STUDY REPORT

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Effect and Remediation of the Loss of Building Lateral Stiffness Caused by Earthquake Loading

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Preface

This is the first report on this topic produced by BRANZ.

Acknowledgments

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BRANZ wishes to acknowledge the help and advice of Hans Gerlich and Richard Hunt of Winstone Wallboards Ltd and attendance at some of the testing.

All building construction was done by Matthew Dixon Building and all plastering by P & J Plastering Ltd.

Note

This report is intended for people involved in post-earthquake repair of houses. In particular builders, contractors, engineers, architects, assessors, EQC, DBH and local authorities.

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BRANZ Study Report SR0265

SJ Thurston

Reference

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Abstract

Following the devastating Christchurch earthquakes some home owners have reported that their houses are noisier when doors are slammed, people climb stairs, heavy vehicles drive by, and during strong winds and aftershocks. Often these houses had only minor apparent earthquake damage. The sensations felt sometimes still occurred after cosmetic repairs.

BRANZ devised an experimental setup in the laboratory to determine how much more flexible houses become following earthquake shaking and the effect of different repair strategies. A small test house was built and exposed to various levels of lateral displacement. The damage and house stiffness were recorded at each stage of testing. Several repair methods were used, the amount of re-stiffening which occurred was measured and recommendations made on the most appropriate repair strategy depending on the degree of plasterboard damage incurred from the earthquake.

Contents Page

1. INTRODUCTION 5

2. TERMINOLOGY 5

3. TEST BUILDING DESCRIPTION 6

4. TEST PROGRAMME 6

4.1 Building racking tests 6
4.2 Building twanging tests 8
4.3 Construction used for the Phase 1 Testing (as built condition) 9
4.4 Construction used for the Phase 2 Testing (following a "cosmetic" repair) 10
4.5 Construction used for the Phase 3 Testing (glued joints broken) 10
4.6 Construction used for the Phase 4 Testing (following a "cosmetic" repair plus strengthening by adding screws) 10
4.7 Compete overlay of plasterboard 11
4.8 Lining and internal walls removed 11

5. TEST RESULTS 12

5.1 Plasterboard damage 12
5.2 Building stiffness 12
5.3 Building natural frequency and damping 13
5.4 Applied force versus wall deflection hysteresis loops 17
5.5 Total building strength 18
5.6 Wall uplift 18

6. CONCLUSIONS 18

APPENDIX A CONSTRUCTION DETAILS AND DRAWINGS 27

APPENDIX B PLASTERBOARD FIXING USED FOR PHASE 1 TESTING 33

APPENDIX C SUGGESTIONS AND COMMENTS ON PLASTERBOARD CRACK REPAIR 43

APPENDIX D DETAILS AND PHOTOGRAPHS OF DAMAGE OBSERVED DURING TESTING AND DAMAGE REPAIR 44

Phase 1 44
Phase 2 44
Phase 3 45
Phase 4 45
Phase 5 45

APPENDIX E BRANZ-RECOMMENDED REPAIR METHODS 58

Figures Page

Figure 1 Plan view of test building showing window and door opening location 7
Figure 2 Photograph of test building 8
Figure 3 Actuator loading test building via load cells 8
Figure 4 Top plate displacements measured in a twanging test 9
Figure 5 Construction for Phase 6.. 12
Figure 6 Illustration of how the test building stiffness was calculated at the end of each test stage.. 14
Figure 8 Change in building stiffness with degree of building racking for each test phase 14
Figure 9 Change in building natural frequency with degree of building racking for each test phase.. 16
Figure 10. Change in percentage of critical damping with wall displacement for each test phase.. 16
Figure 11 Derivation of backbone curves from each test phase 22
Figure 12 Comparison of backbone curves from each test phase 22
Figure 13 Comparison of hysteresis loops for Phase 1 and Phase 2 23
Figure 14 Comparison of hysteresis loops for Phase 2 and Phase 3 23
Figure 15 Comparison of hysteresis loops for Phase 3 and Phase 4 24
Figure 16. Comparison of hysteresis loops for Phase 1 and Phase 4 for displacements up to 11 mm 24
Figure 17 Comparison of hysteresis loops for Phase 1 and Phase 4 for all displacements... 25
Figure 18 Comparison of hysteresis loops for Phase 1 and Phase 5 for displacements up to 11 mm 25
Figure 19 Comparison of hysteresis loops for Phase 4 and Phase 5 26

Tables Page

Table 1 Terminology.. 5
Table 2 Construction used in the various test phases... 6
Table 3 Summary of test building stiffness and dynamic properties at various stages of testing.. 15
Table 4 Relative force resisted at corresponding deflections.. 17
Table 5 Calculation of building bracing strength 19
Table 6 Comparison of predicted and measured building bracing strength 20
Table 7 Uplift measured at the two ends of the internal wall... 21

1. INTRODUCTION

Following the devastating Christchurch earthquakes some house owners have reported their houses have become noisier. They may creak and shake when doors are slammed, people climb stairs, heavy vehicles drive by, and during strong winds and aftershocks. This is referred to as “loss of stiffness” in this report.

Often these houses have had only minor earthquake damage, such as small plasterboard joint cracks. Often the sensations felt still occur even when plasterboard cracks are repaired. Some suggest the “loss of stiffness” is not real and that the owners are just sensitised by having experienced the drama of the large earthquakes. Others suggest there is unseen damage in the house, such as slotting of the plasterboard at fixings which has softened the house.

BRANZ investigated the problem by testing to see how much more flexible houses become when subjected to the deformations expected in earthquake shaking. Racking tests were performed to see how effective different repair strategies are in re-stiffening the house. A small test building was exposed to various levels of earthquake movement whilst the damage and building stiffness was recorded at each stage. Several different repair methods were used and the amount of re-stiffening which occurred was measured. The repairs included:

- Simple cosmetic repair.
- Simple cosmetic repair plus the addition of extra plasterboard screws.
- Using a complete overlay of new plasterboard over the damaged plasterboard and adding wall hold-down anchors.

The tests also examined the effect on house stiffness if glued plasterboard fixings fail. It is thought this sometimes happened in Christchurch because the linings have been reported as feeling loose when prodded.

2. TERMINOLOGY

The following terminology was used in this report. The shorthand name is underlined when used in this report.

Table 1 Terminology

Shorthand name	Full reference
Site Guide	GIB® Site Guide for residential and commercial applications. Dated Jan 2010
Wall hold-down anchor	GIB Handibrac® as detailed in the Site Guide
Standard plasterboard	Winstone wallboard 10 mm GIB® Standard plasterboard
High performance plasterboard	Winstone wallboard 10 mm GIB Braceline® plasterboard
Drywall screws	32 mm x 6g GIB® Grabber® screws
Tradeset	GIB Tradeset® 45 premium jointing compound
Wall glue	GIBFix® All Bond adhesive
Plastered scotia	GIB-Cove® Classic 75 mm

3. TEST BUILDING DESCRIPTION

Appendix A provides the details and drawings of the test building construction. This was a single-room, single-storey building shown in Figure 1 and Figure 2. The building was nominally 2.4 m-high and incorporated window and door openings and two internal walls (one in each direction). It had plasterboard-lined light timber-framed (LTF) walls, a timber-framed plasterboard-lined ceiling with a 20 mm-thick particle board flooring on top. This flooring served to ensure the displacement introduced by the single actuator at the centre of the room was transferred to the outer walls. The outside plan dimensions of the building were 6.49 x 3.69m.

One exterior wall was bolted to the timber foundation beam. The remaining walls were nailed.

A total of 2220 kg of weights were added to the roof. If the building is intended to simulate an 8 m wide house then this represents an average roof weight of 2220/8/6.49 = 42.7 kg/m^2. Note, NZS 3604 [SNZ, 2011] assumes a heavy roof weighs 20-60 kg/m^2.

The building was racked with an actuator which moved a load beam connected to the particle board flooring as shown in Figure 2. The load beam ran the full length of the building and was located mid-width. Thus, the building "roof" moved horizontally, imposing racking deformations on the side walls which is recognised as being similar to the deformations which are imposed by earthquake loading in this direction.

4. TEST PROGRAMME

4.1 Building racking tests

After testing the building in its as-built condition, the building was modified (usually by doing one of the repair strategies) and the building retested. The testing following each modified construction is referred to as a Test Phase. There were six phases which are described in Table 2. Within each phase the testing consisted of a series of stages with each stage being a series of displacement cycles to a designated displacement imposed on the test building. The building was displaced to increasing displacements in successive test stages.

Table 2 Construction used in the various test phases

Test Phase	Building construction
1	As-built condition
2	Cosmetic repair performed after the end of Phase 1.
3	All plasterboard to timber framing glued joints broken
4	Cosmetic repair plus strengthening by adding drywall screws between all adjacent existing screws.
5	A complete overlay of plasterboard added. Wall hold-down anchors added at ends of bracing elements.
6	All lining on Side 1 and 2 walls removed and replaced. Internal walls removed.

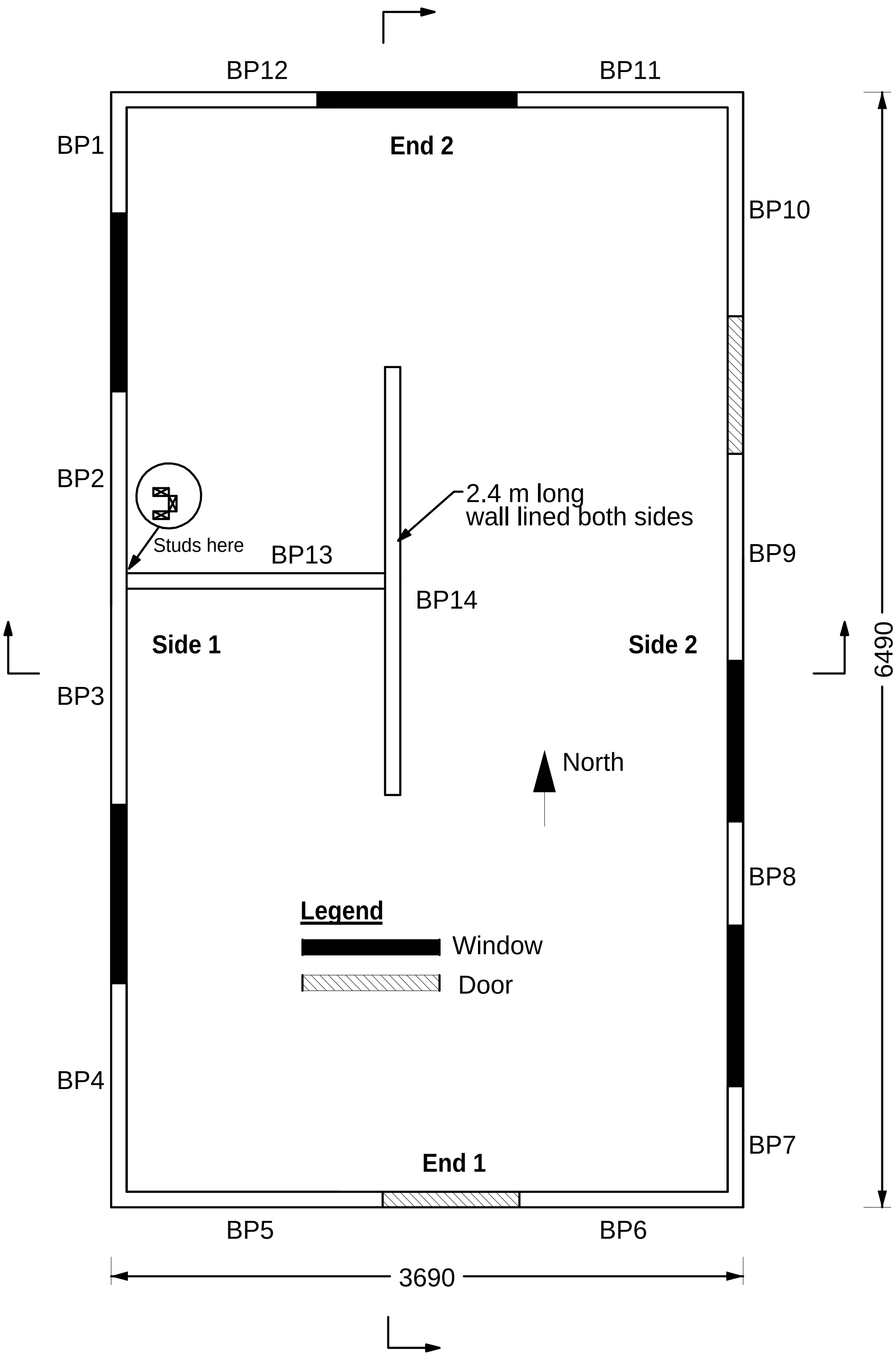


Figure 1 Plan view of test building showing window and door opening location

Added weights

Load beam being assembled

Actuator

Base beam

Figure 2 Photograph of test building

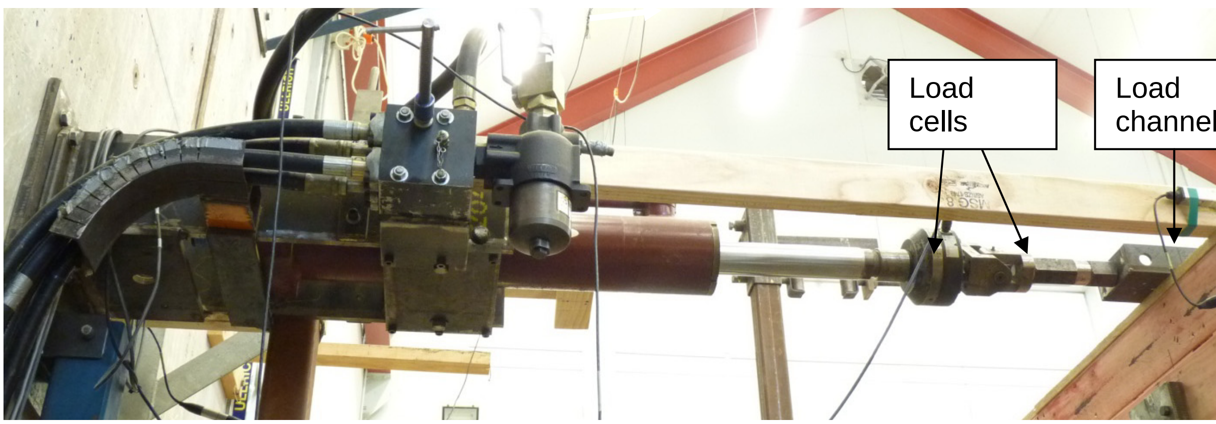


Figure 3 Actuator loading test building via load cells

Each Test Stage is defined with a label in the form, PXDY. The “P” refers to **P**hase and “X” is the relevant phase number. The “D” refers to actuator target **D**isplacement and “Y” is the relevant actuator target displacement. Thus, Stage P2D12 refers to testing of the building in Phase 2, using actuator displacements to ±12 mm.

The top plate displacements of the side walls were significantly less than the actuator target displacement, mainly due to horizontal movement of the strong wall, slip of the load beam on the roof diaphragm and slip between the nailing lines of the roof diaphragm. Table 3 lists the side wall top plate displacements for each test stage. The load rate was sinusoidal with respect to time with an average speed of 4 mm/s.

4.2 Building twanging tests

Between many of the Test Stages the building was subjected to a “twanging test”. This consisted of pushing the building “roof” horizontally by a few millimetres and then performing a quick release. The building oscillation is shown as a decaying vibration in Figure 4. By extracting the displacement and time at the peak points at the "X" symbols in Figure 4 the building's natural frequency and damping given in Table 3 were able to be determined from standard formulae.

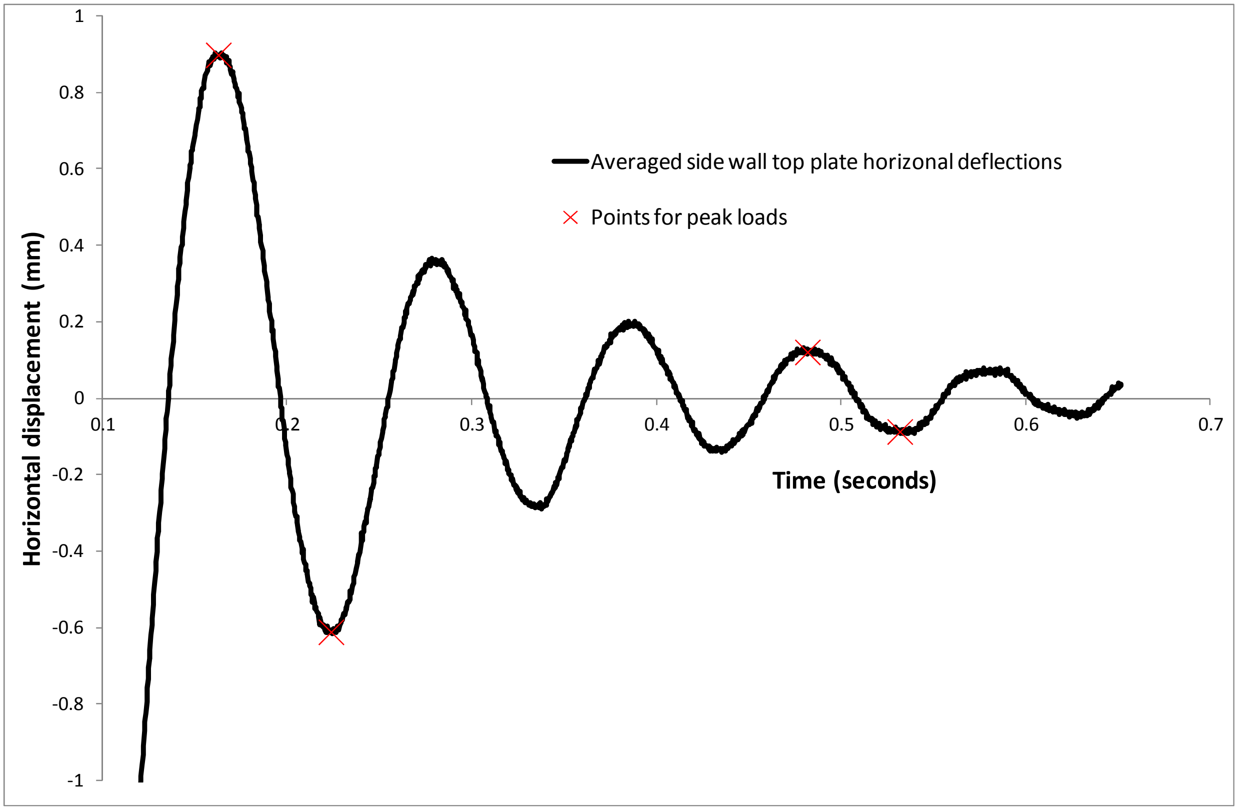


Figure 4 Top plate displacements measured in a twanging test

4.3 Construction used for the Phase 1 Testing (as built condition)

Details of the construction are given in Appendix A and B. The fixings were drywall screws using a fixing pattern of 50 mm along sheet edges from each corner of each bracing element and then at 150 mm from the corner and from then on at 150 mm centres. These fasteners were also used at 300 mm centres at sheet edges in the body of the bracing elements. Adhesive was used to fix sheets to studs in the body of the sheets. The plasterboard joints were formed using paper tape and Tradeset and the adhesive was wall glue.

