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Two-Directional Cyclic Racking of Corner Curtain Wall Glazing

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TWO-DIRECTIONAL CYCLIC RACKING OF CORNER CURTAIN WALL GLAZING

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PREFACE

This study forms the third part of a research programme undertaken by BRANZ on the behaviour of glazing systems under seismic induced racking. The first part resulted in a BRANZ Study Report SR 17 entitled "The Development of a Procedure and Rig for Testing the Resistance of Curtain Wall Glazing". The second part resulted in a BRANZ Study Report SR 39 entitled "The Behaviour of External Glazing Systems Under Seismic Induced In-plane Racking".

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NOTE

The mention of trade names in this report does not imply exclusion of other products or practices for these applications, nor specific endorsement by BRANZ.

This report is intended for structural engineers, architects, designers, manufacturers and other workers in the field of glazing and engineering research.

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BRANZ Study Report SR 44 S J Thurston and A B King

REFERENCE

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KEYWORDS

From Construction Industry Thesaurus - BRANZ Edition:

Curtain Walls; Glass; Glazing; Nonstructural Elements; Secondary Elements; Racking; Test Procedures; Testing; Two-way; Cyclic Sealants; Structural Silicone; Separation; Earthquake; Corner; Multi-storey Buildings; Gaskets, Inter-storey Deflections; Drift

ABSTRACT

In an earthquake, curtain wall glazing systems may be a hazard to both building occupants and nearby pedestrians. This is the third phase of a BRANZ research programme to study earthquake behaviour of glazing systems used for multi-storey buildings. Earlier work looked at in-plane behaviour; this report looks at two-way loading (in-plane and out-of-plane), as would be experienced by glazing near building corners. Three (full-sized) generic wall types are tested: a conventional dry-glazed gasketed curtain wall; a unitised structural silicone system; and a combination unitised system comprising structural silicone on two sides of each glass panel with conventional gaskets on the other two sides. Sinusoidal loading was applied simultaneously in two directions to what was effectively a three storey glazing wall, comprising four panels at each level, arranged in an "L" shape (i.e. corner configuration). Glass failure was low, even under severe imposed seismic deformations. The imposed curtain wall deflections resulted in distinctly different deformation mechanisms in each instance. It was concluded (with some restrictions) that in-plane loading can be used to test curtain glazing walls and a recommended test procedure is provided.

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1.0 INTRODUCTION

It is particularly appropriate that curtain walls are studied intensively in New Zealand; performance demands are more severe in this country than most others in the world. High coastal winds cause corrosion and weathertightness problems. Wall distortion problems are brought about by New Zealand's location on an active earthquake belt. This latter element is especially important, as curtain walls that do not perform to expectations are a potential hazard to pedestrians and building occupants.

This report describes simulated seismic tests of three generic types of corner curtain wall systems (i.e., walls extend in two directions). On the basis of these and other tests, a laboratory test procedure for evaluating the seismic performance of curtain walls is proposed. As small differences can significantly influence wall behaviour, it is essential that laboratory specimens are identical to those installed in the field, including all weather proofing details.

Lim and King (1991a) reported on in-plane racking of various glazing systems. Testing described in this report is an extension of that work, using a modification of Lim and King's test rig. Rather than duplicate portions of Lim and King's report, a summary of which has been published elsewhere (Lim and King, 1991b; King and Thurston, 1992), this report assumes that the reader has access to it. Critical portions required for comparative purposes are, however, summarised. Generally, Lim and King (1991a, 1991b) found that a single plane of curtain wall glazing performed well when subjected to racking deformations. However, glass at corners may be more vulnerable to earthquakes, because of the more complex seismic deformations (in-plane, out-of-plane and twisting). Glass confinement may also be more severe at corners. This study was initiated to investigate corner effects.

Lim and King (1991a) provided a comprehensive literature review. More recent information is discussed briefly below. A recent modification to the draft New Zealand Loadings Code (SANZ, 1992) now limits inter-storey drift to 1.5% of storey height, although this can be increased to 2.5% if an appropriate numerical time history analysis is used. P-delta effects must be included for flexible high-rise ductile structures. For a 2.8 m inter-storey height, used in the test specimens in this report, the 2.5% code limit represents an inter-storey drift of 70 mm. If a curtain wall can survive five test cycles to a drift of 3% without significant loss of glass, the system is considered by the authors to be suitable for general use in New Zealand. This is intended to take into account possible beam "growth" during a maximum credible earthquake, building and earthquake modelling inaccuracies etc. A proposed glazing wall test and evaluation procedure is presented in Appendix A.

Reports of damage in the 1989 Loma Prieta earthquake have also become available (NZNSEE, 1989), since Lim and King's literature review. Many windows broke in older commercial buildings and to a lesser extent in modern low-rise commercial buildings in this earthquake. However there was almost no damage to glazing in modern high-rise buildings.

Deschenes et al. (1991) recently conducted an extensive series of simulated seismic in-plane racking tests on a 3.7 m high by 4.6 m wide curtain wall. These contained three glass panels, 1.8 m (high) by 1.5 m (wide), with aluminium spandrels above and below to make up the rest of the 3.7 m height. Conventional gasket dry glazed framing was used (very similar to the gasket system labelled NG in this report). The following types of glass were tested: annealed monolithic (with and without film backing), fully tempered monolithic, heat strengthened monolithic, annealed laminated, fully tempered laminated and heat strengthened laminated. These tests evaluated the ability of the various types of glass to remain in the curtain wall after breaking. Consequently, the deflection levels at which cracking and breakage occurred were not well reported. It was concluded that the moderate amount of glass fallout observed during the test programme indicated that better test criteria, such as out-of-plane motion, was needed to more accurately represent building motion during earthquakes. It was also noted that glass fallout, known to occur even in moderate earthquakes, may have been the result of poor installation.

Deschenes et al. (1991) used three test phases. Phase 1 included five cycles at 0.5 hertz to 45, 50, 55, 60, 65, 70 and 75 mm amplitude. Phase 2 included 60 cycles at 1.0 hertz to 64 mm amplitude. Phase 3 repeated Phases 1 and 2 with an initial racked displacement of 76 mm.

In Deschenes et al's work, some of the wedges and gaskets worked loose or partially fell out in Phase 1. Most fell out completely in Phases 2 and 3 or became trapped between glass and the inner wall of the glazing pocket. Gasket fallout did not cause the glass panes to fall from the glazing pockets, but did remove the cushion and alignment guide between glass and aluminium. This resulted in minor chipping and corner crushing and cracking of some glass types, but only in annealed monolithic glass did it contribute directly to fallout. Glass damage often first appeared in Phase 1 and worsened during Phases 2 and 3. Gasket fallout sometimes allowed sufficient out-of-plane movement of the glass panes for the edge to "catch" the outer edge of a mullion. Severe cracking or glass fallout then resulted.

No glass fallout occurred during Phase 1 of any test. Twelve annealed glass panels experienced fallout in Phase 2 and four in Phase 3. The other types were more resilient, with three of the different types of laminated glass not experiencing fallout in any specimens in any phase, even though there was severe cracking in both glass panes.

The large number of tests were all performed using the same glazing frame (more than 130,000 cycles). No structural damage was detected and the frame lost little stiffness. After 65,000 cycles some Tek screws became loose and stripped their threads. Two horizontal rail covers fell off.

