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Racking Resistance of LTF Walls with Openings

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Racking Resistance of LTF Walls With Openings

S.J. Thurston[1]

ABSTRACT

Design codes provide guidance for estimating the distribution of lateral earthquake and wind forces to bracing walls in houses. The racking resistance of walls is often determined by summing the strength of relatively short panels between door and window openings. The strength of these short panels is found by tests in which the wall panel is either entirely (most countries) or partially (New Zealand) prevented from rocking as a rigid body. The exception is in the Australian standard tests (Reardon, 1980) where no external forces are applied to prevent this rigid body motion.

To investigate the above methodologies ten racking tests were conducted with 5 different long (up to 6.6 m) wall configurations, incorporating wall returns and typical openings, and using various combinations of sheathings. No external uplift restraints were used. Generally only standard nailing between the bottom plate and the foundation beam provided wall uplift restraint, although in a few instances light steel end straps were also used. The measured wall racking strengths were compared to that calculated from the summation of component panel strengths.

For fully sheathed walls with large window (but no door) openings experimental wall load versus deflection hysteretic curves could be fairly accurately (and conservatively) predicted assuming the component panels were fully restrained against uplift. For walls with door openings the measured strengths were only of the order of 70% of that predicted. The long walls were far stronger than would have been predicted from the Australian test method.

1. Introduction

Most wall bracing systems in New Zealand are tested and evaluated according to the BRANZ P21 test method (Cooney and Collins, 1979) and revision R10 (King and Lim, 1991). The P21 test method has been adopted in NZS 3604 "New Zealand Code of Practice for Light Timber Frame Buildings not Requiring Specific Design (SANZ 1990). The method requires bracing panels to be tested by pseudo-static reverse cyclic racking of three test specimens, first to a serviceability limit state displacement (8 mm) and then to an ultimate limit state displacement. The resistance to wind load is taken as 0.9 times the average of the peak resisted load for the two test directions and the resistance to earthquake load is the average fourth cycle peak load factored to take account of panel ductility. Occasionally the serviceability limit state criteria govern and different equations are then used to obtain the appropriate level of resistance.

The wall bracing panels used in most New Zealand houses are generally only nailed to the floors - i.e., do not use cyclone rods or anchorage bolts as is common in northern Australia. If these bracing panels are isolated from the surrounding structure and laboratory tested under horizontal (racking) loads without any external rocking restraint, they will generally uplift off the foundation beam at relatively low loads at the panel tension end (i.e. rock about one end of the panel). This rigid body rocking motion can result in large panel horizontal displacements with little panel resistance. However, it is recognised that when a panel is built into a house, the

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wall sheathing, framing continuity and gravity effects help resist panel uplifting, and panel resistance to racking consequently increases significantly. Panel uplift is entirely restrained by external means in the test method employed in the USA (ASTM 1976, 1980) to determine the racking resistance of isolated bracing panels. In contrast no external uplift restraint at all is employed in the Australian tests (Reardon, 1980) and panel rocking resistance relies entirely on fastening details used in actual panel construction. The P21 method uses a method between these two extremes, i.e., a partial uplift restraint. The most suitable restraints to be used in tests needs to be determined.

The uplift restraint specified in the P21 method is effectively provided by the shear strength of three 100 x 4 mm nails in timber (irrespective of panel length) as shown in Figure 1. Any actual wall uplift restraint used in practice (such as end straps) can also be used in the P21 test. The bottom plate is blocked to prevent horizontal slip. Note that no external uplift restraint (such as the P21 restraint shown in Figure 1) was used with the long walls tests described in this paper.

New Zealand allows house wall linings to provide the entire lateral resistance to satisfy code specified racking loads (SANZ, 1990). Set-in braces thus become unnecessary in New Zealand houses, with a consequent cost saving. (Relatively inexpensive light metal braces are commonly used in New Zealand to provide stability during construction). Confirmation of good racking performance of New Zealand houses is necessary. The plasterboard manufacturers in Australia have provided brochures detailing rated bracing wall systems with special hold-down details and with only nail (not glue) lining fastenings (e.g. Boral, 1992). However, most Australian houses are constructed with un-rated glued plasterboard linings. These house bracing designs make use of nominal bracing strengths attributed to these un-rated walls implicitly (eg. the National Timber Framing Code AS 1684, SA 1992) or explicitly (Timber framing manuals, eg. TRADAC, 1992). A very low bracing strength is prescribed for plasterboard walls in the Uniform Building Code in the USA (ICBO, 1991). Reliance is instead placed on claddings (e.g. plywood) and robust braces.

This paper is a summary of a BRANZ study report (Thurston, 1994). The study report presents more detailed experimental data than that included here, including uplift deflections, hysteresis loops, sheet diagonal strains and measured slips between sheathing and frame. Full details of the theoretical analysis and nail/sheathing load slip testing are also given. The proportion of wall deflection attributable to rocking is also reported. A literature review of full house and other testing revealed that LTF houses appear to have more resistance to lateral racking than the simple summation of the component bracing wall resistances would suggest. Post event reconnaissance reports generally indicated that wall racking failure was rare in fully constructed houses if the roof remained intact. (Wall bracing failure within houses under construction is more common in these events.) However, the trend of modern construction, with typically large wall openings, may change this result in future events. The literature survey also revealed that if walls are tested with full uplift restraint, then the racking resistance is simply the sum of the resistance of the component items (i.e., sheathing on one or both sides, braces etc), and any wall zone with large openings can effectively be ignored.

Calculation (Thurston, 1994) showed that wind uplift forces can be much greater than gravity loads or racking uplift forces at the critical end of short lengths of wall on a protruding house room (depending on the house geometry). Thus gravity loads cannot be assumed to enhance the racking resistance of these walls if the wind uplift forces are ignored. Gravity loads will result in some rocking stiffness enhancement for walls experiencing earthquake loading if earthquake vertical accelerations are small.

2. Description of Test Specimens

Five different wall configurations were tested with up to three different linings on each wall as shown in Figure 2 and Table 1.

