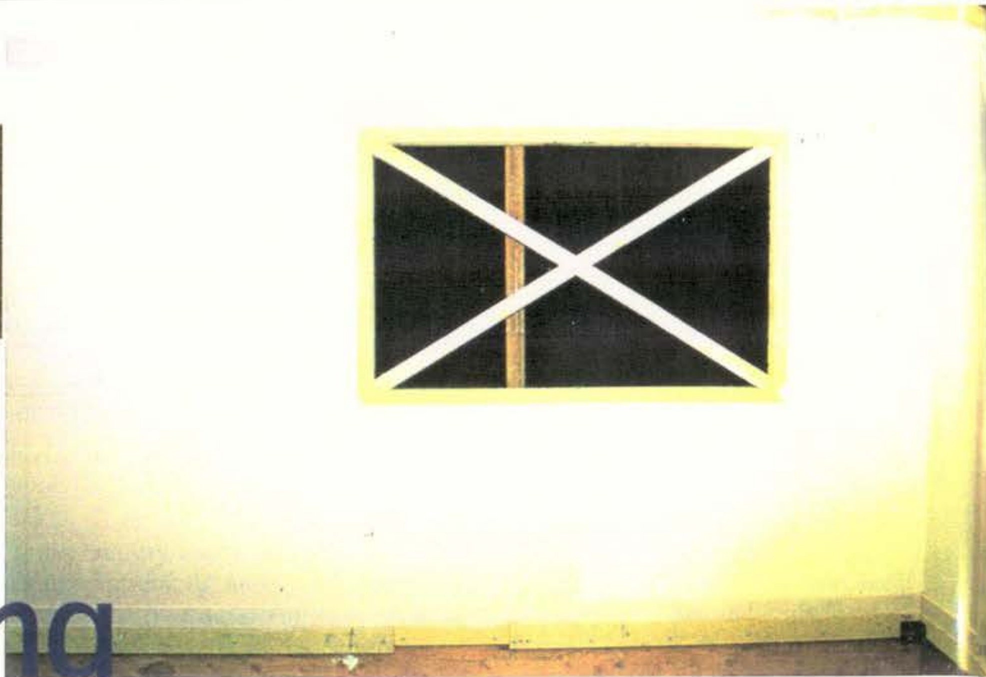

Photo 1: The plasterboard-lined interior of the sheet-clad wall specimen. The painted finish is on the left and the wallpaper on the right.

Repairing earthquake damage to houses

To develop effective repair strategies for houses damaged by earthquakes, BRANZ has been subjecting parts of buildings to simulated earthquakes, repairing them, then racking them again to assess the repairs.

The outcomes of this project, which is funded by the Earthquake Commission (EQC) and the Building Research Levy, are being used to develop a 'damage assessment catalogue' for the EQC. The catalogue will be referred to by damage assessors when conducting inspections after earthquakes. It will provide guidance on how damage appears on the surface, how serious it is likely to be and what needs to be done to repair it successfully.

The building elements which have been investigated so far include:

1. an exterior timber-framed wall with sheet cladding
2. a row of braced piles
3. a brick veneer wall.

The simulated earthquake racking was applied by a computer-controlled ram. The specimens were set up and tested in the BRANZ Structural Engineering laboratory.

Sheet-clad wall

The sheet-clad specimen was lined with gypsum plasterboard, sheathed with fibre-cement sheets and incorporated a window hole. At each end there were short return walls to allow the damage to be assessed at the wall junctions. The plasterboard lining was decorated with paint at one end and wallpaper at the other end, each overlapping the window opening, so that the damage to both finishes could be ascertained – see *Photo 1*. The top plate of the wall was racked backwards and forwards along its length.

The wallpaper served to hide cracking damage in the plasterboard joints for a longer period than the painted finish. *Photo 2* shows the tell-tale sign of racking damage to the plasterboard behind the wallpaper. Plasterboard nails behind the skirting boards also tended to pull through the sheet edge, but this was not obvious until the skirting board had been removed.

A minimum repair involved wallpaper removal and re-stopping of the damaged joints. Re-nailing was also required after significant racking (greater than 30 mm of displacement). It became clear that complete sheet replacement would only be needed if the racking was particularly bad.

The fibre-cement sheet joints were filled with proprietary fillers but there were no texture coatings or paint top coats applied. Cracking of the joints occurred at an early stage of racking. Because this is the weather-resistant sheathing, the cracked joint must be re-sealed to prevent ingress of rainwater. A flexible filler was used to re-seal the joint, applied into a 'V'-shaped cut – see *Photo 3*. For a complete repair on a house it would be necessary to reapply the coating (which might be texture coating or high-build paint).