Deschenes et al's test regime was designed to study the post-breakage behaviour of glass. However, as a test regime to study likely seismic performance, the authors of this report consider that Phase 1 was severe, Phase 2 had an excessive number of large amplitude cycles, and Phase 3 imposed unrealistic levels of deformation. In contrast, King and Lim (1991a) cycled their (annealed only) glass curtain test walls to a more practical upper limit of 4-20 cycles at the maximum inter-storey deflection of 100-120 mm, for simulation of a severe earthquake attack. They concluded that most of the curtain wall systems they tested would perform adequately in such an event, and that in-plane performance could be assessed by laboratory testing full scale specimens. Sliding or rotation mechanisms, either of the glass or the complete frame, were generally tolerant to racking. Stress concentrations, such as those associated with patch fitting systems, can result in premature failure. They also concluded that the rate of test racking displacement should be a minimum of 10 mm/second, after which the results were not sensitive to loading rate. They also noted that the behaviour of glazing systems at corners was not well understood, with many specific details being recommended by different researchers, and recommended the present study for future work.

2.0 TEST PROGRAMME

2.1 Test Rig

Test rig details are shown in Figure 1 and a general view is shown in Figure 2. Columns and levels are labelled in Figure 1 to aid the description below. Glass curtain walls were supported by brackets connecting the glazing mullions to horizontal steel beams (Figure 3a). Three support columns carried the self weight of the specimen (Figure 3b,c,d). The columns were braced to the strong floor to resist the applied horizontal simulated seismic loading.

The steel beams were allowed to slide freely relative to the columns at levels 1 and 2, and were rigidly connected to the columns at levels 3 and 4. Steel beams at levels 1 and 2 were braced together so they would move an equal distance. When the beams at level 2 were displaced horizontally by the actuators, the glazing walls were forced to deform in the shape shown in Figures 1 and 4b. This was because the glazing walls were connected to the beams. This is clearly a severe imposed seismic inter-storey deformation shape. A more typical computed shape is also shown in Figure 4. The difference that the glass "sees" between these shapes is that with the former there is a sudden change in the slope of the mullions at the mullion/transom junction. If this slope change does not occur precisely at the junction, but is instead distributed over a significant length of mullion, then some of the glass/framing clearance will be lost (Figure 4c). However, as the frame appeared to bend fairly sharply at the transom/mullion intersection, without fracturing, it was concluded that the pattern of inter-storey deflection used did not unduly affect results.

At columns 1 and 3 (at levels 1 and 2) the support beams were free to rotate and slide past the columns. They were restrained from out-of-plane movement as shown in Figure 3b. However with both actuators functioning the rig needed to allow movement in both horizontal directions at corner column 2. The vertical support detail provided to achieve this is shown in Figure 3c. Thus, movement of the actuators altered the angle between the curtain walls; this was accommodated by the detail in Figure 3d. In practice, a floor diaphragm will prevent this angle change in a "real" building. Figure 5 shows that the difference the glass experienced is small. In both a "real" building and in the laboratory specimen the top glass transom will be displaced relative to the bottom transom in both directions at the corner. However, transoms in the test panels can only move in one direction at columns 1 and 3. Thus, the laboratory specimens will be subjected also to significantly more "twist" than will occur in a "real" building. Although this twist imparts a slightly more severe glass loading, the difference is not expected to be significant.

2.2 Test Procedure

Three full-sized generic glazing systems (all using 6 mm float glass) were tested in the BRANZ Structural Engineering Laboratory at Judgeford. They were of the following types:

(a) Curtain wall NG, (neoprene gasket glazed system);
(b) Curtain wall S2, (two-sided silicone) sealed in the factory (glass to mullion; hence called unitised) with conventional gasket and mechanical entrapment (transoms to glass);
(c) Curtain wall S4 (four-sided silicone) sealed in the factory (also called unitised).

Tests were carried out under "deflection control". This cyclically displaced the level 2 support beams (sinusoidally at the frequencies subsequently described) using the two actuators shown in Figure 1.

The Moog actuator was displaced by itself with Dowty fixed or the Moog and Dowty actuators were displaced in phase and to the same deflection limits of up to ±60 mm. When greater deflections were imposed using the Moog, the Dowty deflection was limited to ±62 mm.

2.3 Test Instrumentation

The load was applied using a 100 kN Moog Servoactuator (ram) supported off a concrete reaction wall and a 30 kN Dowty Servoactuator fastened to a reaction frame. Rams were initially set near mid-stroke. Both actuators had 90 kN load cells calibrated to BS 1610 Grade 1 accuracy. Full details are provided in Lim and King (1991a).

Total deflections of the frame at each transom level and in each direction were measured using 200 mm linear potentiometers (Figure 6). Ram deflections (representing building rather than glass wall movement) and load in the rams were also monitored. Slip of the two large glass panes (on the Moog side) relative to the framing, at the centre of each glass edge, were measured using 10 mm potentiometers. For curtain walls S2 and S4 and for small applied deflections for Wall NG, the total glass slip trace was monitored. However for Wall NG the slip sometimes exceeded the limitations of the transducer. At medium applied deflections for Wall NG a gap was left between probe and target so that only the peak cyclic values in one direction were recorded. In addition (and at large deflections) a single pulse was applied to peak deflection; by using a calibrated spacer to bridge the gap between target and probe, peak glass slips were recorded.

Scratch marks on the frames were also used to determine mullion/transom slips.

Other instrumentation used for particular curtain walls is described in the results section for that system.

2.4 Description of Test Specimens

2.4.1 Gasket glazed system (Wall NG)

The specimen was built from individual components and dry-glazed in the laboratory. The frame was the same as that previously tested by Lim and King (1991a). The aluminium mullions were 5.8 m long and were fixed to the support UB steel beams at each level, using a mild steel bracket with M12 bolts as shown in Figure 3a (or 3d at the corners). The frame had a mullion cover plate at the corners (Figure 7c) which stopped short of the transoms. Transoms were approximately 1.2 m long and were interlocked to the mullions with a bolt through a lug attached to the mullion, (Figure 4a, Lim and King (1991a)). A vertical section through the mullion which also shows the method used to connect the mullion to the support beam is shown in Figure 4c of Lim and King (1991a).

A nominal 17.5 mm clearance was provided between the glass pane and each side framing member. The panes and had a nominal entrapment depth of 12.5 mm into the mullion and transoms. Foamed neoprene gaskets on the outer face and santoprene gaskets on the inner face were used to seal the glass.

Neoprene spacers (Figure 8), also called antiwalk blocks, were used between the mullions and glass at about 460 mm from the corners. The blocks were installed correctly with the long sides parallel with the glass face. The photograph in Figure 8 shows this block badly distorted from the imposed glass racking. Setting blocks (Figure 8b) were used below the glass to support its weight at about 360 mm in from the corners. There was no spacer between the glass and the frame above the window.

2.4.2 Unitised two-sided silicone system (Wall S2)

The specimen was unitised (factory installed into aluminium frames which mechanically interlock on site). This was achieved using PVC strip seals to provide appropriate weather seals within the interlocking aluminium sections. Structural silicone sealant adhered glass to the mullions. The transom/glass connection was mechanical entrapment with neoprene gasket seals.