TABLE 1 DESCRIPTION OF TEST WALLS

Wall Label	Figure	Sheathing	
		Side 1	Side 2
W1 L1	2(a)	PLB	-
W1 L2	2(a)	PLB	PY**
W1 L3	2(a)	PLB	TX
W2 L1	2(b)	PLB	-
W2 L2	2(b)	PLB*	-
W3 L1	2(c)	PLB	-
W3 L2	2(c)	PLB	PY
W3 L3	2(c)	PLB	PLB
W4	2(d)	PLB	PLB
W5	2(e)	PLB	PLB

Legend
- * 25 x 1 mm straps used at each end of 800 and 1900 mm length panels
- ** 25 x 1 mm straps used at each end of 800 mm length panel. PY cladding not used within wall window opening zone.
- PLB 9.5 mm thick gypsum plasterboard sheet.
- TX 7.5 mm thick cellulose fibre cement board
- PY 7.5 mm thick plywood

Walls W1 to W3 simulated exterior wall construction and walls W4 and W5 represented interior wall construction. Each of these walls had short exterior and/or interior wall returns. Walls W1 and W2 modelled the exterior wall of a protruding room with a typical size window or large sliding door respectively. Wall W3 was longer, with two window openings, and modelled a two room exterior wall of a house. Wall W4 modelled a long unperforated interior wall linking into the mid-side of another room at a door opening while wall W5 modelled a hallway wall with doors to two adjacent rooms. All the walls had PLB lining with fully taped and filled joints (including at the corners) as per the manufacturer's instructions on the interior faces as this is typical of New Zealand construction. Walls W4 and W5 were lined on both faces, except the exterior face of the exterior wall returns which were not clad. The exterior face of the wall W2 return wall was also unclad, while walls W1 and W3 had a variety of exterior claddings as detailed in Table 1.

All sections of the main wall which were longer than 1.6 m had the PLB lining nailed as a bracing panel, i.e., nails spaced at 150 mm centres around the bracing panel perimeter. Elsewhere the PLB lining was nailed to the framing with 30 x 2.5 mm clouts at 300 mm centres around each sheet and to the studs between sheet edges with pairs of nails at 300 mm centres.

The TX and PY claddings were both nailed at 150 mm centres around the perimeter of each sheet. This spacing was also used on internal studs for the TX cladding, but was increased to 300 mm for the PY cladding. The TX was nailed with 40 x 2.5 mm nails and the joints filled and reinforced. The PY was nailed with 30 x 2.5 mm flat head nails, (nail head slightly thicker but smaller diameter then the clout).

The opening was cut out of the sheathing for walls W1 so that joints made at the vertical sheet edges were approximately 300 mm away from the openings as is recommended by all of the sheathing manufacturers to prevent shrinkage cracking. However, in other instances the sheathing sheet edges coincided with the window (or door) trimmer studs (as is common New Zealand practice) for all other walls.

The PY cladding in wall W1L2 was only used for the panels each side of the window opening (i.e., not above or below the window) as this is common practice for bracing panels in New Zealand. The studs at the end of each 800 mm long panel were fixed to the foundation beam with a single 25 x 1.0 mm (nominal) galvanised high tensile metal strap nailed to the stud with 6, 30 x 2.5 mm FH nails. Wall W2L2 used similar end straps at each end of both main panels.

Additional gravity load from loose concrete blocks was placed on wall W5 because wall W4 failed prematurely due to uplift at the openings and wall ends. A simulated ceiling weight of 0.68 kN was applied to both interior return walls and a simulated roof truss load of 6.15 kN was applied to the exterior return wall.

A 25 x 25 mm light gauge galvanised steel angle brace was used in all wall portions with lengths greater than 1.6 m between openings. This brace is commonly used in New Zealand construction practice to facilitate panel erection.

The test specimens were constructed in accordance with NZS 3604 (SANZ, 1990) except that 90 x 35 mm finger jointed No. 1 Framing Grade Radiata Pine was used for framing. (This framing was chosen because it is anticipated that it will become commonly used in New Zealand). Flat head 75 x 3.15 mm nails were used to join the framing (cf. 100 x 4 mm specified in NZS 3604) because the timber was thinner than traditionally used for New Zealand construction. The bottom plates of the exterior walls were nailed to the foundation beam with pairs of 100 x 4 mm flat head nails at 600 mm centres, except for the wall returns of W1 and W2 which were nailed at twice this density. The nail density was doubled for these two wall returns to simulate twice the length of wall returns actually used. Interior walls (W4 and W5) were also nailed with pairs of 100 x 4 nails at 600 centres, except only a single nail at 600 centres was used for the interior wall returns.

A standard aluminium framed window (with timber reveals) was installed in the window opening for some test cycles in all three test configurations with wall W1. The opening clearances between the window reveals and the framing were 16 mm (width) and 5 mm (height). The reveal was nailed to the framing with two 1.3 mm diameter nails, through timber packers where necessary, at each corner of the window.

3. Test Setup

The walls were tested in the vertical orientation. Rollers provided out of plane buckling restraint for the top plate where spans between return walls exceeded 3 m. Load was applied with a hydraulic ram reacting against a strongwall, and was measured with 100 kN load cell; the equipment being within Grade 1 accuracy (BSI, 1985).

Steel channels, screwed to the top plate along the length of the test wall, transferred the actuator load to the wall. A cover channel (not screwed to the test wall) was used to link the channels on either side of the opening to prevent any artificial uplift restraint at the edge of the openings.

Linear potentiometers were used to measure slip of the sheathing relative to the frame, uplift of the studs relative to the ground and horizontal deflections of the top and bottom plate of both main and return walls. Sheathing diagonal strains were measured using Demec buttons.

4. Test Procedures

The wall cyclic test regime can be seen from the hysteresis plots in Figure 3. At each displacement level. the cyclic loading was applied at a rate of 0.1 Hertz using a sinusoidal displacement function. After the 4, 8 and 24 mm cycles the walls were moved to the previous maximum positive and negative displacements and the Demec readings recorded . Additional cycles (to previous wall peak imposed deflections) were applied to wall W1 with the window installed. The window was then removed for the subsequent cycles.

After testing wall W2L1 to ±24 mm, it was observed that the only distress was in the nail/PLB connection along the bottom plate. These nails were removed and replaced with new nails which were offset 50 mm from the original nail holes. A single 25 x 1.0 mm (nominal) high tensile steel strip was then nailed to the studs at the ends of both the 1.9 m and the 0.8 m wide panels with 6, 30 x 2.5 mm FH nails. The wall was relabelled as W2L2 and retested.

5. General Observations

Three types of damage were observed in the test walls: rupture of the sheathing at the corners of the openings (or parting of the joint at this location); localised sheathing damage at nail locations; and separation of the studs from the bottom plate (or the bottom plate from the foundation beam). The taped and filled joints at wall return junctions and sheet joints which were not at opening corners were never damaged.

6. Comparison of Experimental Results and Theoretical Predictions

Panel racking deflections due to nail slip between sheathing and framing and sheathing shear deformations can be calculated using the theory proposed by Patton-Mallory and McCutcheon (1987). The theory predicts the monotonic panel load-deflection curve for walls with complete rocking restraint. (With cyclic loading this can be taken as the envelope, backbone or parent curve - all meaning the curve joining the hysteretic peak points.) The other major component of the horizontal deflection arises from panel rotation due to lifting of the studs at the tension end and crushing of the bottom plate beneath the stud at the compression end. (Deflection due to panel flexure is negligible). A method of predicting this deflection component for panels with P21 Type end restraint is given by Thurston (1994). By combining these two deflection components a complete P21 load-deflection prediction can be made. It was shown (Thurston, 1994) that this method gave good agreement with actual P21 test results.