The locations where various types of scotia was used at the junction between walls and ceiling is defined in Appendix B. There was either none (i.e. square stopped), plastered scotia or timber scotia nominally fixed with 60 x 2.8 brads. 50 mm-high timber skirting was nailed with 60 x 2.8 mm brads at approximately 300 mm centres over the lining at the base of all walls.

The plasterboard was standard plasterboard for all walls and ceilings except one full sheet of high performance plasterboard was used in one corner of Side 2 as shown in Appendix A. Plasterboard installation complied with the Site Guide.

Wall hold-down anchors were used on the studs at the ends of the high performance plasterboard-lined bracing panels. The wall hold-down anchors were coach screwed to the foundation beam and incorporated Tek screws to the studs. The bottom plates of other walls were nailed, bolted or coach screwed to the foundation beam. The location where each type of fixing was used is defined in Appendix A.

4.4 Construction used for the Phase 2 Testing (following a "cosmetic" repair)

At the completion of the testing in Phase 1, the following repair work was performed (see Photographs D.5 to D.12.). The diagonal plasterboard cracks were gouged out by 1-2 mm, all loose and broken material was cut away from vertical crack joints between sheets and a 3-4 mm wide full plasterboard depth groove formed as shown in Photograph D.12, a layer of plaster placed in these areas and a paper tape embedded in this. A second layer of plaster was placed over this approximately four hours later and trowelled smooth. Testing did not commence until at least four days later.

4.5 Construction used for the Phase 3 Testing (glued joints broken)

At the completion of the testing in Phase 2 the glued joints between plasterboard and timber framing were broken. This was achieved by hammering a wooden block placed over the plasterboard inward from the outside of the building at all glue joint locations. To verify the glued joints had broken, a putty knife was moved between stud and plasterboard over the full stud length where the plasterboard had been glued to the studs.

4.6 Construction used for the Phase 4 Testing (following a "cosmetic" repair plus strengthening by adding screws)

The testing in Phase 3 had only been taken to ±10.7 mm and thus cracks were generally minor. However, the crack on sheet BP2 (location defined in Appendix B) was large (see Figure D.14) and thus the full sheet in panel BP2 which was cut around the window was completely replaced. Elsewhere, the following repair work was performed at the completion of the testing in Phase 3:

1. Skirtings were removed from the base of the walls and architraves removed from around window openings. Skirting and architraves were not replaced for the testing in Phase 4.
2. Cracks were cosmetically repaired using a different repair technique from that described in Section 4.2. This is shown in Photographs D.13 to D.19. The method was to cut away and clear all loose and broken material from the crack so that only firm board was remaining and then fill and flush the crack with a setting plaster. A "paper tape" was then installed as per best trade practice and a finish plaster coating placed over the top.
3. On the side walls (but not the end walls) drywall screws were added midway between existing screws along the base of the panels and along all vertical joints on the perimeter of bracing panels which were not at corners. However, they were not added along wall-to-ceiling joints and along the vertical corner joints as these plaster-strengthened joints showed no signs of having being distressed.
4. No strengthening was done of the connections between bottom plate and foundation beam. The end walls were left unchanged as they had experienced little damage.

4.7 Compete overlay of plasterboard

The work described below was only performed on the side walls. The end walls were left unchanged as they had experienced little damage.

1. The testing in Phase 4 had been taken to ±31.4 mm and some sheets were partly detached and cracked with the plasterboard on either side of the cracks not aligned. To correct this damage, screws were removed until the board could be pushed to be flush with the studs and then the screws were replaced.
2. Scotias along the ceiling to wall junction were removed on both side walls.
3. Drywall screws were added along the middle studs at 300 mm centres where the glued joints had been broken.
4. The sheets were scraped flat along broken joints so that a planar surface was left ready to receive the overlay board.
5. A trimmer was added around windows and the door so that the new cover sheet would butt against the trimmer.
6. Holes were cut at the ends of the internal wall and wall hold-down anchors added.
7. Wall hold-down anchors were also added at the ends of side wall bracing walls on external walls where there was not a wall hold-down anchor already.
8. Cover sheets were placed vertically along all long walls so they initially covered window openings and the door opening. Using the windows/door as a guide, the plasterboard was cut from the opening areas. The fixings were 41 x 6g screws using a pattern of 50 mm from each corner of each bracing element and then at 150 mm from the corner and from then on at 150 mm centres. These fasteners were also used at 300 mm centres in the body of the sheets. The plasterboard cover sheets were the same type as the board underneath – i.e. as described in Section 4.3 above.
9. Scotias and skirting were replaced so they were the same as used in the original construction and the wall board joints were plastered as described in Section 4.3.

4.8 Lining and internal walls removed

The internal walls were removed and the plasterboard removed from Side 1 and Side 2 as shown in Figure 5.

Figure 5 Construction for Phase 6

5. TEST RESULTS

5.1 Plasterboard damage

Photographs and a description of damage at each stage of testing is given in Appendix D.

5.2 Building stiffness

Table 3 lists the test building properties measured at each stage of each phase of testing. For each stage of testing this gives the building stiffness (as described below); the average side wall top plate displacements; the building natural frequency and the percentage of critical damping.

The building stiffness, K (kN/mm), taken as being applicable **after** the referenced stage of testing, was calculated from the formula:

$K = \{(P1 – P4)/2 +(P2 – P3)/2\}/2$ ...... (1)

The loads P (in kN) in Eqn (1) were extracted from the **last** cycle of building loading for the particular stage at a wall displacement of +1 mm or -1 mm as applicable. This is illustrated in Figure 6. Thus, the stiffness “K” is the average slope of the hysteresis loop when traversing between -1 mm to +1 mm when the building was being loaded in the push direction and when traversing between +1 mm to -1 mm when the building was being pulled back in the other direction. This is the average slope between the “X” marks on Figure 6.
The **initial** stiffness was calculated from the **first** cycle of building loading for the referenced Test Phase.

Figure 7 plots the change of building stiffness with building deflection for each Test Phase. Values are also summarised in Table 3. In all cases building stiffness drops rapidly with increased wall deflection. Comments on Figure 7 are:

- Phase 2 shows a moderate drop in stiffness values from Phase 1 but this reduces with deflection until it is similar to Phase 1 at the maximum deflection of 7.3 mm. This indicates the cosmetic repair was moderately effective.
- Phase 3 shows similar stiffness values to that achieved in Phase 2 at 10.4 mm deflection. This indicates that breaking the glue bond had little effect on building stiffness.
- Phase 4 shows slightly higher stiffness values from Phase 2 up to 4.2 mm displacement and then it is similar to Phase 2. Note however, that the maximum displacement prior to Phase 4 was 10.4 mm whereas it was only 7.3 mm with Phase 2 and the building had experienced more load cycles with Phase 4. The uplift movement of the ends of the internal wall were similar for Phase 2 and Phase 4. Overall, this indicates the Phase 4 repair was only slightly more effective than the cosmetic repair.
- Phase 5 shows little drop in stiffness values from Phase 1 even though the building had displaced 31.4 mm in Phase 4. This indicates the overlay repair was effective. The wall hold-down anchors placed at the ends of the internal wall were not as effective as expected as the holes for the coach screws had been drilled too large and at displacements of 10 mm the internal wall ends uplifted by approximately 70% of that for Phase 4. Had these hold-downs been more effective, greater stiffness would have resulted in Phase 5 as damage to the internal wall was still relatively small at test completion.

5.3 Building natural frequency and damping

Figure 8 plots the change of building natural frequency with side wall deflection for each Test Phase. Values are also summarised in Table 3. In all cases the building natural period reduces with increased deflection. Comments are:

- Phase 2 shows similar values of natural frequency values as Phase 1 over the range where both were measured (4.2 to 7.3 mm). This indicates that the cosmetic repair was moderately effective.
- Phase 3 shows only a slight drop in natural frequency values to that achieved in Phase 2 at 10.4 mm deflection. This indicates that breaking the glue bond had little effect on building natural frequency.
- Phase 4 shows similar natural frequency values as Phase 2 up to 4.2 mm displacement and then it rapidly reduces below the values measured in Phase 2. This indicates that the test building would be satisfactory at service loads but then became softer in Phase 4 to what it had been in Phase 2 at corresponding building displacements.
- Phase 5 results generally show greater natural frequency values at corresponding deflections than the other test results indicating that the repair strategy was successful.

Figure 9 shows that the change in “percentage of critical damping” increases with increased side wall deflection. The data in Figure 9 is similar for all the test constructions and so no conclusions are made with regard to the damping.

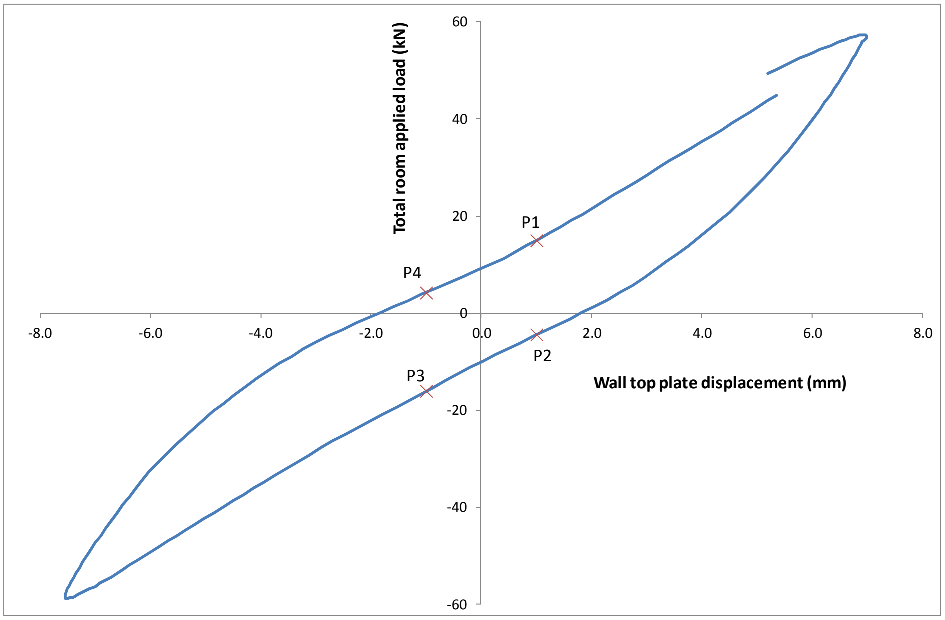


Figure 6 Illustration of how the test building stiffness was calculated at the end of each test stage (Refer to Section 5.2).

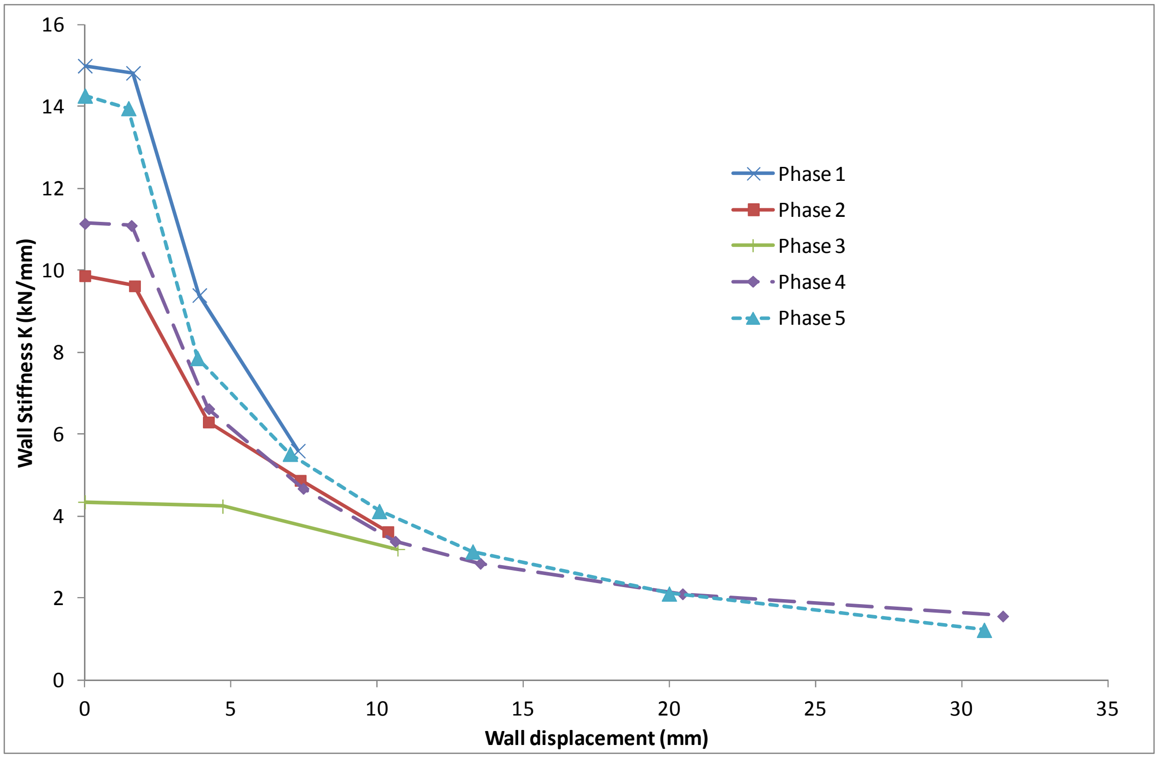


Figure 7 Change in building stiffness with degree of building racking for each test phase

Table 3 Summary of test building stiffness and dynamic properties at various stages of testing

	Measurements prior to twang			
Stage in testing	**Stiffness K (kN/mm)**	**Cyclic def. Δ (mm)**	**Frequency f (Hz)**	**Damping ξ**
Before any tests	15.0	0	12.29	1.83%
After P1D4	14.8	±1.65	-	-
After P1D8	9.4	±3.92	10.61	3.39%
After P1D12	5.6	±7.29	9.81	4.64%
Phase 2 start	9.9	0	-	-
After P2D4	9.6	±1.70	-	-
After P2D8	6.3	±4.23	10.22	3.92%
After P2D12	4.9	±7.37	10.02	4.23%
After P2D16	3.6	±10.37	9.64	4.73%
Phase 3 start	4.4	0	9.52	5.07%
After P3D8	4.2	±4.71	-	-
After P3D16	3.2	±10.70	9.11	5.62%
Phase 4 start	11.2	0	10.52	2.79%
After P4D4	11.1	±1.59	-	-
After P4D8	6.6	±4.24	10.17	3.34%
After P4D12	4.7	±7.47	-	-
After P4D16	3.4	±10.62	8.06	6.12%
After P4D20	2.9	±13.53	-	-
After P4D28	2.1	±20.45	7.36	6.45%
After P4D40	1.6	±31.41	-	-
Phase 5 start	14.3	0	11.63	2.28%
After P5D4	14.0	±1.49	-	-
After P5D8	7.9	±3.85	11.45	3.52%
After P5D12	5.5	±7.02	-	-
After P5D16	4.1	±10.07	11.32	5.66%
After P5D20	3.1	±13.27	-	-
After P5D28	2.1	±19.99	8.37	7.03%
After P5D40	1.2	±30.77	6.60	8.42%

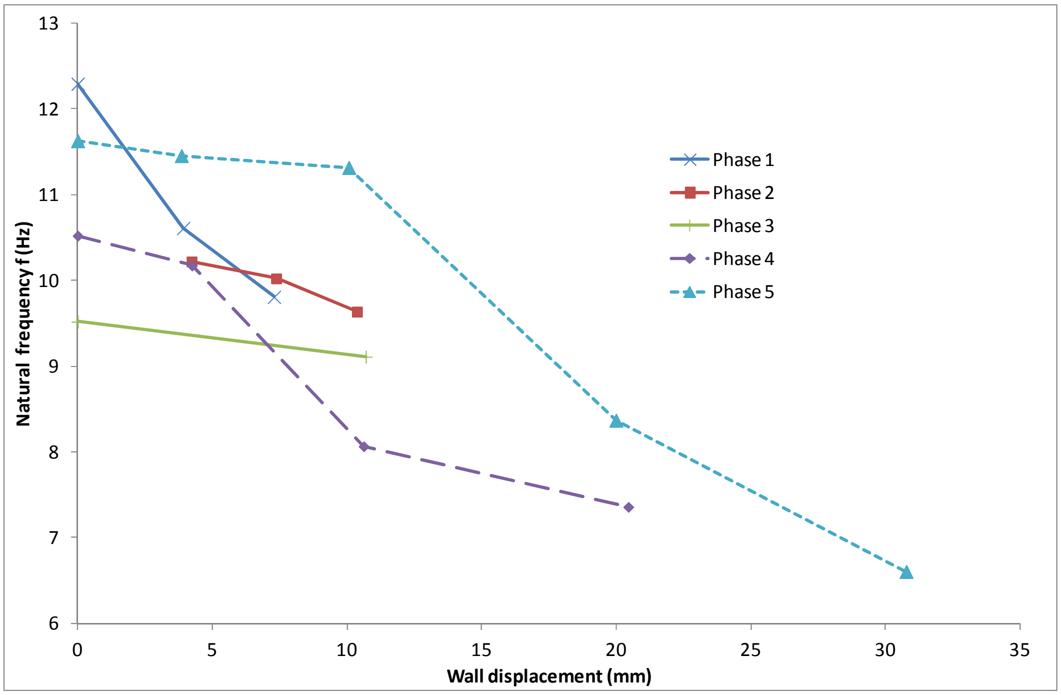


Figure 8 Change in building natural frequency with degree of building racking for each test phase

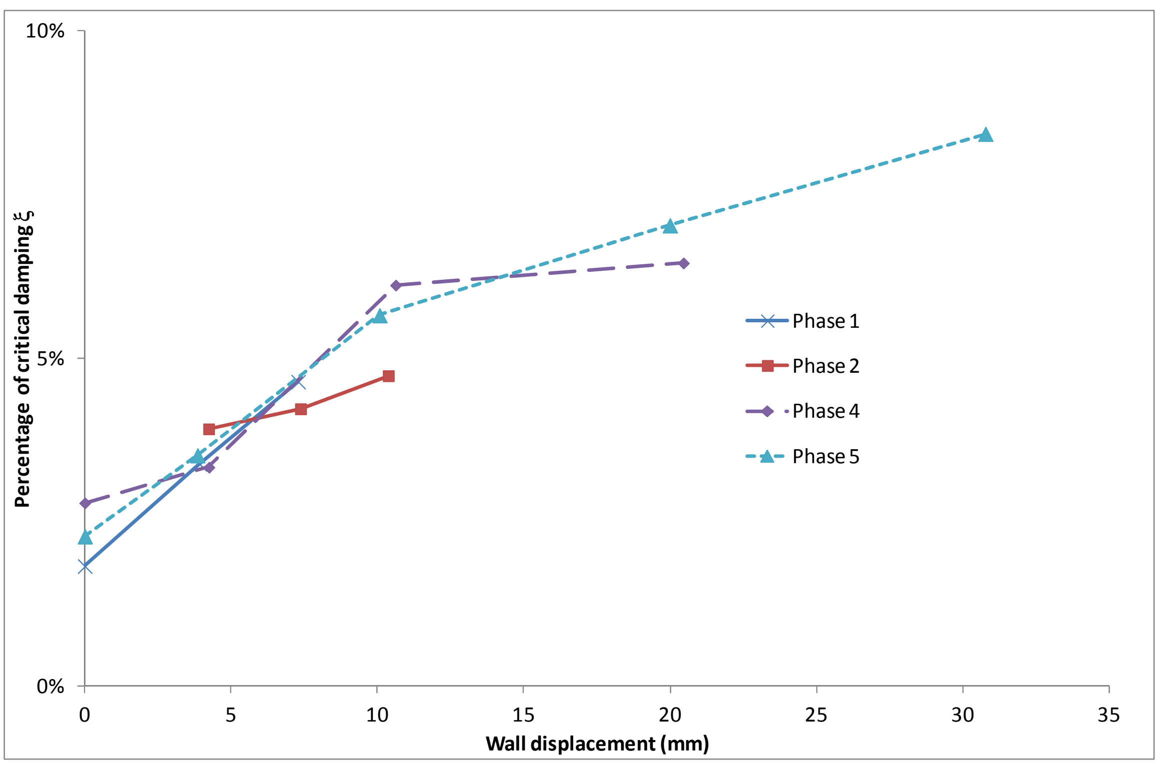


Figure 9. Change in percentage of critical damping with wall displacement for each test phase

5.4 Applied force versus wall deflection hysteresis loops

A single backbone curve was extracted from the total hysteresis loops from each Test Phase as follows. First the data was used to determine a positive and negative backbone as illustrated in Figure 10 for the total load versus displacement data by taking peak values and following data points as much as possible. The average magnitude of the positive and negative backbone curves was then used to get a total backbone curve.

