STUDY REPORT

No. 154 (2006)

Racking Tests on Rooms and Isolated Walls to Investigate Uplift Restraint and Systems Effects

SJ Thurston

Preface

This is the first BRANZ report on seismic testing of half-scale and full-scale rooms in a laboratory. Seismic testing of a full-sized timber-framed New Zealand house was described in BRANZ *Study Report 119* which compared the actual house strength with the strength determined using the NZS 3604:1999 design provisions. The racking resistance of long walls with openings was investigated in BRANZ *Study Report 54*. Field measurements of the seismic performance of timber piles were reported in BRANZ *Study Report 58*. House wall bracing ratings are usually derived in New Zealand from the BRANZ P21 test (BRANZ *Technical Recommendation No 10*).

Note

This report is intended for standards committees, structural engineers, architects, designers and others researching earthquake and wind resistance of low-rise buildings.

RACKING TESTS ON ROOMS AND ISOLATED WALLS TO INVESTIGATE UPLIFT RESTRAINT AND SYSTEMS EFFECTS

Reference

Abstract

By testing both rooms and component walls under seismic racking forces, this project investigates the relationship between racking tests on isolated bracing walls and the racking performance of low-rise timber-framed houses constructed from similar walls. It attempts to assess the extent to which houses are stronger than the sum of the component walls. It also attempts to determine the appropriate level of uplift end restraint to use for tests on isolated walls to simulate boundary end restraints in actual construction. The testing used pseudo half-scale construction. The theory and verification of this method is given in the report.

Keywords

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INTRODUCTION

1.1   Strength enhancement of houses due to systems effects

This project investigated the relationship between racking tests on isolated bracing walls (Figure 1(a)) and the racking performance of low-rise timber-framed houses constructed from similar walls. It attempts to assess the extent to which houses are stronger than the sum of the component walls.

Thurston (1993) cyclically racked long walls with openings and wall returns and concluded that provided a wall contained only window (but not door) openings, then the total performance can be conservatively estimated by assuming that the wall comprises a series of panels between openings and the strength of these panels is obtained from racking tests with 100% 'rocking' end restraints applied.

Thurston (2003) cyclically racked a full-scale single storey house, where the cladding contributed negligible racking strength. The house interior was plasterboard lined and it had a plasterboard ceiling. All plasterboard joints were stopped and taped. It had no doorways in the direction of racking. The strength was 50% greater than that predicted from the sum of all component walls.

Cooney (1979) and Moss (1991) both provide detailed commentaries of the damage to New Zealand houses from extreme wind and earthquake events. Yancy et al (1998) provides a summary of earthquake and hurricane damage in the USA. Both Thurston (1993) and Yancy et al (1998) summarise wall racking tests and full-scale house testing. Fischer et al (2001) reports on shake table tests of a two-storey house. However, although full house testing results are reported, they generally lack a comparison of measured strength with that predicted from component bracing walls. Thurston (2003), as noted in the paragraph above, did provide this comparison. Also, Fischer et al found that the measured resistance was approximately 50% stronger than predicted, although the experimental results did include a viscous damping force which would tend to overestimate this percentage.

The additional racking strength of houses can arise from many sources and, taken as a group, these are referred to as 'systems effects'. These include:

1   The presence of small walls (such as those in wardrobes) which are often ignored in design.

2   The effect of built-in components such as chimneys, shower units, window glass, doors etc.

3   The frame action due to connections having significant moment strength such as between trusses and walls, doorway frames and lintel to stud connections.

4   The effect of openings in bracing walls. Usually only the portions on either side of the opening are considered. However, bracing walls with adequate fixing around a small window can have similar wall bracing performance to construction without the window.

5   The use of strong sheathing joints, particularly plasterboard joints. If racking tests are performed on isolated walls, the plasterboard sheets tend to rotate about their centroid as shown in Figure 1(c). However when built into a house, the plasterboard sheets are restrained from moving relative to the ceiling and adjacent wall boundaries, provided the boundary joints remain intact. The location of these joints is shown in Figure 2.

In unreported tests, BRANZ has found that plasterboard taped and stopped joints can have a shear strength of approximately 8 kN/m. Thus, they are likely to remain uncracked in corners and along the wall-to-ceiling junction. Thurston (2003) racked a full-scale house past its ultimate strength and found no cracking at these locations, although severe cracking did occur at some window junctions. Thurston (1994) made similar conclusions when testing long walls with openings and wall returns.

Collier (2005) racked walls restrained from rocking. One wall (FR3362C) had the lining plastered to restraints at the ceiling line and vertical edges, and the other (FR3362B) was isolated. FR3362C was more than twice as strong as FR3362B, showing the importance of this plasterboard jointing restraint.

6   Walls tested isolated are built into adjoining construction when used in buildings. This boundary restraint, and also the weight of the structure above, help resist the wall responding to lateral forces by 'rocking'. This is discussed in more depth below.

1.2   Wall 'rocking' action and contrived wall uplift restraints

Worldwide, a multitude of bracing tests have been performed on isolated bracing walls. These may include contrived end restraints to simulate actual continuity of construction as depicted in Figure 1(b). Without adequate fixing of a wall to the foundation the wall will 'rock' as shown in Figure 1(c). When 'rocking' motion is prevented most of the wall deformation occurs due to a shearing action shown in Figure 1(d), which largely arises from slip between the wall sheathing and the wall framing.

When a building is subjected to lateral wind or earthquake loading, the restraints which resist the 'rocking' motion may be divided into three groups:

1   Hardware fixing the wall to the foundation, such as steel straps, cyclone rods, bolts, nails or other mechanical devices.

2   The continuity of construction, which is the fixing of walls to adjacent walls/window frames and roof/ceiling as depicted in Figure 2.

3   Weight of building mobilised by uplift motion of wall. This weight may be many times the weight carried by a wall in the static condition.

Most wall racking test procedures used around the world do not simulate the effect of continuity of construction. On the other hand, some use additional restraints to completely resist 'rocking' action. The BRANZ P21 test (Cooney and Collins 1979) is an exception in that it provides partial end restraints. This is a '3-nail' end uplift restraint. It is proposed that this test procedure is replaced by the EM3 test procedure (Thurston 2004) which is similar but increases the end restraint to an '8-nail' end restraint (see Figure 3). However, the final conclusion of this report was that a '6-nail' end restraint was more appropriate.

Continuity of wall at these boundaries may be simulated in test by the contrived end uplift restaints.

(a) Wall in house isolated from adjoining structure and tested.

Racking force

Contrived end restraint

(b) Wall being racked

Rocked frame

(c) 'Rocking deflection'

Sheathing

Racked frame

Frame before racking

(d) 'Shear deflection'
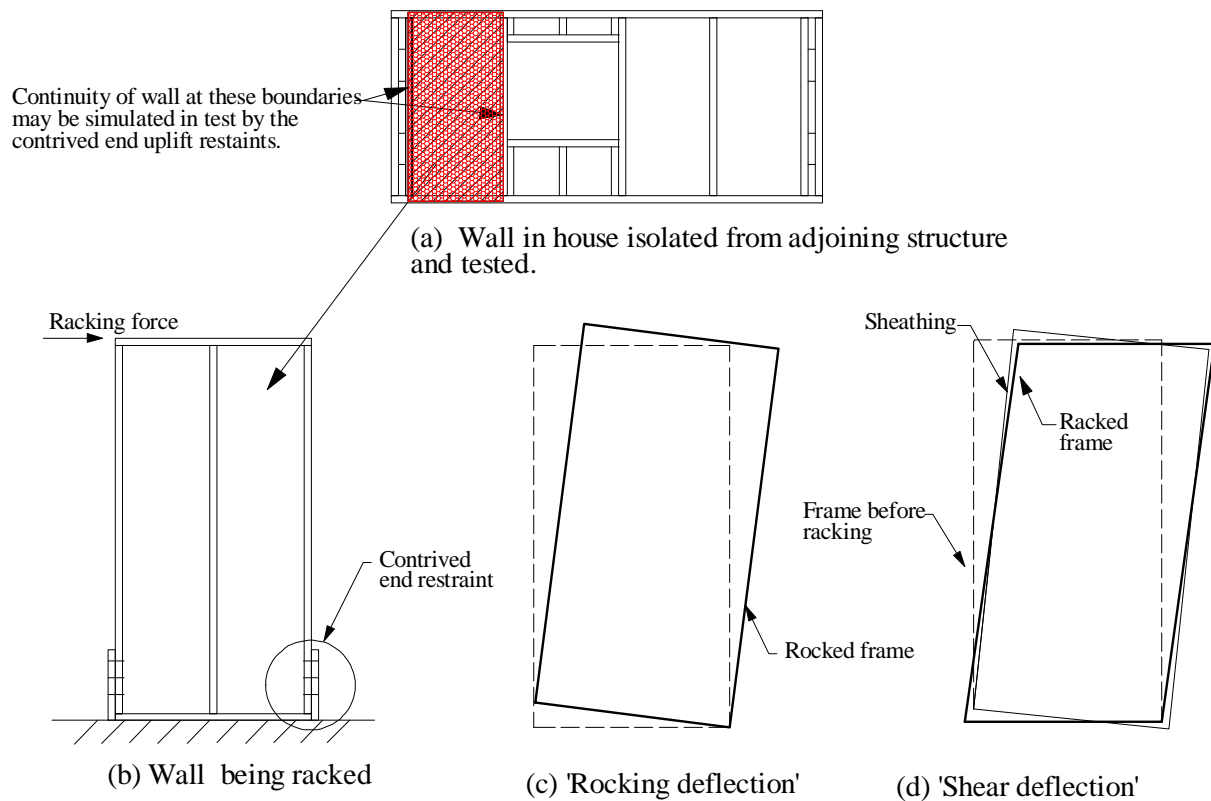
Figure 1. Schematic view of bracing tests and components of deflection

The taped and stopped joint fixes sheet to ceiling lining.

Some restraint to sheet movement above and below window due to sheet joint or sheet continuity.

The taped and stopped joint fixes adjacent sheets together - correctly duplicated in test.

The taped and stopped joint fixes sheet to lining on perpendicular end wall at this corner. This helps resist bracing wall end uplift movement.

Isolated panel used in EM3 bracing test.

Window

Fixing lining to bottom plate under window reduces slip of entire wall lining

Figure 2. Restraint of wall linings in real buildings
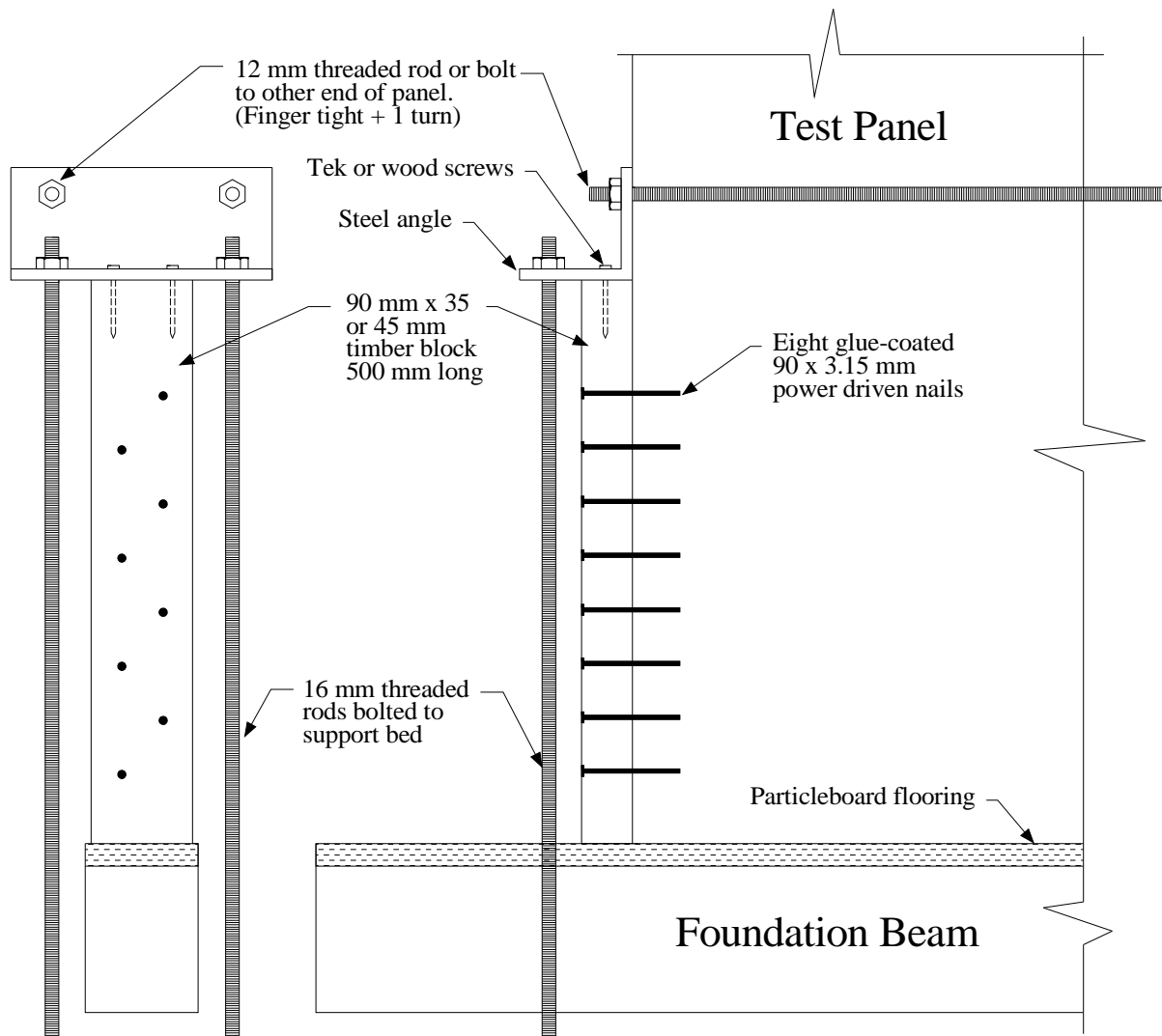
Figure 3. **EM3 '8-nail' contrived end uplift restraint**

1.3   Report scope

This report describes racking tests which were performed on a room using a variety of sheathings, wall openings and bottom plate fixings. Tests were performed on the room constructed both with and without plasterboard joint taping and stopping. The results were compared with an isolated wall tested using the EM3 end restraints. The purpose was to quantify the systems effects, the influence of joint taping/stopping and the suitability of the EM3 end restraint.

The testing was performed on half-scale construction. The validity of this method is discussed in detail.

1.4   Background to NZS 3604

The houses considered in this report are assumed to comply with the New Zealand timber-framed building standard, NZS 3604 (SNZ 1999), and all construction tested herein was

based on this standard. As the results are only directly applicable to this type of construction, the following two paragraphs are provided to describe the essence of this standard and its relationship with the P21 racking test method and earthquake design of houses in New Zealand.

NZS 3604 is effectively a cook book which tabulates all member sizes and connections as a function of member span, spacing and loading. It thereby allows people (such as builders or architects) to design houses without specific engineering input. The loading is obtained from the wind and earthquake zone where a building is located, the building geometry and applicable live load, snow load and weight of building materials used.

NZS 3604 stipulates that the bracing resistance of walls used in the houses must be determined using the BRANZ P21 test method. Manufacturers test their wall systems to the P21 test and publish their results. A designer simply checks that the sum of the strength of all walls at least equals the demand lateral earthquake and wind forces given in NZS 3604.

TEST PROGRAM

1.5   Overview and purpose of testing program

Racking tests were performed on isolated half and full-scale walls and also half-scale rooms. The half-scale rooms consisted of two side walls (parallel to the applied load), two end walls and a ceiling. The side walls consisted of two identical wall bracing elements, separated by a window or doorway, as shown in Figure 4. Each of the half-scale room wall bracing elements was constructed to the same specification as the half-scale test walls. Thus, the half-scale rooms basically consisted of four identical half-scale walls built into the room construction. The isolated wall tests consisted only of the wall plus contrived end restraints to simulate the actual wall continuity as discussed in Sections 1.6 and 1.11(a). A comparison is made in Section 1.17.3 of the strength of the room tests and 4 x wall tests of the same construction.

All half-scale frames were first racked with three cycles to ±36 mm before being lined and then racked to the normal sequence used for the room testing (see Section 0). This preliminary racking of the frames was done because the room test wall frames were also racked this way (for reasons discussed in Section 1.15). Thus, both the frames used for room testing and those used for isolated wall testing were pre-racked before being lined and retested.

The theory in Section 0 showed that the racking behaviour of a full-scale wall was equal to that from a specially constructed half-scale wall provided the racking load in the half-scale test was factored by 2.0. It also showed that the racking behaviour of a full-scale room was equal to that from a specially constructed half-scale room provided the racking load in the half-scale test was factored by 2.0.

This theory was verified by comparing the results from the tests on half-scale walls and full-scale walls (see Section 1.16.3).

Tests were performed on half-scale rooms and the theory used to predict the performance of full-scale rooms.

The purpose of this testing is to compare a room racking strength with the strength of the component walls in the racked direction. The ratio of these strengths is the systems effect factor as described in Section 1.1. These results also provided insight into whether the end restraint used in the isolated wall tests is appropriate.

1.6   Half-scale wall racking tests

Racking tests were performed on all walls used in the room tests that were parallel to the loaded direction. See Figure 5 for photographs of the half-scale wall tests and Figure 6 for a photograph of the room tests. Both the room and these isolated walls were constructed at half-scale. They had the same fixings to the foundations and these were placed at the same spacing. To achieve similitude between half-scale and full-scale tests, the '8-nail' end restraint proposed for EM3 tests on isolated walls was replaced with a '4-nail' end restraint. This is discussed further in Section 0. Timber guides were used to preclude lateral deflection.

Five walls were cyclically racked to failure as summarised in Table 1. The walls were 1.245 m wide and 1.22 m high as shown in Figure 14. Specimens were sheathed on either one side or two, and were either nailed or bolted to a timber foundation beam which was itself rigidly fixed to a concrete floor. The sheathings are identified as being PLB or MDF. Appendix A gives a full description of sheathing type for each of these terms.

Table 1. Half-scale walls tested

Wall	Sheathing		Foundation
No	Side 1	Side 2	Fixing
S1	PLB	None	Nailed
S2	PLB	PLB	Nailed
S3	PLB	MDF	Nailed
S4	PLB	MDF	Bolted
S5	PLB	PLB	Bolted

1.7   Full-scale wall racking tests

Three walls were cyclically racked to failure as summarised in Table 2. Specimens were sheathed on either one side or two and were nailed to a timber foundation beam which was itself rigidly fixed to a steel frame. The purpose of the tests was to provide a comparison with corresponding half-scale wall tests to investigate the accuracy of the scaling method i.e. Wall L1 was compared with 2 x WallS1 etc.

Table 2. Full-scale walls tested

Wall	Sheathing		Foundation	Half-scale
No	Side 1	Side 2	Fixing	comparison wall
L1	PLB	None	Nailed	S1
L2	PLB	PLB	Nailed	S2
L3	PLB	MDF	Nailed	S3

1.8 Half-scale room racking tests

Seven 'rooms' (summarised in Table 3) were cyclically racked to failure as shown in Figure 6. The room walls were built on timber foundation beams which themselves were bolted to a strong-floor. In five of the tests the walls were nailed to the foundation beam as shown in Table 3. In the other two tests the walls were bolted to the foundation beam to simulate construction on a concrete floor. All test specimens were a box-like construction consisting of four walls and a ceiling.

The tested room size was 3.3 m x 2.1 m in plan and 1.2 m high. Four of the rooms used exterior wall type construction (Rooms R1, R2, R3 and R4) as shown in Table 3 and Figure 4(a) and three of the rooms used interior wall type construction (Rooms R5, R6 and R7) as shown in Table 3 and Figure 4(b).

A typical room using the exterior wall set-up is shown in Figure 6. Note that there are no wing walls. It had door openings in the end walls and window openings in the side walls. The room interior was lined with PLB plasterboard and the exterior was clad with MDF for some tests and unclad in others (as defined in Table 3). The PLB plasterboard joints were fully taped and stopped (i.e. plastered) in all tests except Room R1 where joints were not plastered.

A typical room using the interior wall set-up is shown in Figure 7. It had door openings in both the end and side walls. It also included wing walls at each end. Both the interior and exterior of the rooms were lined with plasterboard. In one instance, Room R6, straps were added to hold the wall down to the foundation on both sides of these doorway openings. The PLB plasterboard joints were always fully taped and stopped

The applied load was distributed equally to four ceiling joists.