Load-deflection parent curve predictions were made using the above theory for rigid body rocking restrained and P21 restrained walls. (i.e., 2 theoretical predictions for each wall). Input data included measured nail slip envelopes. These two theoretical predictions (labelled Curves 1 and 2 respectively) are superimposed upon the load-deflection plots in Figure 3. The methodology considered the sheathings on each panel between wall openings separately and then added the resultant panel load-deflection envelopes together to obtain total wall load-deflection envelopes.

The theory (Patton-Mallory and McCutcheon, 1987) assumes that the sheets rotate around their centroids which is probably reasonable for the cladding. The lining, however, was jointed to the wall returns, which would have imposed significant restraint against slip between lining and framing at this location. The walls were therefore expected to be stiffer and stronger than predicted.

The PLB taped and filled sheet joints never failed in the test walls (except at opening edges) so the theoretical analysis for this material assumed the sheets between openings were effectively combined into a single (wide) sheet.

The theoretical load predictions were significantly higher than the experimental measurements for some plots. Hence the theoretical predictions were plotted to the correct scale until they "ran off" the plot and were then factored by a selected value to enable the curves to be usefully drawn on the same hysteresis plot. The unfactored and factored curves were joined by a "wriggly" line to indicate the change in scale and the factors used are noted on the affected plots.

Generally the P21 uplift restraints were found to be sufficiently stiff and strong to effectively provide full uplift restraint for the walls sheathed on one face only where the nail slip strength was low (i.e., Curves 1 and 2 coincide at large deflections for single lined PLB walls). However, where the wall was sheathed on both sides, the total wall strength was almost entirely governed by the P21 uplift restraint and in this instance the wall rocking mechanism became dominant. The same theoretical result occurs where the nail slip strength is high. Note that as the walls were only fastened to the foundation beam by nails the Australian test method would have resulted in very low strengths for the individual panels and hence low predicted long wall strengths.

6.1. Wall W1

Figure 3 shows that Wall W1LI was significantly less strong and ductile than the other walls, with wall W1L2 being the most ductile while WIL3 was the strongest.

Although wall W1L1 was somewhat stronger than predicted in the "pull" direction, the theoretical curves are a reasonable approximation of the experimental data.

The theoretical analysis for full panel end fixity predicted significantly higher loads than were actually measured for Wall W1L2 i.e., the predictions can be unconservative where the cladding is not continuous across an opening. (Note Curve 1 is joined by a "wriggly" line where the Curve factor changes from 1.0 to 0.53.) Agreement between the measurements and Curve 2 is reasonable, i.e., the P21 method gives good (but slightly conservative) results in this instance.

Higher loads were resisted by wall W1L3 than for wall W1L2 (due to the continuity of the cladding below the window). The wall performance can reasonably be estimated by assuming full fixity up to 24 mm deflection. Predictions using P21 restraints were unduly conservative.

6.2. Wall W2

This single lined wall with a large door opening effectively behaved as two separate panels with very little uplift restraint being induced at the door corners. The actual uplift restraint at door openings must have been significantly less than simulated by the P21 restraints as the actual strength was only about 75% of that predicted.

The backbone curve for the wall without straps (W2L1) is also shown in the figure for W1L2. This shows that the strap uplift restraints added to this wall significantly increased its strength.

The theoretical predictions provide reasonable but conservative approximations of actual behaviour. The predictions show greater initial wall stiffness than actual measurements, probably due to the softening experienced by the wall when loaded as W1L1.

6.3. Wall W3

The strongest and most ductile wall was W3L3 and wall W3L1 (lined on one face only) had slightly less than half the strength of the other two walls.

Wall W3L1 was significantly stronger than predictions at large deflections but there was a good agreement for initial stiffness.

The full fixity theoretical parent curve for Wall W3L2 (Curve 1) showed reasonable agreement with measurements, although the wall was stiffer than predicted at low deflections. The same comments apply to Wall W3L3 although there is even more difference in actual stiffness prediction.

6.4. Wall W4

Wall W4 was stiff and strong up to a deflection of 6 mm. At this stage the wall began to behave as two independent rotating panels (i.e., dominated by uplift at the door opening). The peak resisted load remained constant with increasing deflection during the push cycles but reduced significantly in the pull cycles to 24 mm. The wall hysteresis loops became more unsymmetrical at higher displacements. The wall was significantly weaker than predicted although there is good agreement for wall initial stiffness.

6.5. Wall W5

Wall W5 exhibited stable hysteresis loops at large deflections and was stronger in the push direction than in the pull direction. This was attributed to the added masses on the external walls. There were large added masses at the North (external return wall) end, and these resisted wall uplift for the push load. The added masses at the South end were relatively small and provided little resistance to uplift forces during the pull load.

Despite additional gravity load being added to simulate real conditions, this wall was significantly weaker than predicted, and the comments for wall W4 (above) also apply here.

6.6. Summary of Findings From Comparisons

Several conclusions can be drawn from the above comparisons.

- A good (and conservative) estimation of the performance of walls with large window openings (but no door openings) can be obtained by assuming that the wall comprises separated panels between the window openings, and that these have complete uplift restraint. The P21 uplift restraint can be unduly conservative in these instances.
- This conclusion also applies to walls with door openings, where hold-down straps are used on the panel edges bounding the door.
- Both the P21 and full uplift restraint simulations are significantly unconservative where the straps are not used even when accounting for the effects of typical truss and ceiling weights.

7. Influence of Installed Window

Addition of the window made little difference to the total wall performance. The hysteresis loops were slightly "fatter" and the peak loads were 3-12% greater than the residual peak loads of the previous cycle without the window. This increase was greater for the 24 mm cycles than it was for the 8 mm cycles. The load drop off was small during the four cycles with the window. The peak load resisted during the 50 and 60 mm cycles (with the window installed) was close to peak loads measured during the 36 mm cycle.

A general conclusion is that the window "rode out" the imposed wall deformations, with minimal damage at large distortions, and had little influence on the load resisted by the wall.

8. Measured Stud Uplifts

Figure 4 plots the wall uplift deflection profiles at a racking displacement of 8 mm. It can be seen that the graph gradient for panels bounding openings is fairly consistent for all walls. The wall deflection due to this uplift can be computed by factoring this gradient by the wall height. This ranged between 60 and 100% of the applied 8 mm racking deflection, although the actual influence is expected to be less than this for reasons discussed by Thurston (1994).

9. Conclusions

Ten long walls with window and door openings were tested under pseudo-static reverse-cyclic racking providing indicative behaviour of what can be expected to occur with large earthquake or wind loading. The measured wall resistances were compared with theoretical predictions. Wall uplift, force distribution and sheathing slip were also measured. Based on these results the conclusions given in this section were made.