A comparison of the backbone curves for each Test Phase is given in Figure 11. Figure 11 indicates the Phase 5 repair fully reinstated the building load versus deflection behaviour. Phases 2 and 4 show a moderate drop from Phase 1, but the difference is not large.

Table 4 compares the force resisted by the building in testing following building repair with the force resisted in Phase 1 at corresponding building displacements. This shows for low building displacements the Phase 5 repair almost reinstated the building strength but the Phase 2 and 4 repairs did not achieve this. Phase 4 was better at 2 mm displacements but the opposite was true at 4 and 7 mm displacements.

Figure 12 compares the hysteresis loops for Phase 1 and 2. These show almost identical loops for displacements up to 7.3 mm. Greater displacements up to 10.4 mm were applied in Phase 2 and the loops for these are consistent with the notion that the cosmetic repair prior to Phase 2 had been effective.

Figure 13 compares the hysteresis loops for Phase 2 and 3. The Phase 3 loops at the maximum displacement match what would have been expected if additional cycles had been performed with Phase 2. The results are thus consistent with the notion that the glue fixings had added little to the building stiffness or strength.

Table 4 Relative force resisted at corresponding deflections (Phase 1 = 100%)

	Displacement (mm)		
Phase	**2**	**4**	**7**
2	72.1%	81.3%	86.5%
4	78.8%	76.9%	75.8%
5	96.3%	96.1%	96.0%

Figure 14 compares the hysteresis loops for Phase 3 and 4. These indicate the Phase 4 strengthening had added little to the building strength.

Figure 15 compares the hysteresis loops for Phase 1 and 4 up to 10.6 mm displacement. The Phase 4 loops show a moderate drop in the building stiffness and strength from the initial Phase 1 condition. A comparison at greater displacements is shown in Figure 16. Here, the building continued to increase in strength up to 20.4 mm displacement and then showed some load deterioration in resistance.

Figure 16 compares the hysteresis loops for Phase 1 and 5 up to 10.1 mm displacement. The Phase 5 loops coincide moderately closely with the Phase 1 loops showing the repair before Phase 5 had achieved a full recovery of building stiffness and strength despite the high racking in Phase 4.

Figure 18 compares the hysteresis loops for Phase 4 and 5. The Phase 5 loops show a moderate improvement over Phase 4.

5.5 Total building strength

It is interesting to compare the total strength of the building with the predicted peak load bracing strength based on estimations from P21 tests on isolated panels. The predicted strength is calculated in Table 5. This is compared with the building strength measured in each Test Phase in Table 6. It can be seen that the actual strength was far greater than the predicted strength. The ratio between the two is referred to as the “systems factor”. This factor is expected to vary from building to building and the small test building may have achieved a greater systems factor than is typical with real buildings.

5.6 Wall uplift

The measured peak uplift of the bottom plates at the ends of the internal wall is summarised in Table 7. As this wall had an aspect ratio of 1.0, an uplift of “x” mm corresponds to a racking displacement of “x” mm. It can be seen that uplift was large, reaching approximately 50% of the maximum building horizontal displacement in each Test Phase. This would have reduced the effectiveness of the internal wall as a bracing element.

The wall hold-down anchors placed at the ends of the internal wall were not as effective as expected as the holes for the coach screws in the bottom plate had been drilled too large. Uplift should not have occurred at the ends of the internal wall in Phase 5 but the uplifts given in Table 7 were still large. Had these hold-downs been more effective, greater wall horizontal stiffness would have resulted as damage to the internal wall was still relatively minor at test completion.

The bottom plate was nailed to a timber foundation on Side 2. Uplift of the bottom plates on the Side 2 bracing walls was observed to be large in Phases 1 to 4 and the walls “rocked” as well as experiencing shear distortion. This “rocking action” is likely to have protected the Side 2 walls as it reduced the racking shear distortion. This is consistent with the observation that less plasterboard damage occurred in Side 2 walls. The “rocking” will have reduced the stiffness of the walls and hence the effectiveness of the Phase 4 repair strategy.

6. CONCLUSIONS

Loss of glue adhesion in the body of the plasterboard sheets has little effect on building lateral stiffness.

The cosmetic repair prior to Phase 2 testing was moderately effective at reinstating the initial building stiffness. However, the full initial building stiffness was not reinstated by this method. After subsequent racking displacements to approximately 4 mm building displacement, the cosmetic repair had been effectively destroyed.

Performing a cosmetic repair and also adding additional screws to the plasterboard fixings prior to the Phase 4 testing showed little improvement over the simple cosmetic repair of Phase 2. It was expected that this was due to:

1. Walls in Phase 4 rocking under racking load (i.e. uplifting at the ends due to bottom plate nails pulling out). This would have reduced the stiffness of the walls. However, this is likely to be a real effect in building repair using this strategy.
2. Damage to plasterboard under the wall-to-ceiling scotia not being repaired in the repair strategy. This is likely to also occur in building repair using this strategy.
3. Skirtings and architraves having been removed prior to Phase 4.
4. The cosmetic part of the repair used prior to Phase 4 was slightly different and is considered to be less effective than that used prior to Phase 2.

If the effects of (3) and (4) above were removed, it is expected that greater improvement would have occurred with the cosmetic repair plus added screws repair method. However, it is uncertain whether full initial building stiffness would have been achieved by this method.

Using a full overlay of plasterboard sheets and adding wall hold-down anchors to the ends of bracing elements was shown to be an effective repair strategy to reinstate the initial building stiffness. In fact, greater stiffness and strength is expected in practice as the hold-downs on internal walls are likely to be more effective.

In summary, we assess that:

1. Repairing houses using a plasterboard overlay and adding wall hold-down anchors (or equivalent) to the ends of bracing elements is the most effective repair method BRANZ used and can be relied upon to restore or exceed the original house stiffness and strength, and hence avoid the serviceability problems discussed in Section 1.
2. A simple cosmetic repair will not reinstate the initial house stiffness but is moderately effective.
3. A simple cosmetic repair plus the addition of extra screws fixing the plasterboard to the faming is considered to be the second-most effective repair method but in the testing described herein was not greatly more effective than a simple cosmetic repair for construction where bracing wall hold-down connections were insufficient to prevent the bracing panels from rocking.

Table 5 Calculation of building bracing strength

Board	Type	Length (m)	Number	Peak strength (kN/m)	Total house strength (kN)
Standard	Single sided	0.6	3	3.2	5.76
Standard	Single sided	1.2	4	3.5	16.8
Braceline	Single sided	1.2	1	6.7	8.04
Standard	Double sided	2.4	1	4.6	11.04
				Total	41.64

Table 6 Comparison of predicted and measured building bracing strength

Test	Peak applied displacement (mm)	Average of peak strengths from push and pull (kN)	Ratio with predicted strength
Phase 1	7.29	57.39	1.38
Phase 2	10.37	65.94	1.58
Phase 3	10.7	62.27	1.50
Phase 4	31.41	86.90	2.09
Phase 5	30.77	101.57	2.44
Phase 6	39.6	3.72	

Table 7. Uplift measured at the two ends of the internal wall

Stage	Cyclic def. Δ (mm)	U1 (mm)	U2 (mm)	Ratio Av. (U1&U2)/Δ
Phase 1				
P1D4	±1.65	0.46	0.51	0.29
P1D8	±3.92	1.52	1.30	0.36
P1D12	±7.29	3.72	3.06	0.47
Phase 2				
P2D4	±1.70	0.58	0.39	0.28
P2D8	±4.23	1.84	1.34	0.38
P2D12	±7.37	3.65	3.14	0.46
P2D16	±10.37	5.65	5.00	0.51
Phase 3				
P3D8	±4.71	2.03	1.69	0.39
P3D16	±10.70	5.81	5.22	0.52
Phase 4	0			
P4D4	±1.59	0.43	0.57	0.32
P4D8	±4.24	1.47	1.79	0.38
P4D16	±10.62	5.24	5.55	0.51
P4D20	±13.53	7.55	7.53	0.56
P4D28	±20.45	12.85	12.02	0.61
P4D40	±31.41	21.73	22.02	0.70
Phase 5				
P5D4	±1.49	0.31	0.27	0.20
P5D8	±3.85	0.98	0.85	0.24
P5D12	±7.02	2.59	1.66	0.30
P5D16	±10.07	4.64	2.61	0.36
P5D20	±13.27	7.11	3.86	0.41
P5D28	±19.99	12.81	8.00	0.52
P5D40	±30.77	21.92	12.27	0.56

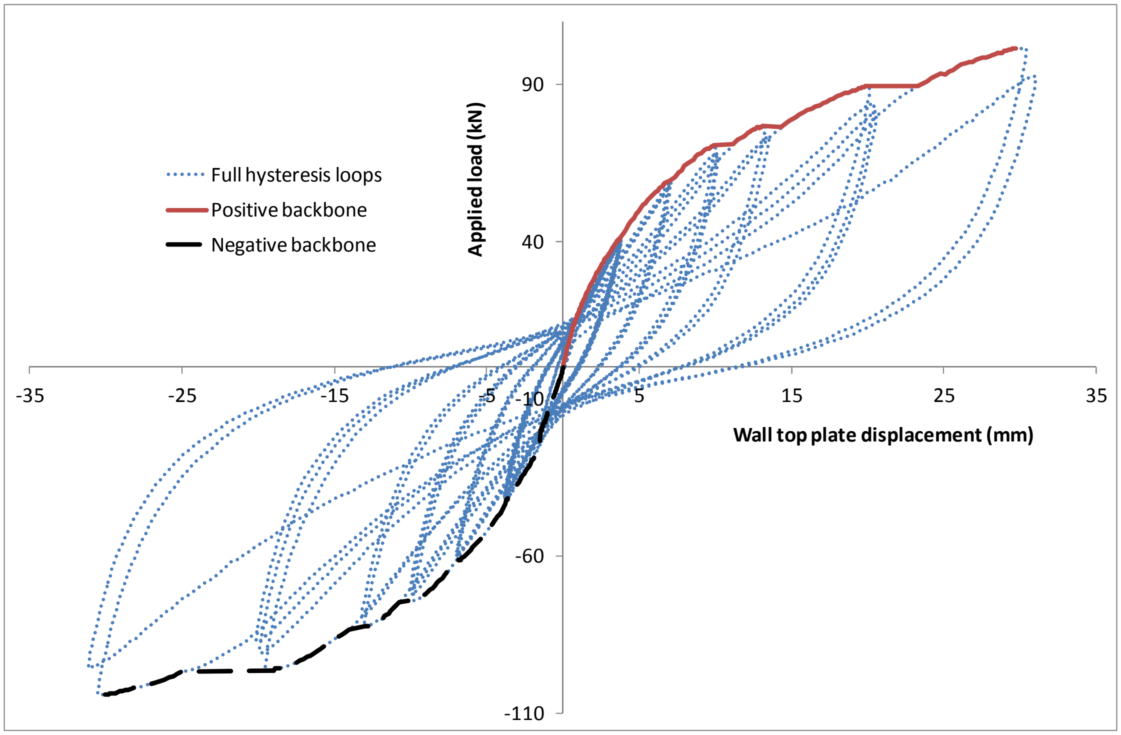


Figure 10 Derivation of backbone curves from each test phase

(Example is Phase 5)

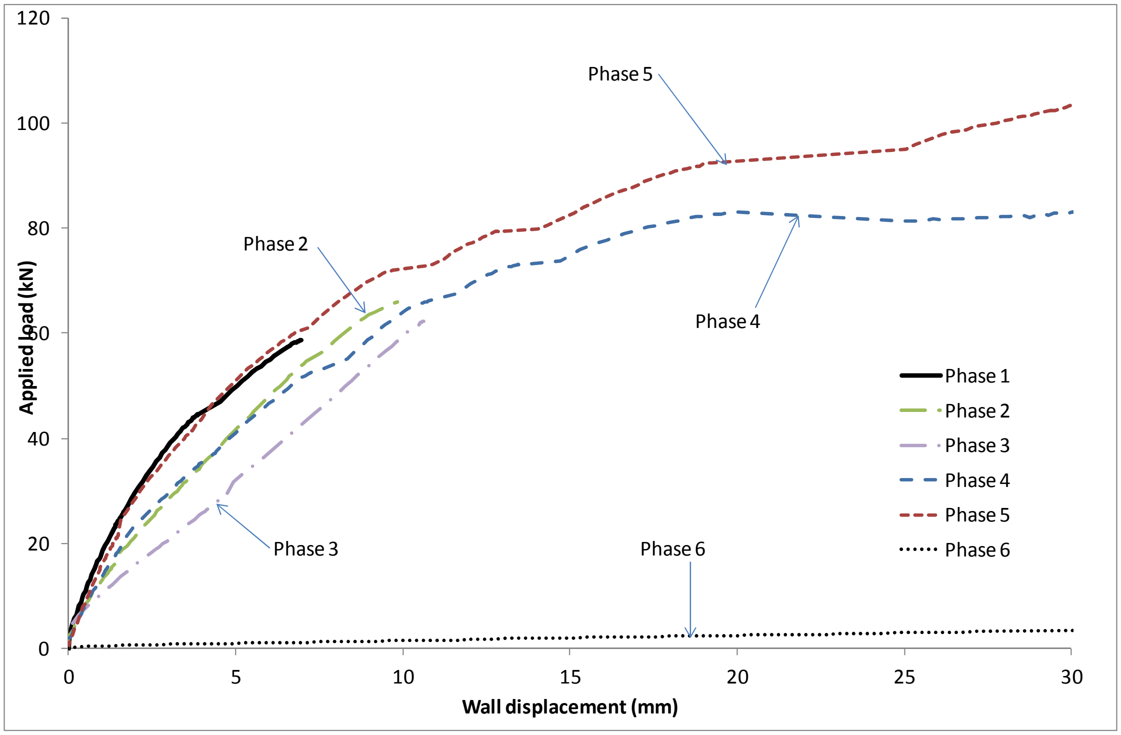


Figure 11 Comparison of backbone curves from each test phase

(Refer to Table 2 for Phase description)