Table 3. Half-scale rooms tested

Wall No	Sheathing*		Foundation Fixing	Interior or exterior construction	Wing walls?	Straps on long-side doorway
	Side 1	Side 2				
R1**	PLB	None	Nailed	Exterior	No	N/A
R2	PLB	None	Nailed	Exterior	No	N/A
R3	PLB	MDF	Nailed	Exterior	No	N/A
R4	PLB	MDF	Bolted	Exterior	No	N/A
R5	PLB	PLB	Nailed	Interior	Yes	No
R6	PLB	PLB	Nailed	Interior	Yes	Yes
R7	PLB	PLB	Bolted	Interior	Yes	No

* See Appendix A for a description of the sheathing.
** Wall R1 PLB joints were not plastered.
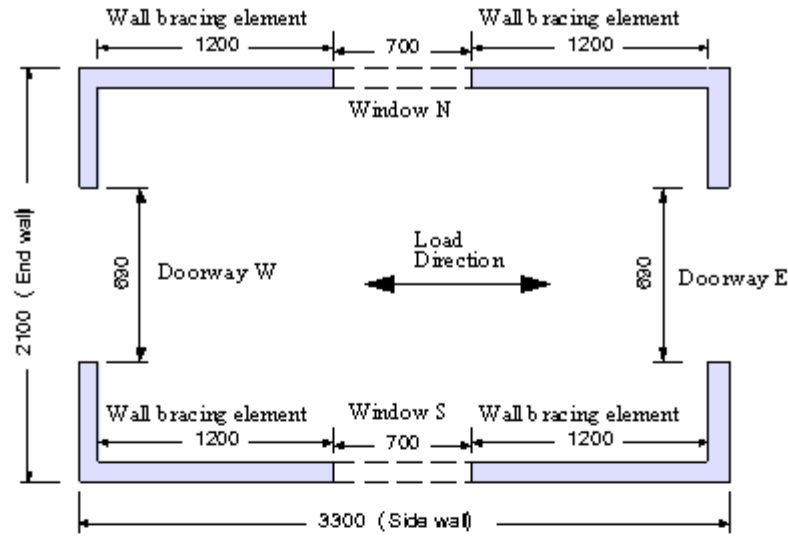
**(a) Plan view of exterior wall construction
(no wing walls).
Tests R1, R2, R3 and R4**
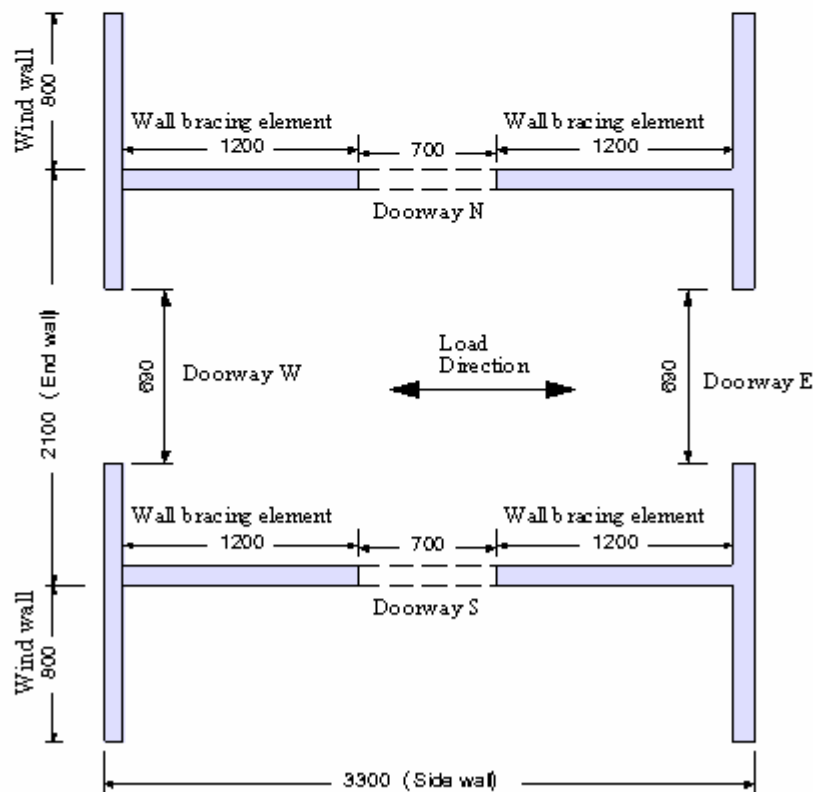
**(b) Plan of interior wall construction
(with wing walls).
Tests R5, R6 and R7**

Figure 4. Plan view of room tests

Figure 5. Photographs of half-scale wall tests
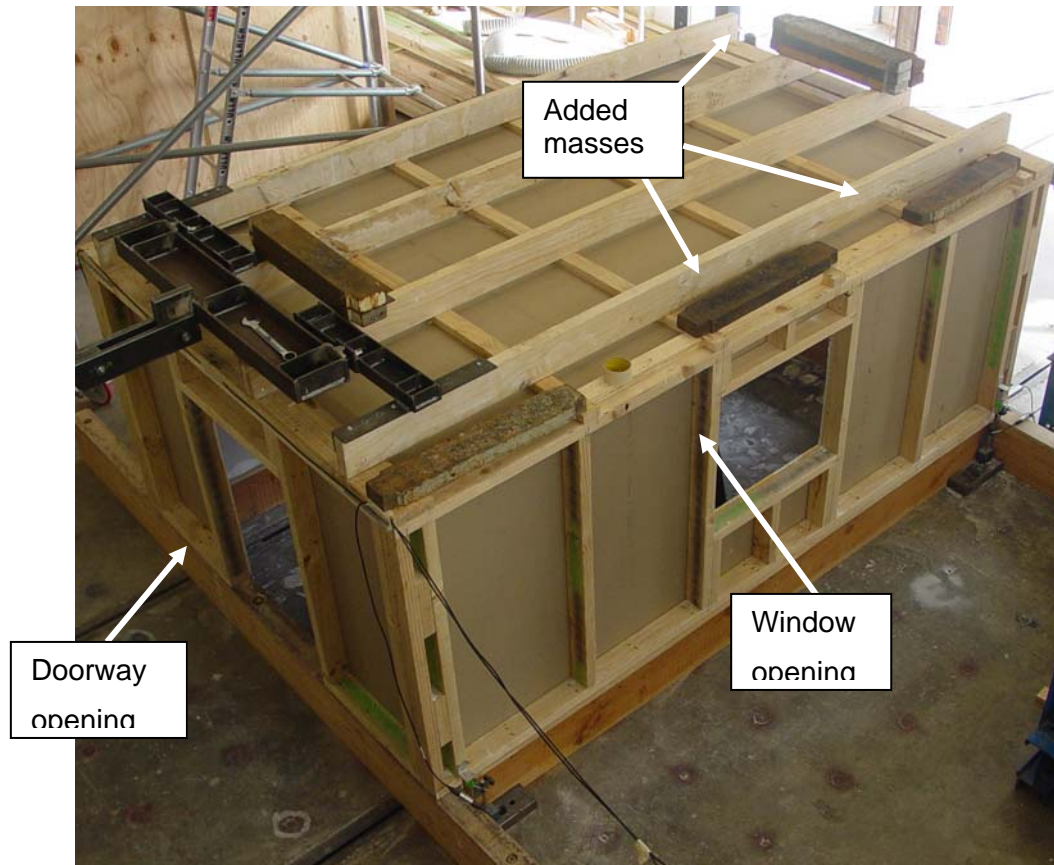
Figure 6. Photograph of tested half-scale room with exterior wall simulated construction

Figure 7. Photograph of tested half-scale room with interior wall simulated construction

HALF-SCALE MODELLING THEORY

1.9   Construction used in half-scale walls and room to achieve similitude

An argument is presented below to show that a specially constructed half-scale model of a wall or room will carry half the racking force and will be half as stiff as a full-scale construction.

Both full and half-scale walls used 90 x 45 mm timber framing (see Figure 8). Studs were at 600 mm centres and thus every second stud of the full-scale walls was omitted. Hence, half-scale modelling was not applied to the wall framing. However, this is not expected to significantly affect half-scale wall bracing strength and stiffness as bracing behaviour is usually a function of the sheathing-to-framing fixing and wall tie-down details. This is considered in detail below.

Both full and half-scale construction used the same sheathing materials and sheet thicknesses as well as fastener type, size and spacing. The half-scale walls were lined with plasterboard sheets which were 1200 mm high and 1200 mm wide to simulate the full-scale 2.4 x 2.4 walls in which the centre joint is plastered. The half-scale wall cladding sheets (where used) were 1200 mm high and 600 mm wide to simulate full-scale cladding sheets of size 2.4 m high by 1.2 m wide.

1.10   Shear strength similitude

If a full-scale wall shown in Figure 8(a) is racked with a force of 2P and the corresponding half-scale wall racked with a force of P, then both half and full-scale walls will have the same shear flow, $\upsilon = P/L$, around the perimeter of the sheets. See Figure 8(b) for definition of P and L and sketch of the forces. Because the same fastener type and spacing is used at the same shear flow, the force per fastener and the slip between sheathing and framing will be the same in both the half and full-scale walls.
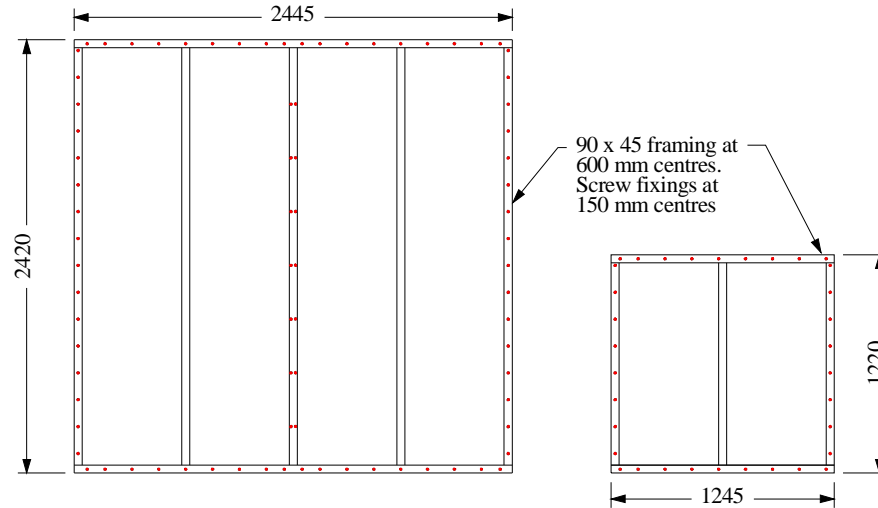
(a) Timber framing for half and full-scale construction
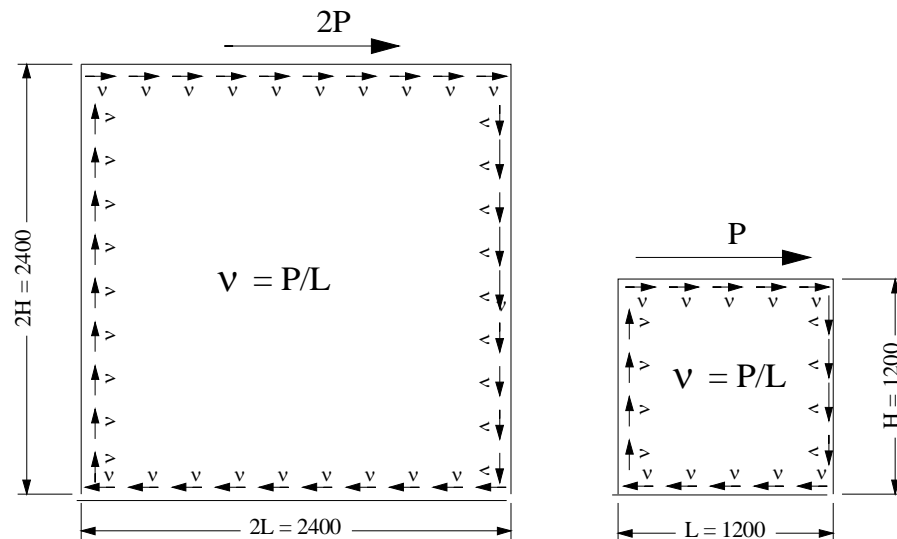
(b) Shear flow around sheet

Figure 8. Comparison of half and full-scale wall framing and shear flow

If sheet shear deformation is ignored and wall 'rocking' deformation is restrained, then wall deflections are purely a function of fastener slip and sheet aspect ratio rather than sheet dimensions (SNZ 1993, McCutcheon 1985). Thus at the same shear flow, the half and full-scale walls are expected to have the same shear deflection. Uplift (rocking) deflection is considered later.

Hence, if failure is governed by fastener connection strength, then failure is expected at the same shear flow in both half and full-scale walls. As sheet thickness is the same in both half and full-scale walls, it is expected that sheet rupture in both full sheets and at sheet corners will occur at a specific shear flow sheet. Thus, sheet rupture is expected to be correctly modelled.

1.11 'Rocking' strength similitude

With reference to Figure 8(b), it can be seen that when the full-scale wall is racked with a force of 2P then the overturning moment = 2P x 2H. When the half-scale wall is

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racked with a force of P then the overturning moment = P x H. Hence, for similitude, the half-scale wall must have 25% the overturning resistance as the full-scale wall. This similitude is considered below.
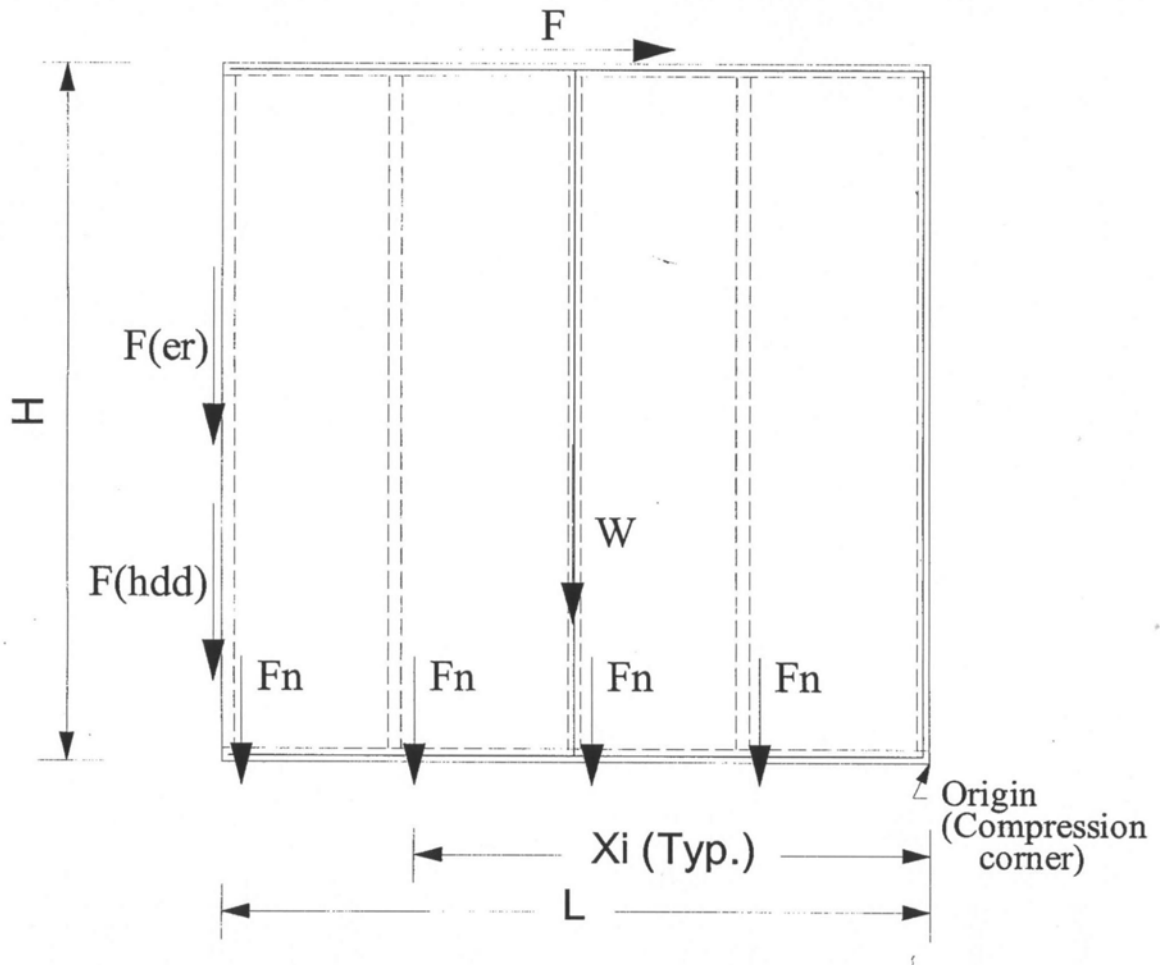
Figure 9. Forces to resist wall 'rocking' motion on a timber foundation

(Free body includes bottom plate)

Calculation of racking force to induce 'rocking'

'Rocking' action can occur due to 'bottom plate uplift' from nails pulling out of the timber foundation beam or else through 'stud-uplift' off the bottom plate. These are considered separately below.

(a) Bottom plate lifting – timber foundations

Figure 9 shows the forces on a wall, from a building, where the 'rocking' mechanism is 'bottom plate uplift'. The end restraint force, F(er), shown in Figure 9, is the force exerted from the adjacent structure to resist 'rocking' of the isolated panel. This is simulated in a P21 test with a '3-nail' end hold down system as shown in Figure 1(b). In addition, the panel may have an end hold down device to resist uplift and this is designated F(hdd) in Figure 9. An example is a steel strap from the end stud to the floor joists. The panel self-weight and axial load on the wall is designated as W.

The mechanism of 'bottom plate uplift' is illustrated in Figure 10. The wall effectively rocks about one corner as a unit and the nails between bottom plate and foundation are pulled out as illustrated in Figure 10(a). It is interesting to note that when the wall is racked in the opposite direction, the nails pulled out from the first loading cycle remain protruded as shown in Figure 10(b).

The racking force, F, as shown in Figure 9, tends to 'rock' the wall about the bottom compression corner marked as the origin in Figure 9. This is resisted by W, F(er), F(hdd) and the nail fixings force (Fn) between bottom plate and timber foundation beam. Each of these nails is taken as having a pull-out strength of Fn which acts at a variable distance from the compression corner – taken as distance Xi – where Xi is the distance from the origin to each nail location.

Taking moments about the origin in Figure 9 results in the following equation:

$$F \times H = (F(er) + F(hdd)) \times L + W \times L/2 + \Sigma(Fn \times Xi) \dots\dots (1)$$

For correct scaling, the half-scale building applied overturning moment F x H must equal 25% that for the full-scale building. This is achieved if:

- Half-scale wall F(er) (simulated end continuity restraint) is half the full-scale wall value:

    - with regard to the testing of isolated half-scale walls, the full-scale construction uses an '8-nail' EM3 end restraint. Therefore, the half-scale wall used a '4-nail' EM3 end restraint

    - with regard to the room test, where the end continuity restraint is the built-in restraint at the ends of the walls, as nail spacing along the junction stud was the same, and the wall height was halved, this criterion was automatically satisfied.

- Half-scale wall F(hdd) is half the full-scale wall value. Thus, if end straps are used, then only half the nail fixings in the strap may be used in the half-scale construction.

- Half-scale wall weight must be half of the full-scale wall weight. However, as it is actually 25% the weight, additional weights must be added in the half-scale tests.

- Looking at the last term in Eqn (1), the half-scale building uses single nails at 300 mm centres, whereas the full-scale building uses pairs of nails at 600 mm centres. This achieves similitude as both Fn and Xi are halved at each nail location.

(b) Stud lifting – concrete foundations

For construction on concrete foundations, the bottom plate is fixed to the foundation by bolts placed at 1200 mm centres in the full-scale walls and 600 mm centres in the half-scale walls. These commence 100 mm inside the wall end studs in the full-scale walls and 50 mm in the half-scale walls. The 'rocking' mechanism is due to a 'stud-uplift' from the bottom plate as shown in Figure 11. For this mechanism to occur there must be a similar movement between the

sheet and bottom plate fasteners (perpendicular to the sheet edge). The tendency for 'breakout' to occur due to 'stud-uplift' is illustrated in Figure 12.

Rather than the total wall (including bottom plate) lifting from the foundations as a unit, the wall lifts from the bottom plate in this model and the bottom plate remains bolted to the foundation. Figure 13 shows the forces on a free body of the wall excluding the bottom plate: Fj is the force between studs and the bottom plate; and Fp is the fixing strength between fasteners and sheathing perpendicular to the sheathing edge. These fasteners also resist uplift of wall from the bottom plate. It is assumed that these fasteners are at a spacing of 's'.

Taking moments about the origin in Figure 13 results in the following equation:

$$F \times H = (F(er) + F(hdd)) \times L + W \times L/2 + \Sigma(Fj \times Xj) + Fp/s \times L^2/2 \ \ldots\ldots (2)$$

As the same fasteners and edge distance are used in both half and full-scale construction, similitude is automatically achieved in the last term of this equation.
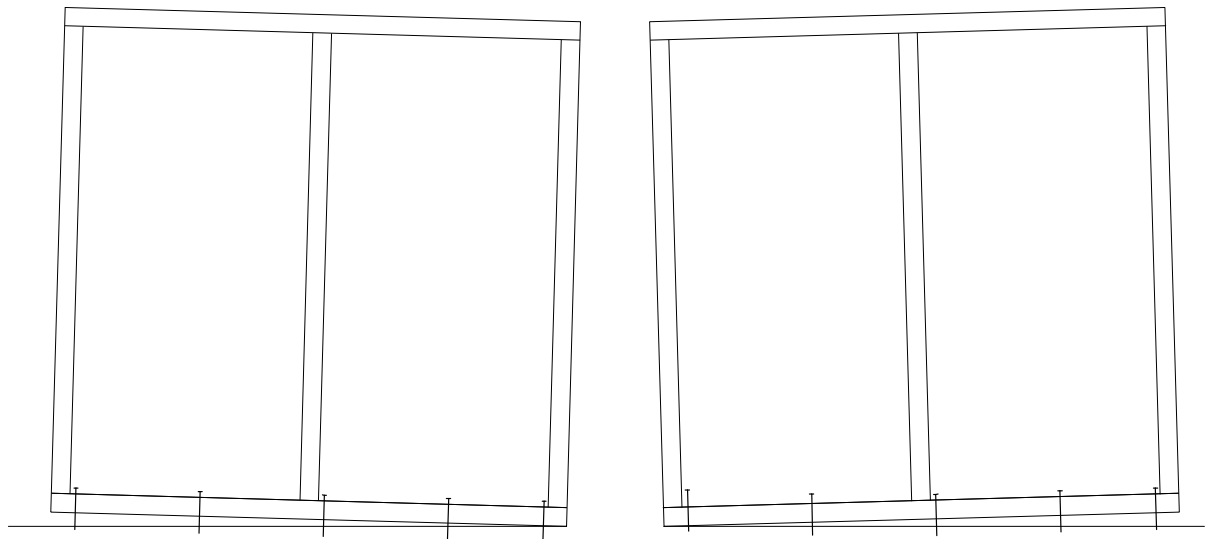
(a) Bottom plate lifting from LH end   (b) Bottom plate lifting from RH end

Figure 10. 'Rocking' action for wall on timber foundations where the mechanism is bottom plate uplift from the foundation beam