The planar unitised panels of dimensions 1164 x 1370 mm (top and bottom panels) and 1164 x 2770 mm (middle panels) were fabricated and cured in the factory, and transported to the laboratory where they were installed in the test frames. The structural silicone sealant (Dow Corning 795) was applied on the inside of the mullions so that a 15 mm by 5 mm plug of silicon was contained between glass and framing as shown in Figure 9. A weather seal of silicone was used on the outside. A conventional neoprene gasket was used between the glass and transoms and two neoprene rubber setting blocks were placed beneath the glass.

The individual units fitted together as follows. At the bottom corners of the mullions (shown in Figure 9a) the mullions were bolted to the support beam as shown in Figure 10b. At the corner (Figure 9a) the mullions were bolted to the transoms by a U-bracket as shown in Figure 9c. There was no vertical support provided for the mullions in the corner and so to carry the weight of the glazing, the test curtain wall used a roller between the bottom corner of the curtain wall and the laboratory floor. The transoms were held together by jamming into place the two seals shown in Figure 9b. The mullions were held by a combination of seals (slid into place) and the mullion bolted connection to the loading beams (both shown in Figure 9d).

The corner panels were a "special" and the design had never before been used by the manufacturer. They had an "L" shape in plan consisting of two orthogonal sides of length 1164 mm and heights as given above. Just inside the intersection of the panes there was a square aluminium section column. Two 15 mm wide beads of silicone sealant bridged the gap between this RHS section and glass as shown in Figure 9. A 10 mm bead of silicone sealant was used to bridge the gap between the glass sheets. During assembly in the laboratory the 2770 mm high panel glass was broken which necessitated re-glazing of this corner panel in-situ. A 3-week curing period was allowed before testing.

2.4.3 Unitised four-sided silicone system (Wall S4)

The unitised panels of nominal dimensions 1164 x 1370 mm and 1164 x 2770 mm were fabricated and cured in the factory. Note, these were the same units previously tested by Lim and King (1991a). The aluminium frames were mechanically interlocked on site using PVC strip seals. On all four sides annealed 6 mm clear float glass was attached to the frames using Dow Corning 983 two-part silicone sealant. Figures 11a and 11b are sections taken through the mullions and transoms respectively. A 152 x 75 x 12 mm angle bracket connected the mullions to the load beams (Figure 11h) at locations shown in Figure 11c., i.e., the panel at the end away from the corners was attached at the top corners to both mullions. The corner panels were then interlocked with these fixed panels and the top (corner edge only) of the corner panels fastened.

The planar test panel had deformed as shown in the photograph in Figure 11f and without additional restraints the set-up shown in Figure 11c would be free to do the same. It was considered that this mechanism would be prevented in a typically constructed corner situation. Details vary in practice. In a recent major New Zealand building a special corner mullion section was used and the transoms were welded to the corner mullions. A preferred method is to use a split mullion as shown in Figure 11d. This detail was modelled in this test using the arrangement as shown in Figure 11e and 11g. This enables the panels to withdraw freely from each other, but a clash results near the glass line when a 5 mm clearance gap is exceeded when the curtain walls move towards the corner. Figure 11g also shows the mullion transom connection detail. Note how the central vertical runner on the transom passes through a slot in the mullion.

3.0 OBSERVATIONS AND RESULTS

3.1 Gasket Glazed System (Wall NG)

3.1.1 Initial loading

Initially four cycles of sinusoidal load were applied with deflections ±10 mm, 20 mm, 30 mm and 40 mm at a frequency of 0.1, 0.25, 0.5, 1.0 and 2.0 hertz using the Moog actuator only. Observation of scratch marks showed the transoms were not slipping across the mullions during these cycles. A faint graunching noise was heard at the 30 mm and subsequent cycling, indicating that the glass was coming into contact with the frame at one point during part of the movement. Two of the santoprene side seals became loose and needed to be pushed back into position using a glazing wheel-tool at one stage of both the 30 mm cycling and 40 mm cycling, and four seals were loose at the completion of this phase of testing. This was considered equivalent to maintenance work that would be carried out after a moderate earthquake.

At this stage the inside aluminium extrusion clips were removed on the large window nearest the Moog actuator to see how much the glass had moved. The measured clearance between the glass and frame both at this stage and after resetting is shown in Table 1. The spacers used between the mullions and glass nearest h and d (see Table 1) were jammed and distorted (Figure 8a) whereas those at b and f were loose. Using the average clearance between glass and frame from Table 1, and Bowkamp and Meehan's formula as described by Lim and King (1991a), the maximum drift that could be tolerated from the window is 140 mm.

3.1.2 Second phase of loading

At this stage both actuators were moved in phase with the amplitude of the four cycles of sinusoidal motion (10, 20, 30, and 40 mm at 0.1, 0.5 and 1.0 hertz, and then 50 and 60 mm at 0.1, 0.25 and 0.5 hertz). At 50 mm, the gap between the corner transoms opened and closed about 10 mm and a vertical gap of about 8 mm opened and closed between the middle corner mullion cover plate and the transoms above and below. The deflection gauges were then removed to prevent damage and subsequently only actuator load and deflection were monitored. Next, the Moog actuator only was cycled at 60 and 80 mm at 0.1 and 0.25 hertz; then both actuators were cycled 0.1 hertz (Moog to 80 mm and Dowty to 62 mm). Generally, about half the santoprene seals needed to be pushed back into position after about every second test (i.e., eight cycles) at imposed deflections greater than 40 mm. After the last testing at 80 mm, the seal beneath the large corner window in the Moog direction became dislodged and difficult to replace. Force was used and the window broke. It was replaced. In subsequent testing, seals were not pushed back between tests. About 25% of the santoprene seal lengths worked loose and some of the outer neoprene seals were twisted and deformed so that it appeared that they would provide some restriction to glass movement.

When the glass was replaced, four cycles were imposed at 80 and 100 mm at 0.25 hertz. On the 4th cycle at 100 mm, the newly replaced glass cracked at the top corner as shown in Figure 12 (Crack A). A small crack also developed in the top corner of the adjacent pane (Crack B, Figure 12). Unfortunately, after this test the pane with Crack A was accidentally knocked out by scaffolding planks. Tests continued without this pane with the video camera focused on Crack B. 24 cycles at amplitude 105 mm were then imposed (the maximum deformation the rig would allow) without any further cracking or crack extension. The glass pane was then replaced again and four cycles to 100 mm imposed. On he fourth cycle a crack occurred that was almost identical to the original one shown in Figure 12. As the video camera had been focused on this spot, a good record of the crack development was obtained. During the subsequent four cycles to this deformation about 20% of the glass pane fell out and crack C (Figure 12a) occurred. A further 30 cycles were imposed and glass loss from this particular pane increased to 80% but the rest of the panes remained virtually intact and no further cracking occurred.

Two corner portions, about the size of 20 cent coins, had broken off the top of the large panes with racking in the Dowty direction. This was noticed after 60 mm deflections. The transoms above the large windows in the Dowty direction were observed to slide with an amplitude of about 2 mm relative to the mullions with imposed displacements of 60 mm, although this amplitude did not noticeably change at higher imposed deflections.

3.1.3 Peak force and deflection measurements

The recorded data showed that peak resisted force at any imposed deflection remained virtually constant, with variations in applied frequency which indicated that the loading rate was not significant. However the shape of the hysteresis loops became narrower with increased loading rate as shown in Figure 13. The area of the loops can be related to the amount of damping present. However, as earthquake frequencies are larger than the test frequency there will be less damping during earthquakes than occurred in the test. The peak force increases with peak imposed deflection as shown in Figure 14. As the maximum Dowty deflection is 62.5 mm the graph levels off for the Dowty load as expected. Peak Moog force dropped by 24% (average pull and push loads at 95 mm) after the glass broke. After 95 mm imposed deflection, clearances in the test rig were exceeded and the monitored forces have little significance.