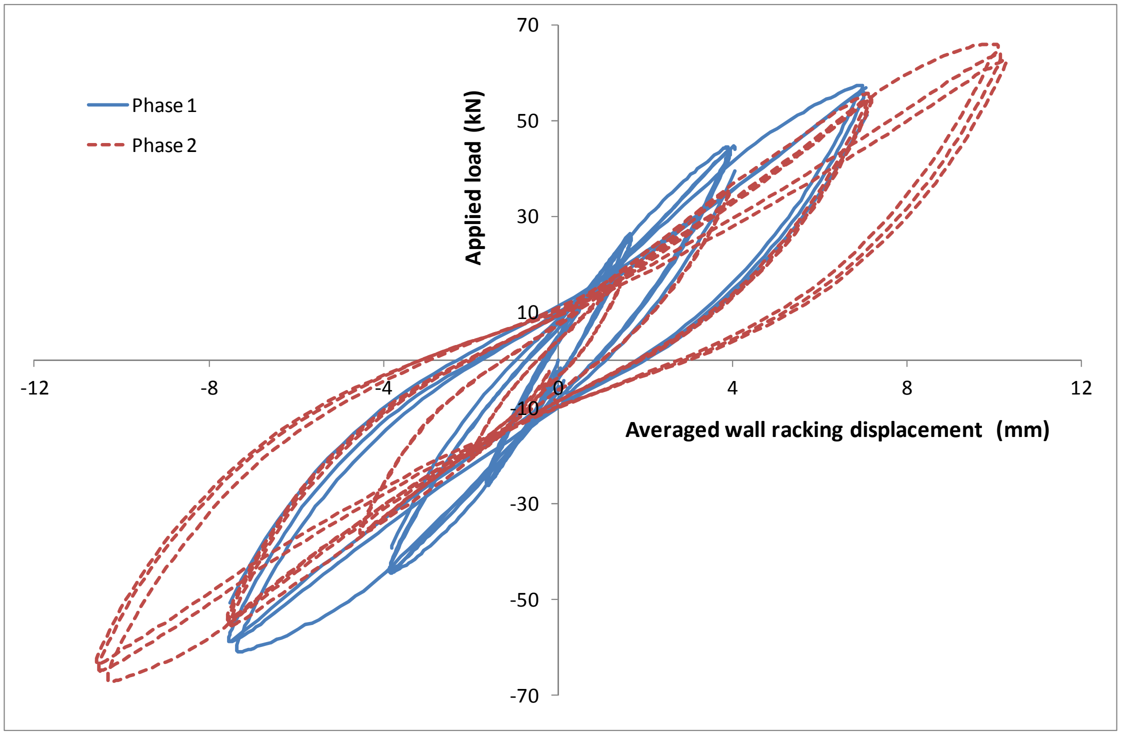


Figure 12 Comparison of hysteresis loops for Phase 1 and Phase 2

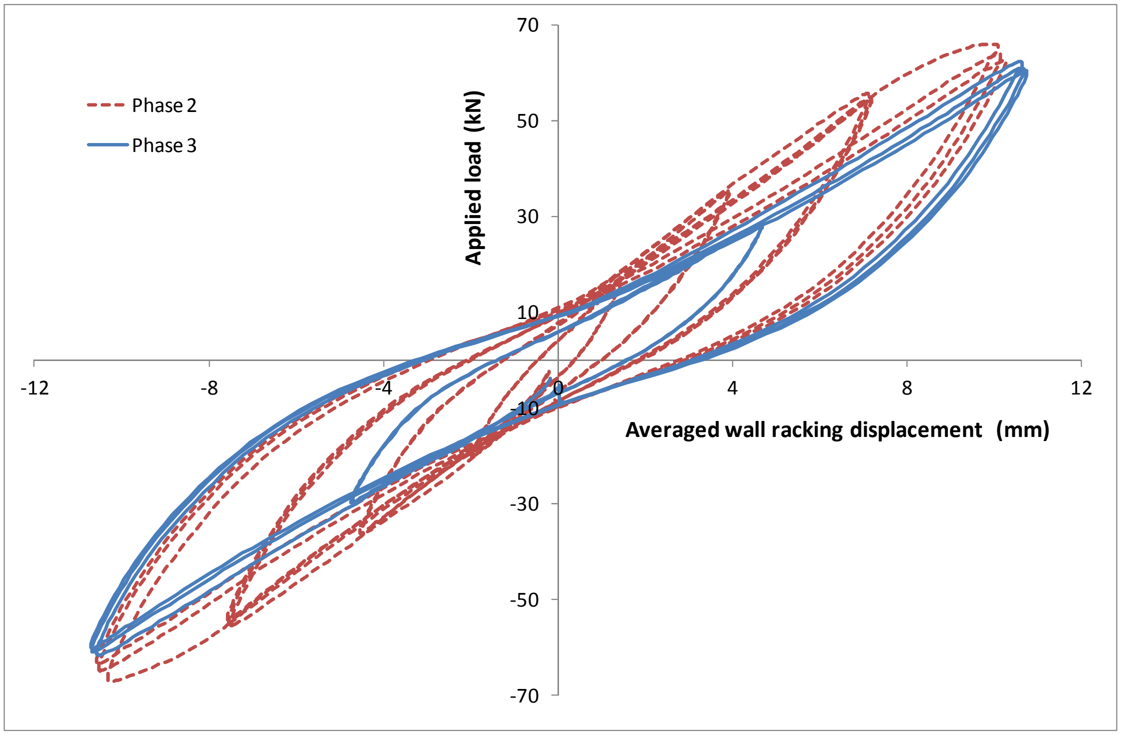


Figure 13 Comparison of hysteresis loops for Phase 2 and Phase 3

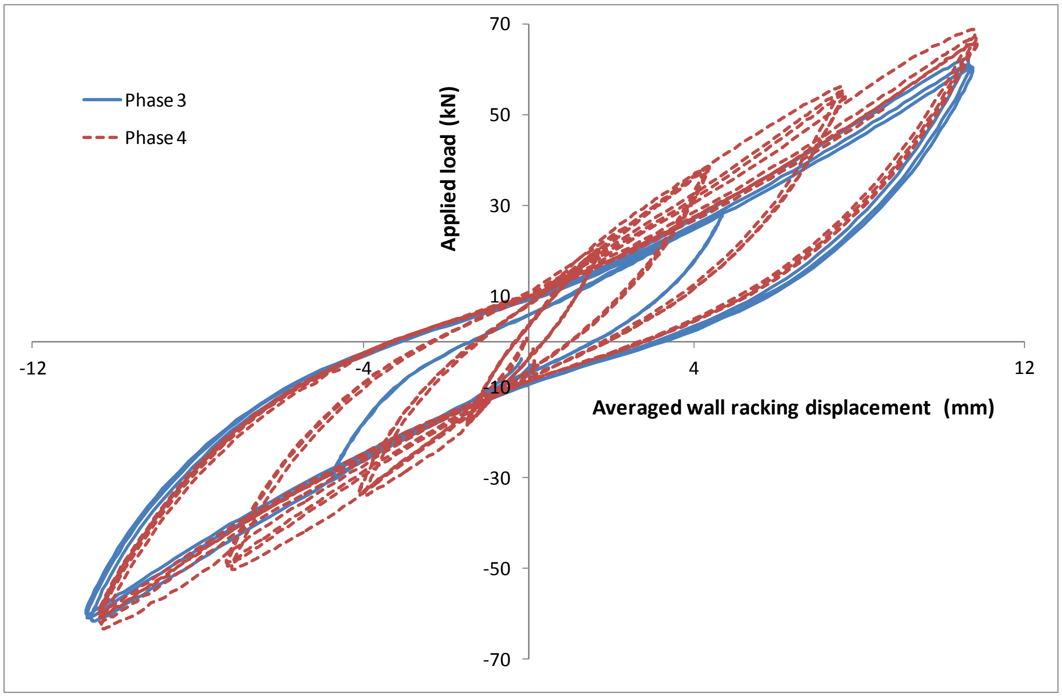


Figure 14 Comparison of hysteresis loops for Phase 3 and Phase 4

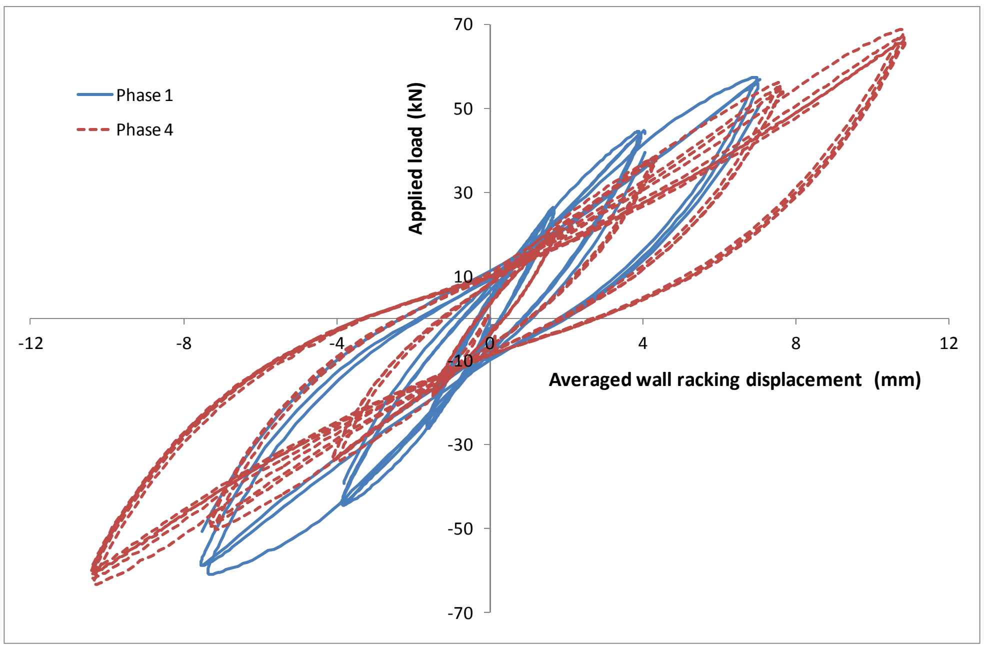


Figure 15. Comparison of hysteresis loops for Phase 1 and Phase 4 for displacements up to 11 mm

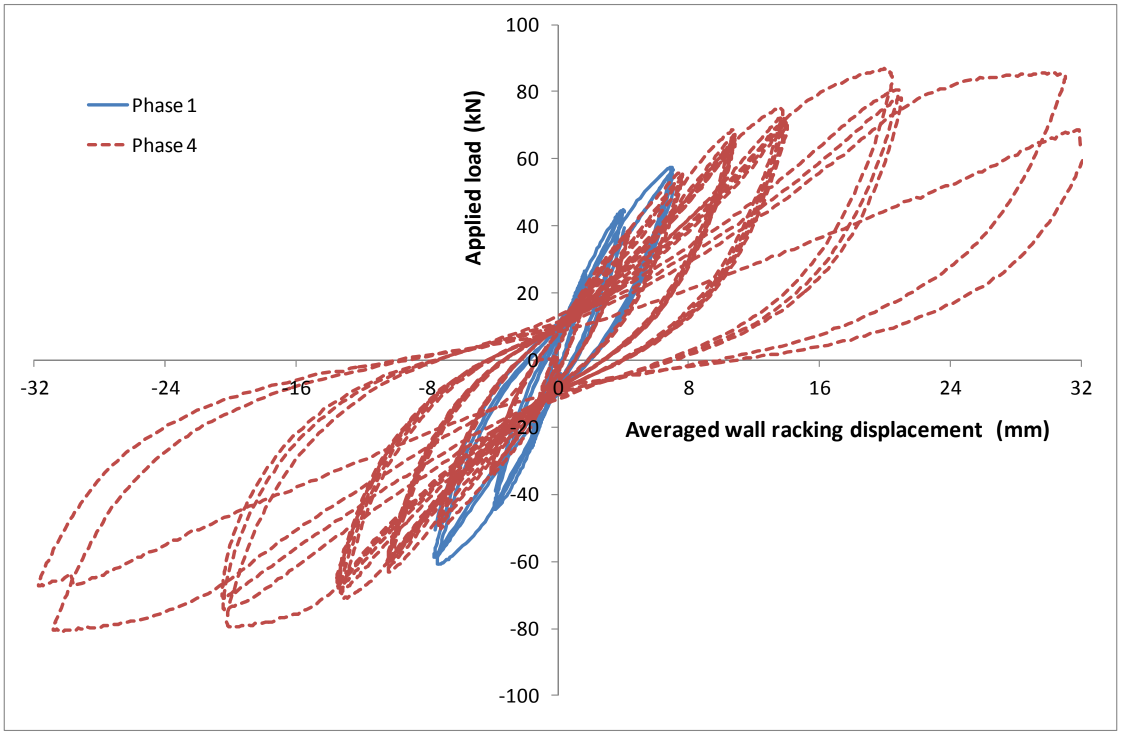


Figure 16 Comparison of hysteresis loops for Phase 1 and Phase 4 for all displacements

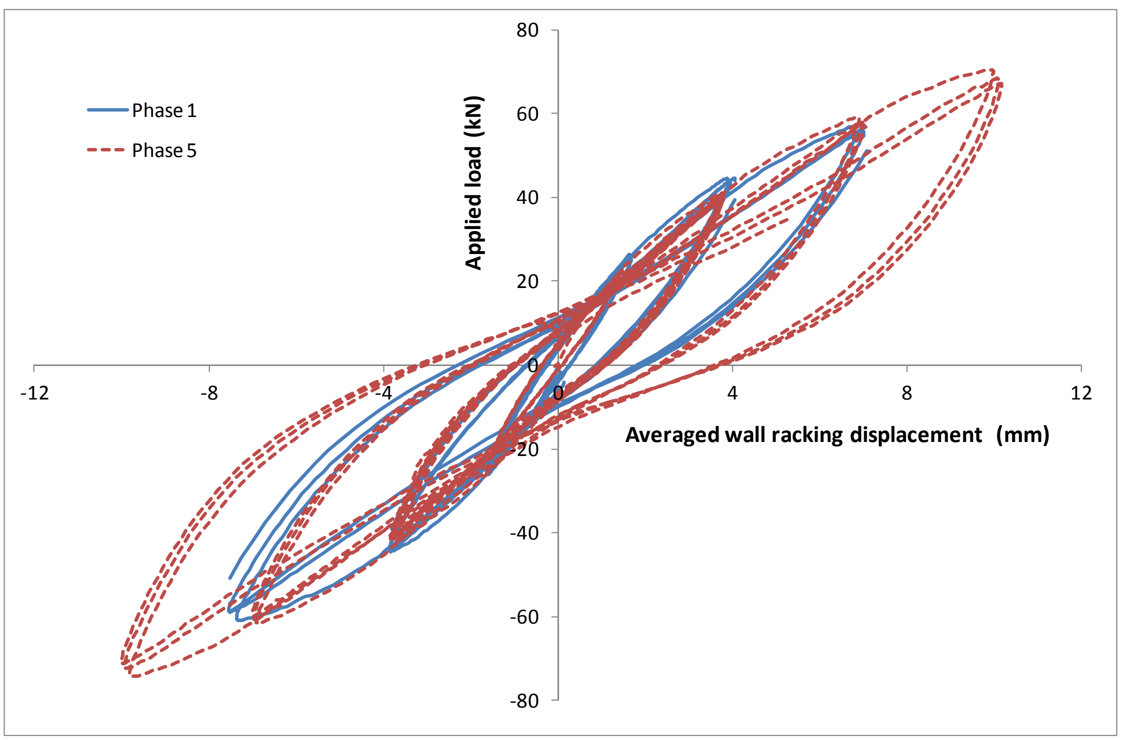


Figure 17 Comparison of hysteresis loops for Phase 1 and Phase 5 for displacements up to 11 mm

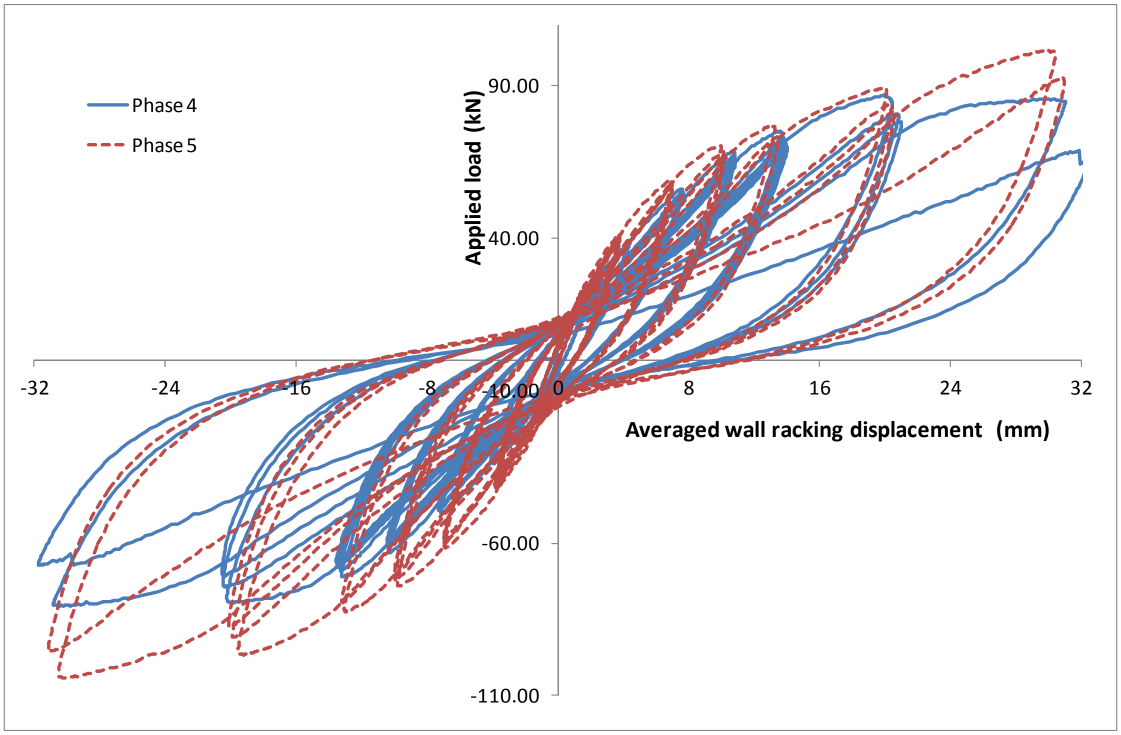
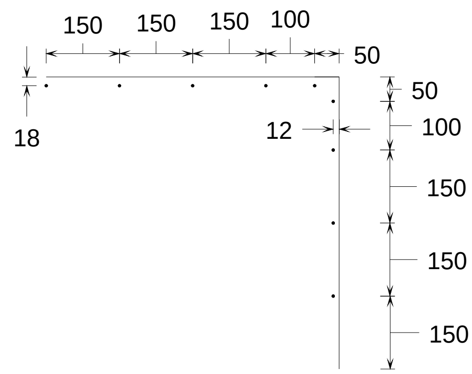


Figure 18 Comparison of hysteresis loops for Phase 4 and Phase 5

APPENDIX A CONSTRUCTION DETAILS AND DRAWINGS

The test building was built as shown in the drawings given in this Appendix. Construction complied with NZS 3604:1999 – except as noted. In particular, the nailing schedule for floors/walls/and ceilings as per Table 7.5, 8.19 and 13.3 from this standard was followed and nail plates at wall top joints and wall intersections used as per Figures 8.15 and 8.16 of NZS 3604:1999.

The walls and ceiling were lined with standard plasterboard except the single 1.2 m-wide element on Side 2 which is noted on the drawings as being lined with high performance plasterboard. Both sides of internal walls were lined. The fixings were Drywall screws for all plasterboard at 150 mm centres around the perimeter of the bracing elements but the screw density increased as shown below at each corner of each bracing element. Construction complied with page 54 of the Site Guide. Wall glue was used in the body of the sheets as per page 32 of the Site Guide.



Wall hold-down anchors were used on the studs at the ends of the panel lined with high performance plasterboard. The wall hold-down anchors were coach screwed to the foundation beam and incorporated Tek screws fixing the hold-down bracket to the end stud.

50 mm skirting was nailed over the lining at the base of all walls using 60 x 2.8 mm brads at approximately 300 mm centres at the base of all walls.

Timber ceiling battens were used at 450 mm centres and the plasterboard was fixed to these using daubs of glue and a fastener spacing as defined for the ceiling as per page 44 of the Site Guide.

A 10 mm gap was used at the bottom of the lining as per page 32 of the Site Guide.
Side1 and End 1 used the following construction:

- The bottom plate of these walls was bolted or coach screwed to the foundation beam at 1.4 m centres starting 300 mm from the building corners.
- The plasterboard edges finished flush with the window or door edges – i.e. as per Drawing 2 on page 37 of the Site Guide.
- A grooved window reveal was used at window edges as per page 36 of the Site Guide.
- Nogs were used in these walls at 800 mm vertical centres.