(a) Before racking   (b) After racking
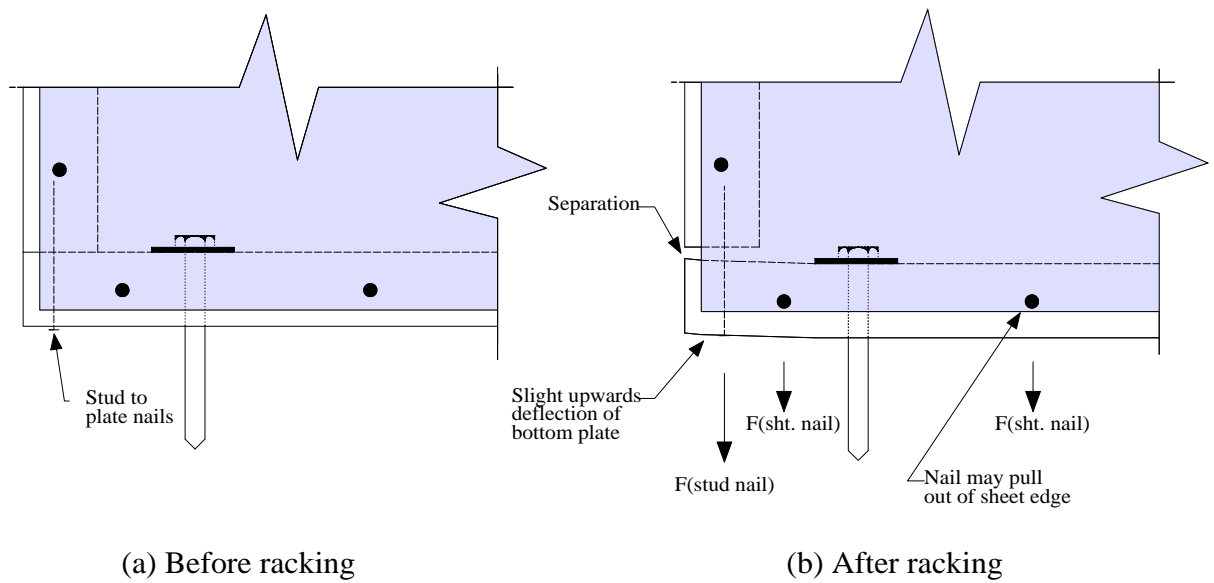
Figure 11. 'Rocking' action for wall on concrete foundations
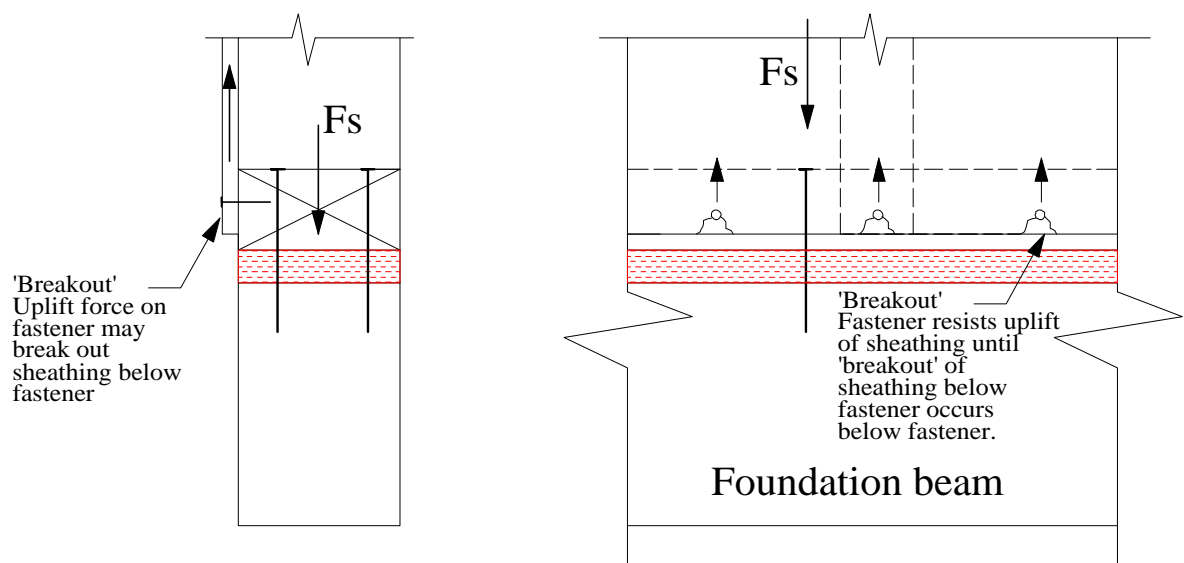
Figure 12. Transfer of sheathing uplift force to bottom plate via bottom sheathing nail
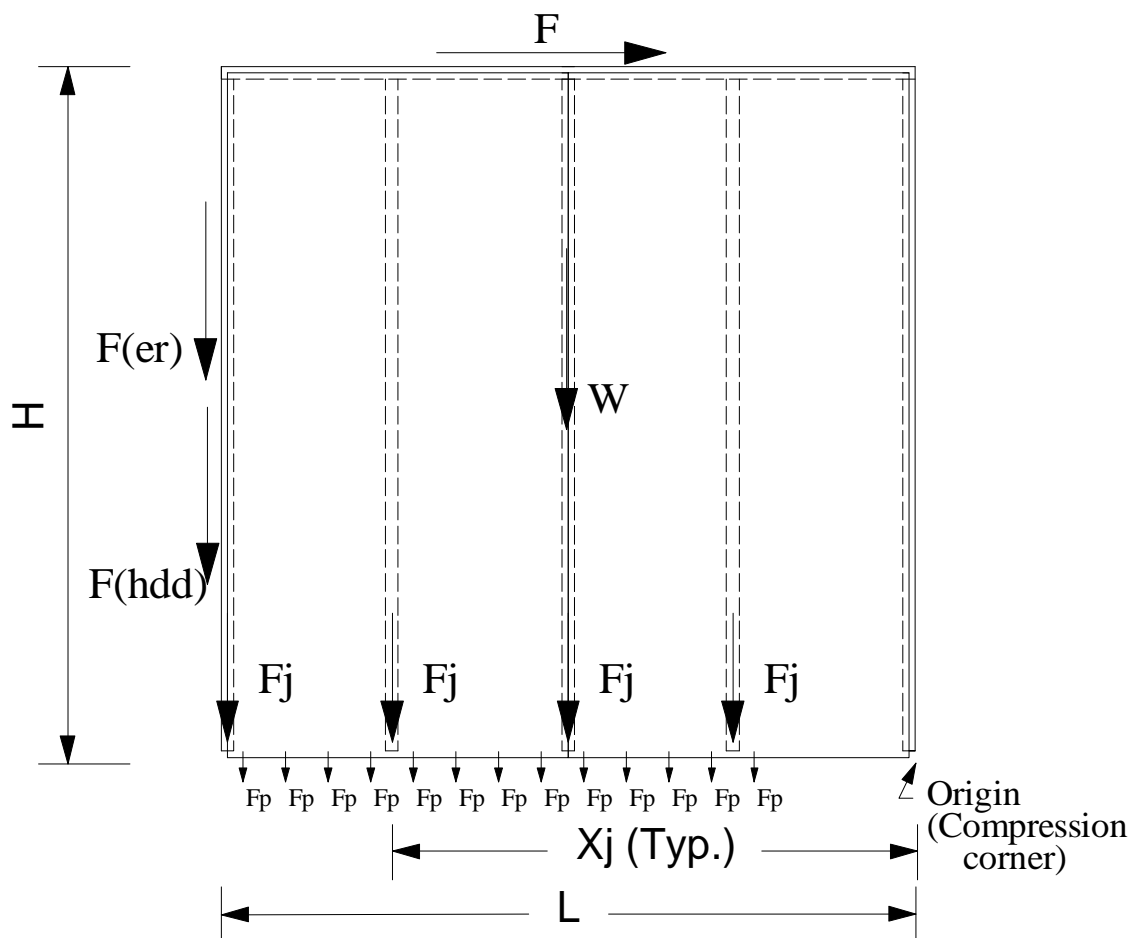
Figure 13. Forces to resist wall 'rocking' motion for a wall on concrete foundations

(Free body excludes bottom plate)

If the same nailing between studs and bottom plate is used in the half and full-scale construction, and this has a pull-out strength of Fj, then for a 2.4 m long wall, the value of $\Sigma(Fj \times Xj)$ becomes 6Fj for the full-scale and 1.8Fj for the half-scale construction. The ratio = 6/1.8 = 3.33, which is less than the required value of 4.0. In this regard similitude is not achieved, but the agreement is considered to be satisfactory. The alternative, of using studs in the half-scale construction at 300 mm centres and using only half the fixing between studs and bottom plates, was rejected as the studs would then be free to twist.

CONSTRUCTION OF TEST SPECIMENS

1.12   General details

All walls were constructed on a timber foundation beam which was bolted to the laboratory concrete strong-floor. This beam showed no movement during the tests and can be considered to be rigidly held. The walls were either nailed to the foundation beam (simulating timber floor construction) or coach-screwed to the timber foundation beam (simulating a concrete floor construction where the coach screw represented a concrete anchor).

Photographs of the half-scale walls tested are shown in Figure 5 and a sketch of the wall framing and location of sheathing fixing locations is shown in Figure 14. Where this varied for the full-scale walls the differences are noted in Section 1.14.

Photographs of the half-scale rooms tested are shown in Figure 6 for the simulated exterior wall construction (no wing walls) and Figure 7 for the simulated interior wall construction (with wing walls). Figure 15 to Figure 17 show the framing and sheathing fixing locations.

The timber framing was constructed from Grade MSG 8 kiln-dried Radiata pine. The wall framing had a section size of 90 x 45 mm. The wall top and bottom plates were fixed to the timber studs with two hand-driven 100 mm x 4 mm flat-head nails.

Where bottom plates were fixed to the timber foundation beam with the intention of simulating bolting to a concrete foundation (see Table 1 and Table 3), M12 coach screws with 50 x 50 x 3 mm washers were placed at 600 mm centres. These commenced at 25-30 mm from the inside face of the end studs.

Where bottom plates were nailed to the timber foundation beam (see Table 1 and Table 3), single 100 mm x 4 mm nails were placed at 300 centres, with alternate nails staggered 25 mm from the plate centreline. These commenced at 15 mm from the inside face of the end studs.

A 20 mm thick particleboard strip was nailed to the foundation beam using two 60 x 2.8 jolt-head flooring nails at 150 mm centres.

Fixings for the PLB plasterboard sheets were 32 mm x 6 g drywall screws using a 12 mm edge distance. Fixings for the MDF sheets were 30 x 2.5 mm flat-head galvanised steel clouts using a 10 mm edge distance.

1.13 Half-scale isolated wall tests

Sheathing fixing and framing details are shown in Figure 14. Walls constructed are summarised in Table 1.

1.14 Full-scale isolated wall tests

The construction followed that described in Section 1.12, except the fixing of coach screws and nails commenced at twice the distance from the inside face of the end studs and the 100 x 4 mm nails were placed in pairs at 600 centres.

The sheathing was fixed at the same corner placement as shown in Figure 14 and continued at the same spacing around the sheet perimeters, except that the sheet sizes were 2400 mm long by 1200 mm wide. The sheets were placed with vertical orientation. The centre joint between the plasterboard sheets was stopped and reinforced with a paper tape.

1.15 Half-scale room tests

A plan view of the two types of room wall layout used is shown in Figure 4. Table 3 provides details of the walls tested. The enclosed room had a rectangular shape. The racking load was applied parallel to the long sides of the rectangle. There were two layouts used:

1   Room with simulated exterior walls on all four sides. These had a single window on each long side and a single door on each short side. This arrangement was used for room tests R1, R2, R3 and R4. The walls were lined with plasterboard (see Figure 17) and either sheathed with nothing (simulating brick veneer construction) or with MDF (see Figure 16).

2   Room with simulated interior walls on all four sides and four wing walls to simulate adjacent construction of corridors or adjacent rooms. This arrangement was used for

room tests R5, R6 and R7. These had a single door on each side. The walls were lined on both sides with plasterboard.

Window and doorway openings were left unfilled i.e. did not incorporate a window or doorway.

Sheathing fixing details are given in Figure 16.

A plan view of the ceiling is shown in Figure 18. The load was equally shared between the four ceiling joists. However, during Room test R4 it was observed that significant movement was occurring between ceiling and wall. To allow the construction in subsequent tests to transfer sufficient load from the ceiling-to-walls to fail the walls, the ceiling diaphragm was strengthened as noted in Stage 2 of Figure 19.

The following fixings were used:

- 140 x 40 double top plate to top plate: single 100 mm x 4 mm flat-head nails at 250 mm centres. Alternate nails were staggered 25 mm either side of the plate centreline

- ceiling battens to top plate: single 75 mm x 3.15 mm nails

- ceiling battens to ceiling joist: two 75 mm x 3.15 mm nails

- joists to 140 x 40 double top plate: two 100 x 4 mm nails skewed at joist ends to the double top plates. Where the side joists are directly above the side wall, two skewed 100 x 4 mm nails at the battens i.e. at 600 centres

- ceiling lining: the ceiling was lined with 10 mm PLB plasterboard with the sheets running perpendicular to the ceiling battens. Within the body of the sheet, each sheet was fixed along each batten at 200 mm centres. Sheet internal joints were formed over battens using fixings at 200 mm centres. Fixings around the room perimeter were at 200 mm centres using 12 mm sheet edge distance.
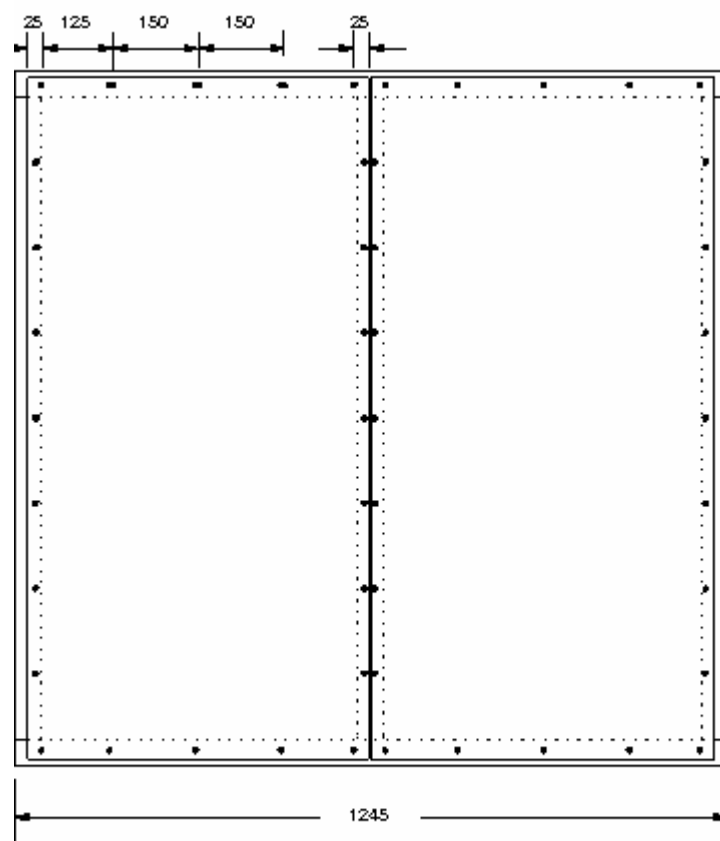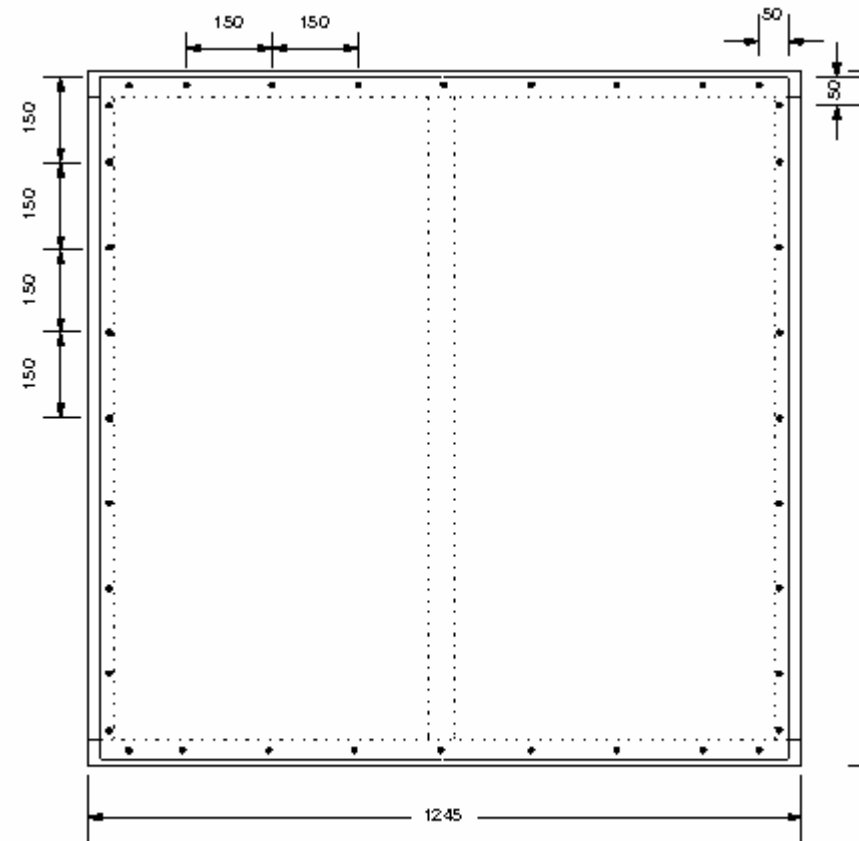
Figure 14. Sheathing fixing and framing of half-scale wall tests

(Fastener locations are represented with a black dot)
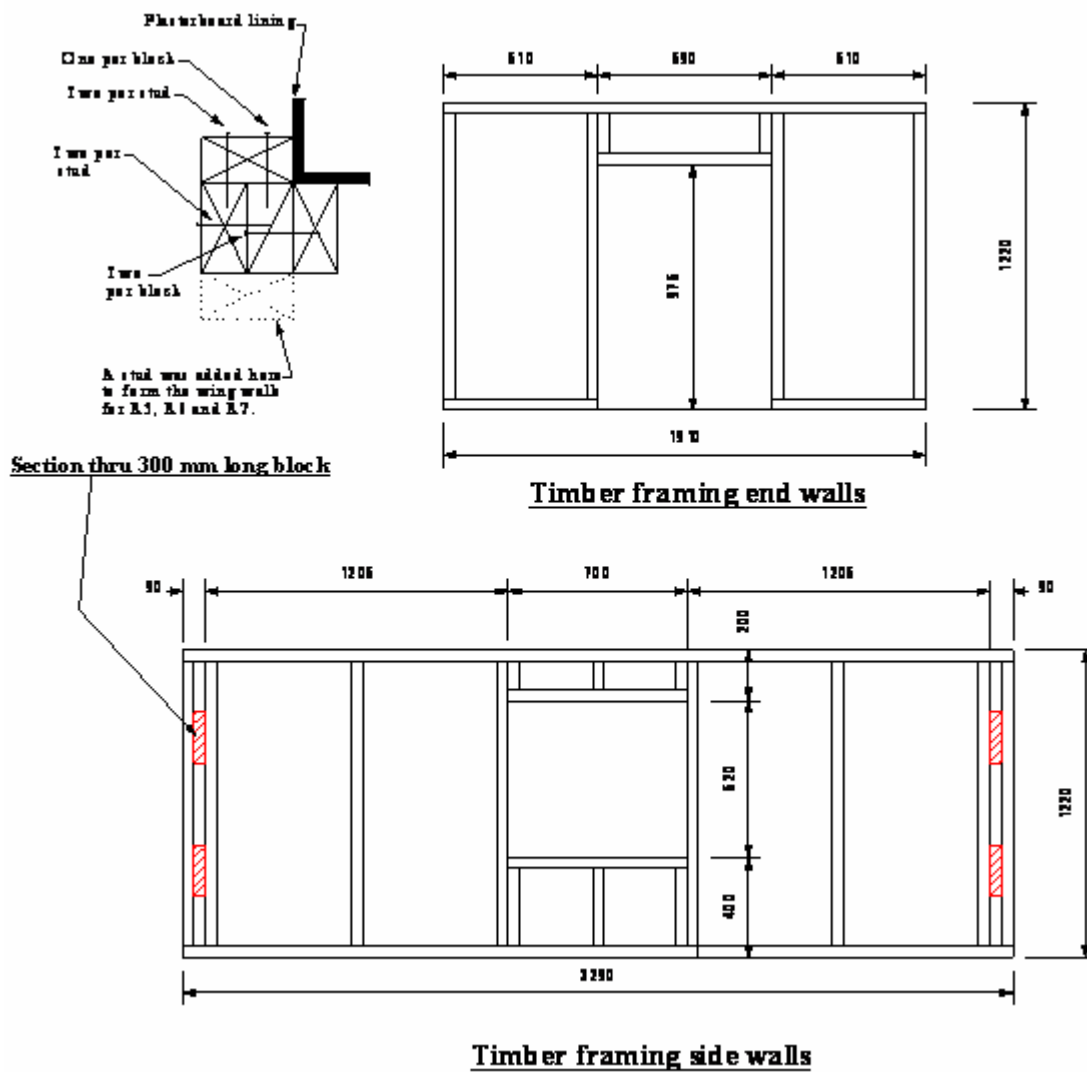
Figure 15. Timber framing for walls R1, R2, R3 and R4
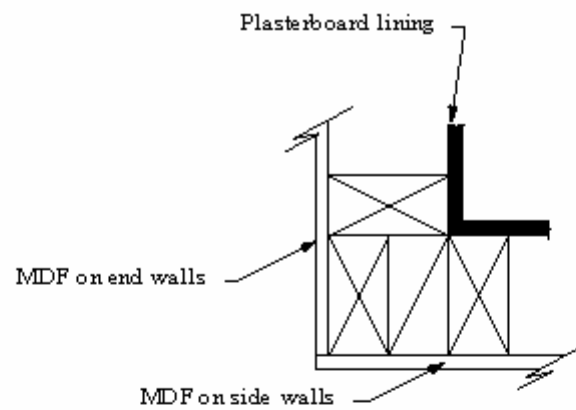
Corner detail
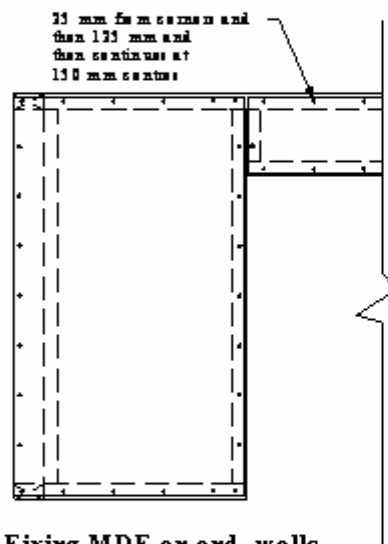
Fixing MDF on end walls
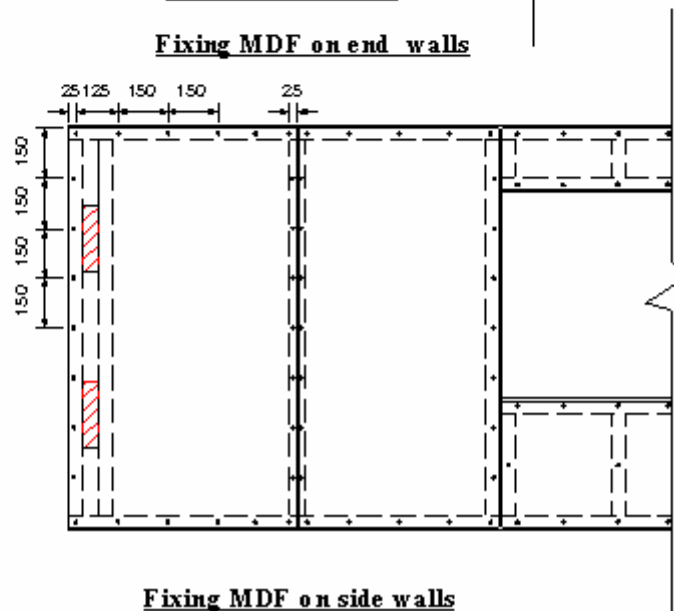
Fixing MDF on side walls