For a wall with large window openings (but no door openings) a good (and conservative) estimation of wall performance can be obtained by assuming the wall comprises separated panels between the window openings, and these have complete uplift restraint. The P21 uplift restraint can be unduly conservative in these instances. This conclusion also holds where a wall has a door opening and hold-down straps are used on the panel edges bounding the door. However, where a wall has door openings (and straps are not used) both the P21 and full uplift restraint simulations are significantly unconservative.

For the walls and sheathings tested, there appeared to be little difference in racking strength between walls where sheets are jointed at window openings and those where sheets are cut for the openings with the nearest joint 300 mm or more away from the vertical opening edge. (The latter construction is recommended by the manufacturers to resist shrinkage cracking.) In the former instance the sheets separate at the joints, at about 6 mm wall racking deformation, while in the latter situation sheet rupture occurs at the opening corners at about 6 - 16 mm racking deformation and the rupture extends to the top (or bottom) of the sheet at 12-16 mm racking deformation.

The window installed in the walls "rode out" the imposed wall deformations, with minimal damage even at large distortions, and had little influence on the level of wall racking strength or stiffness.

The sheets of paper faced gypsum plasterboard used were fully taped and filled at corner joints and other sheet junctions. The only failure which occurred in these joints was over the short lengths above window openings so it is concluded that properly formed full sheet-height joints can be relied upon to transmit racking vertical shear forces in actual construction.

Racking deformations comprise of several component deformations. The two most dominant components are rocking of the entire panel and sheet rotation relative to the frame arising from fastener slip between sheathing and frame. Measurements indicated that the former mechanism contributed 60-100% of the total movement (although this may have been overestimated as some of the vertical movement measured may have been from top and bottom plate flexure rather than panel rotation). The second mechanism accounted for between 10-50% of the total movement. These results indicate that panel rocking is an important deformation mechanism in practice and suggests that wall stiffness's determined from testing procedures using full uplift restraint need to be reduced for application in real buildings. It is therefore concluded that a theoretical analysis assuming full uplift restraint gives the best agreement with experimental results for walls without doors which indicates that "other" resisting mechanisms than assumed in the theory were significant in increasing the wall stiffness's.

By comparing wall strengths for construction with only internal lining to wall strengths with internal lining and external cladding, it was concluded that the wall strength is approximately the sum of the sheathing panel strengths (i.e., sheathed on one face only). This is the result which would be obtained from the theory assuming full uplift restraint. However, both theoretical and experimental work using the P21 method indicates that there is only a small total wall strength gain attributable to the second sheathing, which is a limitation of the P21 uplift restraint.

10. Recommendations

The investigation summarised in this paper has shown that a conservative bracing rating for a wall is obtained by summing individual panel bracing ratings obtained from both BRANZ P21 tests and tests using full panel uplift fixity, except where the bracing panel terminates at a door opening or where a sheathing is only used in discrete lengths between openings (such as the plywood in wall W1L2). Based on the W2 series test results, if it is wished to use a panel bracing rating from tests using external fixity, it is recommended that an additional 6 kN connector is used to connect the stud bounding the door opening to the foundations where a bracing wall terminates within (say) 1 m of a door opening. It is also recommended that a theoretical study be made of the maximum size a window opening may be before it is necessary for 3 or 6 kN uplift restraints to be used at studs bounding the window. With either of the above exceptions the bracing rating determined from the Australian type tests (Reardon, 1980), can be used, i.e., tests without any external restraints.

Bracing walls rarely fail in a major seismic or wind event (if the roof remains intact). This suggest that bracing wall design need not be unduly conservative. The trend for fewer internal walls and wall with many large openings suggests care is still required. It is recommended that bracing rating calculations sum the bracing lengths of sheathings between openings. The sheathing bracing ratings shall be determined from tests with walls under full uplift restraint. Where a bracing panel terminates within 1 metre of a door it is recommended that a 6 kN strap be used at this location. Otherwise the bracing rating for the panel must be obtained in a test where no uplift restraint is used. The Queensland practice (TRADAC, 1992) of attributing a specific bracing rating to nominal walls is recommended. The question of the appropriate reduction factors to use on test results is not addressed.