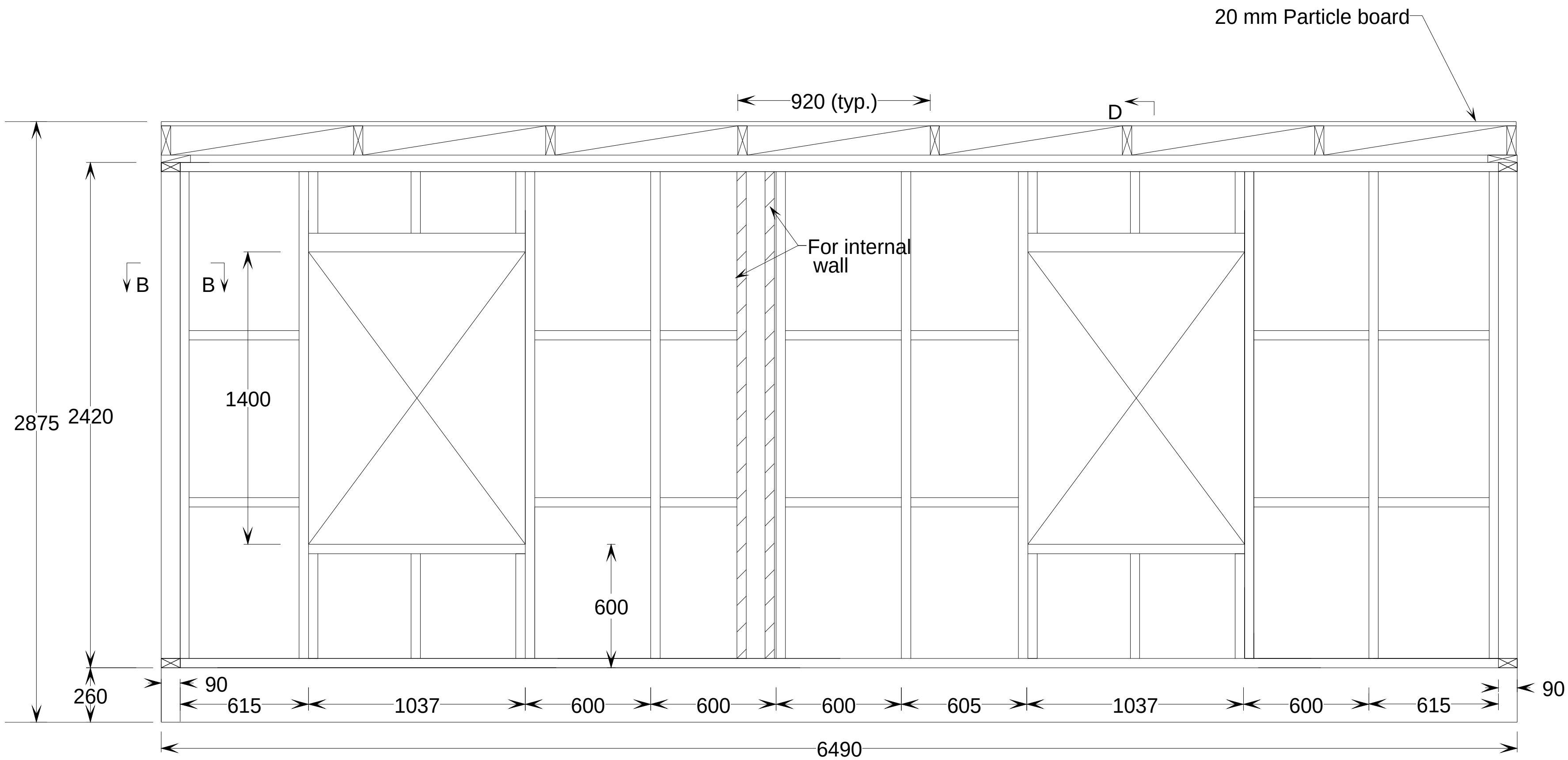
- Square stopped wall/ceiling junctions were used on End 1 and on Side 1 north (see Figure 1) of the internal wall. A plastered scotia was used on Side 1 south of the internal wall.

Side 2 and End 2 used the following construction:

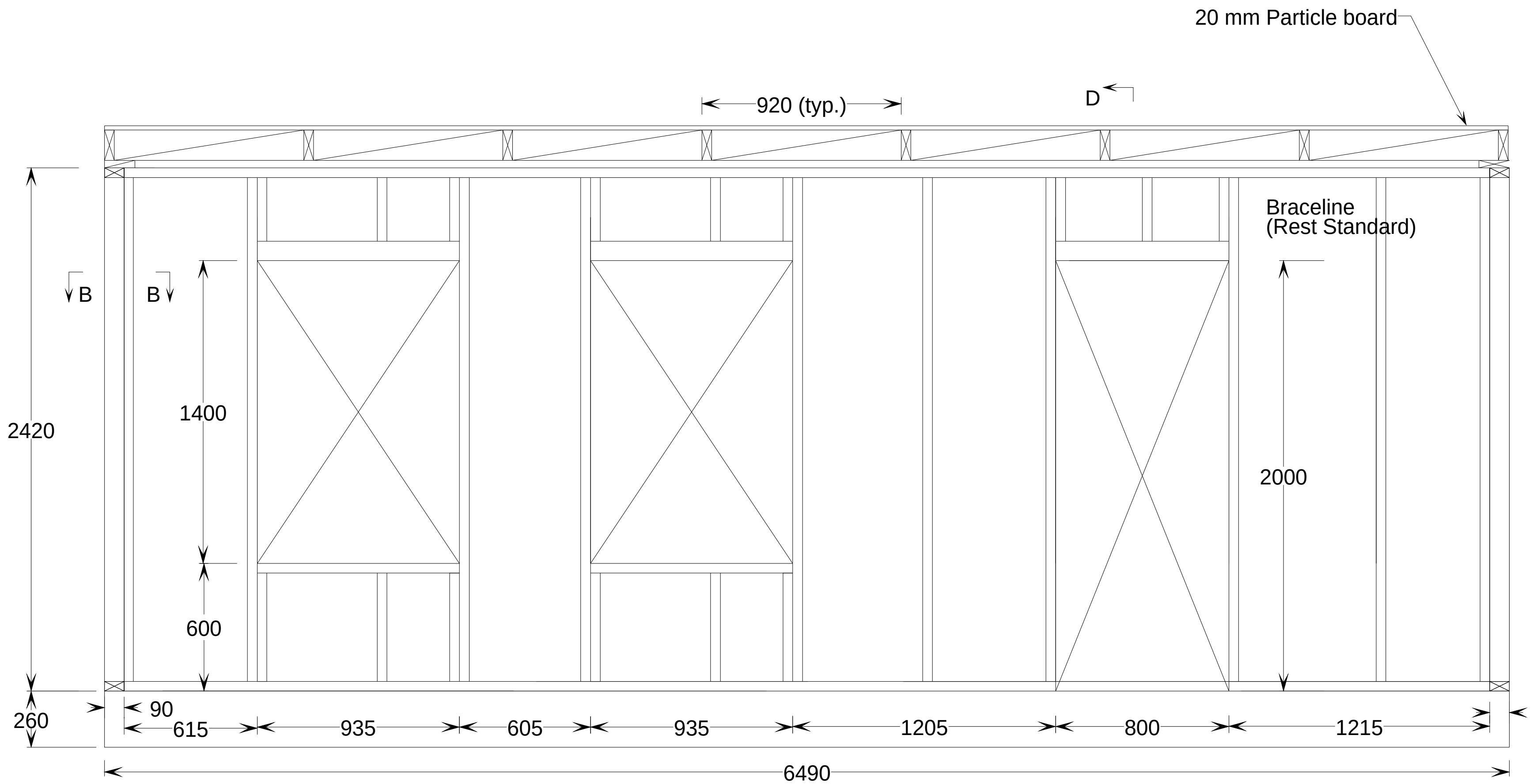
- The bottom plate of the walls was nailed to the foundation beam at 0.6 m centres with two hand-driven 100 x 4 flat head (FH) bright nails starting close to the end studs. These nails were also used along the panel lined with high performance plasterboard.
- The plasterboard edges were cut around the window or door edges – i.e. as per Drawing 4 on page 37 of the Site Guide.
- An architrave was used at window and door edges.
- A nailed scotia was used along wall/ceiling junctions.

Internal walls used the following construction:

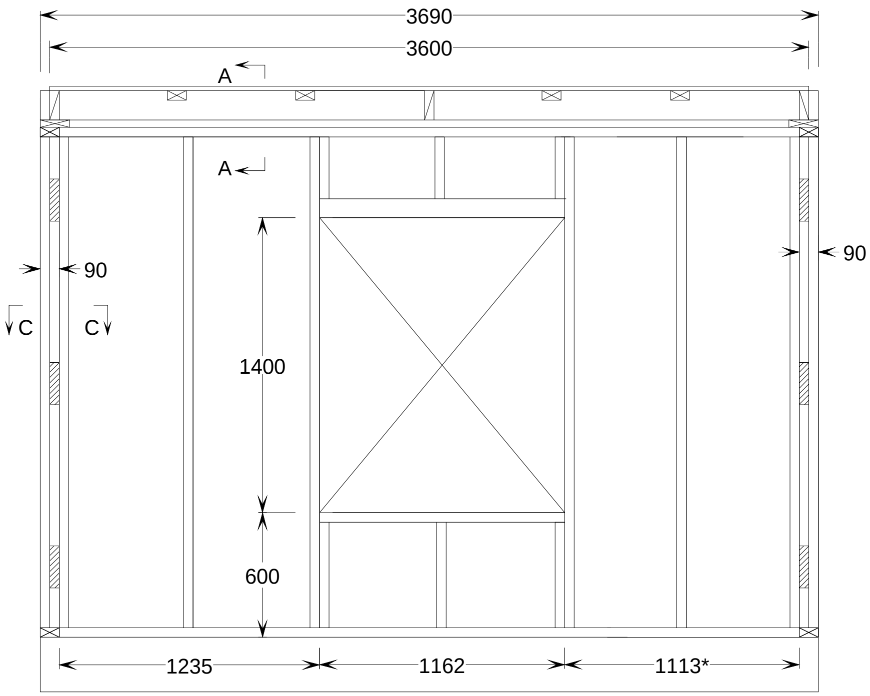
- The bottom plate of the walls was nailed to the foundation beam at 0.6 m centres with two hand-driven 100 x 4 flat head bright nails starting close to the end studs.
- Both sides of the wall were lined.
- A plastered scotia was used along wall/ceiling junctions.