Figure 16. MDF sheathing fixing for walls R1, R2, R3 and R4

(Fastener locations are represented with a black dot)

Corner detail

Fixing plasterboard on end walls

Fixing plasterboard on side walls

Figure 17. Plasterboard sheathing fixing for walls R1, R2, R3 and R4

(Fastener locations are represented with a black dot)

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Figure 18. Plan view of ceiling framing and loading
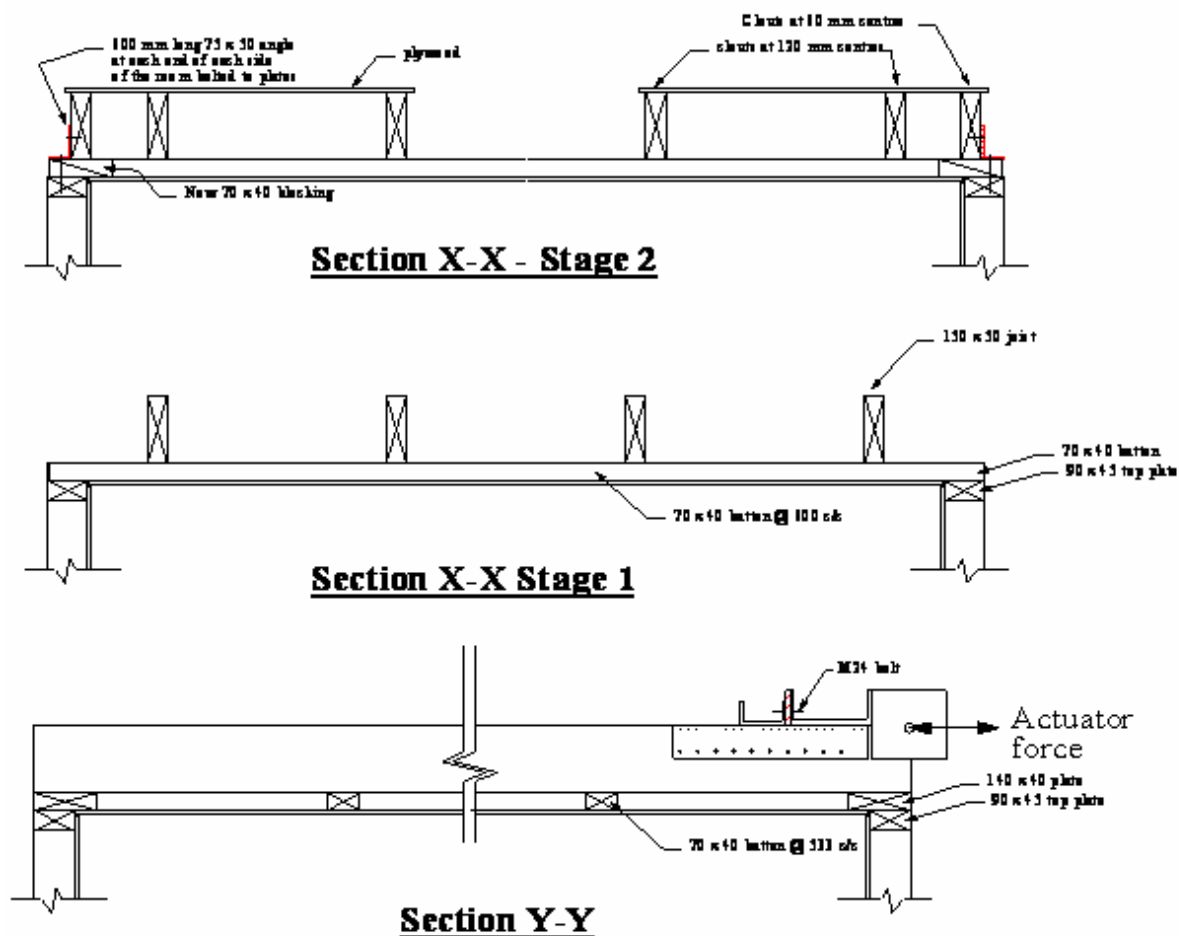
Figure 19. Cross-sections of ceiling framing and loading

LOADING AND TEST PROCEDURE

The loading was applied through a series of articulated steel beams all resting on the ceiling joists which transferred the load equally to four ceiling joists. Views can be seen in Figure 6, Figure 18 and Figure 19.

The cyclic deflection controlled regime used can be seen by examining the hysteresis loops presented in Section 0. Three cycles were performed at each deflection limit using a sinusoidal time history with average speed 4 mm/second in any cycle. After each three cycles the specimen was examined for damage before commencing the next step.

The frames were used for several tests using different claddings. Pre-racking of all test frames before the sheathing was placed was performed to ensure <u>all</u> frames had degraded before the tests reported herein were carried out, as this was considered to make subsequent comparisons more valid. The sheathings for each test were then placed, the test regime imposed and then the sheathings removed. The bottom plate nails were replaced and any repair deemed warranted carried out between tests.

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Section 1.11(a) showed that similitude required mass to be added to simulate doors, windows, sheathing, framing and ceiling so the weight of the half-scale construction was one-half the weight of the full-scale construction. Roof weight was not added as it was assumed that this was carried by other walls than the tested walls. The equipment used to apply load which rested on the ceiling (steel channels etc – see Figure 18) was taken into account. The mass added can be seen as a series of 700 mm long steel blocks stacked around the ceiling perimeter in Figure 6.

TEST RESULTS

1.16   Isolated wall racking tests

Five half-scale and three full-scale walls were tested. Details are given in Table 1 and Table 2 respectively.

1.16.1   Half-scale wall racking test results

A typical set of load-defection plots (hysteresis loops) from the half-scale bare frame racking is given in Figure 20. Figure 21 to Figure 25 give the hysteresis loops of the five half-scale sheathed walls listed in Table 1. The lateral resistance of the frame alone varied between 8-16% of the sheathed walls. Repeat loading of the frame alone to the same deflection did not cause a large reduction in the strength resisted.

> **(a)   Wall S1.** This wall was lined on one side with 10 mm PLB plasterboard. The other side was not sheathed. The wall deformed in a 'shear mode' with 'rocking' deflection being negligible. When the wall was racked to deflections greater than ±10 mm, the screws gouged out the adjacent plasterboard around the entire wall perimeter, but particularly the top and bottom, creating a slot in the plasterboard through which the screw shank could move with little resistance. For ease of description this process is subsequently referred to as 'screws working'.

> **(b)   Wall S2.** This wall was lined on both sides with 10 mm PLB plasterboard. Approximately 60% of the applied deflection was taken up by wall 'rocking' due to the nails in the bottom plate pulling out of the timber foundation beam (see Figure 10). There was no separation between studs and plates. The first observable damage to the wall itself was during deflections to ±21 mm when 'screws were working' along the top plate. During deflections to ±28 mm this damage was noted around the entire wall perimeter. It was concluded that the 'rocking' strength of this wall was similar to its shear strength.

> **(c)   Wall S3.** This wall was lined on one side with 10 mm PLB plasterboard and on the other with 10 mm MDF. The wall bottom plate was nailed to the foundation. Approximately 85% of the applied deflection was taken up by wall 'rocking' due to the nails in the bottom plate pulling out of the timber foundation beam. There was no separation between studs and plates. At ±22 mm the 'screws were working' along the top plate. During deflections to ±28 mm this damage increased, but damage elsewhere around the wall remained small for the entire test.

> **(d)   Wall S4.** This wall was lined on one side with 10 mm PLB plasterboard and on the other with 10 mm MDF. The wall bottom plate was bolted to the foundation. Approximately 55% of the applied deflection was attributed to wall 'rocking' (see Figure 11), which was mainly due to separation between end studs and plates. At ±10 mm

wall deflection this separation was measured at 3 mm and the plasterboard on the bottom plate was being pulled upwards causing damage near the end studs. The damage at this location was becoming severe at applied wall deflections of ±16 mm, but the MDF slip relative to the framing was slight. However, from ±21 mm wall deflection the movement of the MDF relative to the framing was significant. At ±28 mm applied deflection the plasterboard was almost dislodged from the framing and the MDF movement relative to the framing was 5-10 mm with some nails partially pulling out of the MDF.

(e) Wall S5. This wall was lined on both sides with 10 mm PLB plasterboard. The wall bottom plate was bolted to the foundation. Up to a deflection of ±28 mm, 45-50% of the applied deflection was attributed to wall 'rocking'. This subsequently reduced until at ±39 mm deflection less than 30% of the movement was due to rocking. The 'rocking' movement was mainly due to separation between end studs and plates. At ±10 mm wall deflection this separation was measured at 3 mm and the plasterboard on the bottom plate was being pulled upwards causing damage near the end studs. The damage at this location was becoming severe and was along the entire bottom plate and half-way up the end studs at applied wall deflections of ±16 mm. At ±21 mm wall deflection there was severe plasterboard damage at all screw connections.

1.16.2   Comparison between isolated half-scale wall hysteresis loops

Wall S2 was like Wall S1 but lined on both sides. If the strength was governed by shear it would be expected that the hysteresis loops for 2 x S1 would be similar to S2. This comparison is made in Figure 26. Wall S2 did have a large 'rocking' component in its deflection, whereas Wall S1 was governed by shear as discussed in Section 1.16.1.

The results in Figure 26 show that initially 2 x S1 was stiffer than S2. This is as expected as the deflection of Wall S2 had a far greater 'rocking' component than Wall S1. However this protected the wall, in a somewhat similar fashion to base isolation, and limited the Wall S2 strength. For deflections greater than ±15 mm, Wall S1 deteriorated rapidly as the lining 'screws worked'. This 'working' was significantly less in Wall S2 and the strength decay from this action and the 'rocking' action was less.

1.16.3   Comparison between isolated half-scale wall hysteresis loops and full-scale wall hysteresis loops

The purpose of these comparisons was to verify the theory in Section 0 which predicts that a half-scale wall will only have half the bracing strength of a full-scale wall. Therefore, for the comparisons in this section, the measured resistance of the half-scale walls are factored by 2.0.

The results for half-scale Wall S1 (PLB plasterboard one side only) are compared with a previously tested full-scale 2.4 m wide wall (L1) in Figure 27. Both walls used the same screw-fixing option with vertical sheet placement. However, only the full-scale wall used a light gauge diagonal steel brace.

Figure 27 shows a comparison of Wall S1 (with the load factored by 2.0) and the full-scale wall. Agreement is good for the direction where the brace was in compression and buckled, but the half-scale wall did not reach the strength of the full-scale wall in the other direction. The difference is expected to be due to the strength of the light gauge diagonal brace.

The strength of these walls is governed by shear rather than overturning. Thus, the modelling is reasonable for shear deformation.

Similarly, results for half-scale Wall S2 (PLB plasterboard both sides) are compared with an otherwise identical full-scale 2.4 m wide wall in Figure 28. This provided a reasonable agreement. The strength of these walls was governed by both shear and overturning. No braces were used in either tests.

Finally, results for half-scale Wall S3 (PLB plasterboard one side and MDF the other) are compared with an otherwise identical full-scale 2.4 m wide wall in Figure 29. No braces were used in either wall. This provided a reasonable agreement. The strength of these walls is governed by overturning.

Thus, it was concluded that the modelling is reasonable for both shear and overturning deformation mechanisms.

Figure 20. Typical hysteresis loops from racking of the timber frames used for the isolated half-scale wall tests
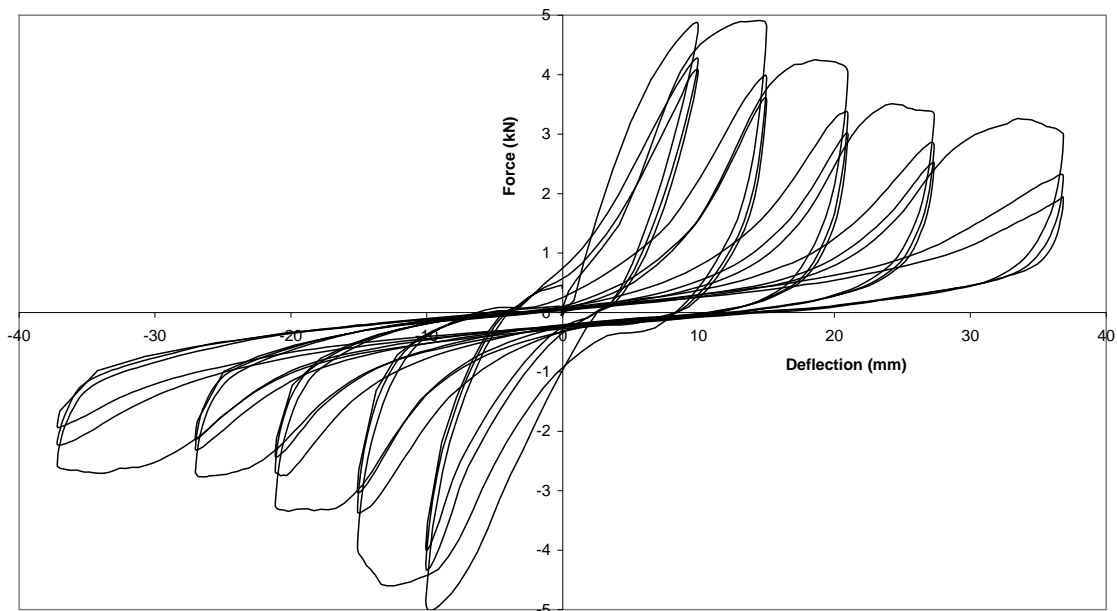
Figure 21. Wall S1 hysteresis loops
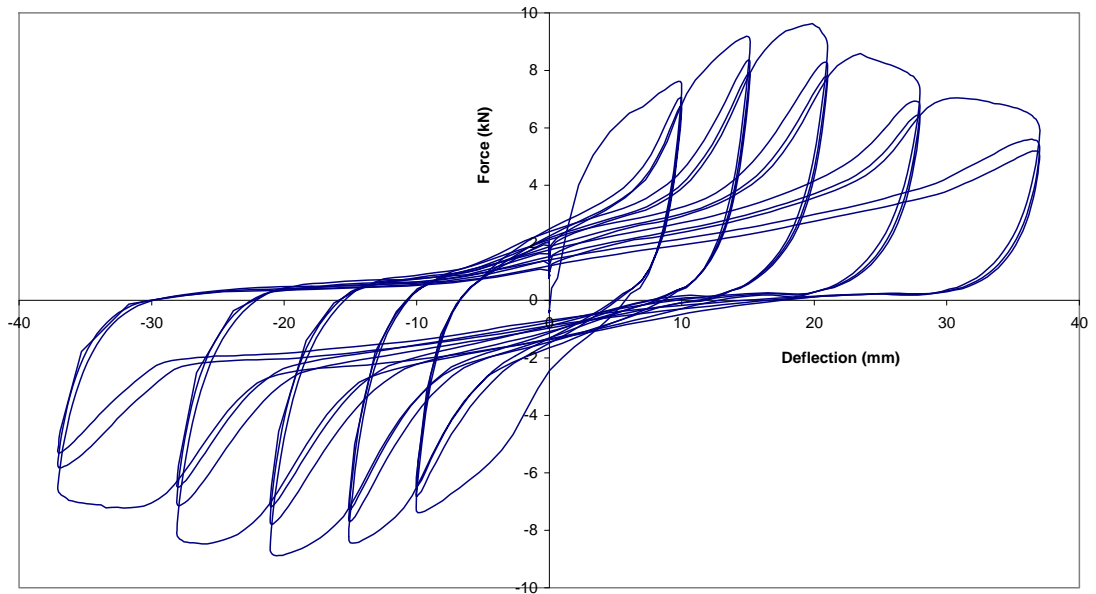
Figure 22. Wall S2 hysteresis loops
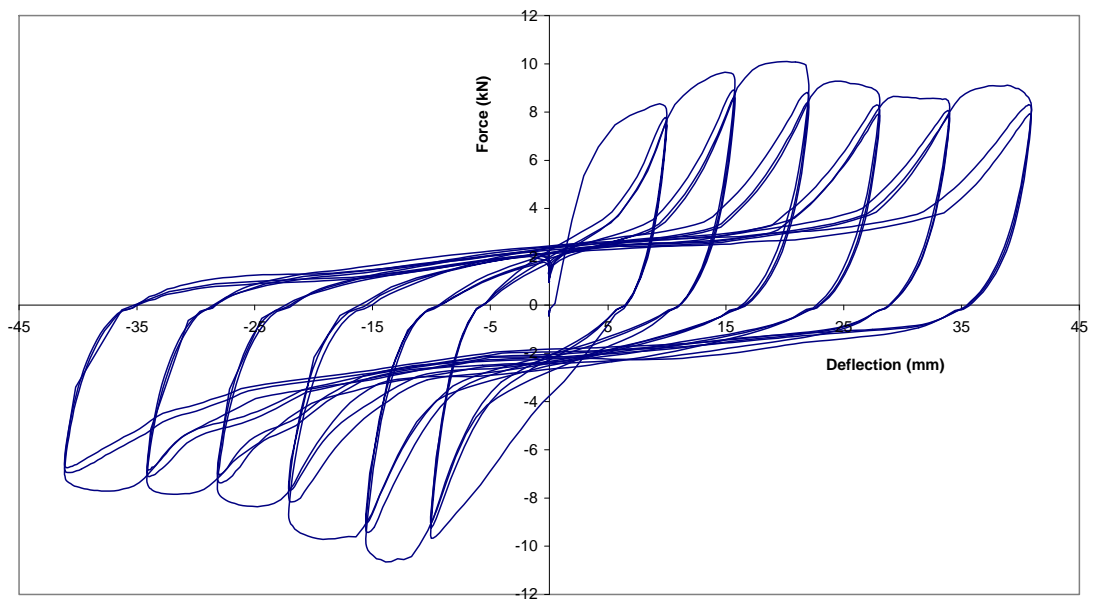
Figure 23. Wall S3 hysteresis loops
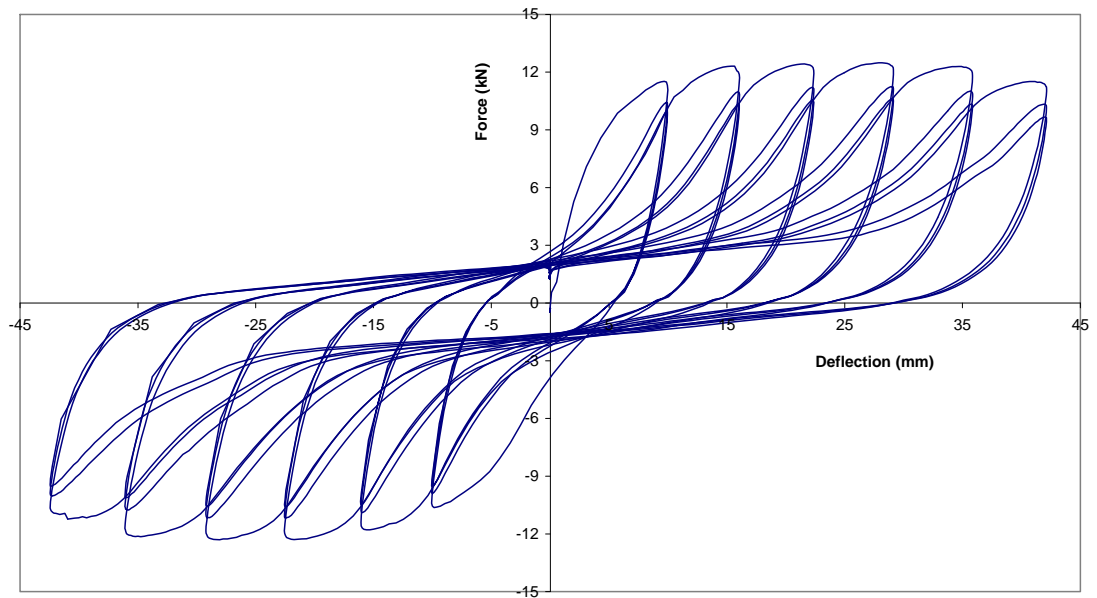
Figure 24. Wall S4 hysteresis loops
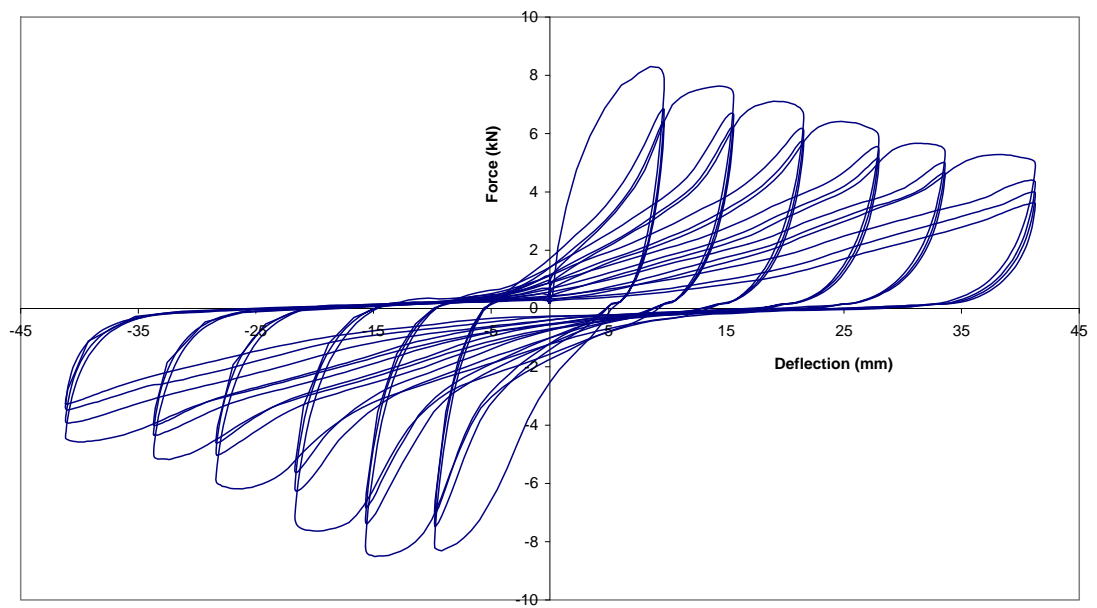
Figure 25. Wall S5 hysteresis loops
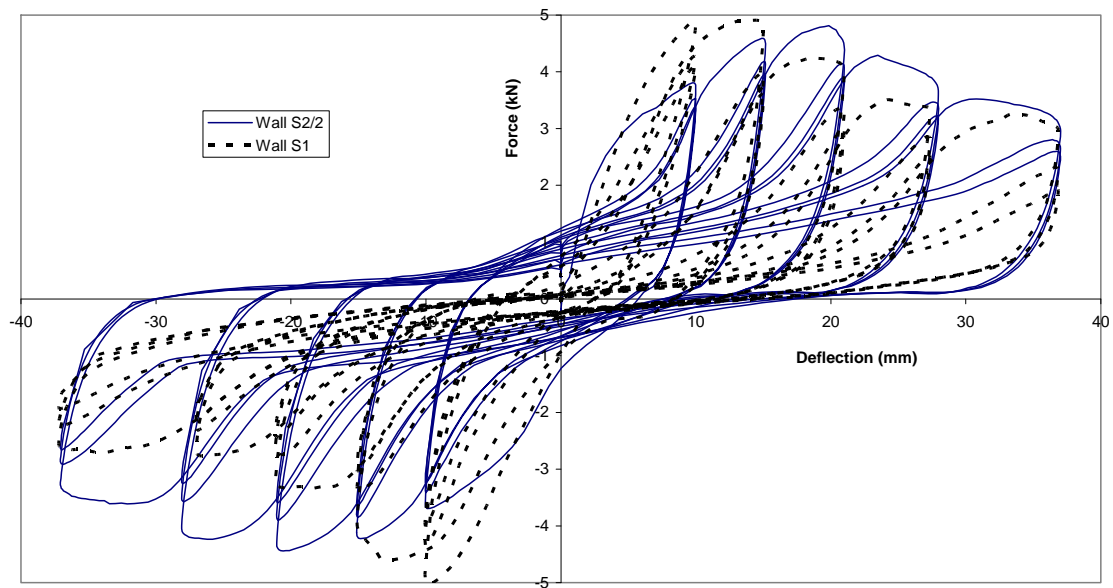
Figure 26. Comparison of Wall S1 and Wall S2/2 hysteresis loops
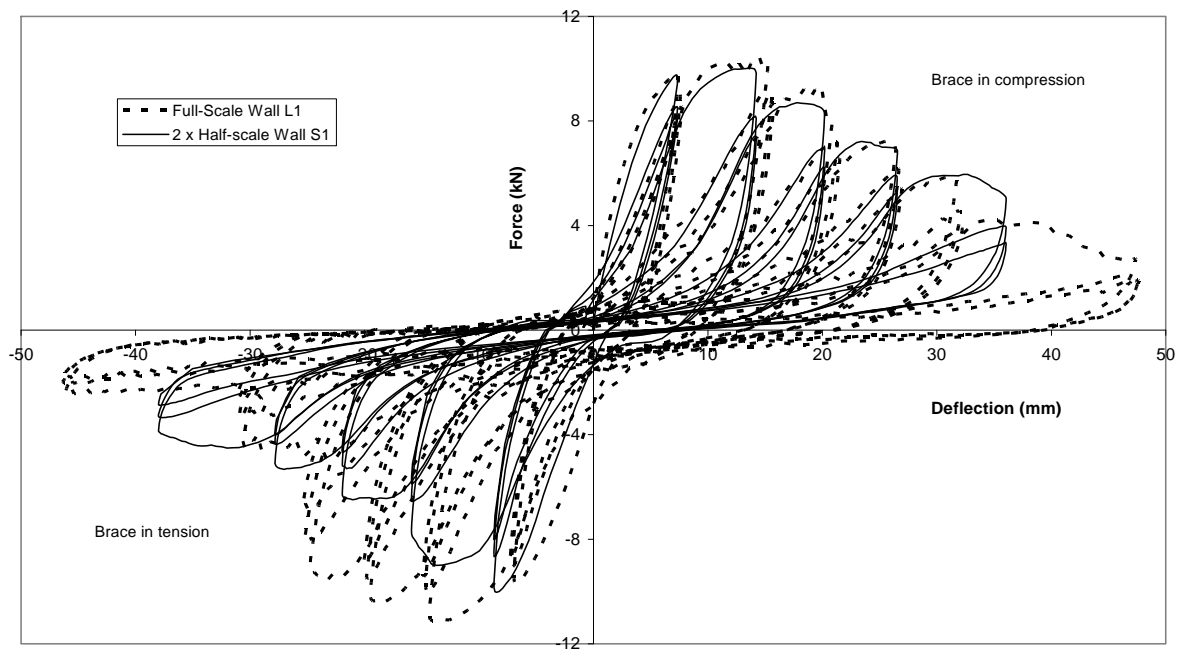
Figure 27. Comparison of half-scale Wall S1 and full-scale hysteresis loops from an equivalent full-scale test (Wall L1)
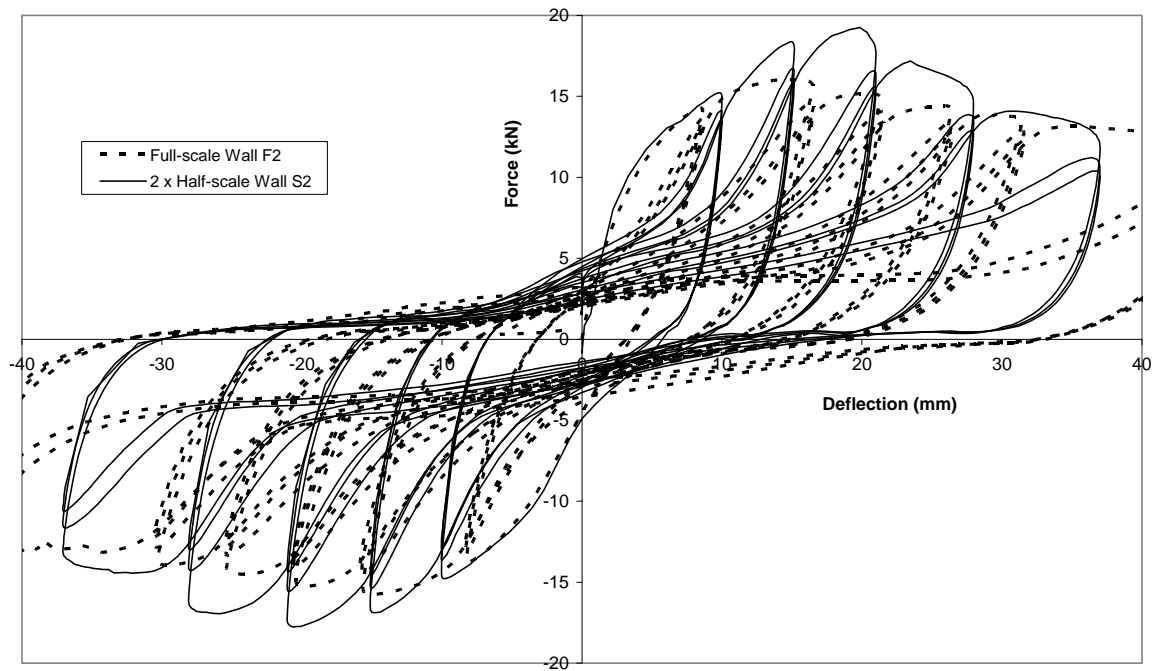
Figure 28. Comparison of half-scale Wall S2 and hysteresis loops from an equivalent full-scale test (Wall L2)
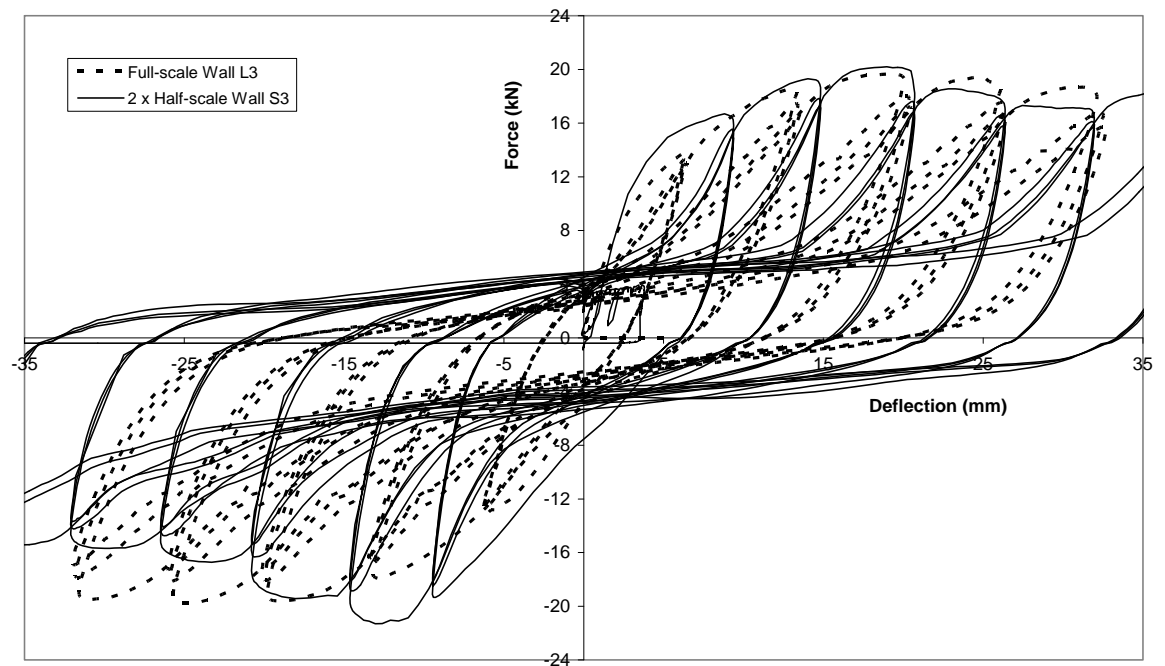
Figure 29. Comparison of half-scale Wall S3 and hysteresis loops from an equivalent full-scale test (Wall L3)