From the forces shown in Figure 14, it can be shown that stiffness and shear force resistance from glass is small compared to multi-storey building seismic strength and stiffness. Thus, curtain wall glazing will have little influence on the earthquake responses of a building. The force values reported will be useful in glazing frame design.

The relationship between applied deflection and that recorded at gauges at the four frame levels shown in Figure 1 are plotted in Figures 15 and 16 for the Moog and Dowty direction, respectively. The gauge deflections were taken as the difference between the peak positive and negative deflections. In the Moog direction, the rig was effective in preventing movement at the top of the large sheets of glass. This was not so in the Dowty direction, mainly due to the eccentricity between the support beam and column brace. The inter-storey deflection curve has also been plotted in Figure 16. The effectiveness of an extra bolt used to reduce slip between support beam and column, after the 20 mm cycling had been completed, can be seen in this figure. Flexibility of the Dowty reaction frame has resulted in the recorded Dowty actuator deflection being slightly more than the recorded deflection at the same level and direction on the curtain wall. The close agreement between the Moog actuator deflection and glass deflection at the same level, shows that connections between the mullions and load beam were effectively rigid. (For the same curtain wall, Lim and King (1991a) noted that the mullions twisted, resulting in the glass wall deflecting 35% less than the load beams.)

From first principles, the inter-storey deflection due to slip between glass and frame can be obtained from a simple formula (see Figure 17). A comparison of the measured inter-storey deflection and the predictions from the formula are shown in Figures 18 and 19 for the two frames in the Moog direction. The data at 60 mm were derived from a quick pulse load of both actuators to peak deflection, and holding this deflection while measurements were taken. The other data were from sinusoidal loading of the Moog actuator only. The plots show that slip at the bottom of the glass was small whereas that at the top was about 20% of the total movement. However, it was rotation of the glass, as monitored by the side gauges, that contributed most to the deformation capability of the system. Generally, the slip measured on one side gauge was between two and eight times the magnitude (and of opposite sign) of the slip measured on the other side. When the load was applied in the other direction the opposite relationship applied. As can be seen from Figures 18 and 19 the agreement between the predicted and measured deflections was excellent.

3.2 Two-Sided Silicone System (Wall S2)

3.2.1 Observations during testing

During testing, there was far less movement of the glass within the framing compared to the gasket glazed system. The elastic shear distortion of the silicone sealant at the glass edges was, however, clearly discernible. The main components of deflection appeared to be the sub-frame rotating within the mechanical fixings attaching it to the support beams. This resulted in obvious slipping between the interlocking mullions, and gaps opening and closing between the corners of the panels during from the early stages of cycling. Figure 10 shows detail of the mullion connection and locations are given in Figure 9a. The aluminium joining lug is bolted to the mullion with two horizontal M12 bolts (bolts A, Figure 10), and is also bolted with a single horizontal M12 bolt (bolt B) directly to a steel angle which itself is firmly fastened to the support beam. During construction, the weight of the glazing wall is transmitted to the support beam by an M12 height-adjustment bolt (bolt C). Uplift of the mullions is resisted by bolt B. This results in a torque on the aluminium lug. This torque appeared to give enough flexibility to the system to allow the mullions to move vertically. To monitor this distortion, the additional instrumentation shown in Figure 20 was used.

In all tests on this curtain wall the two actuators moved in phase. Three tests, each of three sinusoidal cycles at 0.5 hertz, were performed at amplitudes 10, 20, 30 and 40 mm. An extra 30 cycles at 40 mm were then imposed for the purposes of video camera recording, and then normal test loading of nine cycles to 60 mm at 0.25 hertz was recorded. No damage was noted. All deflection gauges, apart from those shown in Figure 20 were then removed to prevent damage. Next, three cycles to 80 mm at 0.25 hertz on the Moog actuator (and 62 mm on the Dowty actuator) was applied. During the latter half of these three cycles, a crack formed in the glass (see Figure 21a) at the locations shown in Figure 9a. During the subsequent three cycles to 100 mm at 0.1 hertz, a large portion of glass fell out leaving the panel as shown in Figure 21b. A further 70 cycles were then imposed to 105 mm with no further damage occurring to either the glass or frame. The broken glass in panel 1 remained attached to the silicone sealant at the edge.

3.2.2 Peak force and deflection measurements

The peak forces resisted increase with peak deflections as shown in Figure 22 and are of similar magnitude to those for curtain wall NG (Figure 14).

The relationship between the applied deflection and that recorded at gauges at various heights up the glass wall is plotted in Figures 23 and 24 for the Moog and Dowty direction, respectively. As expected these are similar to those for Wall NG (Figures 15 and 16), except that in the Moog direction there is slightly more movement at the top of the large panels and a larger difference between the actuator movement and the bottom recorded deflections. In the Dowty direction, some additional welding on the test rig reduced the deflection in the top half of the wall.

Using the same technique as per Wall NG, the measured inter-storey drift is compared with the predictions from the measured glass slip, relative to the framing in Figure 25. The slip of each panel is the sum of slips (a + c) as defined in Figure 17, and the rotation component is (b + d) (glass aspect ratio). It can be seen that movement of the glass in the framing can only account for about 25% of the total drift. The rotation component is only a small part of the total prediction with panel 1, whereas it dominates with panel 2, which butts onto the corner. In Figure 26, the formulae in Figure 17 are adapted to predict the drift using deflections monitored by the gauges in Figure 20. The sum of the slip at the top and bottom of the frame relative to the transoms (Gauges 2 and 4) accounts for only 16% of the drift. The addition of frame solid body rotation brings this to 40%, and with glass movement added from Figure 25 brings the total to 59%. Thus, 41% of the movement is unaccounted for. It is thought that most of this discrepancy was due to the following reason: Gauges 1 and 4 (Figure 20) were measured relative to the transoms, which themselves were noted to be moving up and down, resulting in an under-estimate of the recorded deflections. Measured deflections from these gauges are given in Table 2. Note, after the 30 mm reading, Gauge 5 was changed to measure relative to the transom rather than relative to the sill.

3.3 Four-Sided Silicone System (Wall S4)

3.3.1 Observations during testing

The test regime is shown in Table 3. Usually, this consisted of sinusoidally cycling both actuators. In the latter part of the test programme, however, the Dowty actuator was pushed forward and held at a static displacement whereas the Moog actuator was cycled. Between the dynamic cycling, both actuators were displaced to the previous peak displacements so photographs could be taken and the deformation mechanism studied.

There was negligible slip of glass relative to the frame by shear distortion of the silicone sealant. The distortion mechanism was as shown in Figure 11c with panel 7 rotating and sliding on the bottom transom and panel 8 not rotating but sliding on the bottom transom. The slip in panel 8 was responsible for 70 to 80% of the applied deflection. This is clearly illustrated in Figures 27 to 29. There was negligible vertical movements of mullions 1, 3 and 4; mullion 2 did have significant vertical movement. Top and bottom half-sized panels appeared to remain undistorted. There was no glass damage or frame failure at test completion.