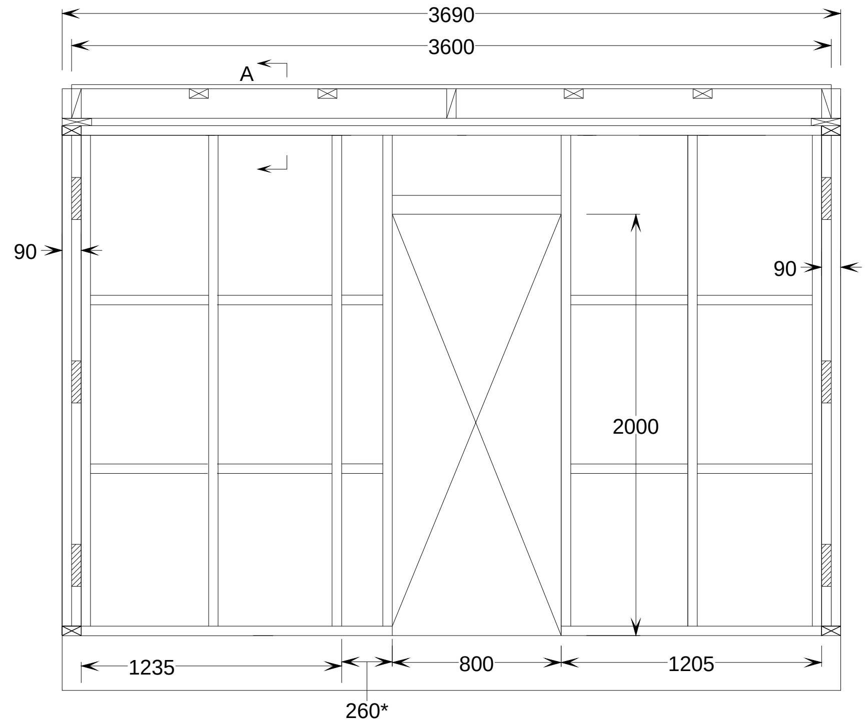
Drawing 1 Side 1 wall framing



Drawing 2 Side 2 framing

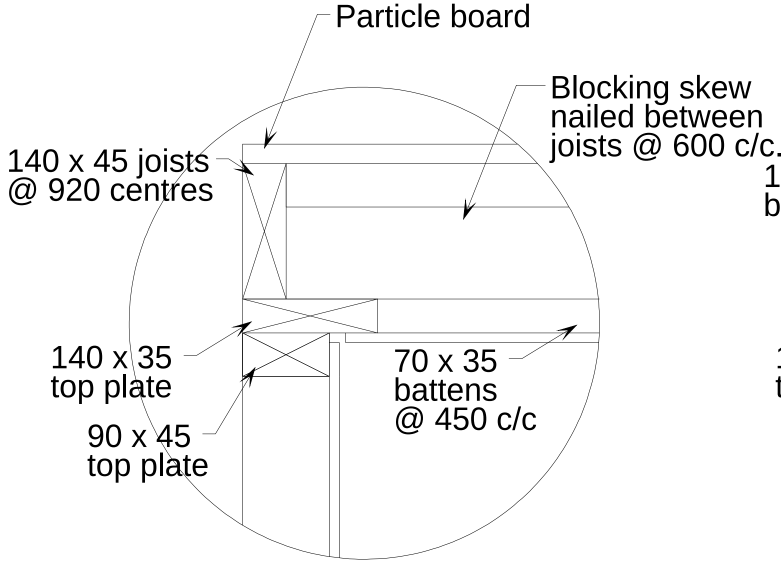


Elevation of End 2

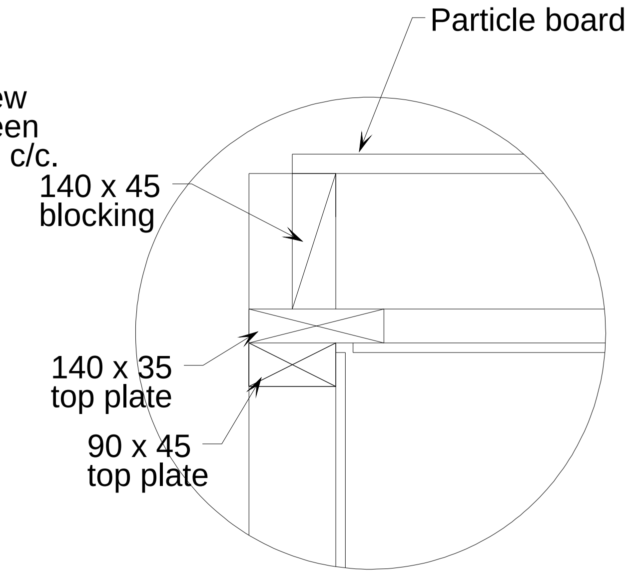


Elevation of End 1

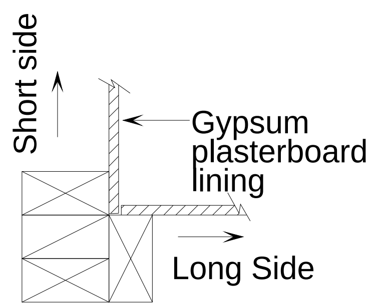
Drawing 3 Framing used in the end walls



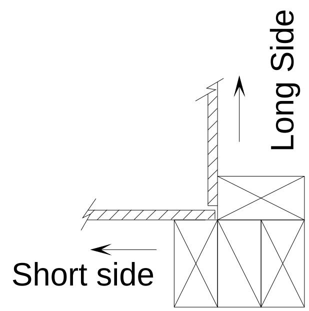
Section A-A



Section D-D



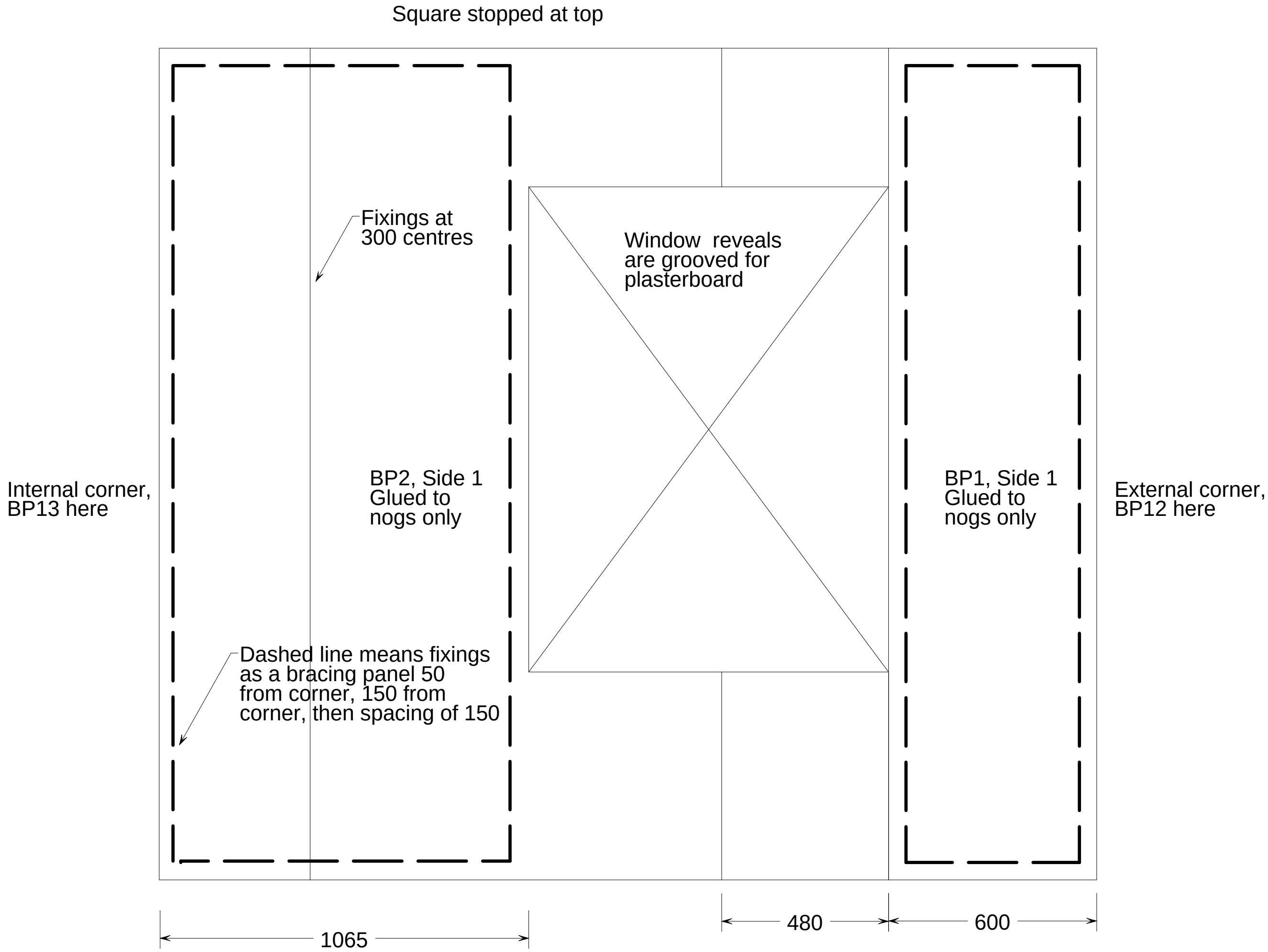
Section B-B



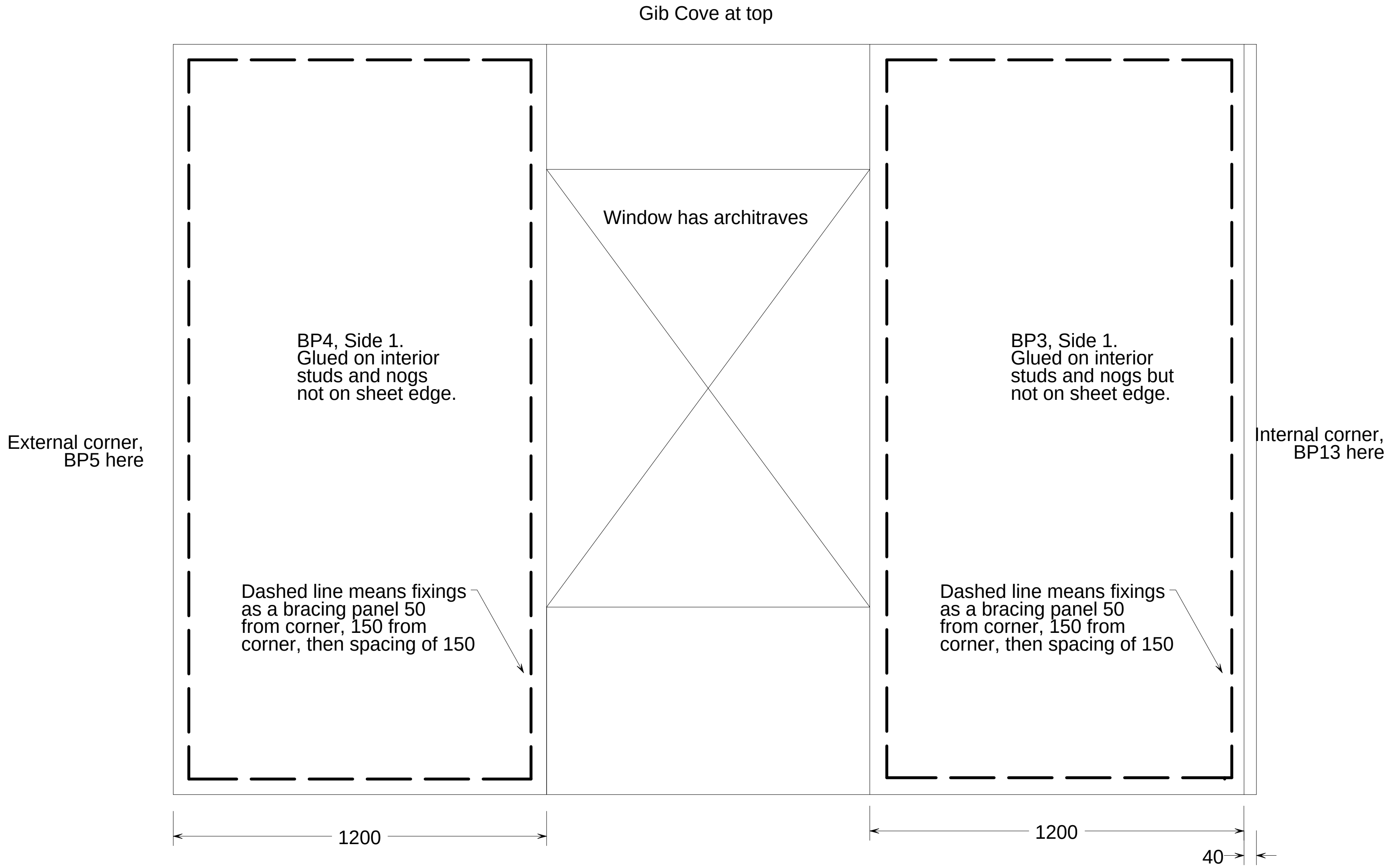
Section C-C

Drawing 4 Details

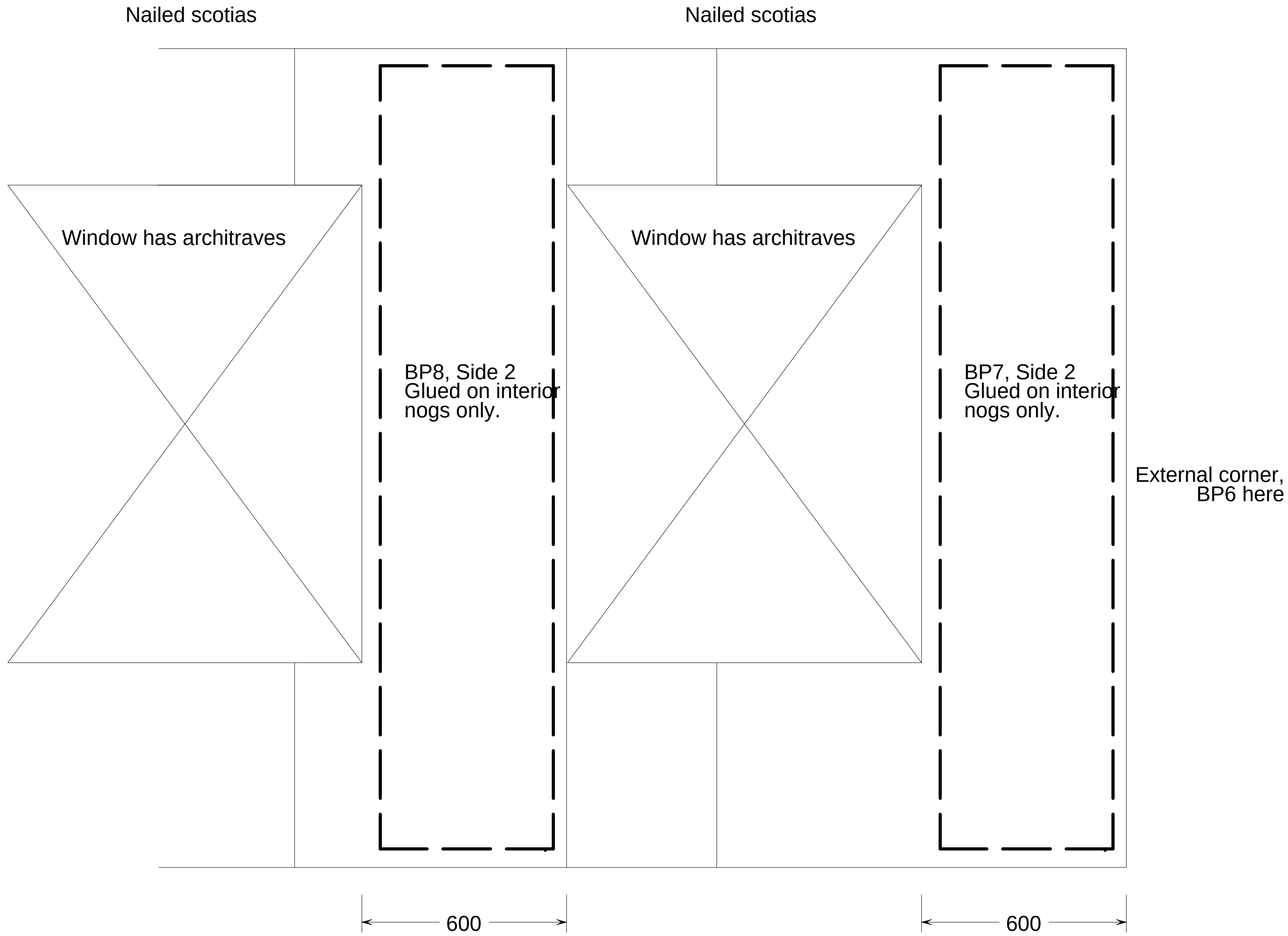
APPENDIX B PLASTERBOARD FIXING USED FOR PHASE 1 TESTING



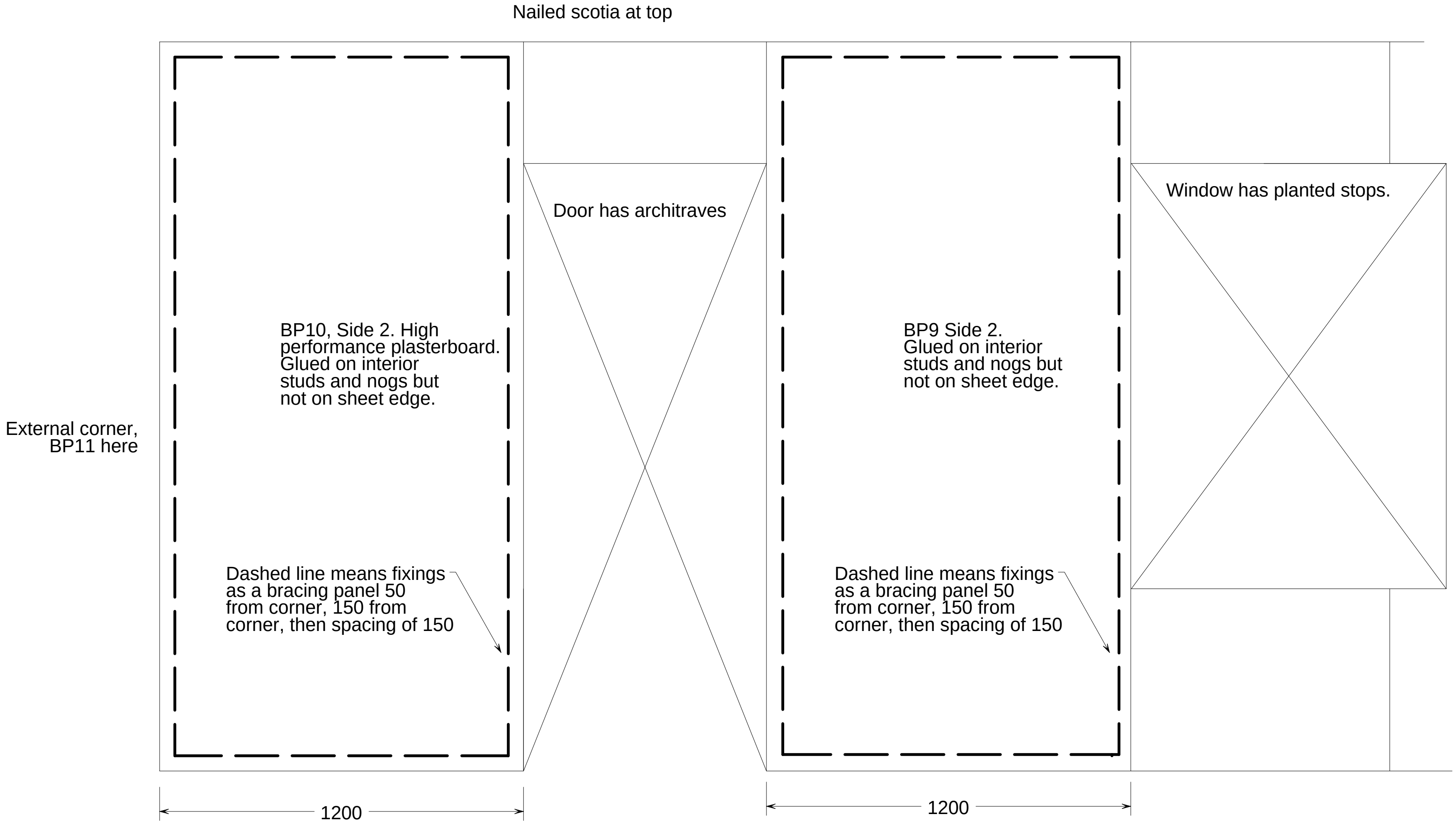
Panels BP1 and BP2 on Side 1



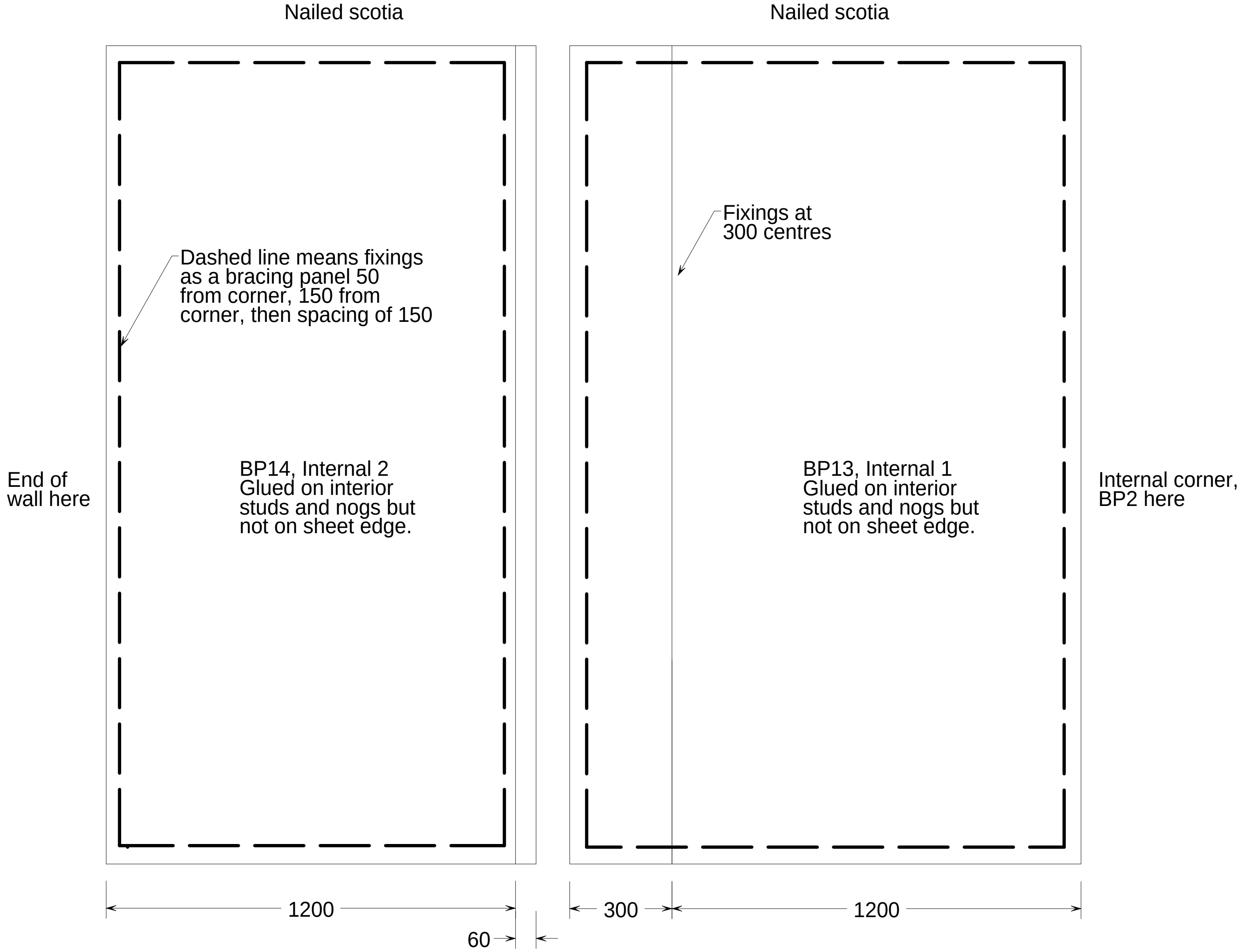
Panels BP3 and BP4 on Side 1



Panels BP7 and BP8 on Side 2

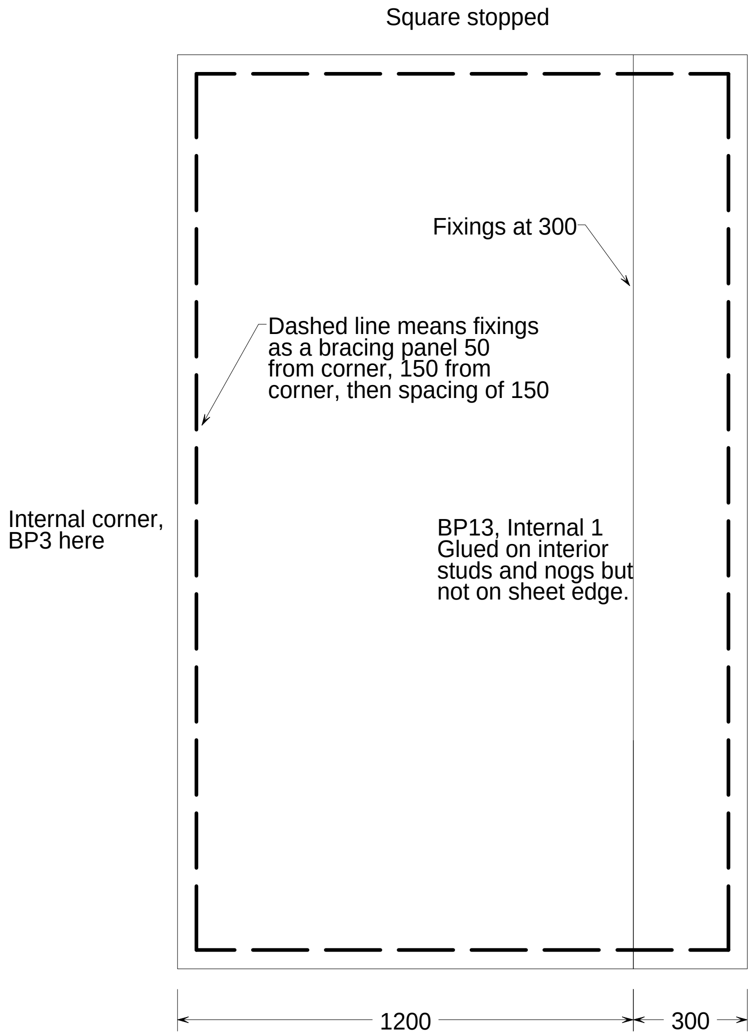


Panels BP9 and BP10 on Side 2

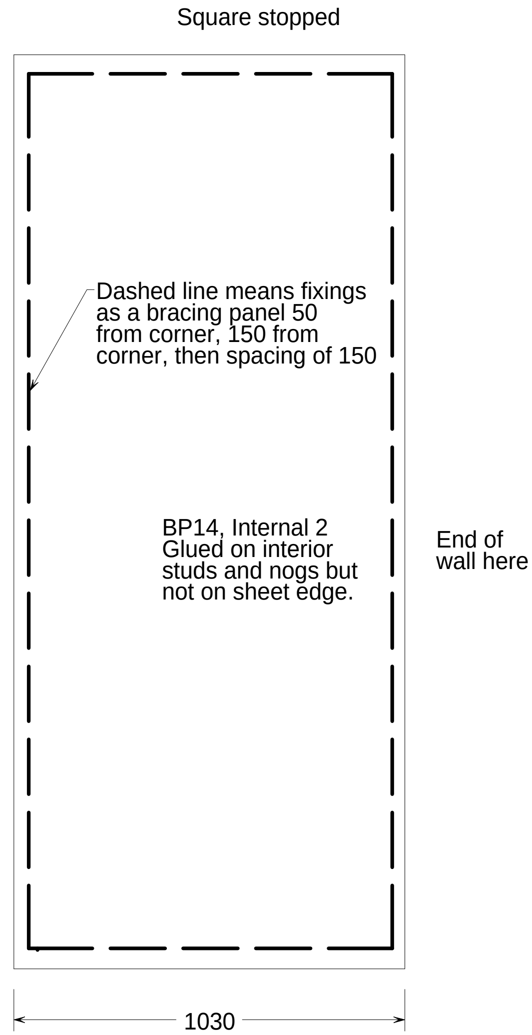


Panel BP14. Internal 2 Face 2, Strong wall end.