Braced piles

A row of three braced piles was set up with a sheet-clad wall on top – see *Photo 4*. The setup was subjected to racking loads of increasing intensity.

Slippage occurred at the M12-bolted pile-to-brace interface during the racking, but the only sign of damage was a vertical misalignment of the piles. However, when the joint was disassembled, there was significant 'slotting' (elongation) of the bolt holes in both the piles and the braces at their mating surfaces. Filling the slots with builders' fill and re-drilling the bolt holes was found to be an unsatisfactory fix for the joint. The most successful repair involved turning the braces over and installing M16 bolts through larger re-drilled holes.

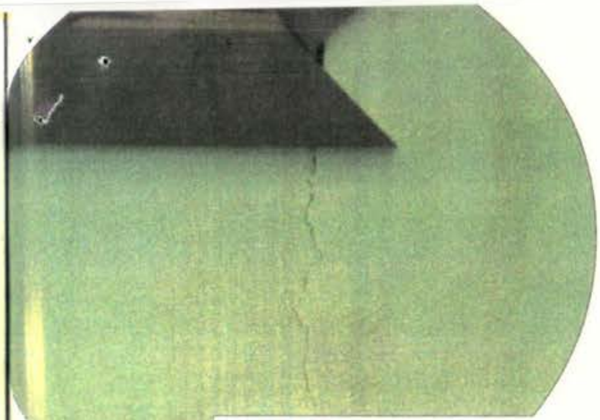

Photo 2: This small tear in the wallpaper is the only evidence of the cracking of the joint beneath. The damage was much more visible on the painted portion of the lining.

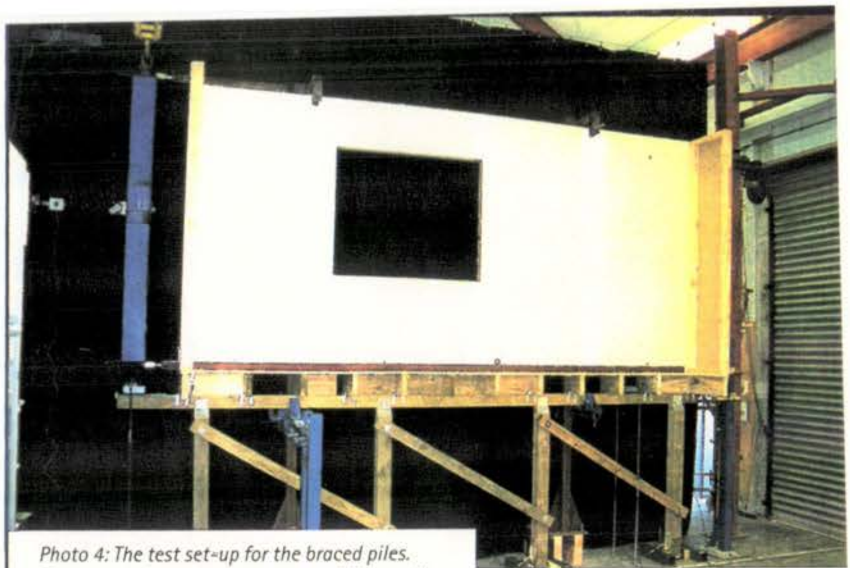

Photo 4: The test set-up for the braced piles. The most serious damage was not visible until the pile joints were dismantled.

Photo 3: Cracking in the exterior fibre-cement joint was successfully repaired with flexible filler. It would then need to be re-coated.

Brick veneer corner

The brick veneer wall specimen, representing a typical clay masonry veneer panel, was 2.4 m long with a 1.2 m long return wall to assess the effect of earthquake racking on a corner – see *Photo 5*. The bricks were attached to light timber framing with nail-fixed flat galvanised ties resting on the bricks' top surface. The interior face of the wall was lined with painted gypsum plasterboard, complete with cornice, skirting and ceiling. The racking was applied to the specimen along the top plate of the long wall. The nails fixing the plasterboard sheets to the studs left no evidence on the outer surface but pulled through the back of the sheets, making them loose to touch. However, the nail pull-through damage that occurred at the bottom of the sheets was masked by the skirting board. Repairs involved removing the skirting board, re-nailing the sheets and re-stopping cracked joints.

There was no sign of damage to the veneer visible from the veneer face. However, testing an element allowed the ties to be viewed from above and from the ends of the walls. Inspection revealed that most of the top row of ties had either extracted the nails from the framing or had sheared off. This damage would only be discovered in whole buildings if a borascope (like a small periscope) was used to explore the cavity. A repair for this damage would involve the installation of proprietary spiral ties inserted from the outside face of the veneer.