At applied deflections of between 20 mm and 60 mm, the aluminium angles at the corner (shown in Figure 11e) clashed at peak push, offering some restraint to the slip mechanism of Figure 11c. Above 60 mm, the out-of-plane distortion at the corner resulted in no clashing. The interlocking mullions at the corner (Figure 11e) withdrew and were pushed back together during cycling as (see Figure 28). At 60 mm plus, the Dowty actuator was deformed statically before cycling the Moog actuator. This resulted in some clash on the inner edges of the panels at the corner, but did not cause any damage.

After loading 5 as defined in Table 3, the grooved top portion of the end mullion (Figure 11g) had slid off the runner of the lower interlocking transom, moved sideways and became lodged in this distorted position. This was dislodged manually and the frames prodded back into their undistorted locations. To prevent this happening in subsequent tests, a runner extension was used as shown in Figure 30.

After loading 10 (Table 3) panel 7 was left with a large vertical offset from panel 8 (as defined in Figure 1), and had risen off and disengaged from the runners of panel 12 at the RHS end (i.e., at the corner). A slight out-of-plane movement at this location resulted in the slotted corner mullion becoming disengaged from the runners in the transom, which wedged the two apart as shown in Figure 30. This is a mechanism that is likely to occur in an actual building in a large earthquake. Panel 7 was held in place only by the runners at the bottom RHS, top LHS and bracket attaching it to the support frame at the top LHS. This appeared to be a stable attachment mechanism that would allow the panel to have extreme in-plane deformation without inducing panel distress or failure.

3.3.2 Peak force and deflection measurements

The peak forces generally increase with deflection (Figure 31) and are about half the magnitude of the other two walls. The Dowty load at 60 mm is not shown, as the deformation in this direction was applied statically. The Moog load drops at the 80 mm cycling, probably due to panel 7 disengaging as above.

The relationship between applied deflection and that recorded at gauges at various heights up the wall, is plotted in Figures 32 and 33 for Moog and Dowty direction respectively. These are similar to the other two walls. The deflection at "Middle Lower" Figure 32 was measured at the Moog end, 100 mm below the transom, rather than the corner. This indicated that at higher deflection, the curtain wall at this level lagged behind the load beam deflection. Gauge "Bottom" showed a significantly higher deflection than the load beam at 60 mm imposed deflection. This is likely to be an error as the gauge was also experiencing large deflections in the perpendicular direction. The deflections being registered by the Dowty actuator (Figure 33) were higher than those monitored by the two bottom gauges - probably due to take up of the reaction frame.

Deflection components are shown in Figure 34. It can be seen that the slip of the glass in the frame of Panel 8, due to shear deformation of the silicone sealant, was very small. In panel 7 it would likely have been even less, as this panel could deform as a single unit fairly freely. There was an extremely good agreement between the applied inter-storey deflection of panel 7 and the measured mechanical slip plus rotation of the panel as a rigid body. About 40% of the movement came from base slip and 60% came from rigid body rotation.

4.0 COMPARISON WITH IN-PLANE RACKING BEHAVIOUR FROM LIM AND KING

4.1 Gasket Glazed System

Lim and King's (1991a) two walls both experienced 100 mm inter-storey deformation without failure. Subsequent failure was the result of gasket loss which caused clashing of glass and mullion due to misalignment. A scallop shaped crack was generated in one corner which shortly after developed into multiple cracks, whereupon the glass fell from the frame. The working loose of gaskets at early stages of testing and the panes rotating within frames reported in Lim and King, was very similar to that described in the current report for the same system.

One significant difference between the planar and corner specimens, was that in the former, significant twisting along the mullion axis was noted. This was caused by eccentricities between the "floor" and the plane of glass (over 125 mm). This twisting accounted for about 35% of the imposed maximum inter-storey deformation. The mullions of this system had little torsional rigidity which accentuated the amount of twisting. Twisting didn't happen in the corner specimen, however, because of the rigid connection piece between load beam and corner mullion.

When installed in a building, the eccentricity between floor beam and glass (and hence extent of seismic twisting of the mullions not at the corners) will be similar to that noted above during testing by Lim and King. Twisting restraint at the corners is also likely to throw more load onto the corner connections. However, as far as loading of the glass panels is concerned, a test regime providing only in-plane loading is appropriate, as long as imposed inter-storey deflections are measured at the glass line and not the load beam.

4.2 Two-Sided Silicone System

Different systems were used for the planar and corner test specimens. The planar specimen was entirely factory assembled (i.e., arrived on site as one large unit consisting of the required number of glass panes) whereas the corner specimen was unitised (factory installed into aluminium frames which mechanically interlocked on site and were held together by neoprene gaskets which were slid into position in shaped slots). Both used structural silicone sealant joints between each glass pane and the supporting mullion, and conventional entrapment of the glass into an aluminium transom using a dry-glazing (neoprene gasket) system. The planar specimen mullion was formed from an "T" shaped aluminium section on to which an aluminium box section "glazing bar" was fixed using stainless steel screws.

With the planar system, at an imposed inter-storey deflection of 25 mm, the components of deformation appeared to be shear distortion of the silicone sealant as the glass attempted to rotate within the frame and mullions rotated at their splice points. (Mullions were spliced at the lower quarter point of each panel, this being the point of contraflexure as designed by the manufacturer's engineer as a wind-face loading consideration.) At peak displacements of 60 mm, screws fastening the glazing bar to the mullion failed, some in shear and others by head pull-through, after which the panels were free to slide over the face of the glazing bar while remaining entrapped in the transom. Once screw failure occurred, resistance to displacement dropped markedly and the glass slid within the transom. A 120 mm inter-storey displacement was imposed without causing glass failure. Throughout the test, gaskets remained installed within transoms.

In the corner test configuration, only about 25% of the total movement was attributed to the glass movement within the frame (by shear deformation of the silicone sealant). Most of the imposed deflection was absorbed by rotation of the complete unitised frame and by relaxation of the frame to "floor" connections. An initial glass crack was observed at an inter-storey displacement of 80 mm. A substantial portion of glass fell from this frame during the subsequent 100 mm inter-storey displacement cycle.

Distinctly different distortion mechanisms developed in the planar and corner specimens; as they were of different construction they couldn't readily be compared. The slip mechanism of the planar system meant effectively that the load beam was moving but leaving the glass wall behind. At a corner, where the load beam was moving away from the corner dragging the wall perpendicular to the beam with it, the perpendicular wall would clash with the parallel wall and try to push it in the direction of the load beam. This may dislodge the perpendicular wall from the load beam, relieving the situation. It could be concluded from this that as long as deflections are measured at the glass line, and not at the load beam, a planar test specimen can conservatively be used for testing. For walls which develop the rotation mechanism, as noted on the corner specimen, a planar test specimen would suffice.

4.3 Unitised Four-Sided Silicone System

The planar panels were subjected to displacements in excess of 80 mm without failure. The imposed deflections were absorbed by a combination of slip between units and relaxation of the support bracket. At high drift levels, the complete panels were observed to rotate (being eccentrically supported), at which stage the panels disengaged from each other as shown in Figure 11f. One of the large glass panes developed a diagonal crack due to out-of-plane distortion which occurred following this disengagement. However, the glass remained attached to the frame through the silicone sealant and no glass fell out. The deformation mechanism shown in Figure 11c generally cannot freely occur in most corner details used in real buildings (or at discontinuities in the glass wall such as at an interface with a concrete shear wall). Therefore, the actual restraint to this deformation will be a function of the actual construction details used.