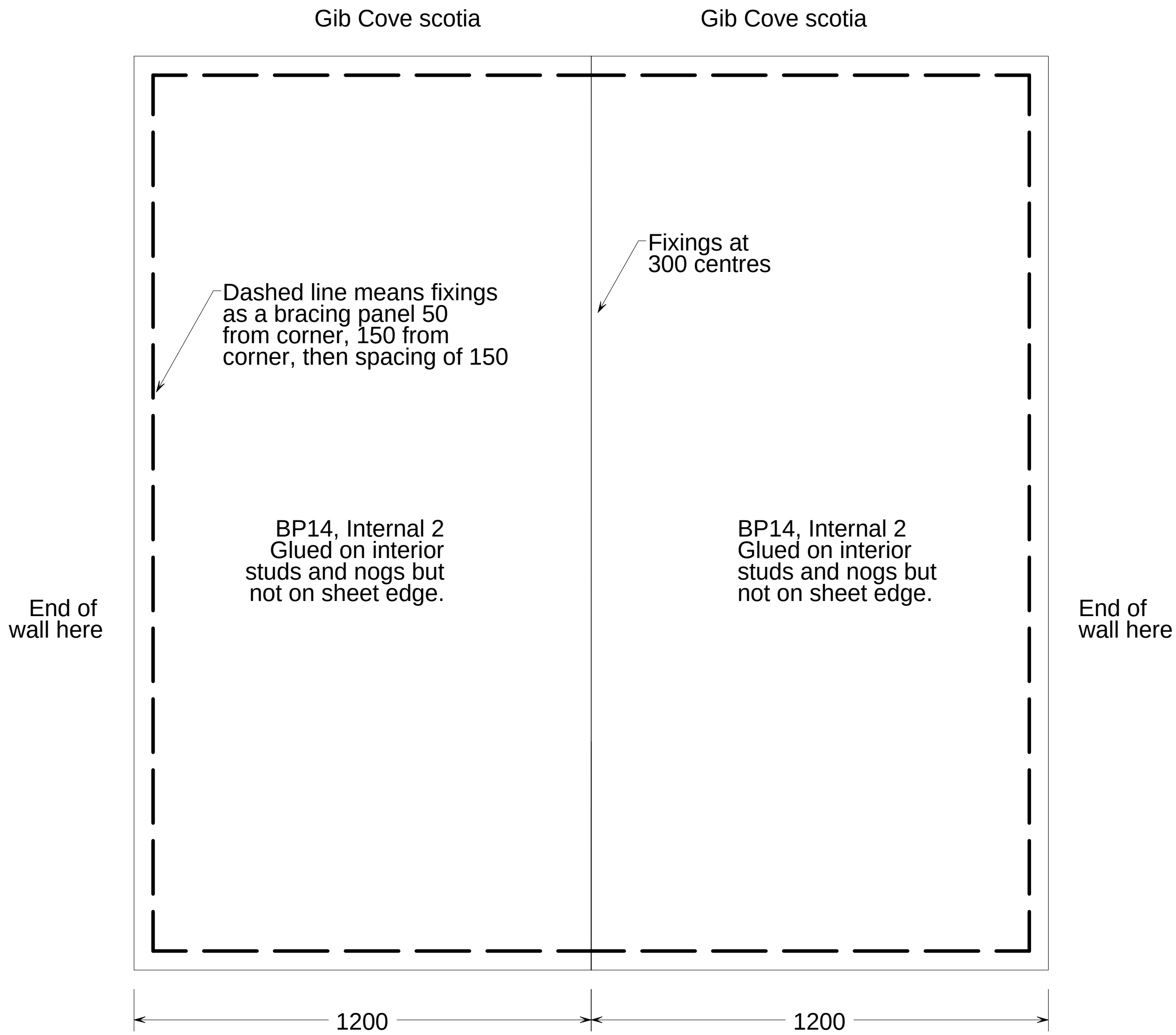
Panel BP13. Internal 1 Face 1



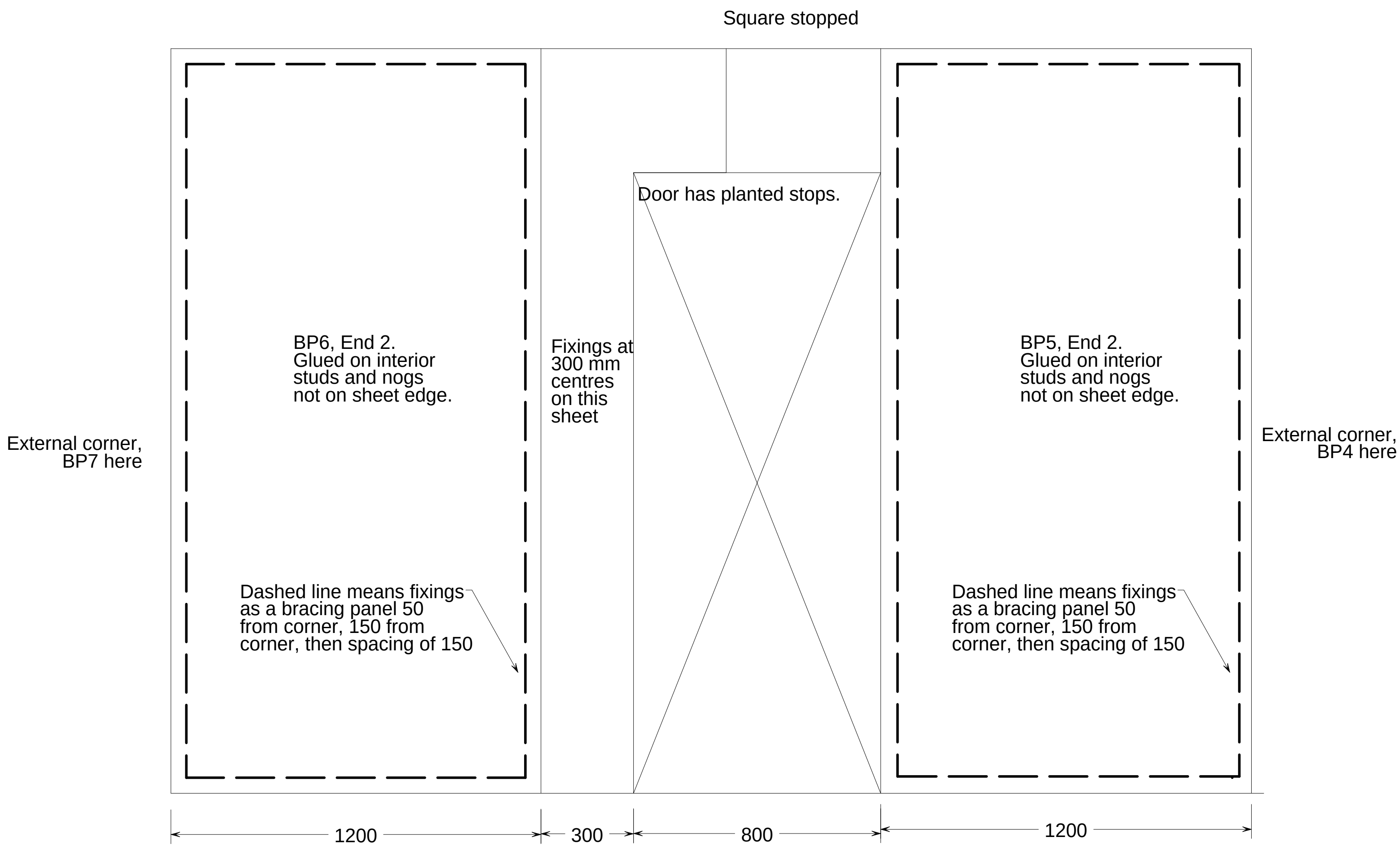
Panel BP13. Internal 1 Face 2



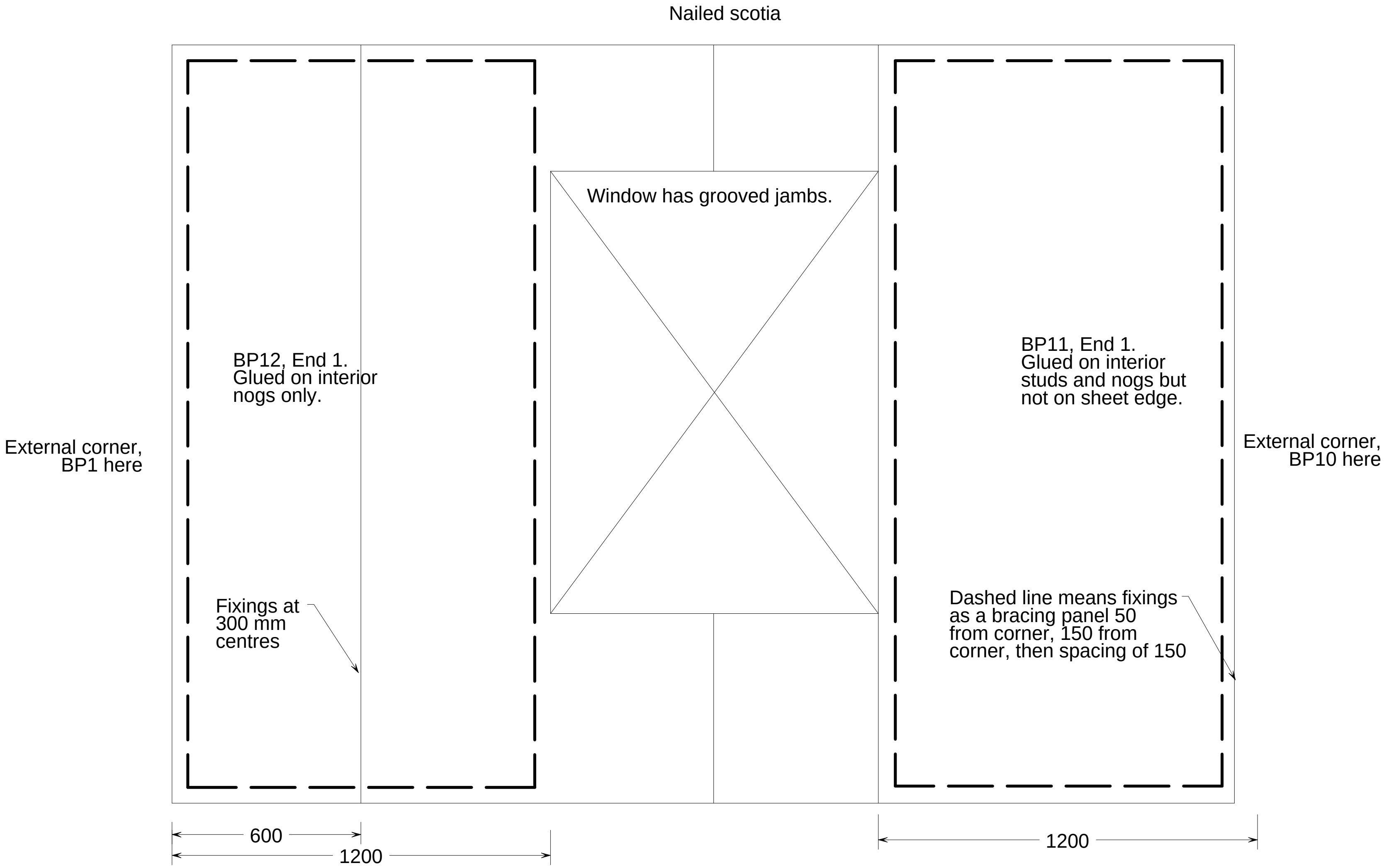
Panel BP14. Internal 2 Face 2 Roller door end



Panel BP14. Internal 2 Face 1



Panels BP5 and BP6 on End 1



Panels BP11 and BP12 on End 2

APPENDIX C SUGGESTIONS AND COMMENTS ON PLASTERBOARD CRACK REPAIR

The following suggestions on plasterboard crack repair were provided by Peter Carr of P & J Plastering.

Any repair is a balance of several factors – cost/time, strength and quality of the finish. A repair can be anything from adhesive fibreglass mesh over the crack and a quick couple of coats to replacing a cracked area of board.

<u>Recommendations and method:</u>

1. Make sure the cause of the crack and any stress on the board has been eliminated or minimised.
3. Cut away and clear all loose and broken material from the crack so that only firm board is remaining. If the board in the area is firm but deformed, the deformed area should be cut away.
4. Make sure the board either side of the crack is not moving. Screw or back block as necessary.
5. If the existing board has been painted, the area that will receive the plaster should be sanded and painted with an alkyd flat sealer. This is to give the plaster a good chance of binding to the existing surface.
6. If the existing board has been wallpapered, the area that will receive the plaster should be stripped of wallpaper, sanded and painted with an alkyd flat sealer as described above.
7. Fill and flush the crack with a setting plaster.
8. Install and finish "paper tape" as per best trade practice.

APPENDIX D DETAILS AND PHOTOGRAPHS OF DAMAGE OBSERVED DURING TESTING AND DAMAGE REPAIR

Damage to the plasterboard and other observations are discussed below. Photographs showing damage at various stages of the testing are also given. Photographs of the cosmetic repair are given.

Phase 1

P1D4 Δ = ±1.65 mm. Photograph D1.
At +1.65 mm the plasterboard paper facing at two vertical plasterboard joints formed compression ridges and at -1.65 mm another two vertical joints formed compression ridges. These flattened at zero displacement and were hard to detect. The joints which compression ridged were only where adjacent sheets had been jointed at opening edges (hereafter called the “J@Openings detail”). Where sheets had been cut to fit around openings, as is recommended by Winstone Wallboards (hereafter called the “J_NOT_Openings detail”), no distress was noted.

P1D8 Δ = ±3.92 mm. Photograph D2.

At corners with the J@Openings detail, more pronounced compression ridges formed at peak loads along all vertical joints and cracks formed on most. At unload the cracks (and sometimes the compression ridges) were still visible.

Where the J_NOT_Openings detail had been used, small diagonal bulges formed at some window corners in compression at peak loads but these were not visible on unload. However, on unload, it was noted that at two window corners diagonal plasterboard cracks approximately 10 mm long had formed at window corners.

Mitre joints on architraves around window openings, opened and closed during the racking.

P1D12 Δ = ±7.29 mm. Photograph D3 and Photograph D4.

Plasterboard vertical joint cracks emanating from opening corners which had the J@Openings detail now reached the bottom skirting or top Scotia as applicable. At four places where the J_NOT_Openings detail had been used small diagonal cracks had formed from the corners. The largest of these was approximately 150 mm long and is shown in Photograph D4.

Repairs after Phase 1. Photographs D5 to D12.

Photographs of the repair after Phase 1 are shown.

Phase 2

P2D4 Δ = ±1.70 mm. More than half of the cracks that had been repaired after Phase 1 testing had now formed a compression ridge but where the J_NOT_Openings detail had been used there were no cracks or compression ridges.
P2D8 Δ = ±3.92 mm.

All cracks that had been repaired after Phase 1 testing had now re-cracked to be similar to the condition before repair from Test P1D12.

P2D12 Δ = ±7.37 mm.

Not much change.

P2D16 Δ = ±10.37 mm. Photograph D13 and Photograph D14.

Crack widths had increased. Diagonal crack lengths had increased.

Phase 3

P3D16 Δ = ±10.70 mm. There was little change in the vertical cracks but the diagonal cracks had increased in severity.

Repairs after Phase 3. Photographs D15 to D19.

Photographs of the repair after Phase 3 are shown. It can be seen that this second plasterer used a different technique.

Phase 4

Skirting at the base of the walls and all architraves around windows and doors had been removed to examine the damage and to allow placement of additional screws before test commencement.

P4D4 Δ = ±1.59 mm. No observed damage.

P4D8 Δ = ±4.24 mm. Vertical cracks had formed at 65% of the J@Openings joints. These varied in length from 25% to 100% of the distance from opening corner to skirting or scotia as applicable. At 50% of corners which used the J_NOT_Openings joint detail, diagonal cracks no greater than 50 mm long had formed.

P4D12 Δ = ±7.47 mm. Full height vertical cracks had formed at all J@Openings joints. At all J_NOT_Openings joint details, diagonal cracks of between 40 and 100 mm length had formed.

P4D16 Δ = ±10.62 mm. At all J_NOT_Openings joint details diagonal cracks of between 100 and 400 mm length had formed.

P4D40 Δ = ±31.41 mm. The damage described above was accentuated with cracks being significantly wider. Diagonal cracks generally almost extended approximately 75% of the distance to the scotia or base of the wall as applicable. Two plasterboard sheets had become partially detached. The plaster scotia appeared to be intact on Side 1 and was still attached to the plasterboard paper facing but the paper under the plaster scotia had separated from the plasterboard core. Where located over plastering the plaster scotia had separated.
Cracks in the joints between side walls and end walls generally had cracked over the bottom 300 mm but otherwise were intact.

Phase 5

The overlay boards all used the J_NOT_Openings detail except at one Side 2 doorway edge.