11. Acknowledgments

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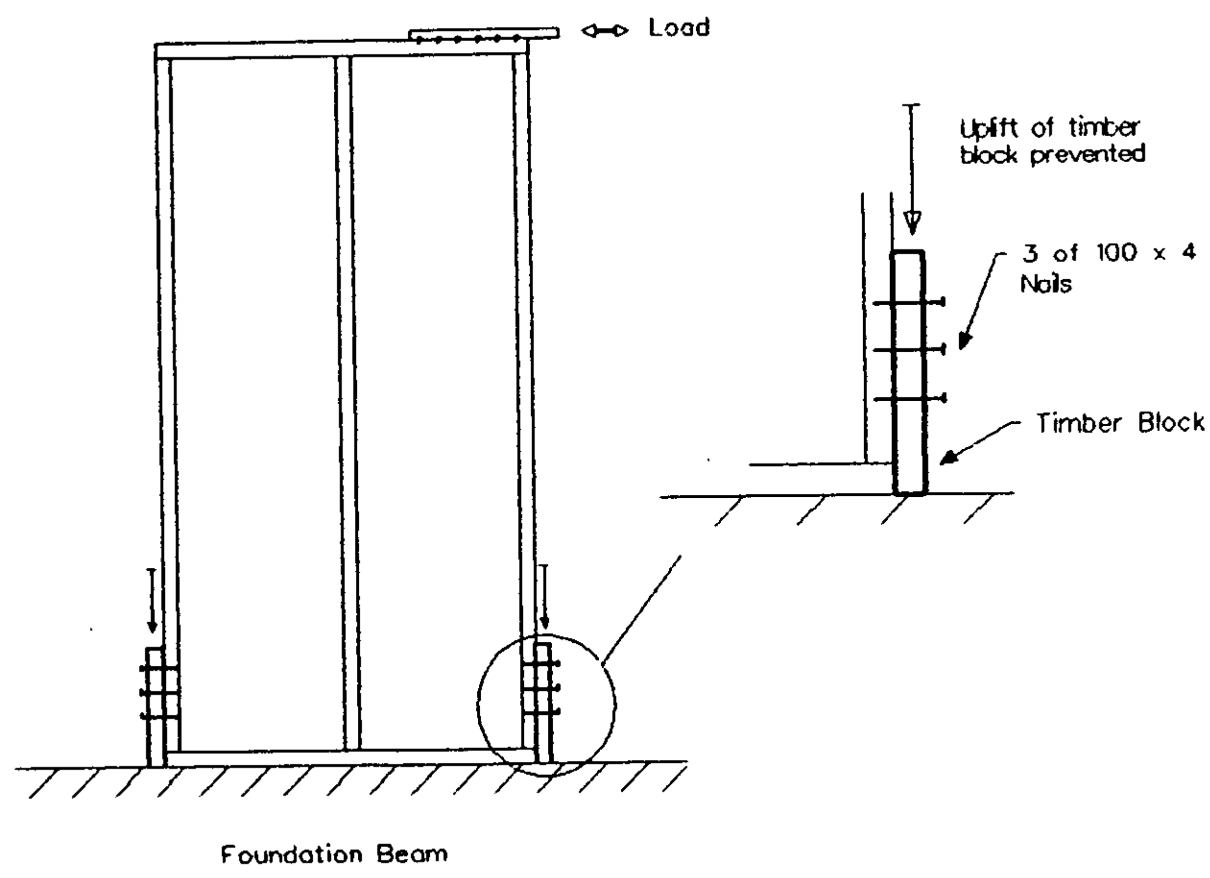
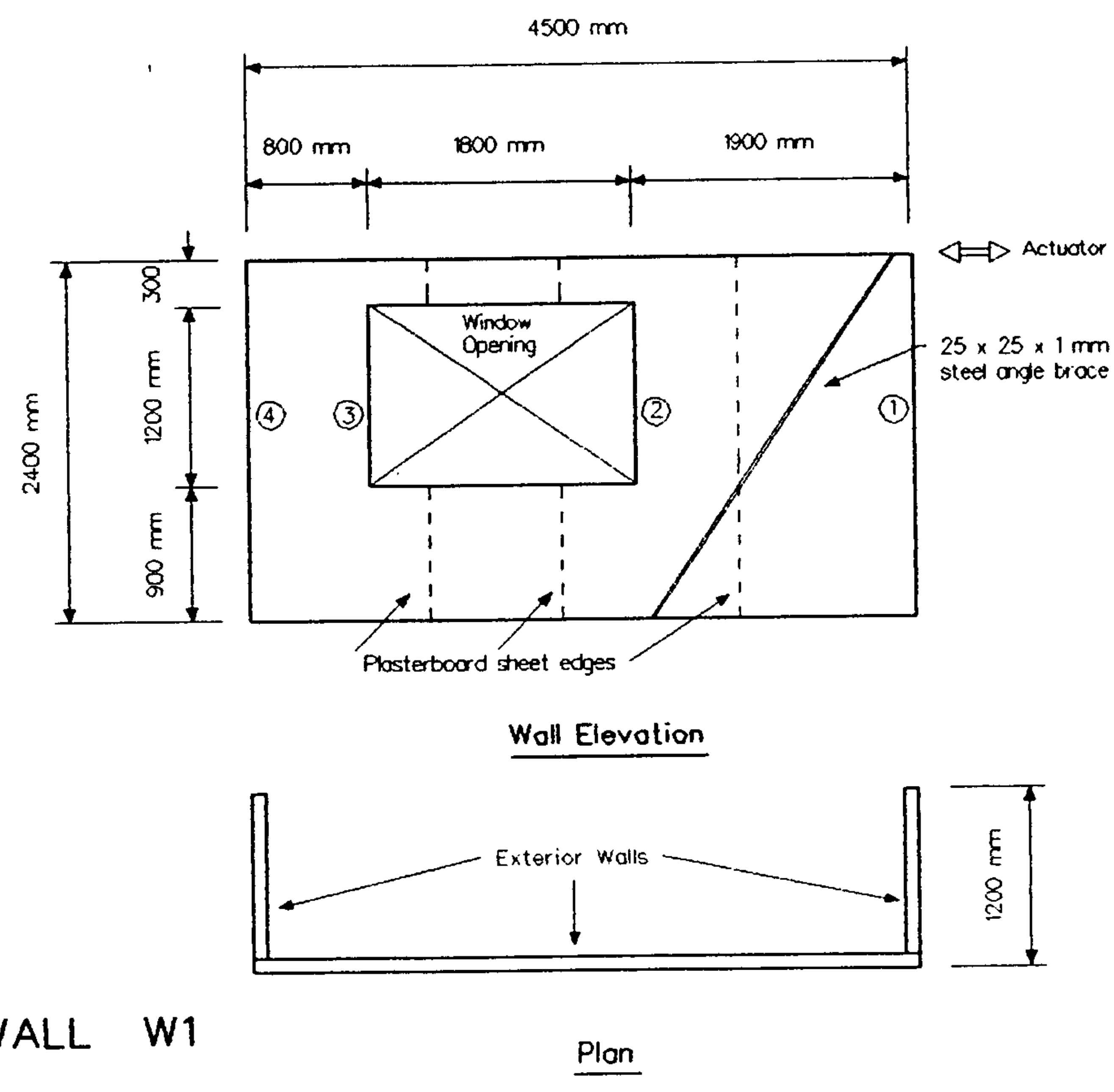
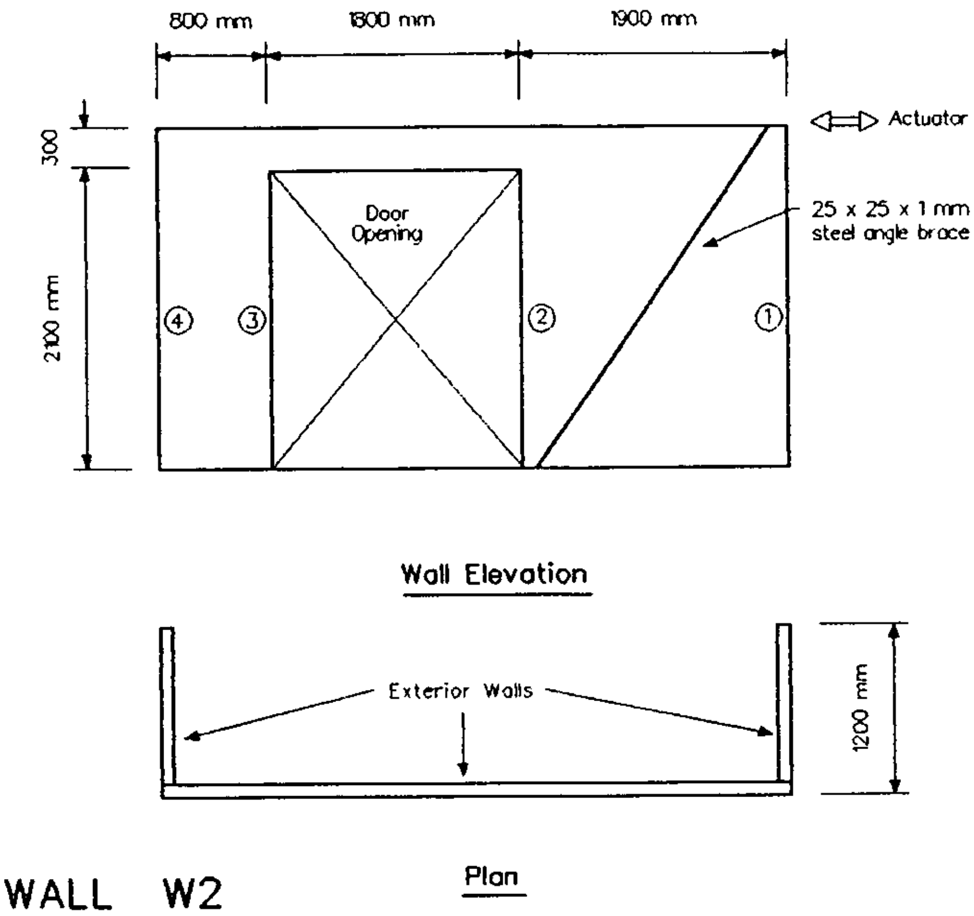