1.17 Half-scale room racking tests

Seven half-scale rooms were constructed. Details are given in Table 3. All frames were racked with three cycles to ±36 mm before being lined and then racked to the normal

sequence used for the room testing (see Section 0). This preliminary racking of the frames was done for reasons discussed in Section 1.15.

1.17.1   Observations and test results

Two wall arrangements were used. The first set simulated the exterior of a building and did not use the wing walls. This arrangement was used for room tests R1, R2, R3 and R4. The second set of framing simulated the interior of a building and used the wing walls for the adjacent construction of corridors or adjacent rooms. This arrangement was used for room tests R5, R6 and R7.

Hysteresis loops from the bare framing (no sheathing) racking tests for both sets of wall framing is given in Figure 30. Figure 31 to Figure 37 give the hysteresis loops of the seven fully sheathed rooms listed in Table 3. The lateral resistance of the frame alone was between 4-10% of the sheathed walls. Repeat loading of the frame to the same deflection did not cause large reduction in the strength resisted.

In the observations below, comments are made of the percent of the total movement due to 'wall rocking'. The wall 'rocking' movement was calculated from the uplift movement at the ends of wall sections, such as between window edges and corners, using the equation:

'Rocking' movement = $\Delta_R = (\Delta_1 - \Delta_2)/L_{1-2}$
Where: Δ_1 = vertical movement at End 1 of the section, Δ_2 = vertical movement at End 2 of the section and L_{1-2} = the horizontal distance between the ends of the section.

(a)   Room R1

This room was lined with 10 mm PLB plasterboard. The joints between sheets were not stopped and taped. The room exterior faces were not clad. The side walls (parallel to the applied load) deformed in a 'shear mode' with 'rocking' deflection being negligible.

During the cycling to ±7 mm wall deflection, there was significant vertical movement between sheets and framing on the room side walls along the bottom plate. This movement also occurred between the vertical edges of adjacent sheets at room ceilings, corners and windows and the doorway edges of the end walls. There was minor damage at window openings (see Figure 38.)

After cycling to ±12 mm deflection, there was significant screw 'working' on the room sides, particularly along the bottom plate and to a lesser extent on the studs adjacent to the windows. This 'working' increased as the test progressed until, after ±24 mm deflection, all screws in the side walls were working hard. There was less than 2 mm uplift of the studs relative to the bottom plate. At the end of the test the sheets on the room side walls had partially dislodged from the framing. The ceiling lining screws had also 'worked'.

(b)   Room R2

This wall was lined with 10 mm plasterboard on the interior face and the exterior faces were not clad. The plasterboard joints, both wall-to-wall and wall-to-ceiling, were taped and stopped. The room exterior faces were not clad.

After cycling to ±12 mm deflection, all screws along the bottom plate had worked. The bottom 300 mm of two of the four corners had cracked between side and end walls.

After cycling to ±18 mm deflection, two of the four wall panels between openings had cracked for the full panel length along the wall-to-ceiling junction. A diagonal crack from the top corner of the window to the top of the wall had formed in another panel. Consequently, the load dropped off sharply. The panels tended to be rising as a unit, lifting at the corner and reducing to only about 25% of this uplift at the windows. The cracking in the interior plasterboard joints at two corners had increased, but there was still no cracking at the other two corners. The screws along the bottom of the wall had 'worked' so hard it appeared that they could not carry a significant load (see Figure 39).

At ±24 mm deflection, the lining on three of the four bracing elements 'popped off' at the bottom of the wall.

For the cyclic racking up to and including ±18 mm imposed deflection, approximately 50% of the applied deflection was caused up by wall 'rocking' of wall sections. The mechanism was both nails in the bottom plate pulling out of the timber foundation beam and separation between studs and plates. These were both of approximately equal magnitude of 4-5 mm. The stud uplift movement had tended to lift the sheet up from the bottom plate, ripping the plasterboard at the screwed connection in the process.

Subsequently, after the room walls weakened rapidly as discussed below, the deformation mechanism changed and the 'rocking' component reduced to 5-10% of the total side wall horizontal movement.

(c) Room R3

This room was lined on one side with 10 mm plasterboard and clad with 9 mm thick MDF. The wall bottom plate was nailed to the foundation.

During the cycling to ±5 mm wall deflection, vertical cracks formed in the plasterboard below the windows. However, there was no cracking in the corners.

After cycling to ±10 mm deflection, the cracking had widened. The bottom plate had lifted from the foundation beam by 5-7 mm at the corners.

After cycling to ±18 mm deflection, the vertical cracks had extended above the windows and cracks had formed along approximately half the wall height at three corners. Approximately 30% of the side wall wall-to-ceiling junction had cracked. The bottom plate had been sliding by approximately ±8 mm and the corners had lifted by 10-15 mm. Shortly afterwards the end walls lifted off the foundations (the bottom plate nails had completely pulled out) accompanied by a large drop-off in load.

For the cyclic racking up to ±18 mm, 70-80% of the applied deflection was caused by wall 'rocking' of the entire side walls i.e. not of the sections between openings or corners. The mechanism was nails in the bottom plate pulling out of the timber foundation beam and with no observed separation between studs and plates. Subsequently, after the room end wall had lifted off the foundations, the

deformation mechanism changed and 'rocking' accounted for almost 100% of the total side wall horizontal movement.

(d)   Room R4

This room was lined with 10 mm plasterboard and clad with 9 mm MDF. The wall bottom plate was bolted to the foundation.

During the cycling to ±5 mm wall deflection, vertical cracks formed in the plasterboard lining along the full height of all window edges. There was no cracking in the corners.

After cycling to ±10 mm deflection, the ceiling had cracked along the full length of the each main wall-to-ceiling junction. There was ±1-2 mm movement along the MDF joints.

After cycling to ±17 mm deflection, vertical cracks at all wall corners had extended approximately 40% of the wall height commencing from the bottom at all corners. There was significant movement between walls and ceilings. The ceiling wall junction had cracked on the end walls (transverse to applied force). There was significant working of the screws along all the wall base on the long sides.

After cycling to ±24 deflection, the cracking at the wall corners was approximately 60% wall height. The wall lining had partially separated from the framing along the side walls. There had been ±2-4 mm movement along the MDF joints. The room ceiling had deflected to ±38 mm, but the walls had only deflected to ±24 mm, with the rest of the movement being taken up in the ceiling and slip at the ceiling-to-wall joints. If this had been realised at the time greater deflections would have been imposed.

After the test the plasterboard was taken off the interior and three more cycles to the previous maximum deflection were imposed. It was noted that the stud uplift was 6 mm at the windows, but only 2 mm at the corners.

Approximately 30-40% of the applied deflection was attributed to wall 'rocking' of the entire side walls, which was due to separation between end studs and wall bottom plates.

(e)   Room R5

The room was lined on both sides with 10 mm plasterboard. The wall bottom plate was nailed to the foundation beam.

During the cycling to ±5 mm wall deflection, vertical cracks formed above the door edges. However, there was no cracking in the lining joints at the corners.

After cycling to ±10 mm deflection, the wall-to-ceiling junction had cracked along approximately 30% of the side walls. The whole of the end walls had lifted as a unit from the foundation beam. The vertical movement across the cracks above the doorway edges had been approximately 6 mm.

After cycling to ±15 mm deflection, nails had broken out of the sheet edges along the bottom plate and on the studs at the window edges. The bottom sheet had moved approximately ±3 mm relative to the bottom plate. Cracks in the ceiling-to-wall joints on the main walls extended along 50% of the junction. There had been no slip movement between walls and ceilings.

After cycling to ±27 mm deflection, cracks in the ceiling-to-wall joints on the main walls extended along 70% of the junction. The bottom sheet had moved approximately ±6 mm relative to the bottom plate.

At test completion the main wall lining had effectively separated from the framing on both the room interior and exterior for half of the long side walls. The lining at the corners had cracked for approximately 500 mm on both the room interior and exterior. There were no cracks at the doorways on the end walls.

Approximately 60% of the applied deflection was attributed to wall 'rocking'. The 'rocking' movement was mainly due to uplift of the wall at the doorway opening on the side walls and uplift of the end walls and wing walls as a unit. Most of the vertical movement at doorways was due to bottom plate uplift, although there was some stud uplift from the bottom plate, particularly in the latter stages of the test.

(f)   Room R6

This room was identical to Room R5, except that a 3 kN end strap (i.e. with three rather than the usual six nails) connected the studs to the foundation beam at each doorway opening. The wall bottom plate was nailed to the foundation beam.

During the cycling to ±5 mm wall deflection, vertical cracks formed above the door edges of the side walls in the room interior. The cracking on the room exterior was less severe.

After cycling to ±9 mm deflection, the ceiling had cracked along the main wall-to-ceiling junction for approximately 50% of the side walls. The plasterboard wall sheets had moved horizontally by approximately ±5 mm at the bottom. This was a combination of bottom plate movement and movement of the sheet relative to the bottom plate. Stud uplift at the corners could not be seen, but was estimated to be only 1-2 mm from the measured upwards deflection of the lining at the corners. Nails had broken out of the edge of the plasterboard along the bottom plate on 20% of the length of the side walls.

After cycling to ±16 mm deflection, nails had popped along 70% of the bottom of the side walls and on three of the four studs at the window edges. A diagonal crack had formed in one side wall corner starting at the bottom at 200 from the corner and finishing 300 mm vertically up at the corner. There was 4 mm slip between wall and ceiling across the joint in one side wall.

After cycling to ±22 mm, a similar diagonal crack had occurred in another corner. The plasterboard had come off the screws along most of the top of the side walls. Thin cracks had occurred at all interior corners between adjacent perpendicular walls, but only for 30% of wall height on the exterior. The plasterboard was moving approximately ±10 mm at the bottom. This would have been a combination of bottom plate movement and movement of the sheet relative to the plasterboard.

At the end of the test, the lining of all side walls had separated from the framing on three sides, being largely held in position by the corner plasterboard jointing. The end walls were effectively undamaged and had not lifted off the foundation beam.

Moderately large uplifts at doorway openings still occurred, and 'rocking' (mainly by stud uplift in spite of the straps) accounted for 30-35% of the movement at the top plate.

(g) Room R7

This room was identical to Room R5, except that the walls were bolted to the foundation beam.

During the cycling to ±5 mm wall deflection, vertical cracks formed above the door edges on all vertical doorway edges in the side walls in the room interior. However, the cracking on the room exterior was less severe. Studs at doorway openings were separating from the bottom plate by about 3 mm. There was no cracking elsewhere.

After cycling to ±10 mm deflection, the ceiling had cracked along the main wall-to-ceiling junction for 40-50% of the length. Studs at side wall doorway openings were separated vertically from the bottom plate by about 7 mm. The plasterboard had moved by ±2-3 mm at the bottom. This would have been a combination of bottom plate movement and movement of the sheet relative to the bottom plate. Screws had started to break out of the bottom of the sheets along the side walls on both the interior and exterior as illustrated in Figure 12. Studs at end wall doorway openings were separating vertically from the bottom plate by approximately 2 mm.

After cycling to ±18 mm deflection, screws had popped for the full height of all doorway vertical edges in the side walls. The interior wall-to-wall junctions had cracked for full junction height. The ceiling-to-wall junction had cracked for full wall length on both side walls. Studs at side wall doorway openings were separated vertically from the bottom plate by about 14 mm.

After cycling to ±33 deflection, all side wall sheets had dislodged from the wall on all edges except at the corner plasterboard joints.

'Rocking' action by stud uplift at doorway openings accounted for 60-65% of the racking movement. Uplift at corners was low.

1.17.2 Comparison between isolated half-scale room hysteresis loops

A comparison of test results from similar room tests is given below and general observations made.

(a) Rooms R1 and R2

Rooms R1 and R2 were both internally lined with plasterboard and had no external cladding. They were identical, except that with Room R2 the joints between plasterboard sheets were taped and stopped.

The comparison in Figure 42 shows that at low deflections Room R2 was stiffer. It resisted greater forces showing that the jointing was effective in increasing wall shear strength and stiffness. However, after the peak load was reached Room R2 deteriorated faster. This was because the walls in Room R2 were 'rocked' partially by stud uplift which damaged the screw connection between lining and bottom plate (thereby reducing the shear strength). Cracking along the stopped and taped joints reduced their effectiveness.

It was concluded that the additional strength of Room R2 was sufficient for the applied forces to instigate a 'rocking' mechanism by stud uplift and this mechanism is brittle and quickly reduces wall shear strength.