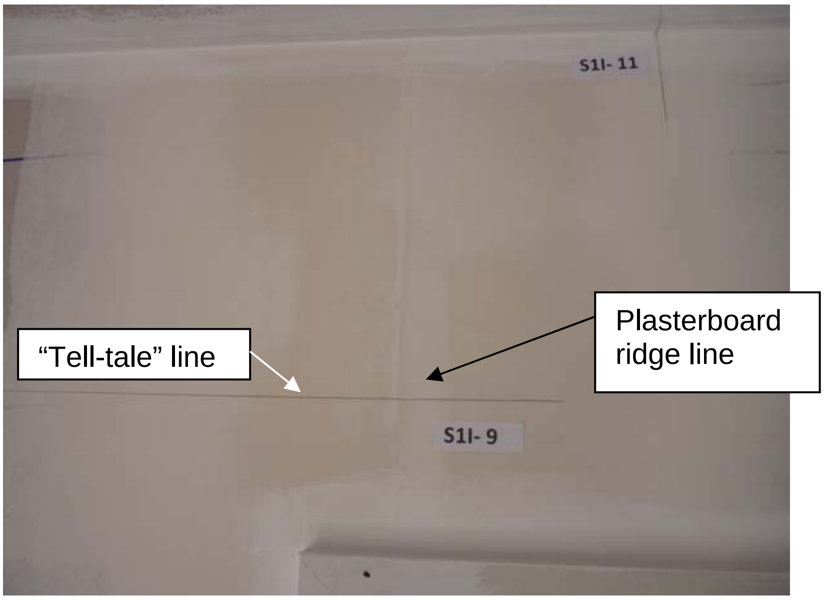
P5D8 Δ = ±3.85 mm. The only observed damage was a vertical crack above one Side 2 doorway edge.

P5D12 Δ = ±7.02 mm. Diagonal cracks only occurred from five opening corners. These ranged from 45 to 100 mm long.

P5D16 Δ = ±10.07 mm. Diagonal cracks occurred from all opening corners. These ranged from 70 to 390 mm long except one crack which was 550 mm long.

P5D28 Δ = ±19.99 mm. Diagonal cracks ranged from 150 to 730 mm long with four being over 500 mm long.

P5D40 Δ = ±30.77 mm. All diagonal crack lengths were greater than 300 mm long and cracks from adjacent corners of the same opening sometimes joined up.



Photograph D1 taken at peak load in test P1D4. Typical plasterboard vertical ridge line which formed along plasterboard joints constructed at window corners (ridge lines flattened at zero displacement and were hard to detect).

Photograph D2 taken after test P1D8. Typical plasterboard crack and ridge line which formed along most plasterboard joints constructed at opening corners

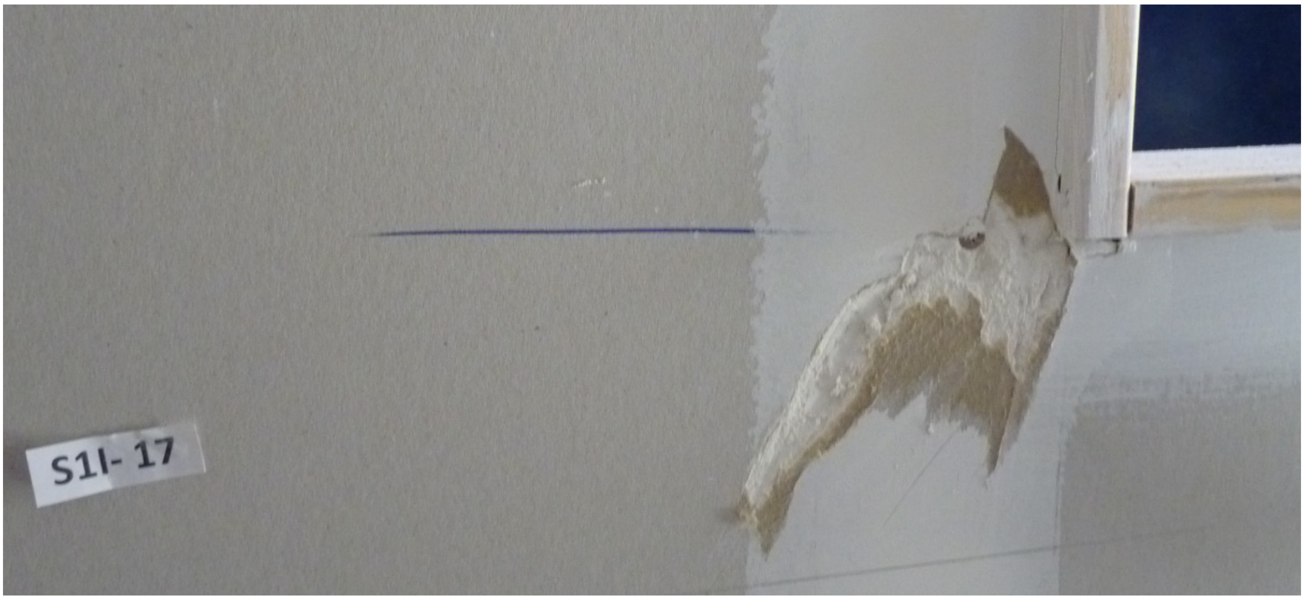
Photograph D3 taken after test P1D12. Typical plasterboard crack along plasterboard joints constructed at opening corners

Photograph D4 taken after test P1D12. This is the largest of the diagonal cracks emanating from opening corners for construction complying with the J_NOT_Openings detail

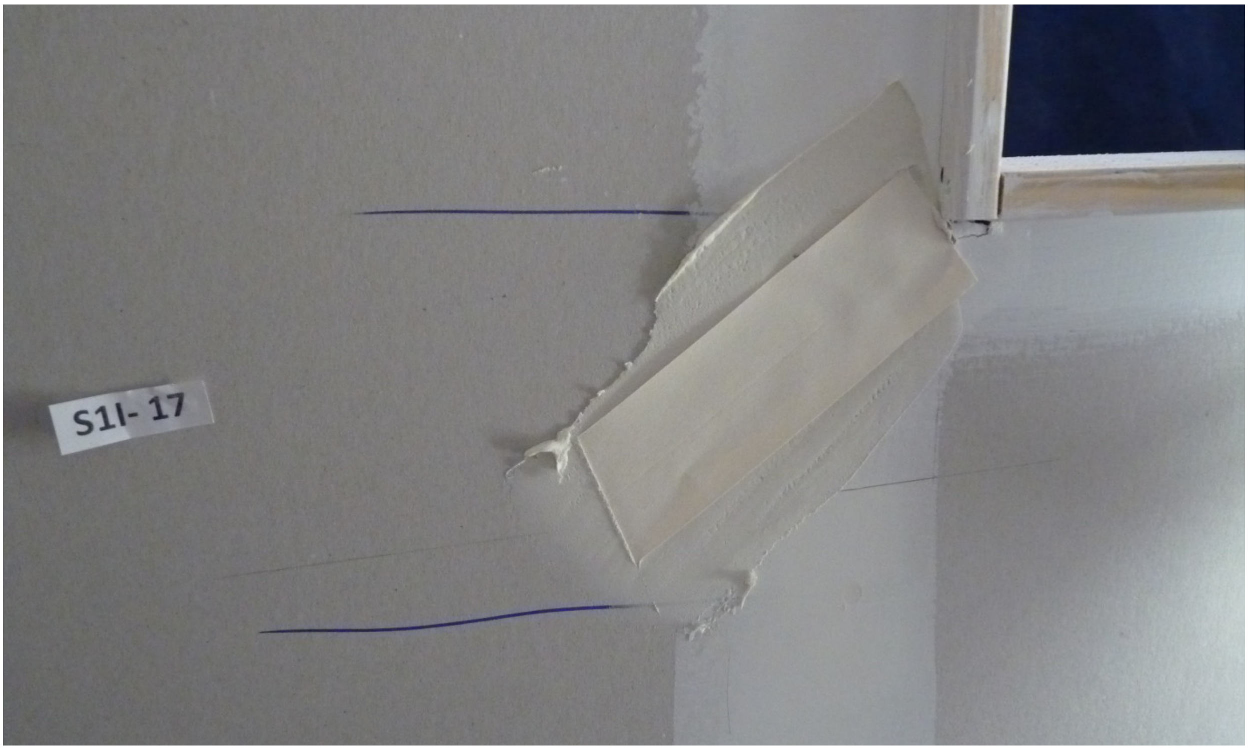
Photograph D5 cosmetic repair after Phase 1. Gouging out diagonal crack

Photograph D6 cosmetic repair after Phase 1. Plaster coating and adding paper reinforcing

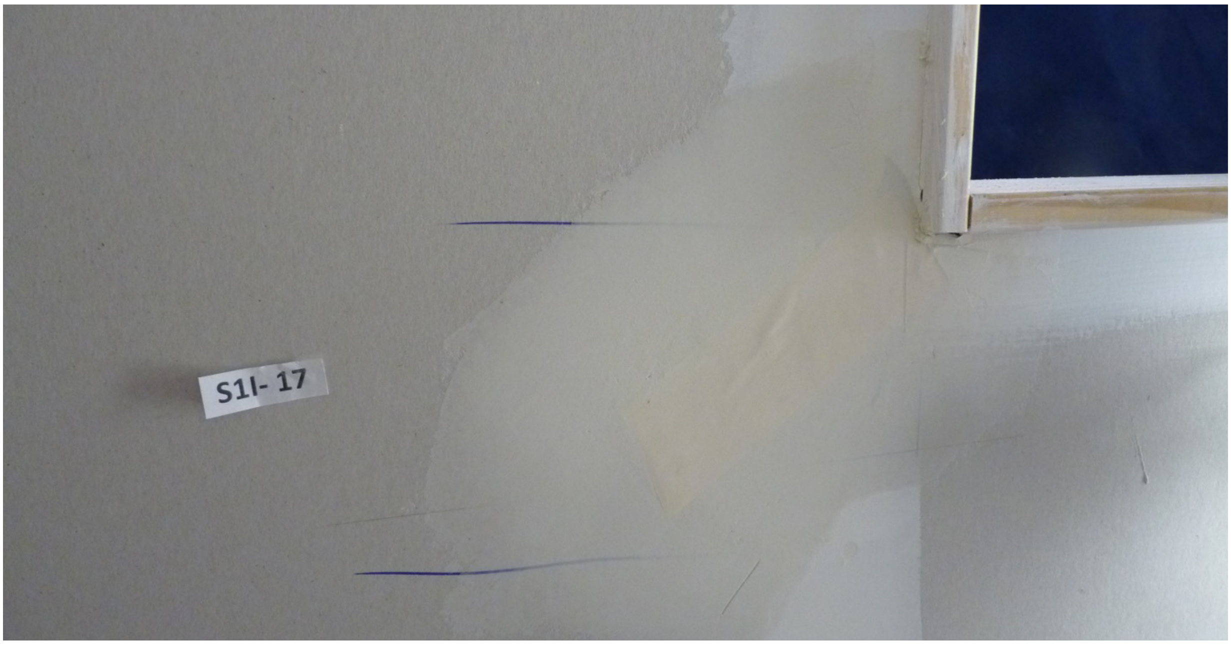
Photograph D7 cosmetic repair after Phase 1. Repaired diagonal crack before final plaster finish



Photograph D8 cosmetic repair after Phase 1. Gouging out a second diagonal crack



Photograph D9 cosmetic repair after Phase 1. Plaster coating and adding paper reinforcing



Photograph D10 cosmetic repair after Phase 1. Repaired diagonal crack

Photograph D11 cosmetic repair after Phase 1. Vertical crack gouged out and paper tape added

Photograph D12 cosmetic repair after Phase 1. Before final coat over vertical crack

Photograph D13 taken after test P2D16. Vertical plasterboard cracks had increased in severity

Photograph D14 taken after test P2D16. The largest of the diagonal cracks had now increased in length

Photograph D15 taken during repair after Phase 3

Photograph D16 of the crack repaired in Photograph D15

Photograph D17 of another vertical crack repaired after Phase 3

Photograph D18 during repair of a crack after Phase 3

Photograph D19 taken during repair after Phase 3

Photograph D20 taken after test P4D40. Vertical crack widths had increased in width and some sheets had become loose

Photograph D21 taken after test P4D40. Note that diagonal cracks had formed at both the J_NOT_OPENINGS and J@Openings joints

Photograph D22 taken after test P4D40 showing diagonal cracks from both the J_NOT_Openings and J@Openings joints

Photograph D23 taken after test P4D40. Plasterboard distress at screw locations

Photograph D24 taken after test P5D16. Crack length = 550 mm

APPENDIX E BRANZ-RECOMMENDED REPAIR METHODS

Suggested repair methods, based on the testing undertaken, are given below. The method most suitable for application in a particular situation depends on the assessment of actual earthquake-induced damage.

1, COSMETIC REPAIR OF PLASTERBOARD DAMAGE

When to use this method

This method is applicable for houses where there is only light damage mainly consisting of thin vertical joint cracks emanating from the corners of openings. There must be no damage visible at wall-to-ceiling joints, no ceiling damage and no indications of wall uplift. Diagonal cracks from opening corners up to 50 mm long may be present. Some loss of adhesion or fastener 'popping' may have occurred in the centre of the sheets.

How to use this method

1. A drywall screw must be fixed adjacent to any plasterboard screws or nail fixings that have popped.
2. Any plasterboard sheet centres that are loose ('drummy') must be refastened.
3. On all walls exhibiting damage, use the cosmetic repair guidelines recommended by reputable gypsum plasterboard manufacturers.

Expected result

Although this repair may not reinstate building stiffness to that of a new house and small cracks may reappear in future serviceability wind or earthquake events, this damage is expected to remain cosmetic only.

2. COSMETIC REPAIR OF PLASTERBOARD DAMAGE PLUS ADDITION OF EXTRA PLASTERBOARD FASTENING SCREWS

When to use this method

This method is applicable where damage is more substantial than present for Repair Method 1 and includes situations where plasterboard cracks may emanate diagonally from the corners of openings up to 50 mm long and/or where wall-to-ceiling or wall-to-wall junctions show stress by visible cracking, fastener movement, wallpaper creasing or similar. Where there is evidence of bottom plate or stud uplift, framing connections must be reinstated and Repair Method 3 or 4 must be used.

How to use this method

1. Remove all architraves and skirting in the affected areas and check for fastener stress at the bottom of the sheets, which may indicate bottom plate or stud uplift.
2. Any diagonal cracks greater than 50 mm long or where sheet edges are dislodged will require a repair in accordance with Repair Method 3 or 4.
3. Add suitable drywall screws in a bracing pattern around the perimeter of all full-height wall sections that are to be redecorated. Extra fastenings will not be required behind undamaged plastered or coved wall-to-ceiling junctions.

4. Tape and stop repaired joints and plasterboard cracks in accordance with good trade practice.

Expected result
Although this repair may not reinstate the building's stiffness to that of a new house, it is expected to be sufficiently stiff to prevent small cracks from reappearing during future serviceability wind or earthquake events.

3. OVERLAY NEW PLASTERBOARD OVER THE DAMAGED PLASTERBOARD AND ADD WALL HOLD-DOWN ANCHORS IN AFFECTED AREAS

When to use this method
This method may be used on all walls with significant diagonal cracking, in lieu of replacing damaged sheets (Repair Method 4). Ceilings that have been cracked must be treated in a similar fashion.
This method is only applicable where there is no damage to the wall framing.

How to use this method
1. Remove architraves, scotias and skirting.

2. Small cut-outs are made in the corners of all plasterboard bracing elements and stud-to-plate connections are reinstated. Ensure the bottom plate is tight with the floor. This may require the installation of new plate-to-floor connections

3. Ensure the building is plumb and level.

4. All loose plasterboard is screwed tight using suitable drywall screws that penetrate the timber framing by at least 20 mm, and sheets should be scraped flat along broken joints to leave a smooth planar surface to receive the overlay board.

5. Add screws along middle studs at 300 mm centres, even if glued originally, as the glued joints may have broken.

6. Overlay (either horizontally or vertically) damaged walls and ceilings with new plasterboard which is at least the same quality as the original. Cut the sheets around openings as per Figure E1.

7. Fix the overlaid plasterboard with suitable drywall screws that penetrate the timber framing by at least 20mm. Fix at 50 mm and 150 mm from each corner of each full-height wall element and then at 150 mm centres around the perimeter of that element. These fasteners are also used at 300 mm centres in the body of the sheets if fixed vertically or to each stud if fixed horizontally.

8. Tape and stop all joints and fastener heads in accordance with good trade practice.

9. Replace architraves, scotias and skirting

Expected result.
This repair is expected to result in a similar or better strength and stiffness compared to the original construction.

4. REMOVE ALL WALL LINING AND REPLACE WITH NEW LINING IN AFFECTED AREAS

When to use this method
This method is to be used where the building structure is or can be made sound. There is expected to have been very significant damage to the wall linings (for example, extensive diagonal cracking). Ceilings that have been cracked must be treated the same way.

How to use this method
1. Remove scotias, skirting and plasterboard wall linings in the affected areas. Ensure temporary bracing is in place and ensure building is plumb and level.

2. Repair any damage to wall framing and framing connections.

3. Fix the framing and bottom plate to the foundation as if it is a bracing element.

4. Replace the damaged sheets with comparable components (that is, enhanced plasterboard must be replaced with enhanced plasterboard). All new sheets should be fixed in a bracing pattern. Cut the sheets around openings as per Figure E1.

5. Plasterboard joints are to be paper taped and plastered in accordance with good trade practice.

6. Replace architraves, scotias and skirting

Expected result
This repair is expected to result in a construction that will have stiffness and strength very close to that of the house prior to the earthquakes.
If it is necessary to replace all plasterboard lining in the house, a bracing design in accordance with NZS 3604:2011 must be carried out and bracing elements installed to provide the required bracing. While the plasterboard lining is removed, a check should be made of the bottom plate fixings. Any damaged fixings should be replaced. This will result in a construction with the strength and stiffness of a new house.

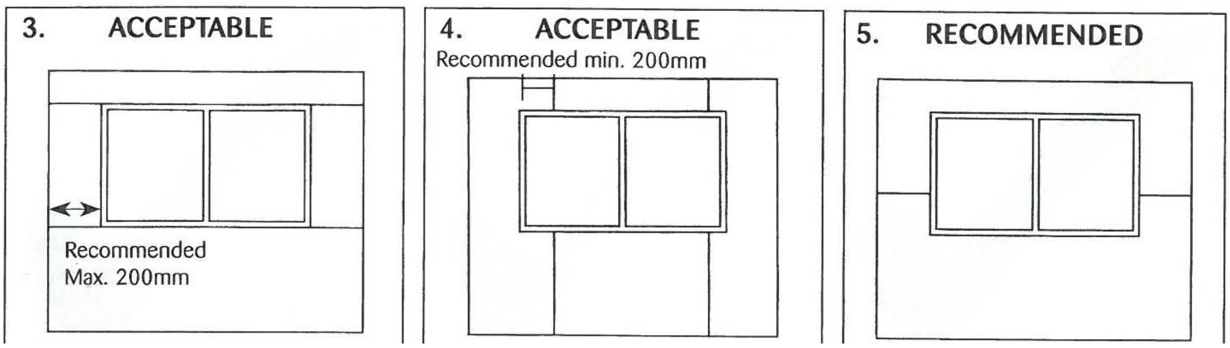


Figure E1. Sheet layout around openings