The corner specimens deformed in a similar manner, with little restraint developing at the corner. This was either due to the special clash details provided or due to clash of adjacent inside edges of the mullions. At 80 mm imposed inter-storey deflection, the corner panel became partially disengaged from the bottom transom, and wedged in the deformed position when the slotted mullions ran off the transom runners. The imposed out-of-plane forces thrust the mullion sideways and prevented re-engagement of the runners and mullion slot. If this wall is to be realistically tested as a single plane, some out-of-plane thrust, such as the "skew" used by Lim and King (1991a) is recommended.

5.0 CONCLUSIONS

The "shape" of the in-plane inter-storey displacement pattern and the slight twist imposed by the method of applying the out-of-plane displacements are more severe than would occur in a real building. However, they are not thought to have unduly affected the results. The following conclusions can be drawn from the study:-

1. By using a simple formula, the inter-storey deformation of the gasket glazed system can be directly related to glass slip on the four sides of the window and to the glass aspect ratio. Another formula, (section 3.1.1), relating the maximum drift that can be tolerated by this system, as a function of glass clearance and aspect ratio, was found to overestimate deflection capability by about 40%. This could be because of the finite size of the neoprene spacers and setting blocks and/or the observation that the seals became distorted and restricted movement.

2. The glass in the gasket glazed system cracked in the 4th cycle at an in-plane inter-storey displacement of 100 mm (3.6% drift) and out-of-plane inter-storey displacement of about 45 mm. When the glass was replaced, a repeat test produced an almost identical result and the glass fell out. Although cracked in both top corners, the other panel survived a large number of cycles at 100 and 105 mm displacement without any glass falling out. From these observations and results reported by Lim and King (1991a) it was concluded that the most constrained glass panels generally broke first. The only exception was wall S2. Deschenes et al. (1991) found that the gasket glazed system they tested was able to sustain a large number of cycles of imposed severe inter-storey drifts without glass failure.

3. Shear distortion of the silicone sealant bonding the glass to the frame accounted for only about 25% of the drift with the glazed two-sided silicone wall. The main source of movement appeared to be the sub-frame rotating within the mechanical fixing attaching it to the support beams. The glass cracked during cycling at an in-plane inter-storey displacement of 70 mm and an out-of-plane displacement of about 48 mm. Some glass fell out at an inter-storey drift of 90 mm (3.2% drift), although the edge portions remained fastened to the silicone sealant.

4. There was negligible slip of the glass relative to the frame by shear distortion of the silicone sealant with the four-sided silicone system. The distortion mechanism was due to corner panels rotating and sliding on the bottom transom and other panels not rotating but sliding on the bottom transom. This accounted for the bulk of the imposed inter-storey deflection. There was no glass damage or frame failure at test completion, which included 30 cycles at 100 mm (3.6% drift) imposed inter-storey deflection. The corner panel became partially disengaged from the bottom transom and wedged in the deformed position at 80 mm imposed inter-storey deflection.

5. A comparison of corner and planar specimen test results, and a study of the failure mechanisms that occurred during testing, can be used to conclude that planar test specimens can, in general, be used to test glass curtain walls if: (a) the inter-storey deflections are measured at the glass line; (b) the interlocking transoms of unitised test specimens are provided with appropriate relative slip restraints at simulated corner locations; (c) the free ends of test walls, simulating further continuity of the glass panels, are provided with an added rail system to prevent the transoms from slipping off the rails and becoming jammed; (d) a skew is added to provide a small angle difference between the direction of the applied load and the curtain wall plane.

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Appendix A

DRAFT BRANZ Technical Recommendation

PROPOSED TEST AND EVALUATION PROCEDURE FOR EXTERNAL CURTAIN WALL GLAZING SYSTEMS TO SIMULATE SEISMIC LOADING

S J Thurston and A B King

DESCRIPTION

This Technical Recommendation specifies a laboratory test procedure to enable the seismic performance of external glazing systems to be assessed. It also specifies an evaluation method that uses the test results to provide the seismic deformations that can be safely sustained by the glazing wall system, if properly installed in a building. The relationship between computed inter-storey deflections, as calculated during design and that required during testing of the glass curtain walls, is discussed. It is recognised that many of the glazing failures that have occurred in historic earthquakes may have been the result of poor installation procedures and inadequate attention to detail and the common use of semi-rigid putty and bedding compounds which restrict glass edge movement.

RELEVANCE

How curtain wall glazing systems respond when buildings are subject to seismic loading is not fully understood and may represent a hazard for nearby pedestrians and occupants of the building. A suitable test and evaluation procedure for determining earthquake performance of such systems is required. The test method can be used to determine behaviour of traditional, modern or innovative glazing systems, and to demonstrate that they can achieve the performance criteria set out by New Zealand building codes.

The test method seeks to evaluate the performance of glazing systems and their associated components when subjected to simulated in-plane racking movements. In particular, the maximum test inter-storey displacement (in-plane) that a particular glazing system can achieve before failure (as defined below), can be determined.

SANZ (1992) requires that secondary elements be capable of accommodating building inter-storey deflections, determined from the calculated code loading deflections factored by the building ductility factor. Ideally, glazing separation should allow glazing systems to be unstressed when buildings deform under seismic loadings. Appropriate criteria would be that curtain wall glazing (a) sustains no damage during moderate earthquakes and (b) does not fall from the building in a manner that threatens life, under severe earthquakes.

SCOPE AND ACCEPTANCE

This Technical Recommendation details how to assess performance of external glazing systems when they are installed on buildings subject to earthquakes. It is essential that laboratory specimens be precisely the same as installed in the field, including all weather proofing details, as small differences can significantly influence behaviour. The window size may be reduced for testing purposes but it must be at least half size and the aspect ratio cannot be reduced. Only an in-plane test configuration is required, although an adjustment in some end details and the application of non-planar skewness is recommended. Testing (Thurston and King, 1992) has indicated that inclusion of out-of-plane loading on the in-plane loading does not result in a significantly more critical loading case. For glazing systems where this is unlikely to be correct, this recommendation is not applicable.

It is recommended that glazing systems tested and evaluated in accordance with this Technical Recommendation be accepted as achieving under seismic loads the factored inter-storey displacement tested in the laboratory.

SPECIFICATION

Specimen and Construction

A single full-sized specimen of either a double storey (configuration "d", Figure A1) or a single storey plus two half storeys (configuration "s", Figure A2) shall be supplied by the manufacturer for testing. Glazing systems which incorporate a primary structural system which is supported only within each floor level, and which includes some mechanism within the plane of the glazing system that permits discontinuity, shall be tested using configuration "d". Systems where the floor level occurs part way up a glazing panel shall also be tested in configuration "d". Systems which have the glazing supporting members (such as the mullion framing members) continuous between adjacent floors, should be tested using configuration "s". The two half-storey panels of configuration "s" should not rotate within the plane of the glazing system. Where applicable, glazing systems incorporating "vision" and "opaque" panels shall also be modelled in the specimen. The eccentricity and connections between test load beam and glazing panel shall be similar to that used in actual construction.