Real house test

In the next stage of the research, selected interior walls within an existing house are being racked to test the repair strategies on older, and complete, construction. The house is a 1950s two-storey duplex unit (which is earmarked for demolition due to fire damage in the other unit) – see *Photo 6*. The aim is to rack the interior walls of this house and investigate appropriate repair strategies for the damage. Then the repaired structure will be racked again to determine the effectiveness of the repairs. The results will be reported in the next edition of *BUILD*. ><

Photo 5: The brick veneer wall specimen set up for racking. The ram applying the racking force is on the left side.

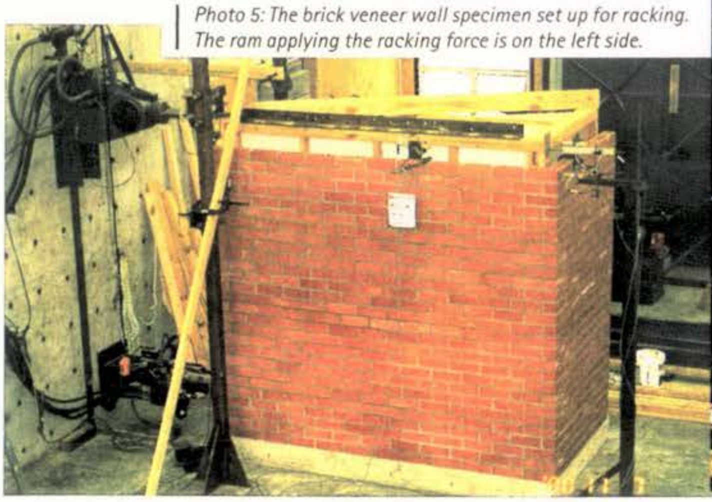

Photo 6: To test the repair strategies on an older, complete house, the left unit of this duplex is being racked, repaired and then racked again.

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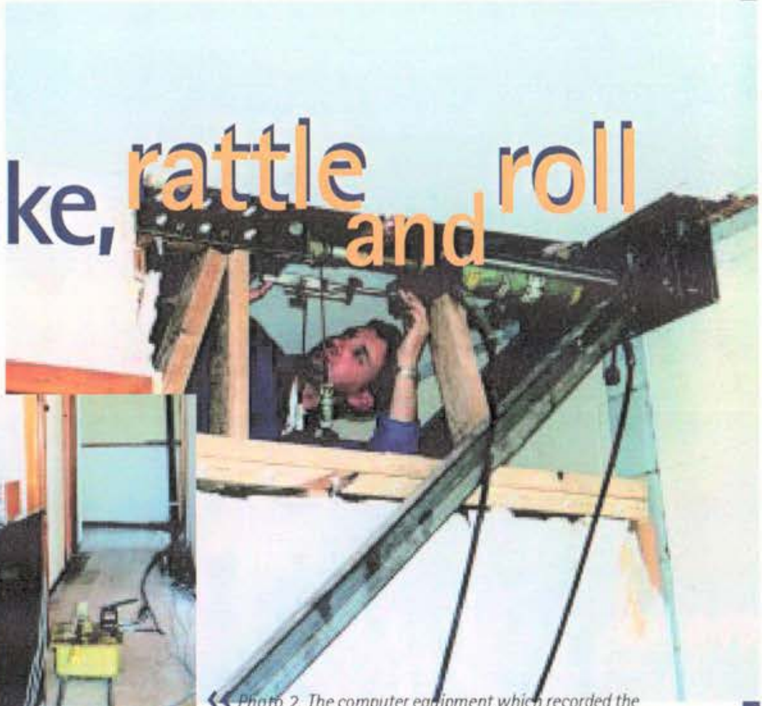
research

by Graeme Beattie, the BRANZ Engineer in charge of the earthquake house project

'Quake, rattle and roll



›› *Photo 1. BRANZ Engineer Stuart Park making adjustments to the loading equipment on the upper floor of the test house.*

– Real house tests show 1960s timber houses are very strong

‹‹ *Photo 2. The computer equipment which recorded the loading force of each test.*

If you live in an older timber-framed house on a good foundation, you can rest easy at night knowing that if there is an earthquake, your house is likely to suffer only minor, non-structural damage.

In the March/April 2001 *BUILD*, the article on Pages 46–47 described a project of simulated earthquake testing being undertaken by BRANZ for input into an upcoming Earthquake Commission manual showing likely earthquake damage to New Zealand houses and the best repair strategies. The article described how, as part of the project, a real house was going to be subjected to racking to simulate the effects of an earthquake. The damage was to be assessed and repaired, and then the house racked again to test the effectiveness of the repairs. This real house testing is now completed, and the procedure and results are described below.