FIGURE 1 TYPICAL P21 TEST

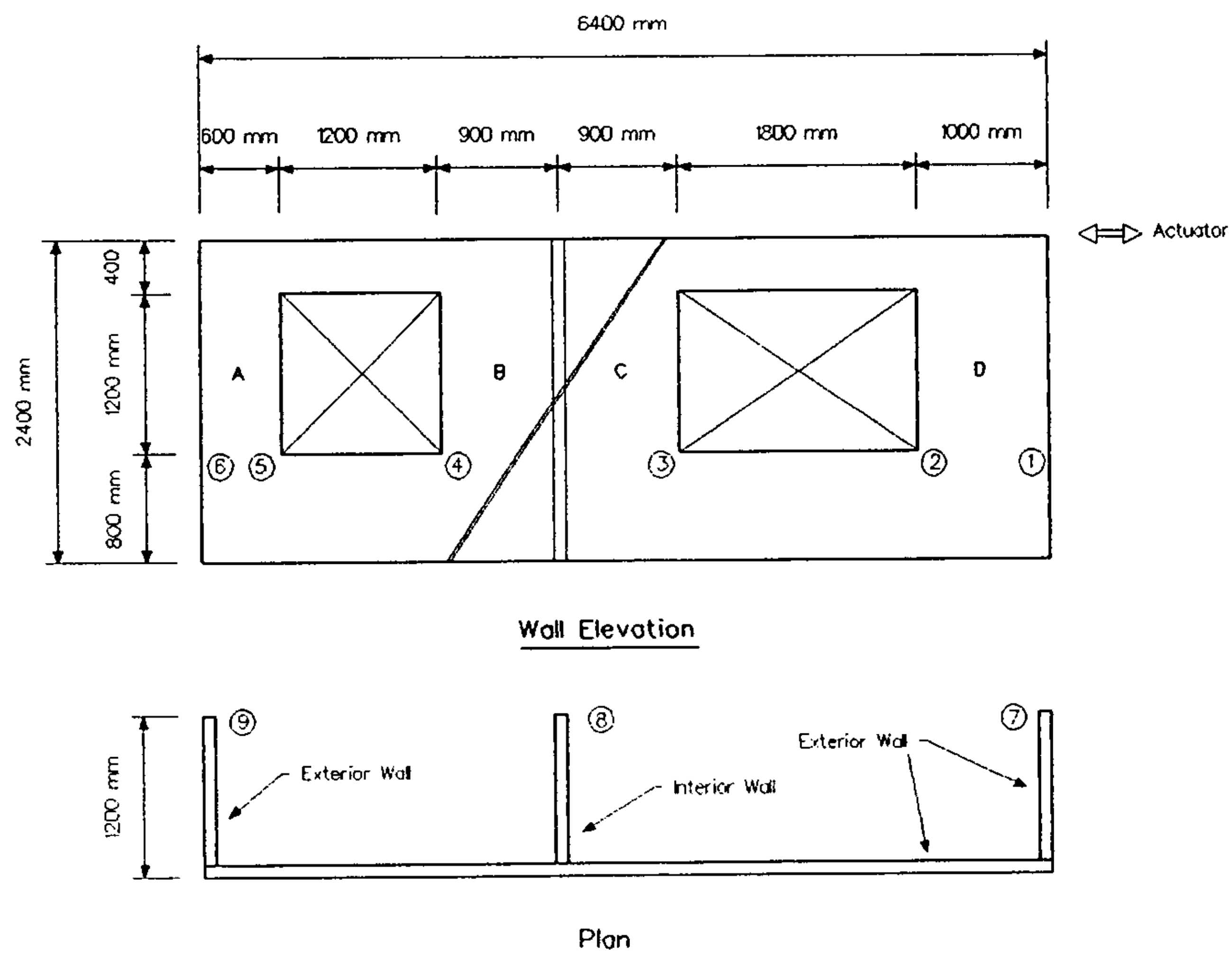


(a) WALL W1

FIGURE 2 GEOMETRY OF WALLS

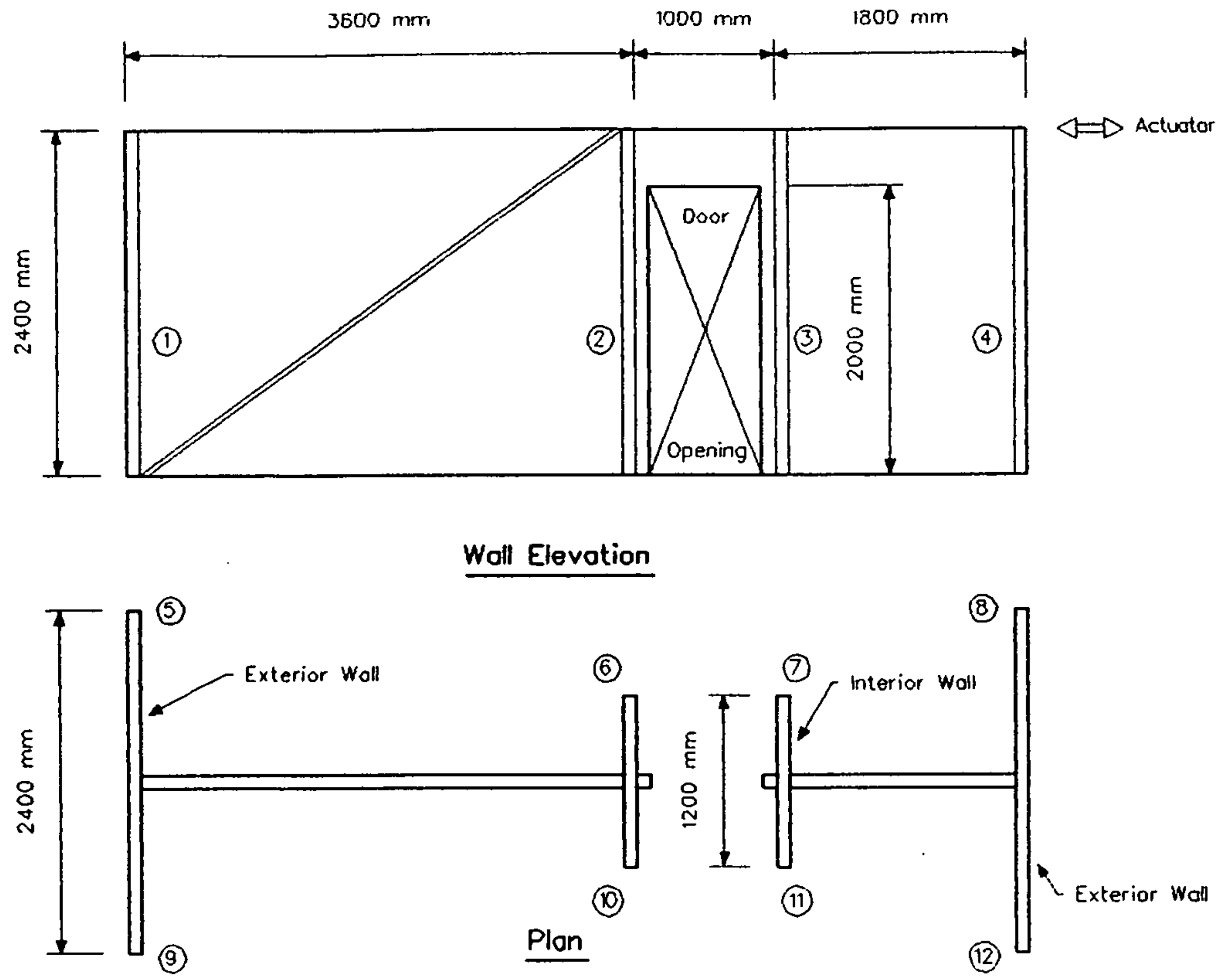


(b) WALL W2

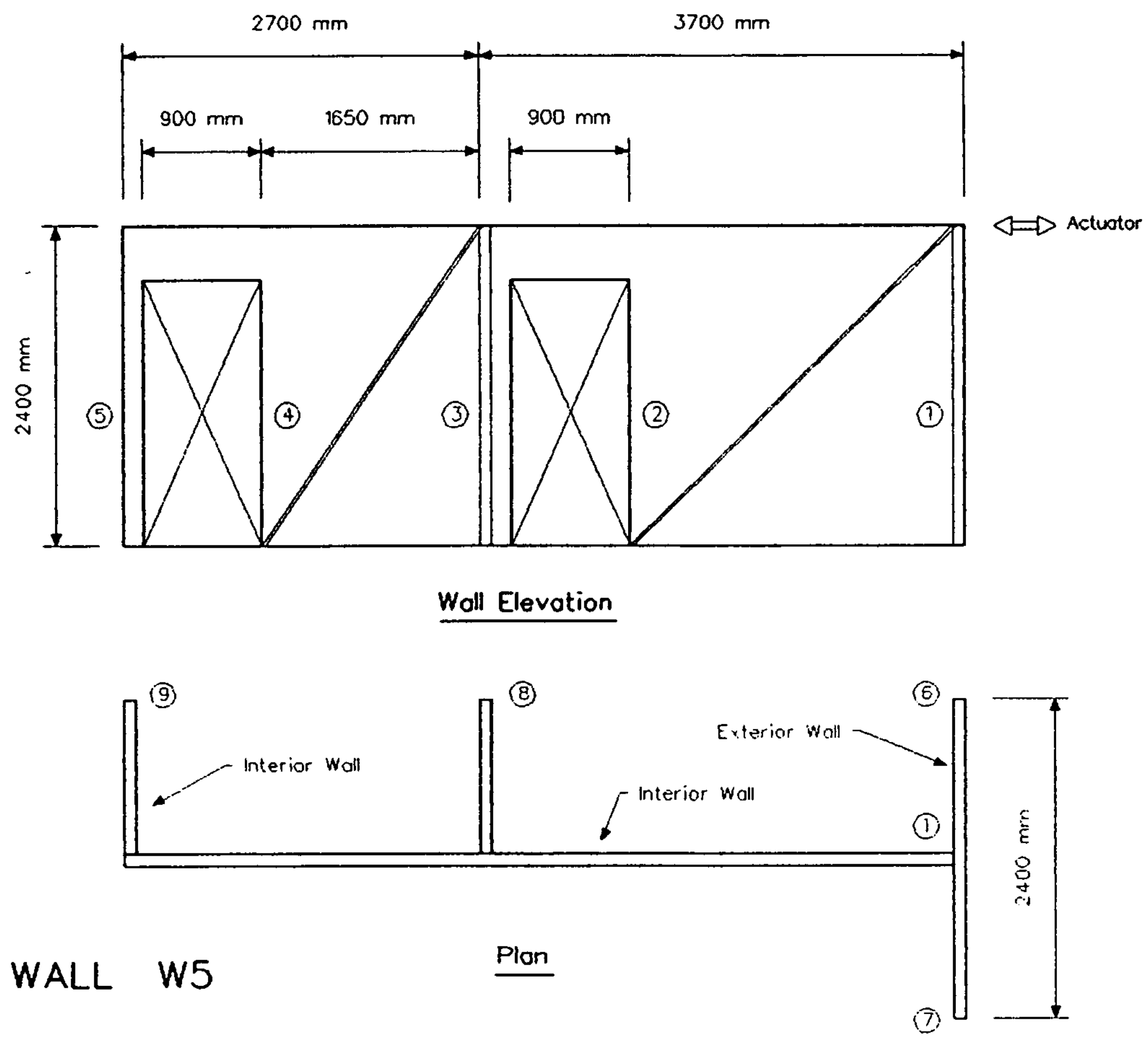