Specifications of components and type of glazing system shall be provided by the manufacturer and shall include (although not be limited to) the following:

(a) description of the glazing system and the anticipated mode of accommodating the in-plane deformation;

(b) type and properties of framing members (mullions/transoms) if applicable;

(c) details of fixing of the members to the equivalent floor level of a building;

(d) type, thickness, setting details, entrapment, and clearance of the glass (to framing members) where applicable;

(e) type and properties of gasket/silicone sealant (including bead dimensions).

The erection of the glazing specimen shall be carried out in accordance with manufacturer's specifications. The specimens shall, as far as possible, be representative of the minimum construction levels specified by the manufacturer with respect to dimensions, material and fixings. An average standard of workmanship is to be used. Where practicable, specimens shall be assembled and tested in conditions representative of the actual condition, e.g., if the glazing system is to be factory assembled and transported to site, then this method of fabrication shall be followed. The number and type of fixings between the glazing system framing members and building shall be specified by the manufacturer, and form an integral part of the test specimen.

The components to be included in the test shall be as the same used in a finished glazing system of a real building. Architectural coverings such as transom or mullion covers shall be included.

Drift Limits

The racking test may either target a predetermined drift limit, or test a glazing system to destruction, to determine the upper bound of the drift limit that can be tolerated. In the former, the test drift limit shall be determined by multiplying the calculated inelastic interstory seismic drift by the factor FDRIFT. In the latter, the drift limit that can be tolerated by a particular glazing system shall be determined by dividing the achieved test drift limit by FDRIFT. The factor FDRIFT accounts for analytical uncertainties (i.e. concrete beam inelastic "growth" during a large seismic event), and shall be taken as 1.0 for structures where the primary seismic resisting elements are designed to have a structural ductility factor less than or equal to 3. FDRIFT shall equal 1.3 for a structural ductility factor of 6. Linear interpolation shall be used for intermediate ductility factors. Should the drift limits be governed by wind rather than seismic loading, FDRIFT is 1.0.

The calculated seismic drift limit shall either be derived from inelastic analysis or from elastic (modal or static) analysis factored by the ductility factor, as detailed in DZ 4203 (SANZ, 1992) using material properties as detailed in the appropriate materials codes. Values in frame buildings computed by static or modal analysis should be increased by 30% to allow for variations in the post-elastic building deflected shape. Torsion and P-delta effects should be conservatively estimated if not included directly in the analysis. Stiffening effects of non-structural elements may be ignored. The serviceability seismic drift limits can be taken as one sixth of the ultimate limits (SANZ, 1992).

Test Rig

The test rig shall have the ability to have either "free sliding" or "locked" horizontal beams, which are sufficiently rigid to support the specimen without distortion, both at rest (under self-weight) and during racking. The beams simulate the floor levels of buildings and shall be attached to columns which are rigidly restrained from movement in any direction. The load shall be applied at an angle (skew) of 1% to the plane of the glass curtain wall. This provides some out-of-plane loading and twist on the wall. In particular this is to ensure that if a grooved sliding portion of the frame comes off a guide or runner, then the frame will move sideways, preventing realignment of the groove and runner on the return stroke. Skewness can be introduced by installing packing plates in the sliding connection between the load beam and supporting column of the load rig.

For unitised systems two additional features are required:

(a) Include appropriate allowances for secondary element clearances. In particular, at locations simulating building corners or connection to a concrete shear wall in the same plane, the interlocking transoms of unitised systems shall be partially restrained from slipping relative to each other using a system of equal or greater strength and stiffness than will be used in actual buildings. As this slip may be a major deformation mechanism that will occur in practice, completely locking the slip may be unduly conservative.

(b) Slip surfaces shall be extended to ensure that unrealistic misalignment at the extremities of the test specimen is prevented. For instance, at the ends of the test curtain walls simulating the situation where the glass wall continues indefinitely, a common situation is where one grooved mullion can slide along and eventually off a runner of the transom below. A slight lateral shift then prevents re-alignment on the return stroke, and the transoms are prevented from sliding back to their initial positions. This is shown in Figure A3. Although this may occur at a corner or discontinuity in a glass curtain wall, it will not occur in a continuous wall as the adjacent panel provides a continuation of the runner preventing the grooved section of mullion from shifting laterally. Thus an extension of the runner is required as shown in Figure A4.

The test rig shall be able to accept a double storey (configuration "d") or a single storey plus two half storeys configuration (configuration "s").

The rig shall also be able to impose zero inter-storey drift of the adjacent storey to the specimen during racking as shown in Figure A1. This shape conservatively models the curvature of a building as it deforms under earthquake excitation. To achieve the required deformations in configuration "s", the two bottom horizontal members shall be permitted to slide. They should be braced to ensure both members move in unison.

Specimen Dimensions

Most buildings have inter-storey heights ranging from 2.4 to 4.0 m. Ideally the test rig should be able to test details and storey height for a particular real building. To avoid altering a test rig for each storey height, an inter-storey height of H may be used in the test and the results extrapolated for other inter-storey heights; if the following limitations are satisfied: (a) the actual storey height can be no more than 50% more or 20% less than H; (b) the actual glass aspect ratio (height/width) shall be no more than 30% more or 5% less than that tested. The allowable displacement limits for other inter-storey heights shall be determined by multiplying the test displacement with the factor of actual height divided by H.

The minimum width of the specimens shall be 1.5 x H and a minimum of three panels shall be tested.

Displacement Rate and Displacement Pattern

A displacement frequency of F Hz shall be applied for inter-storey displacements of D mm, where F lies between 20/D and 60/D.

The test shall be carried out using a double amplitude cyclic procedure incrementing the displacement in selected increments to the test inter-storey displacement, or to failure. A saw-tooth or sinusoidal displacement function, with five cycles being conducted at each amplitude, shall be used throughout.

TEST PROCEDURE

The test procedure is designed to determine performance of the curtain wall at serviceability deflections and the maximum inter-storey deflection that the wall can be cycled to without failure. The testing organisation shall also determine the source of major deformations in the wall system whereby the wall achieves the imposed inter-storey deflections. The methods to achieve this shall include:

(a) marking potential slip surfaces, e.g., use felt pen or similar to draw a straight line across the glass to frame junction at the middle of each glass pane side, mark interlocking transoms and mullions for relative slip, etc.;

(b) at suitable stages of testing, statically push the wall to deflection X, measure slips at marked locations and photograph zones of noted deformation. Then pull the wall to deflection -X, photograph and measure as above. The value X shall be taken (as a minimum) as the serviceability deflection and as a deflection of at least 0.5 x TD, where TD is the target test deflection.

(c) from the photographs, measurement as in (b) above, comparisons of load beam and glass-line deflections, and other observations, determine the source of major deformations.

Using the appropriate deflected shape regime as shown in Figure A1, carry out the following procedure:

(a) Calculate a target test inter-storey displacement (TD) from the calculated drift limit as defined above.

Example: A concrete building of ductility factor = 4 (i.e., FDRIFT = 1.10) with a 3.4 m inter-storey height is calculated as having a code (SANZ, 1992) force level inter-storey deflection of 11.4 mm, using a static elastic analysis (i.e factor of 1.3 required as above). A 15% allowance is also made for torsion and P-delta effects are considered to be negligible. The estimated building maximum probable earthquake inter-storey deflection is thus 1.1 x 11.4 x 4 x 1.3 x 1.15 = 75 mm. If the test inter-storey height = 2.8 m then the maximum required test displacement = 75 x (2.8/3.4) = 62 mm.