House structure

The house was a timber-framed, two-storey duplex unit built in 1964 with a concrete block wall separating the two dwellings. On both the top and bottom storeys there was an internal wall that ran parallel with the ridge through the length of the unit. It was this central wall that was investigated in the tests. Between two bedrooms on the top floor wall there was a 100 x 25 mm cut-in diagonal timber brace. Downstairs, there was a 150 x 25 mm cut-in diagonal brace.

Walls are generally assumed to carry lateral loads from the proportion of the house that is supported on these walls. However, we know that there are many other load-resisting mechanisms and interactions in houses that are never taken into account in the design because it is too difficult to determine their exact contribution. This is particularly the case in older style houses like this one which have several intersecting walls and relatively small rooms.

Top floor

The investigation began on the top storey. We removed a section of the central wall to install a hydraulic ram and loadcell at the top plate level. Diagonal steel struts carried the reaction forces from the ram to the floor beneath the bottom plate, and the concrete block masonry wall between the two units transferred any vertical forces to the foundation – see *Photos 1 and 2*.

The ceiling lining of fibrous plaster was initially left intact over the whole of the upper storey as it was thought that the nailing along its edges would not be strong enough to transfer the load from the interior wall to the outer walls. However, it soon became clear ››

Photo 3. Bottom plate on the upper floor jacked up by the racking tests.

Photo 4. Distorted bedroom door during the upper storey racking tests.

Photo 5. Cracked plasterboard joint above a door.

Photo 6. Rig set-up straddling the downstairs test wall, which has one of the loading angles attached to the bottom of each of the joints.

Photo 7. Cracked plasterboard joint during repair. Trimming back, re-nailing and then re-stopping was all that was required.

that the ceiling was behaving as a diaphragm through which an unknown proportion of the applied load was being transferred to the outer walls. So, to isolate the central wall, we cut through the ceiling lining between the interior and outer walls. Then we racked the wall again. Shear movement was visible between the two sides of the cuts and there was some reduction in stiffness.

Minor damage

The loaded wall was now showing signs of minor distress. The wallpaper was wrinkling on vertical lines above the top corners of doorways where joints in the lining were forced together. The skirting boards lifted and slipped a small distance horizontally along the floor – see *Photo 3*. The doors were no longer square with their frames – see *Photo 4*.

When the loading direction was reversed, the wrinkled wallpaper straightened out and then tore under tension load as the joint in the linings opened – see *Photo 5*. The doors largely returned to a square orientation. Despite the damage at the joints, the wall was still capable of resisting large forces and this was found to be due to the effectiveness of the cut-in diagonal brace.

Re-stopping the cracked joints and retesting the wall resulted in a racking resistance approximately the same as the original wall. The tests indicated that after a large earthquake, the required repairs to walls with let-in timber braces can be expected to be only minor cosmetic fixes to the linings and wall coverings.

The skirting boards should be checked to make sure that the bottom plate has not uplifted and remained that way after the earthquake. In this house, the weight of the roof structure appeared to be enough to force the wall back down after racking.

Lower floor

The loading rig was then moved to the lower floor and installed so that the racking load was introduced to the underside of the upper floor joists adjacent to the top plate of the wall under test – see *Photo 6*. This was done so that the integrity of the connection between the floor joists and the top plate would be included in the lateral load path.

To isolate the test wall from the outside parallel walls, the ceiling lining was again cut the same as on the top storey. For the same reason, four adjacent tongue and groove floorboards on either side on the upper floor were removed. So that there was no chance of load being transferred to the upper storey ceiling plane, we also removed all the linings on the wall above and cut its diagonal brace.

Large strength reserve

The lower storey wall was able to withstand more than 120 kN of applied load at a deflection of 16 mm. The damage caused was once again superficial and could be easily repaired by re-stopping the joints in the wall linings and redecorating – see *Photo 7*.

When an NZS 3604 *Timber Framed Buildings* bracing calculation was undertaken on the unit, the total demand on the lower floor walls was 35 kN (700 bracing units). If this is compared with the 120 kN test load achieved, it is clear that the house has a large strength reserve available. The transfer of load from the joists to the top plate was also achieved with ease. Very little difference in displacement was recorded between the loading beam and the top plate.

The simulated earthquake tests on this house have shown that it has a strength well in excess of the bracing demand given in NZS 3604, and that damage from earthquakes to this type of house can be expected to be relatively minor and non-structural. ><