(b)   Rooms R2 and R3

Room R3 was similar to Room R2, but had an MDF exterior cladding added. The comparison in Figure 43 shows that from approximately 5 mm deflection, Room R3 was significantly stronger and showed less load decay than Room R2 until the end walls lifted. Clearly Room R3 had greater shear strength due to the presence of the MDF cladding. The cladding also prevented the studs from separating from the bottom plate and thus the damage to the plasterboard lining was less severe. This enabled the more ductile mechanism of nails pulling out of the bottom plate to dominate. The higher loads resisted by Room R3 resulted in greater slip between bottom plate and foundation beam.

(c)   Rooms R3 and R4

Rooms R3 and R4 were both lined with plasterboard and clad with MDF. They were identical, except that with Room R4 was bolted rather than nailed to the foundation.

The comparison in Figure 44 shows that Room R4 was both stiffer and stronger than Room R3 and showed no load decay. This was attributed to the bolting fixing preventing the bottom plate lifting. This action limited the strength of Room R3, but added to its flexibility. The strong fixing between MDF and bottom plate limited the stud uplift (only 2-6 mm measured) of Room R4, which is the other 'rocking' mechanism as described in Section 1.11. This is not expected to be the case with only plasterboard lining (see (e) below).

(d)   Rooms R5 and R6

Room R5 and R6 both were lined internally and externally with plasterboard. They were identical, except that Room R6 had nail straps holding the trimmer studs down to the foundation at doorway openings. These had been found to be very effective at these locations (Thurston 1993). Most of the movement in Room R5 was the result of 'rocking' action by bottom plate uplift, which thereby limited the force in the walls and hence damage from 'screws working'. Significant separation of the stud from the bottom plate still occurred at doorway openings in Room R6 and accounted for 30-35% of the racking deflection. However, there was little uplift at corners.

The comparison in Figure 45 shows that at deflections up to ±15 mm, the room with end straps (Room R6) was significantly stiffer and reached higher strengths. The surprising result was the subsequent rapid reduction in strength. The straps all remained intact, but there was still moderate uplift at doorway openings. However, the stud uplift at the corners was only 1-2 mm at deflections up to ±15 mm. This vertical movement would have weakened the lining fixing along the bottom plate. Note that this was where the damage was observed and where the greatest slip movement occurred. In addition, the greater shear load in Room R6 walls is expected to have induced brittle failure at the lining fixings.

(e) Rooms R5 and R7

Room R5 and R7 were both lined internally and externally with plasterboard. They were identical, except that Room R7 was bolted rather than nailed to the foundation.

At 10 mm room deflection, the studs at the doorway openings were lifting by 7 mm, although uplift in the corners was small and screw fixings were starting to break out of the sheets along the bottom plate along the side walls. This resulted in rapid strength deterioration.

The comparison in Figure 46 shows a similar result up to deflections of approximately ±15 mm. From this stage the strength of Room R7 deteriorated, whereas the strength of Room R5 stayed moderately constant. This is in marked contrast to the comparison in (c) above. It is expected that this is due to the strength of the plasterboard linings being inadequate to prevent stud uplift, whereas the MDF was adequate.

1.17.3 Comparison between isolated half-scale wall hysteresis loops and half-scale room hysteresis loops

(a) Construction tested

Racking tests were performed on isolated half and full-scale walls and half-scale rooms. The half-scale rooms basically consisted of four identical half-scale walls built into the room construction as discussed in Section 1.5. The isolated wall tests consisted only of the wall plus contrived end restraints to simulate the actual wall continuity as discussed in Section 1.6 and 1.11(a).

(b) Proposed end restraint and systems effect factor

It is proposed that the end restraint in the half-scale wall tests be reduced from four to three nails i.e. the end restraint is reduced by ¾ and the results can be interpreted assuming the room construction is stronger than the sum of the isolated walls by a systems effect factor = 1.30. A comparison of test force versus deflection plots of the room tests with the plots from the sum of the component walls (i.e. 4 x wall test of one component wall) is given below and the validity of the proposal examined for each construction type. Having made all these comparisons, a conclusion is reached in (h) below and carried through to the conclusions of Section 0.

For rooms governed by wall shear strength, the systems effect factor can be obtained directly from the ratio of total room strength divided by the sum of the

component wall strengths as these will not be influenced by the 'rocking' end restraints.

For rooms governed by rocking, where the end restraint used in the component wall tests is reduced by a factor of ¾, the systems effect factor = 4/3 x the ratio of total room strength divided by the sum of the component wall strengths. Thus, in the comparisons made below where both the walls and rooms were governed by rocking, and where the room strength is at least as great as the sum of the component walls, the proposal will be conservative as 1.30 is less than 4/3.

The proposal is for half-scale wall tests using a '3-nail' end restraint, which similitude (see Section 1.11) suggests is the same as a '6-nail' end restraint in full-scale walls. Thus, if the proposal is shown to be valid, then it is recommended that the full-scale tests are performed with a '6-nail' end restraint and a systems effect factor = 1.30 be used for application of the results to NZS 3604 type construction.

(c) Room R1 and 4 x Wall S1

The walls of both Room R1 and Wall S1 were lined with plasterboard on one side only and did not use cladding. Room R1 did not have the joints between plasterboard sheets taped and stopped.

The comparison in Figure 47 shows that Room R1 was stronger than 4 x S1 (maximum loads resisted being 14% greater). As both walls were governed by shear strength, rather than rocking, no conclusions can be made about the suitability of the end restraints. It is concluded that the systems effect factor in construction governed by shear where plasterboard joints are not taped and stopped is small, and should be taken as 1.0.

(d) Room R2 and 4 x Wall S1

Before a comparison is made with Wall S1, it should be noted that Rooms R1 and R2 were identical, except that the joints between plasterboard sheets of Room R2 were taped and stopped.

The comparison in Figure 48 shows that Room R2 was significantly stiffer and stronger than 4 x S1 (maximum loads resisted being 36% greater). Hence, the systems effect factor can be taken as 1.36, or more conservatively as 1.30. Subsequent to the peak load, Room R2 deteriorated fast for reasons noted in Section 1.17.2 (a).

Wall S1 was governed by shear, whereas approximately 50% of the deflection of Room R2 was due to 'rocking' in spite of the restraint of the end walls. This may imply that the contrived end restraint used with Wall S1 was too great as it prohibited 'rocking'. The high shear load resisted by Room R2 is likely to be the cause of the plasterboard cracking at joints and openings, thus isolating walls and facilitating wall rocking.

If the end restraint in the half-scale Wall S1 test is reduced by ¾, this may have an effect on the strength of the wall and hence make the systems effect factor determined by testing greater. (It will only affect the strength if the wall becomes governed by 'rocking' rather that shear.) However, using this reduced end restraint and a systems effect factor = 1.30 (i.e. less than 1.36) will provide a

conservative result for a bracing wall test and evaluation procedure for this wall construction and thus the proposal holds.

(e) **Room R3 and 4 x Wall S3**

Rooms R3 and Wall S3 were both lined with plasterboard and clad with MDF.

The comparison in Figure 49 shows good agreement between Room R3 and 4 x Wall S3 until the end walls lifted in Room R3 at about ±25 mm and the load resisted dropped off (see Section 1.17.1).

For both constructions, the motion was mainly by 'rocking' by bottom plate uplift (clearly the MDF was effective in precluding stud uplift). From these results, it is concluded that the proposal is valid for this construction using the argument in the third paragraph of (b)above.

(f) **Room R4 and 4 x Wall S4**

This is a similar comparison to (c) above, except that the bottom plate was bolted down.

The comparison in Figure 50 shows good agreement between Room R4 and 4 x Wall S4 – with Room 4 being slightly stronger. Both constructions had 30-50% of the movement attributed to 'rocking' by stud uplift. From these results it is concluded that the proposal is valid for this construction.

(g) **Room R5 and 4 x Wall S2**

The room and wall were lined both internally and externally with plasterboard.

The comparison in Figure 51 shows good agreement between Room R5 and 4 x Wall S2. Both constructions had approximately 60% of the movement being due to 'rocking' by bottom plate uplift. From these results it is concluded that the proposal is valid for this construction.

(h) **Room R6 and 4 x Wall S2**

Room R5 and R6 were both lined internally and externally with plasterboard and bolted to the foundation. They were identical, except that Room R6 had nail straps holding end studs down to the foundation at doorway openings which is intended to limit 'rocking' action but proved to be only partially effective (see Section 1.17.1).

The comparison in Figure 52 shows that at low deflections Room R6 was significantly stiffer and stronger than 4 x Wall S2. After reaching peak load it subsequently rapidly deteriorated for reasons given in Section 1.17.2(d). As Wall S2 did not have end straps, no conclusions on the adequacy of the end restraints or systems effects can be made.

(i) **Room R7 and 4 x Wall S5**

The room and wall were lined both internally and externally with PLB plasterboard and bolted to the foundation.

The comparison in Figure 53 shows a moderate agreement. Both had a similar initial stiffness. Room R7 reached slightly higher peak loads, but deteriorated faster than Wall S5. From these results, it is concluded that the proposal is valid for this construction.

(j) Conclusion on suitable end restraint

It was proposed that the end restraint in the half-scale wall tests be reduced from four to three nails i.e. the end restraint is reduced by ¾ and the results can be interpreted assuming the room construction is stronger than the sum of the isolated walls by a systems effect factor = 1.30.

For rooms governed by wall shear strength, the systems effect factor found from the ratio of total room strength divided by the sum of the component walls strength was greater than 1.30, and so the proposal is valid as discussed in Section 1.17.3 (b). No conclusion can be made about end restraint from such construction.

For construction governed by rocking, the room strength was always at least as great as the sum of the component walls. Therefore the proposal is valid and conservative as discussed in Section 1.17.3 (b).
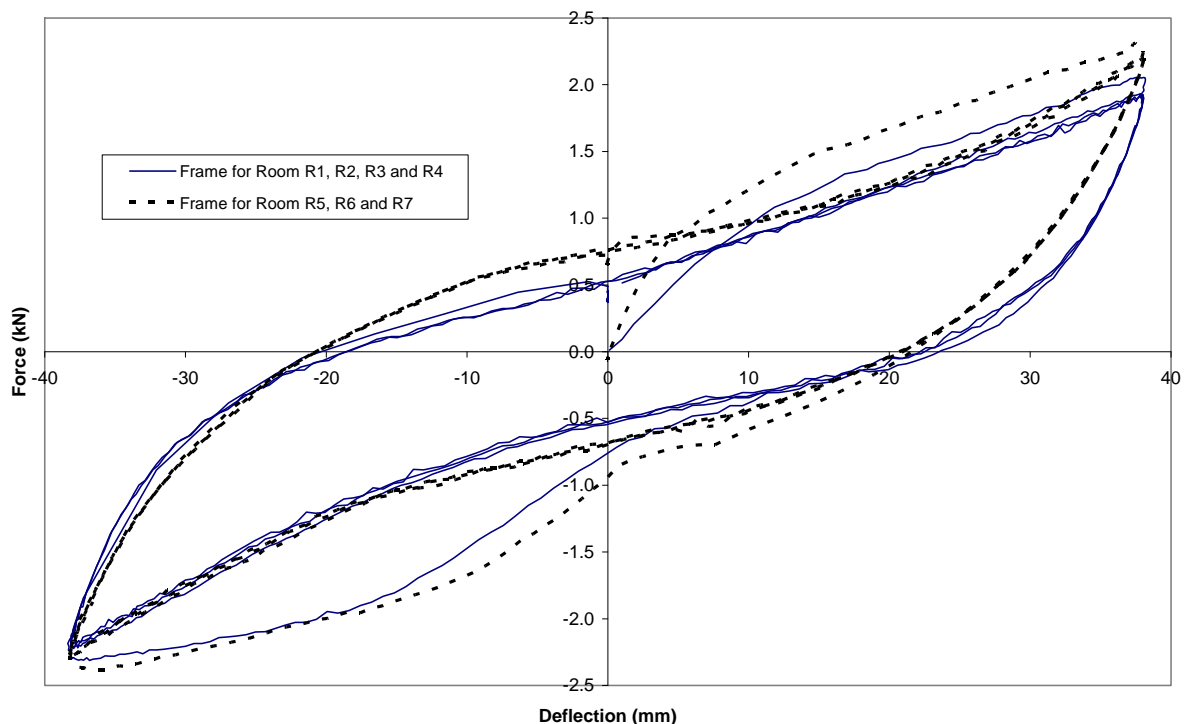
Figure 30. Hysteresis loops from racking of the bare timber frames used for the half-scale room tests
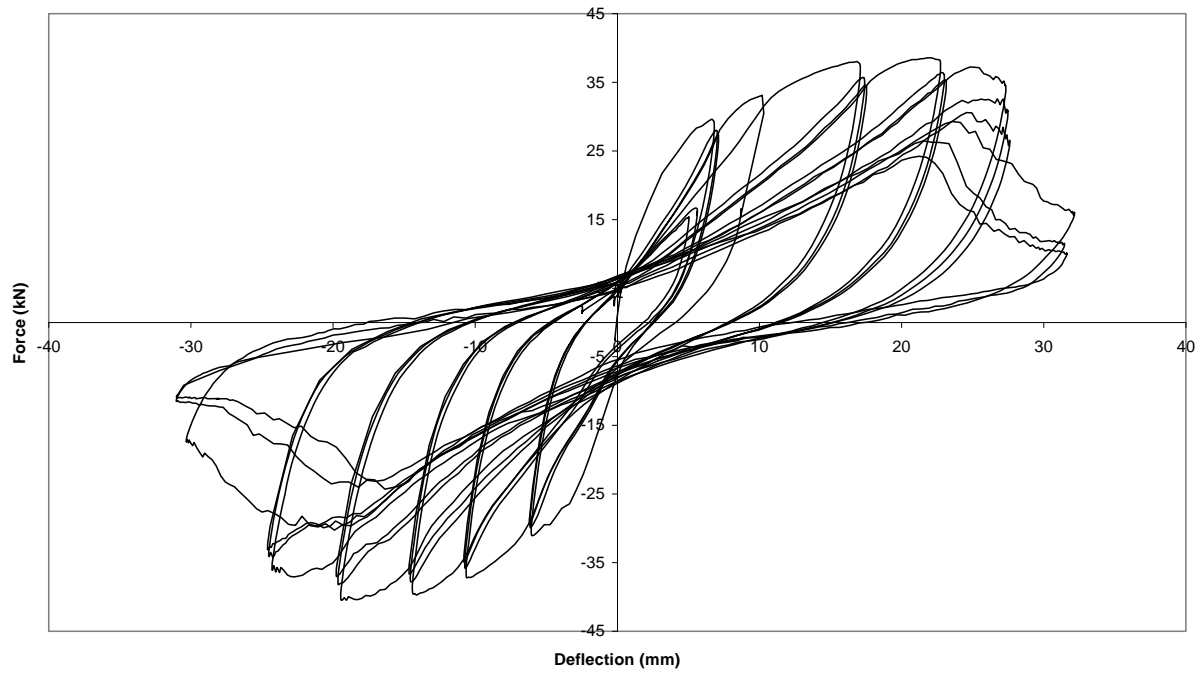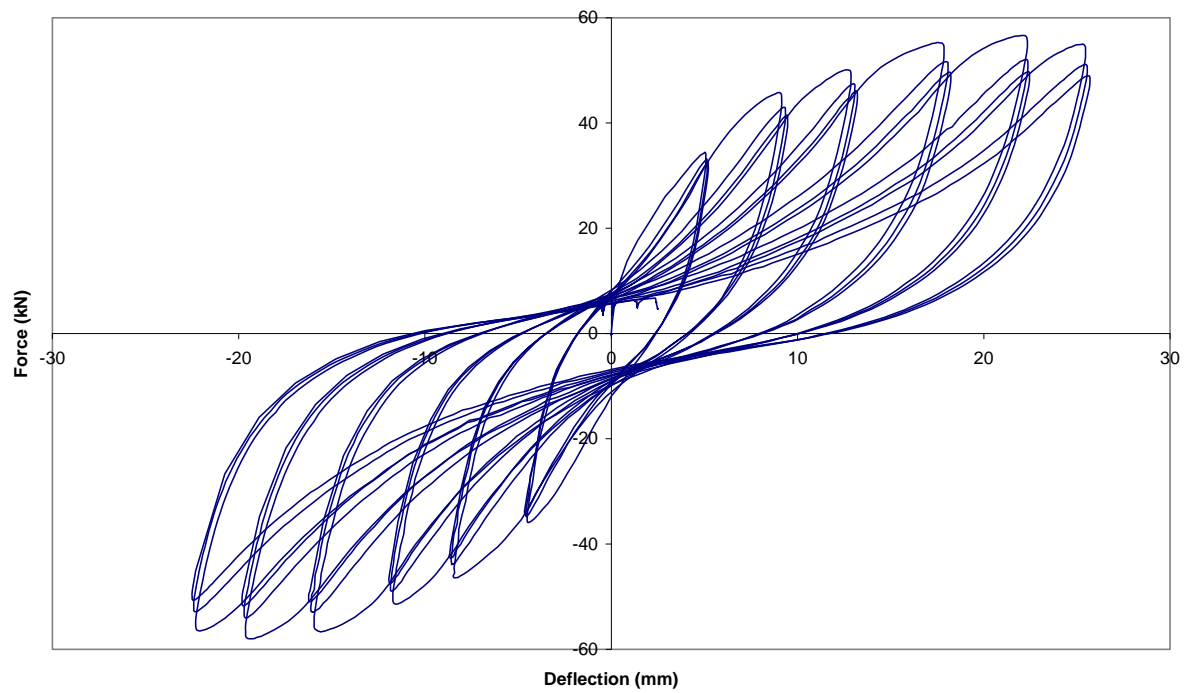
41
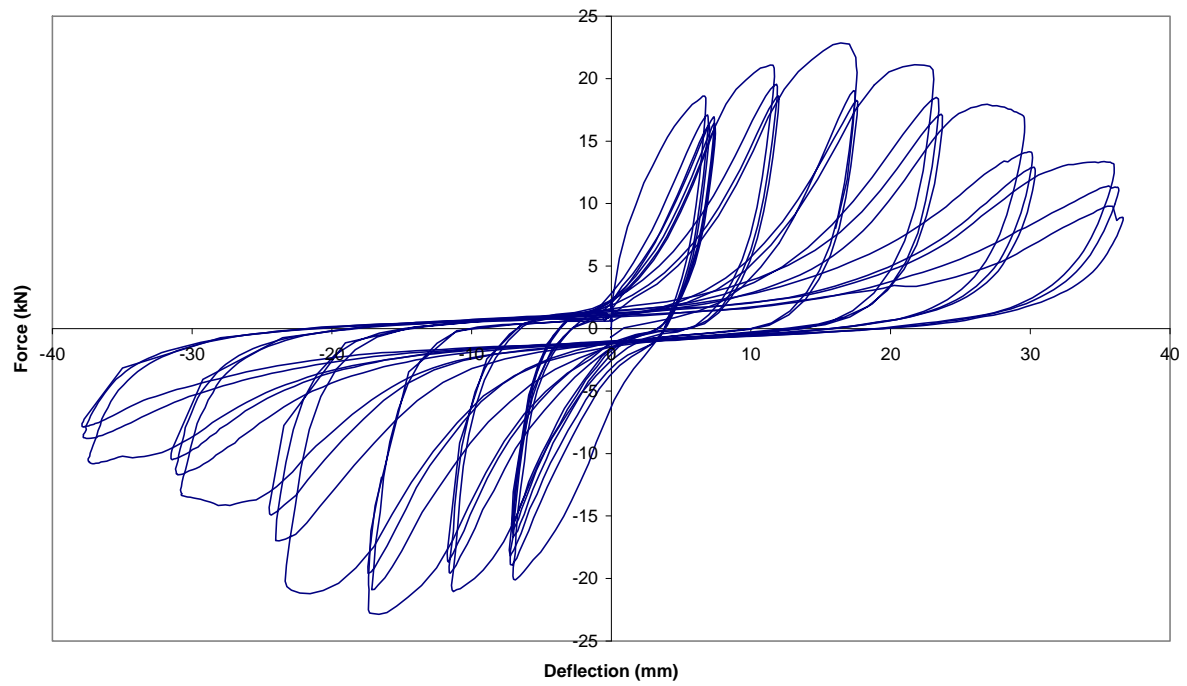
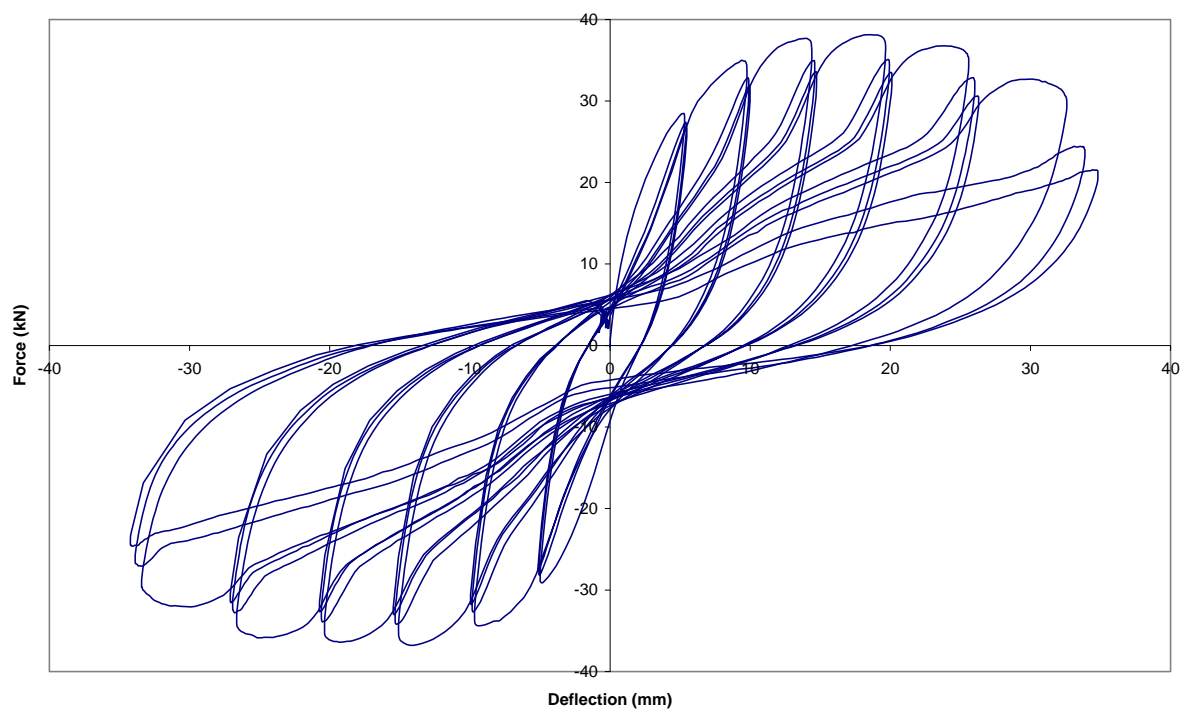**Figure 31. Room R1 hysteresis loops**
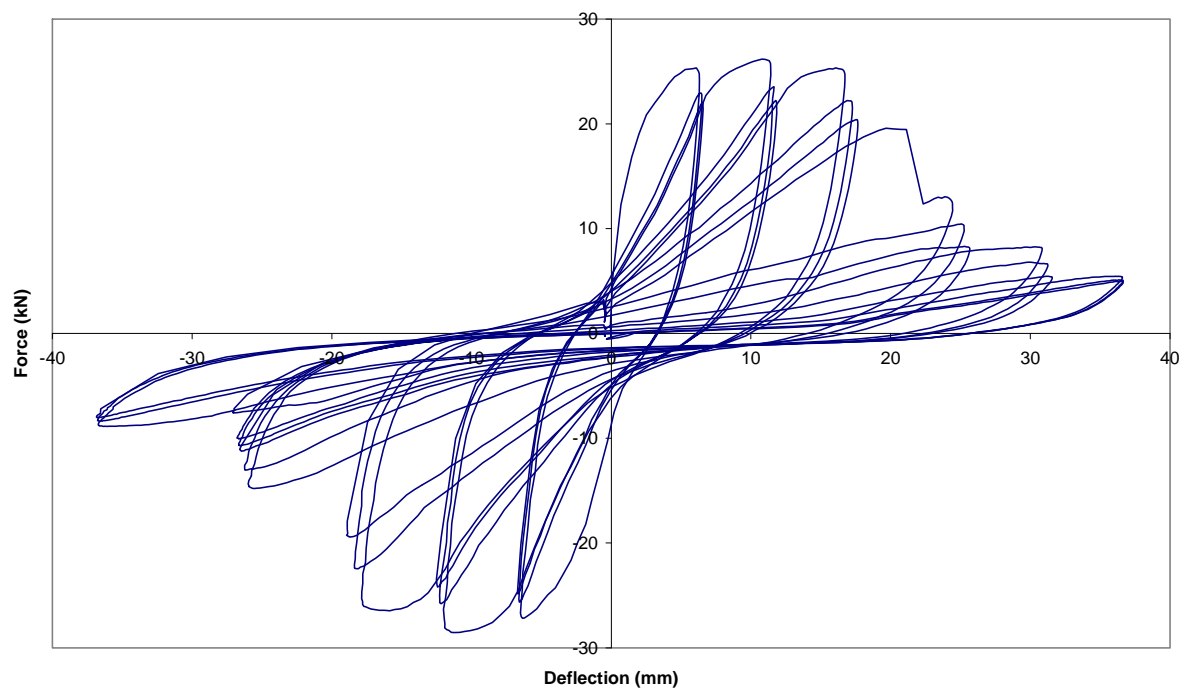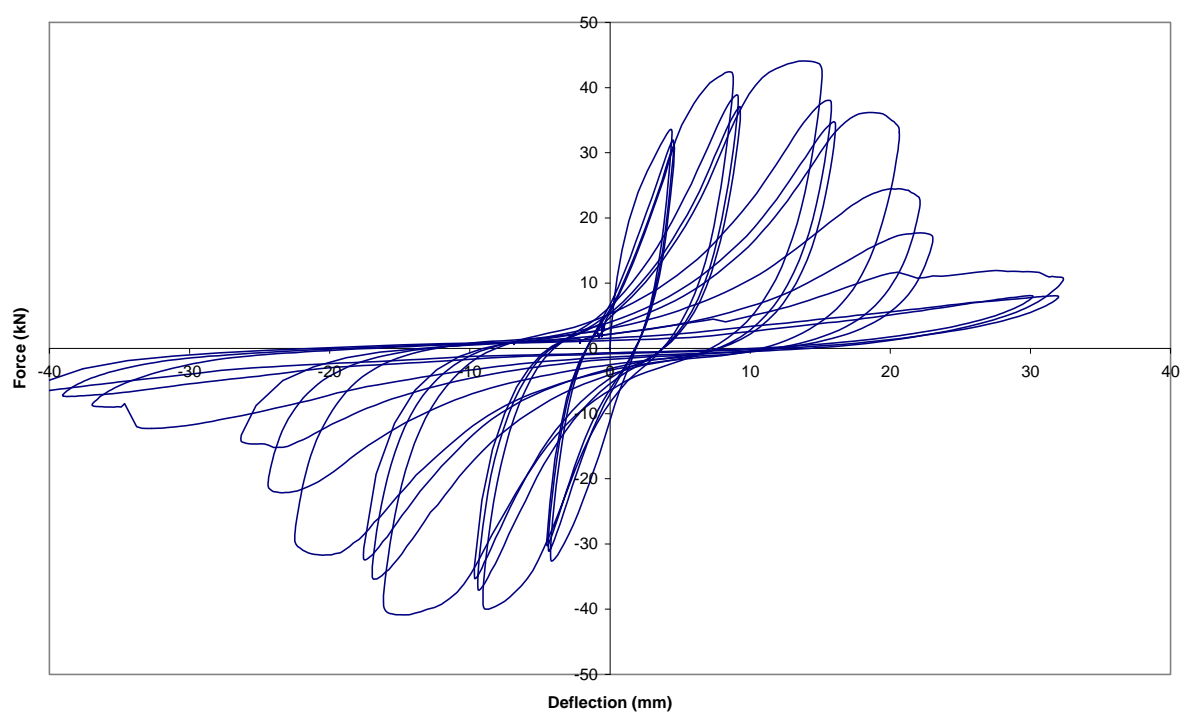