(c) WALL W3

FIGURE 2 CONTINUED



(d) WALL W4



(e) WALL W5

FIGURE 2 CONTINUED

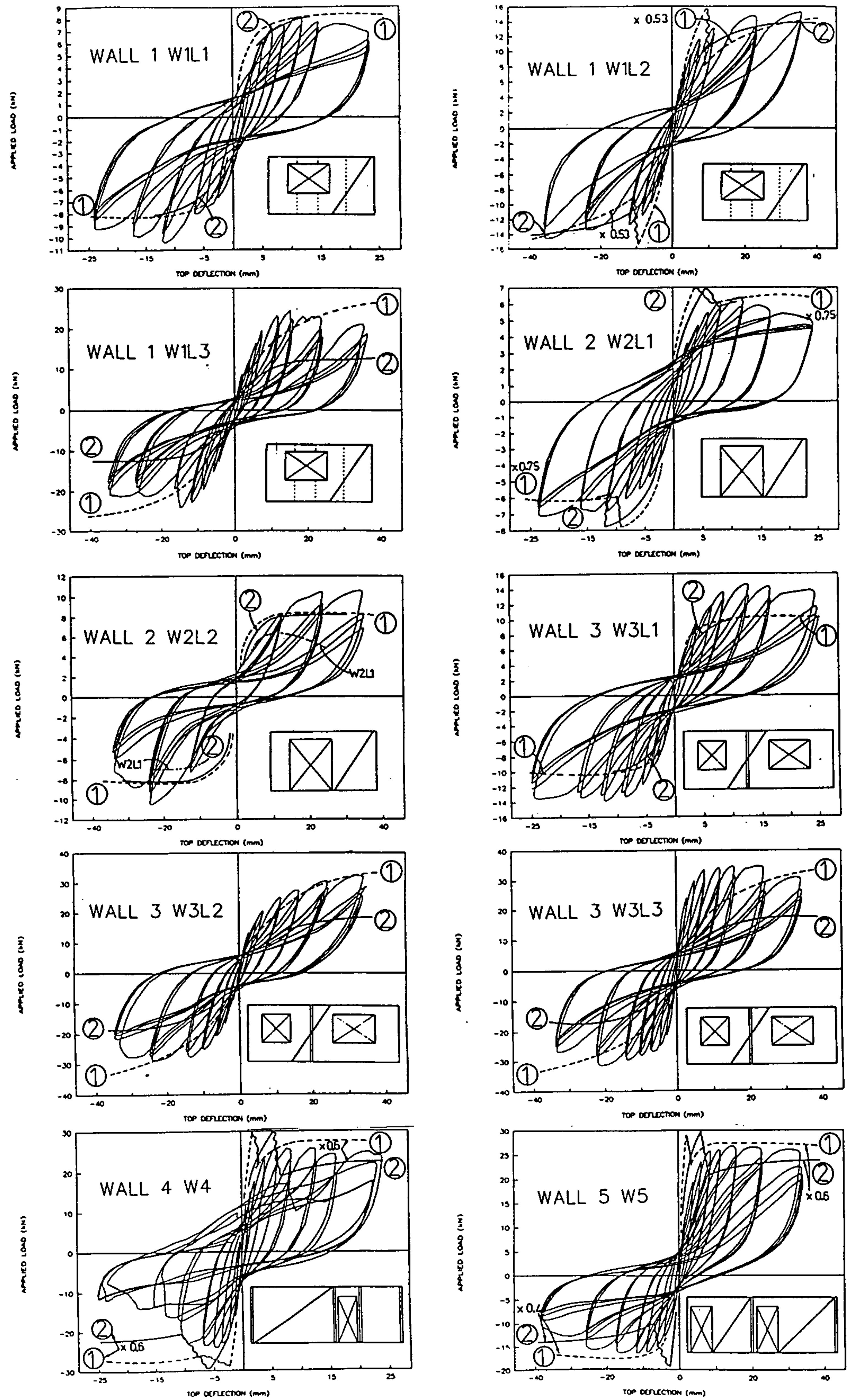


FIGURE 3 WALL HYSTERSIS LOOPS

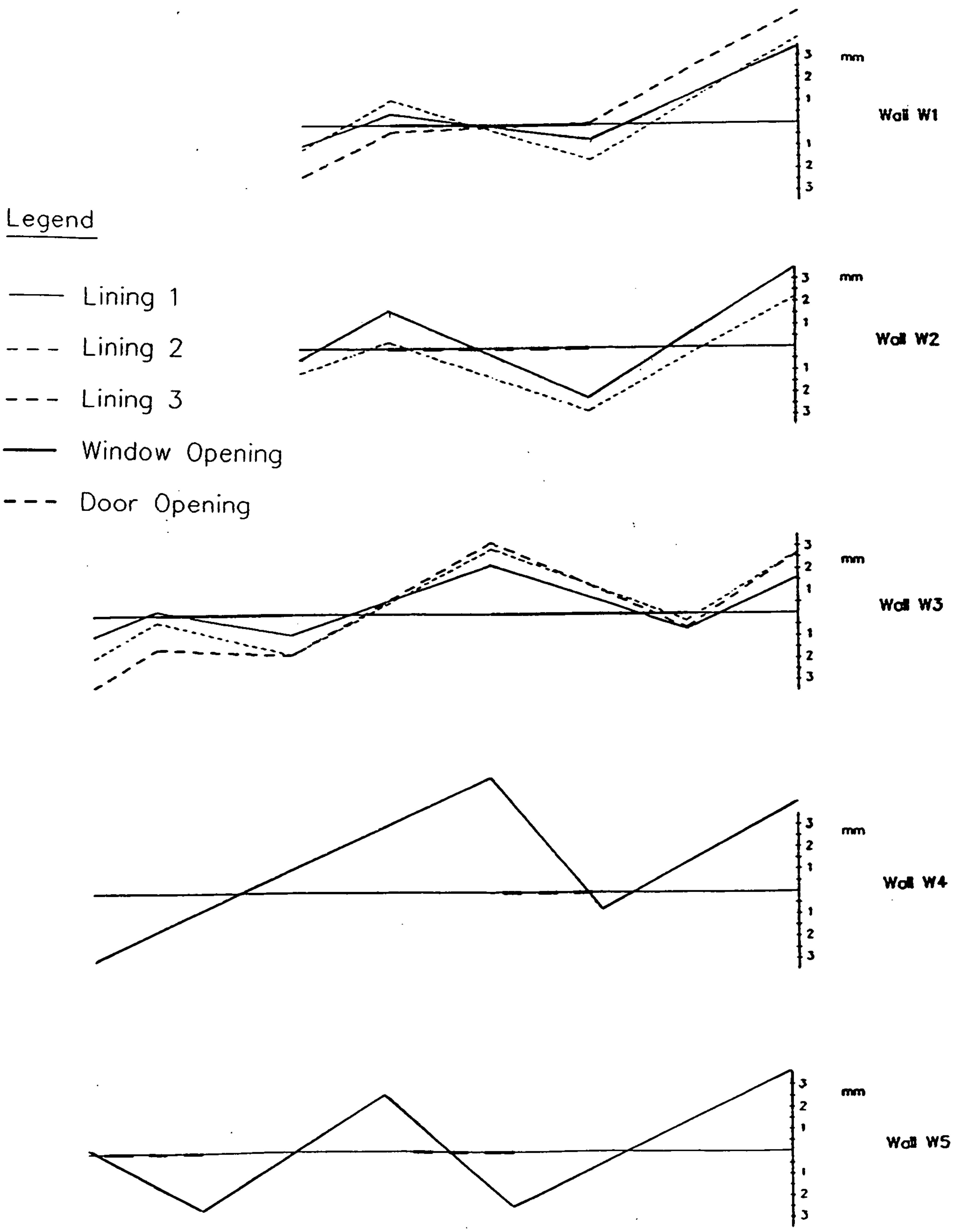


FIGURE 4 Wall Uplift Deflection Profiles at a Racking Deflection of 8 mm

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Racking resistance of LTF
walls with openings.!/Bui

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