Figure 32. Room R2 hysteresis loops

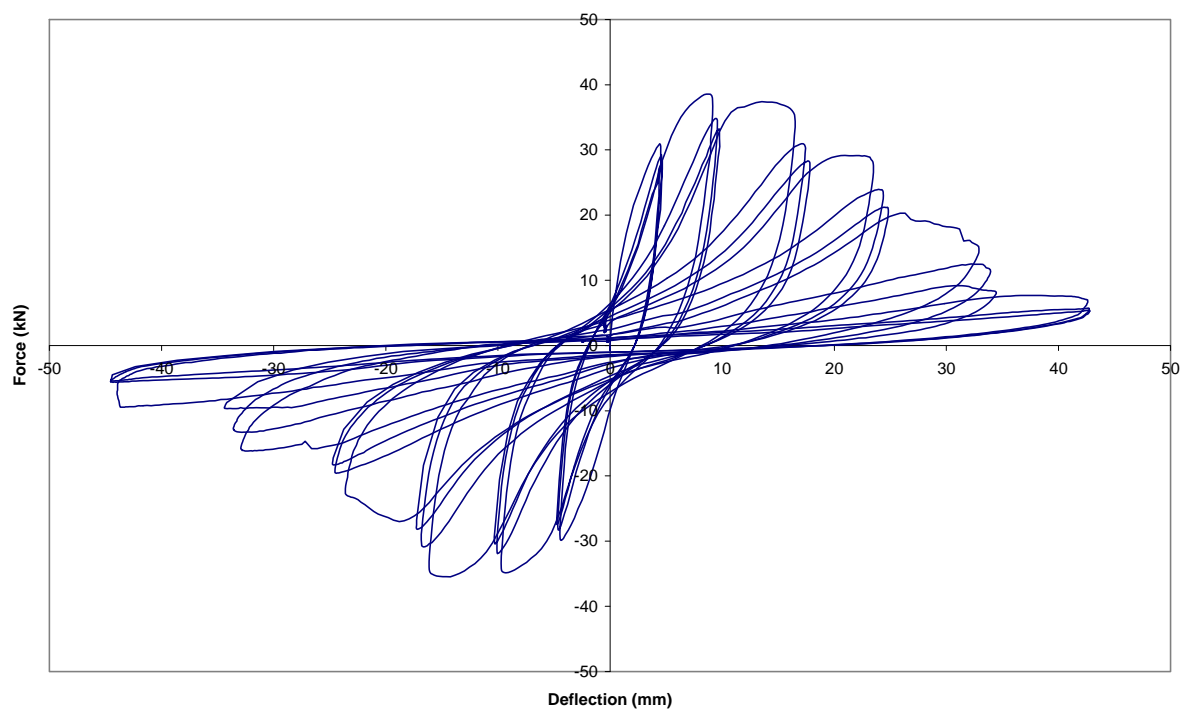**Figure 33. Room R3 hysteresis loops**

Figure 34. Room R4 hysteresis loops

Figure 35. Room R5 hysteresis loops

Figure 36. Room R6 hysteresis loops

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Figure 37. Room R7 hysteresis loops

Figure 38. Room R1 – photograph of damage to the interior plasterboard screw fixings at 7 mm wall deflection on the room long sides at the window openings
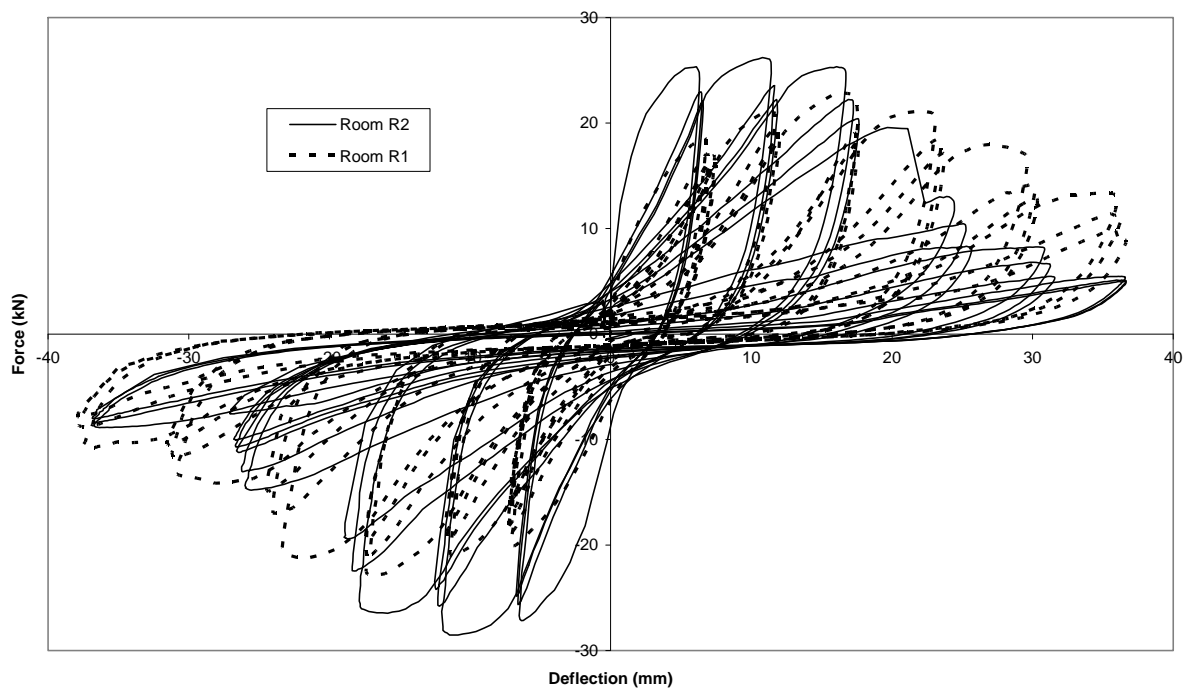
Figure 39. Room R2 – movement at wall long side doorway opening near test completion

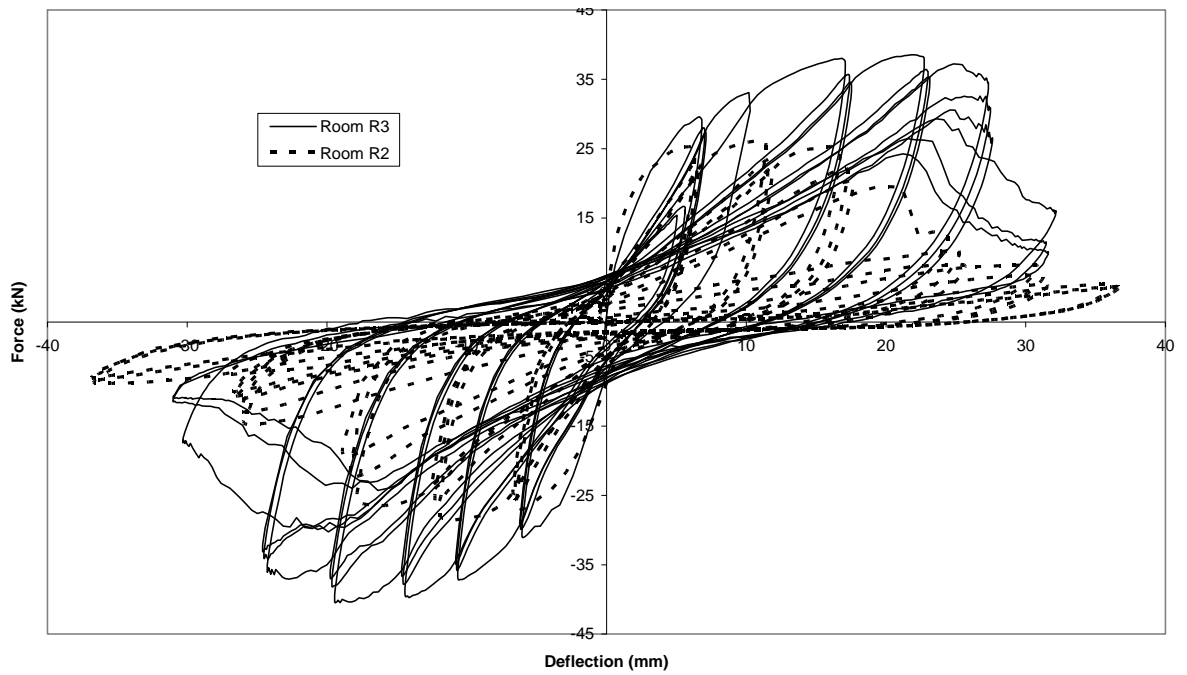

Figure 40. Room R2 – stud uplift on long side walls

Figure 41. Room R5 – photograph of vertical movement at wall long side doorway openings
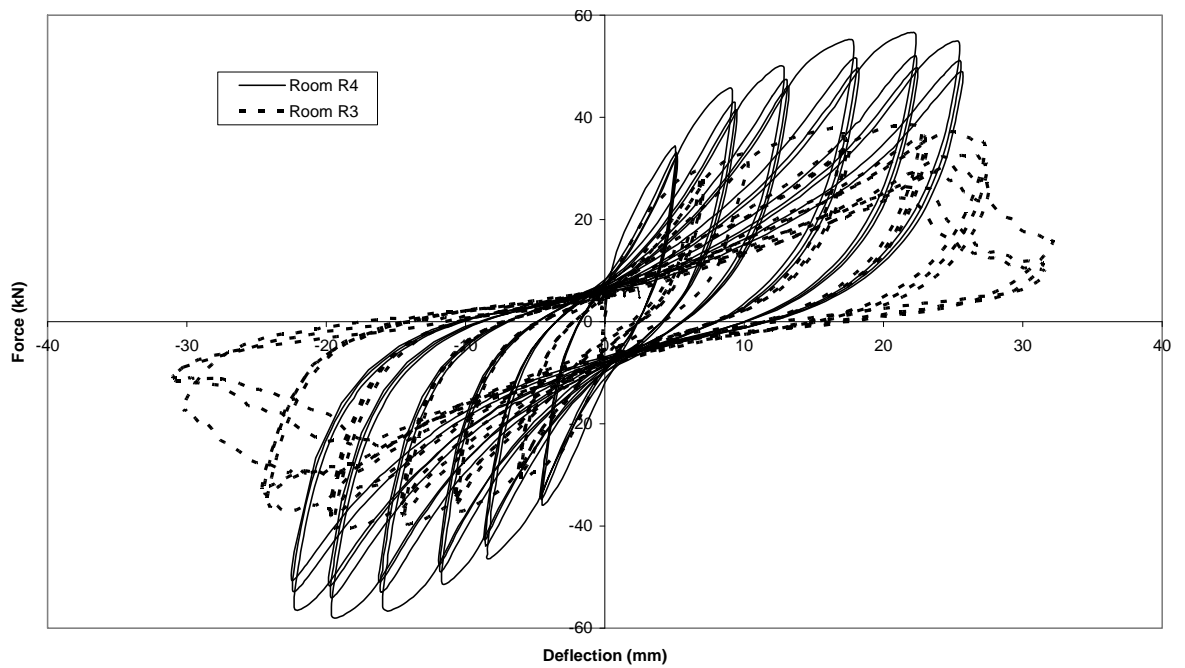

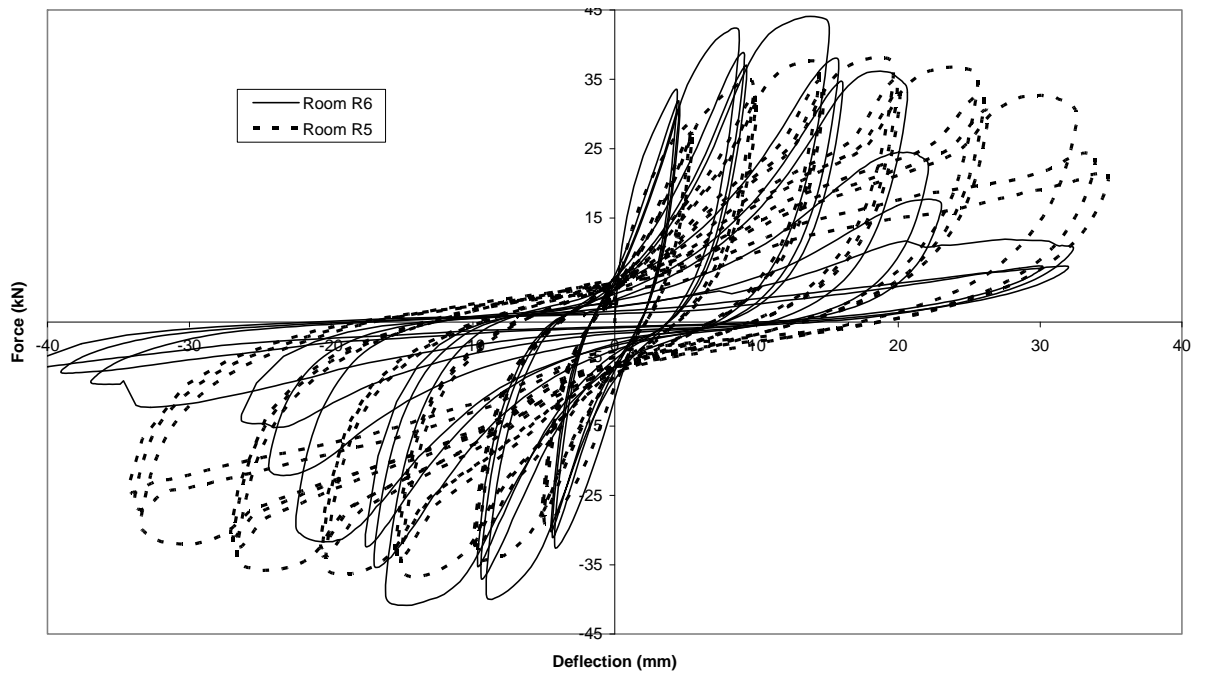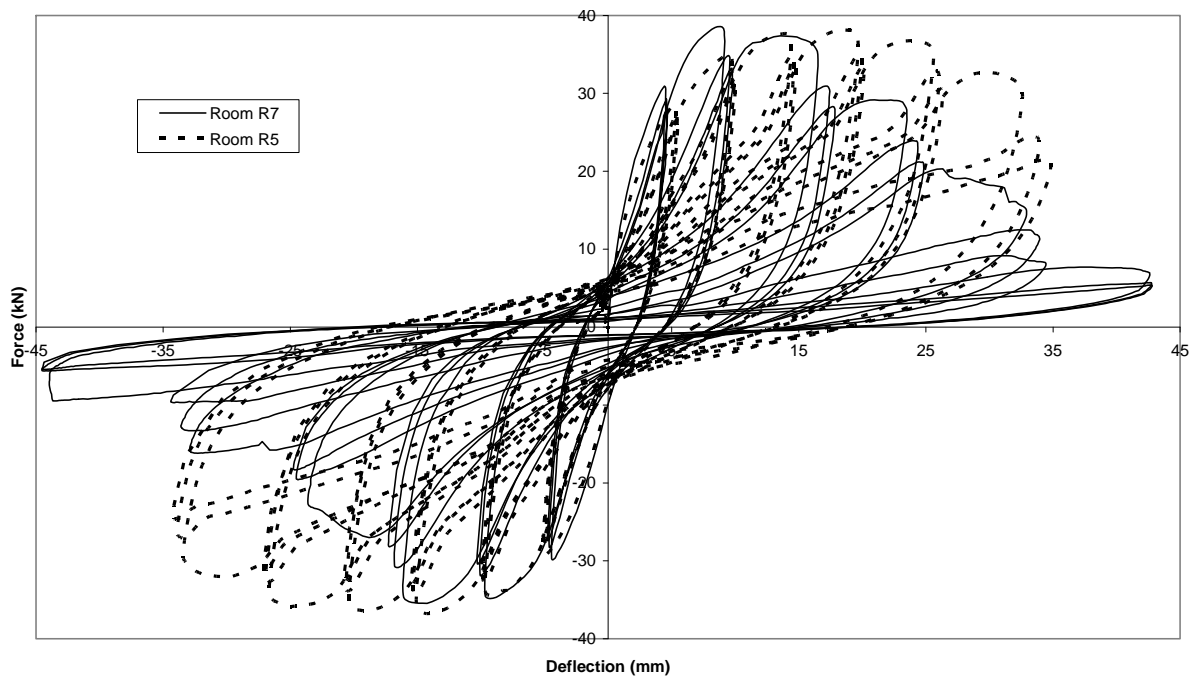**Figure 42. Comparison of test results for Rooms R1 and R2**

Figure 43. Comparison of test results for Rooms R2 and R3

Figure 44. Comparison of test results for Rooms R3 and R4
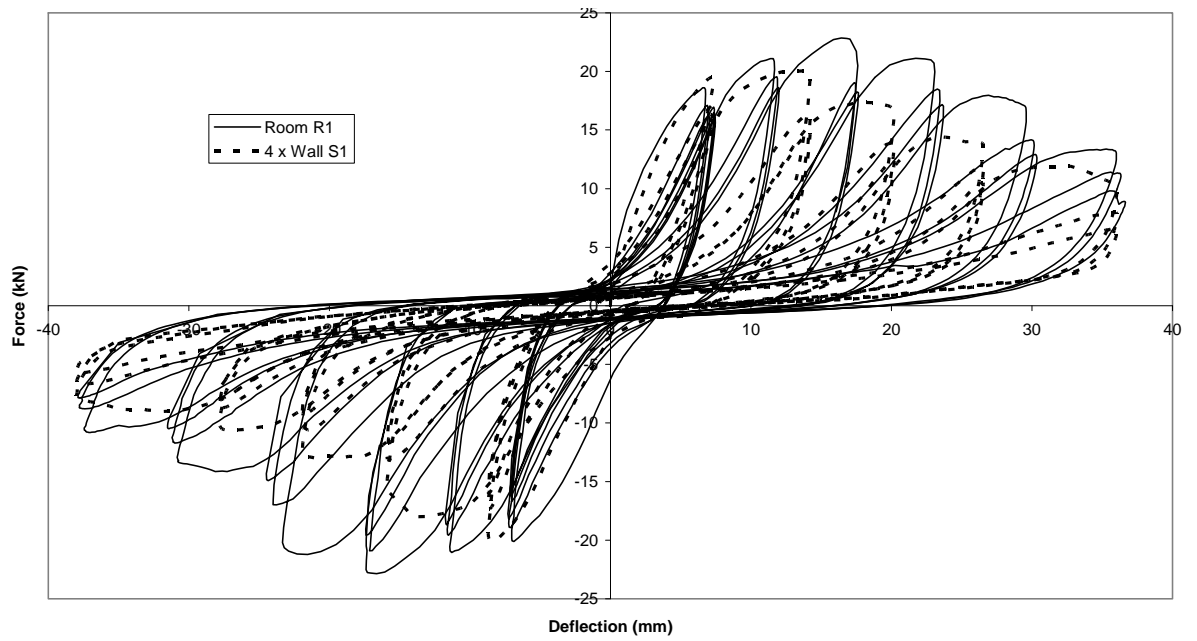
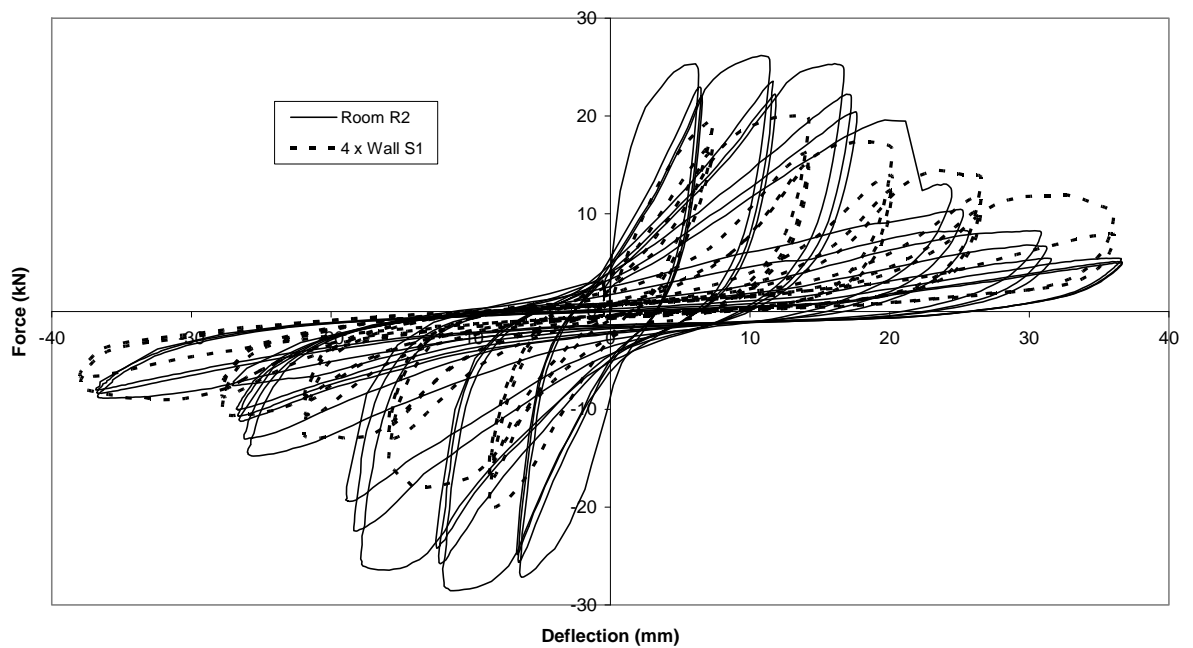**Figure 45. Comparison of test results for Rooms R5 and R6**

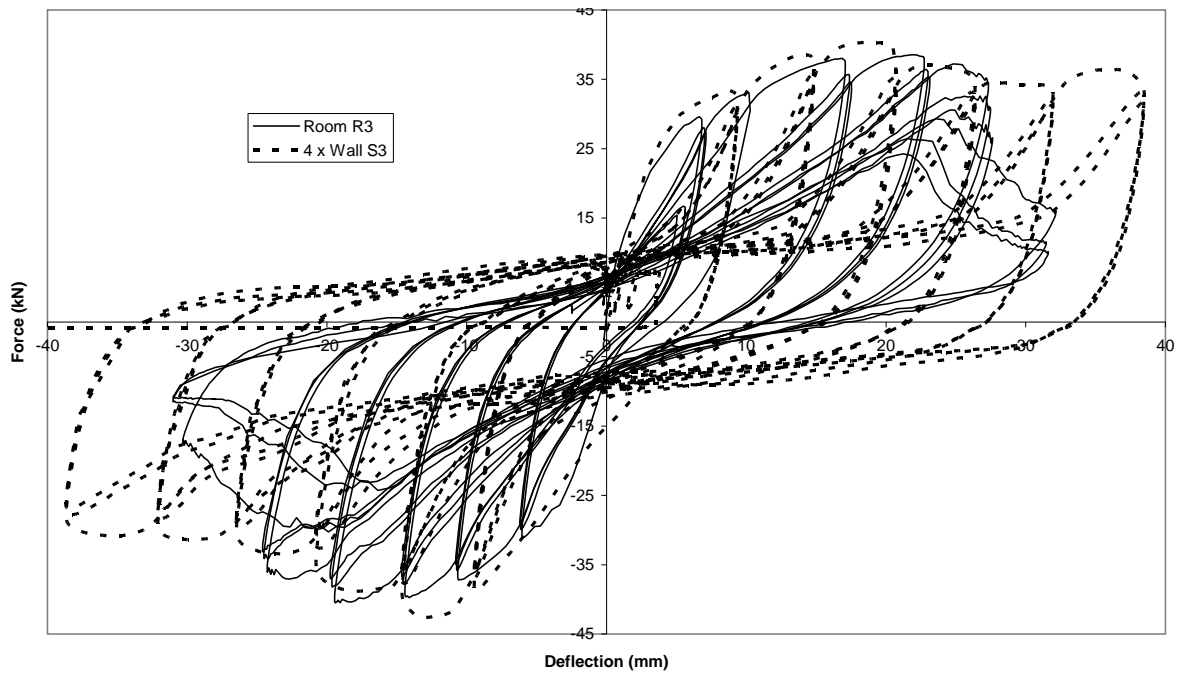**Figure 46. Comparison of test results for Rooms R5 and R7**

Figure 47. Comparison of test results for Room R1 and 4 x Wall S1

Figure 48. Comparison of test results for Room R2 and 4 x Wall S1

Figure 49. Comparison of test results for Room R3 and 4 x Wall S3
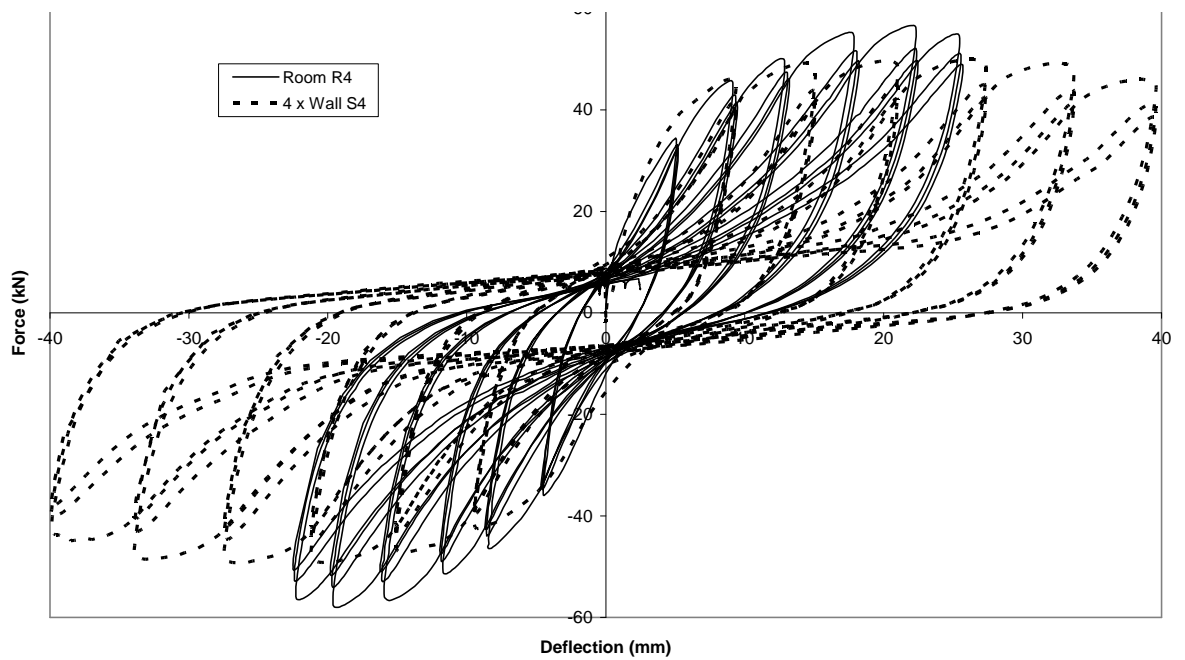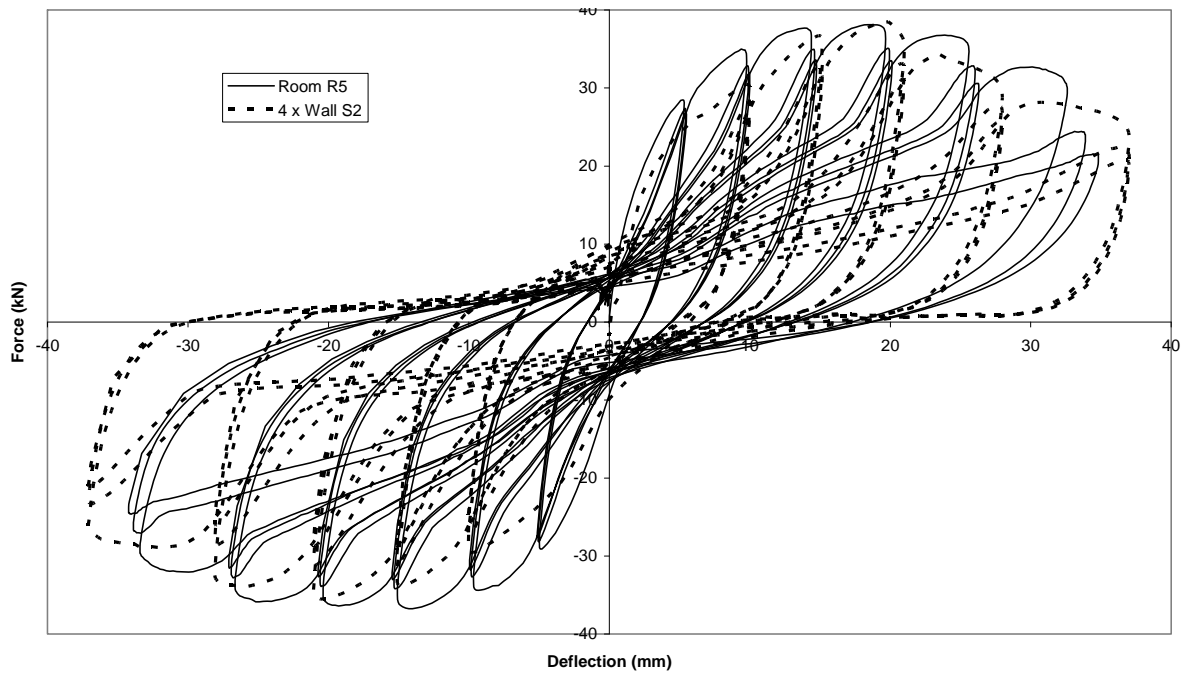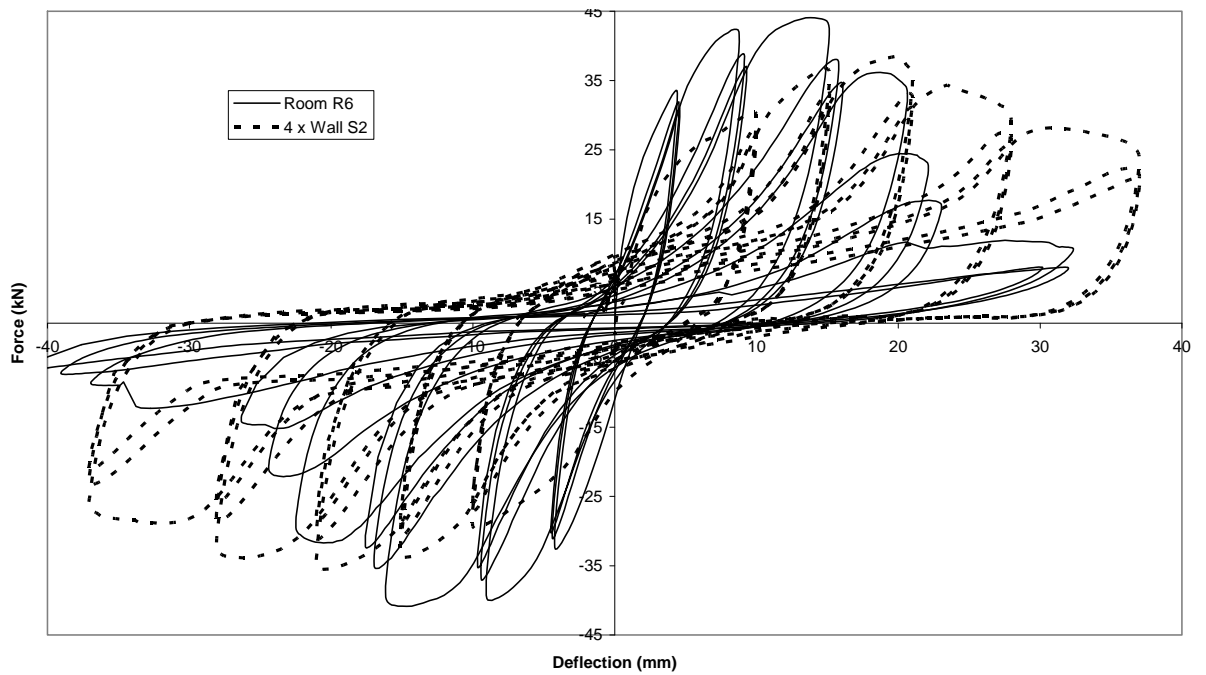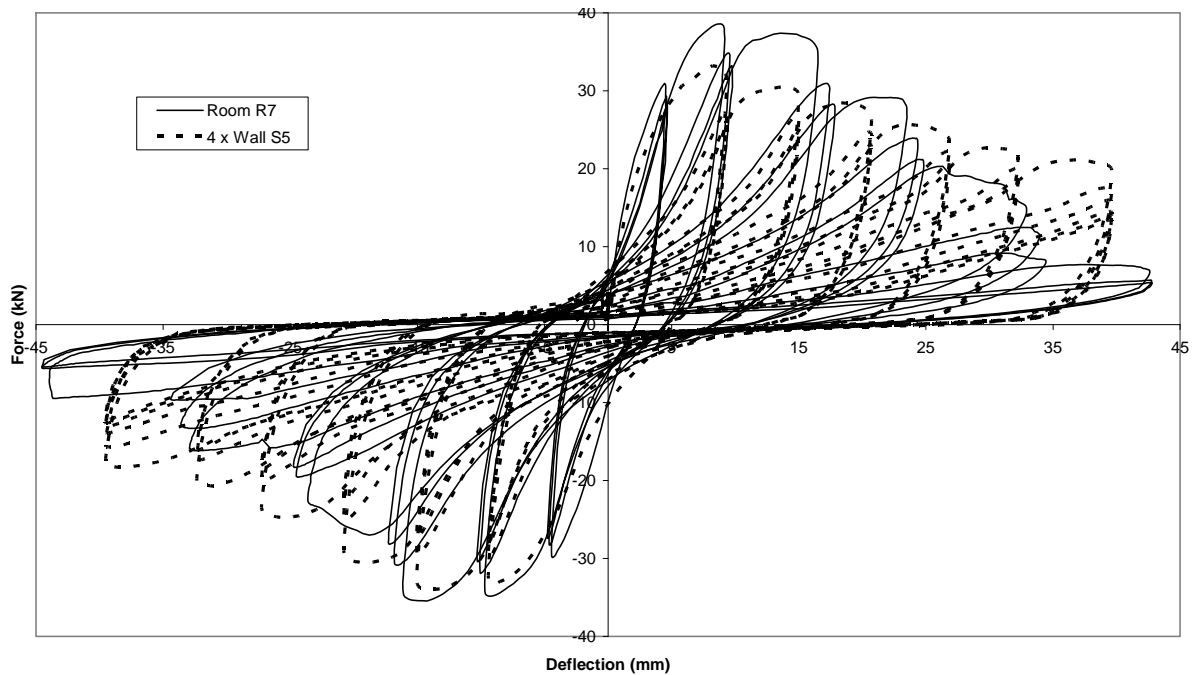

Figure 50. Comparison of test results for Room R4 and 4 x Wall S4

Figure 51. Comparison of test results for Room R5 and 4 x Wall S2

Figure 52. Comparison of test results for Room R6 and 4 x Wall S2

Figure 53. Comparison of test results for Room R7 and 4 x Wall S5

DISCUSSION

1.18 Scope and overview

Tests were performed to assess how much stronger a full room construction was than the component walls. It was assumed that findings could be directly applied to typical house construction. The results are only applicable to timber-framed construction lined with plasterboard with joints taped and stopped.

A house is made up of many rooms and, provided the tested room is representative of other rooms in the house, the conclusions are expected to be applicable to a full house provided the effect of the roof (not used in the room tests) is negligible and can be conservatively ignored. The roof only affects bracing wall performance by virtue of its self-weight which helps resist wall overturning ('rocking') forces. If the roof weight is carried by trusses to walls perpendicular to the earthquake direction, then its weight will add little to the bracing resistance and should be ignored. Hence, the room tests may be considered representative of whole house behaviour.

1.19 Systems effect factor and end restraint recommended

The summary of Section 1.17.3 (j) concluded that:

- the end restraint in isolated full-scale wall tests be based on a '6-nail' end restraint

- a systems effect factor = 1.30 be used for application of the results to NZS 3604 type construction with taped and stopped plasterboard joints.

Constructions with doors in the walls will tend to have lower systems effect factors than those with windows (Thurston 1994). Thurston (2003) measured the systems effect factor on a single storey house in a direction with no doors, but only windows in the walls as 1.5. For construction, including doors, the factor of 1.30 is considered to be more valid.

It is also recommended that the systems effects for timber-framed buildings without taped and stopped plasterboard joints on all internal walls be taken as 1.0 (see Section 1.17.3(c)). These structures are rare. However, the conclusion could also be applied to timber plank or log houses which are not lined.

1.20 Derivation of bracing resistance from racking tests in New Zealand

Although not discussed in this report, it is recommended that the ultimate limit state wall racking wind resistance be taken as the average peak load from the two direction of cyclic loading. The method of obtaining the serviceability limit state wall racking wind resistance is described by Thurston (2004). However because walls experiencing racking wind loads can also be loaded with wind uplift forces, and because there is insufficient evidence to increase wind wall ratings by a large amount, it is recommended that the systems effect factor of 1.3 not be used for wind (at least not for upper storey walls).

The derivation of earthquake resistance from a racking test is more complex as it depends on the assumed ductility of the loadings standard. Thurston 2004 presents a method or use with NZS 3604 loadings (SNZ 1999), but this will need modifying for the new systems effect factor and the S_p factor now recommended in NZS 1170 (SNZ 2004). The method uses the average third cycle peak load to a given deflection. Significant increases in wall earthquake ratings are not expected using the proposed procedures.

CONCLUSIONS

These conclusions are only applicable to timber-framed construction lined with plasterboard with joints taped and stopped.

The theory and test results showed that the lateral resistance of rooms and houses can adequately be determined from half-scale construction.

It is recommended that test procedures for measuring the bracing resistance of isolated bracing walls for use in house design use construction with a '6-nail' end restraint as defined by Thurston (2004).

It is also recommended that the bracing resistance determined from the test assume a systems effect factor of 1.3 for applying the results to NZS 3604 house design for earthquake loading, but not for wind loading of upper storey walls.

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APPENDIX A: PROPRIETARY PRODUCTS USED

Three proprietary sheathings were used in the experimental programme described in this report and referred to as Type PLB or MDF. These products are defined below:

Type PLB was nominal 10 mm standard Gib® Gibraltar Board manufactured by Winstone Wallboards. This was an off-white paper-faced gypsum plaster-based board.

Type MDF is a nominal 9 mm thick medium density fibreboard manufactured by Carter Holt Harvey Ltd.

Note: results obtained in this study relate only to the samples tested and not to any other item of the same or similar description. BRANZ does not necessarily test all brands or types available within the class of items tested and exclusion of any brand or type is not to be taken as any reflection on it.

This work was carried out for specific research purposes, and BRANZ may not have assessed all aspects of the products named which would be relevant in any specific use. For this reason, BRANZ disclaims all liability for any loss or other deficit following use of the named products, which is claimed to be reliance on the results published here.

Further, the listing of any trade or brand names above does not represent endorsement of any named product nor imply that it is better or worse than any other available product of its type. A laboratory test may not be exactly representative of the performance of the item in general use.