(b) Install the glazing system in the test rig. Condition the specimen for a minimum of 15 days if silicone sealant is used in the assembly.

(c) Cyclically displace the glazing system to the serviceability inter-storey deflection (measured at the glass line) for 20 cycles at a frequency of F hertz defined above using a sinusoidal displacement pattern. Record any damage to the glazing wall and repair if desired. Any reduction of the capacity of the system to provide a water seal should be noted.

(d) Optionally apply 5 cycles at F hertz to the glazing system at deflections less than TD. Record damage. It is required that deflections be measured at the glass line for calculations of inter-storey deflection. Where this exceeds the capability of the deflection gauges, the deflection of the actuator may be proportioned as long as the relationship between actuator deflection and glass deflection is determined at an imposed deflection of at least 60 mm.

(e) Apply five cycles at F hertz to the glazing system at deflection TD. Record damage.

TEST INSTRUMENTATION AND DATA RECORDING

Measure peak displacement (both directions) at all sliding beam members and at the glass line at all "floor" locations. Measure peak applied loads. Measure and photograph slips as described in the previous section at peak static deformations.

Record the behaviour of the system throughout the test. Note the displacements and cycles when either glass, gaskets, frame or other elements are dislodged from their installed position or show signs of distress. Gaskets may be reinstalled on completion of the given cycle groups. Details and photographs of glass failure (location, general shape, stage in testing) shall be provided. In addition, the recording and reduction of data shall include the following:

(a) Description and specification of glazing system;

(b) Load-deflection plots as measured at the glass line up to an inter-storey displacement of 60 mm. For greater displacements the load versus actuator displacement plot will suffice;

(c) Plots relating actuator deflection to the deflection recorded at other gauges;

(d) Summary of measured slips and a description of the system deformation mechanism.

EVALUATION

During an earthquake the main hazard identified with curtain wall glazing is falling glass or glazing components. The safety of occupants trying to get out of buildings and the safety of pedestrians in the vicinity of buildings is the main concern.

The glazing system shall be deemed to have satisfied a "test inter-storey displacement" only when no failure occurred after five cycles to this displacement, applied as above. Failure shall be deemed to have occurred when either glass fallout of shards of glass more than 50 mm long or total glass fallout of greater than 200 cm^2 (in small portions) or potentially dangerous framing elements (e.g. weight more than 0.5 kg or "spear-like") have fallen. This material includes the weight of any glass, architectural cover, fixings, bolts, etc. The glazing system shall be deemed to have achieved the test displacement when no failure occurs.

Where failure (as defined above) occurred before the required test displacement was imposed, the glazing system shall be deemed to have achieved 1/FDRIFT multiplied by the maximum inter-storey displacement achieved without failure.

BASIS

Studies were undertaken by BRANZ (Building Research Association of New Zealand; Wright, 1989) to consider the types of in-plane deformation that can be imposed on a glazing system and to determine the significance of these deformations on the overall performance of glazing systems. The studies concluded that the main deformation affecting exterior curtain wall glazing system is in-plane racking. A test programme and test rig was developed to evaluate the seismic resistance of full-size specimens simulating inter-storey deflections and building curvatures.

Using the recommended test rig, full-sized in-plane racking tests on five different generic exterior glazing systems were carried out at BRANZ (Lim and King 1991; King and Thurston 1992). This was extended to three generic glazing systems which included an exterior corner (Thurston and King, 1992). It was concluded that the ability of full-size curtain wall glazing systems to withstand major racking actions could be modelled within a laboratory environment using an in-plane loading system applied to a planar structure.

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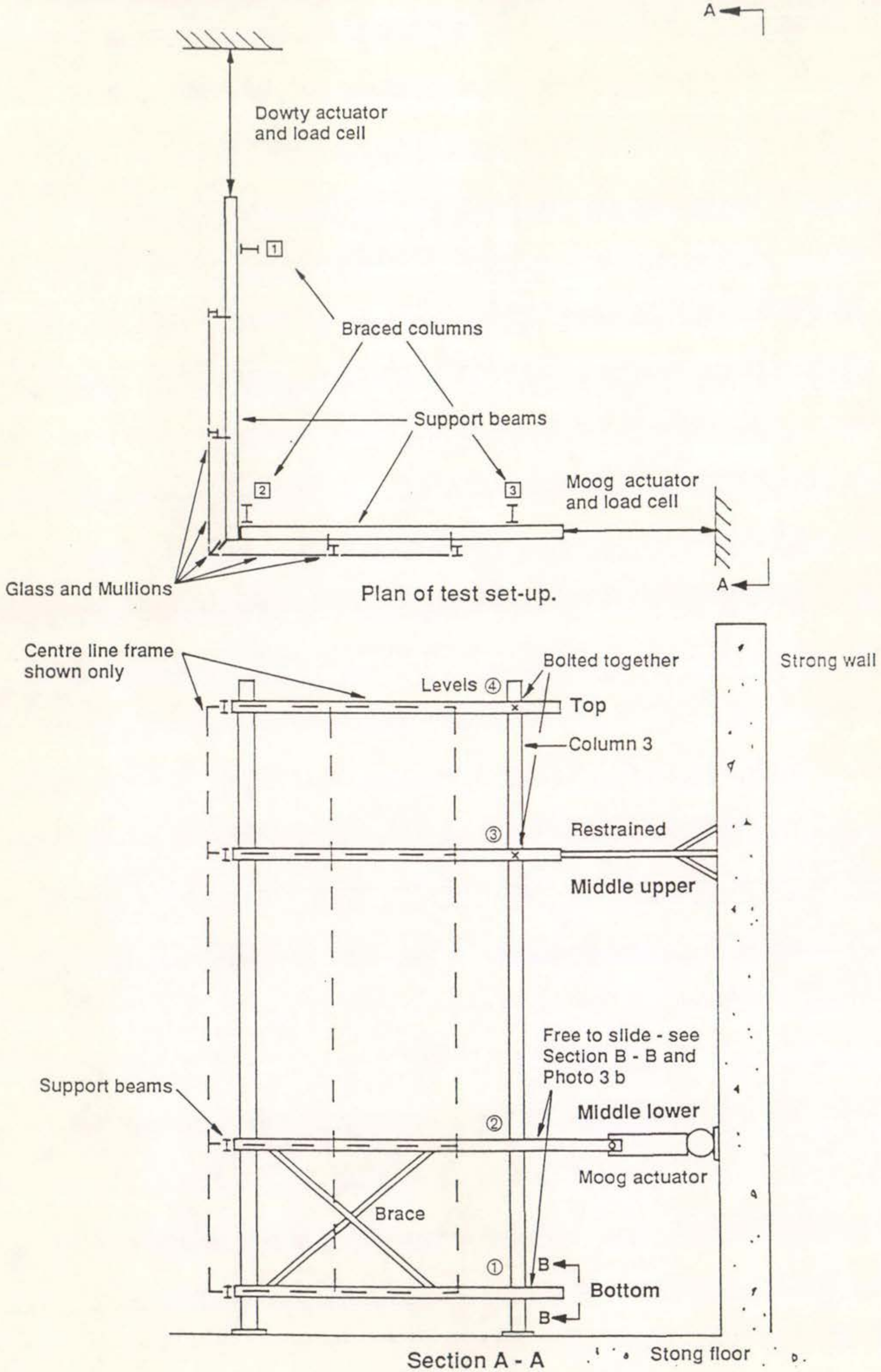
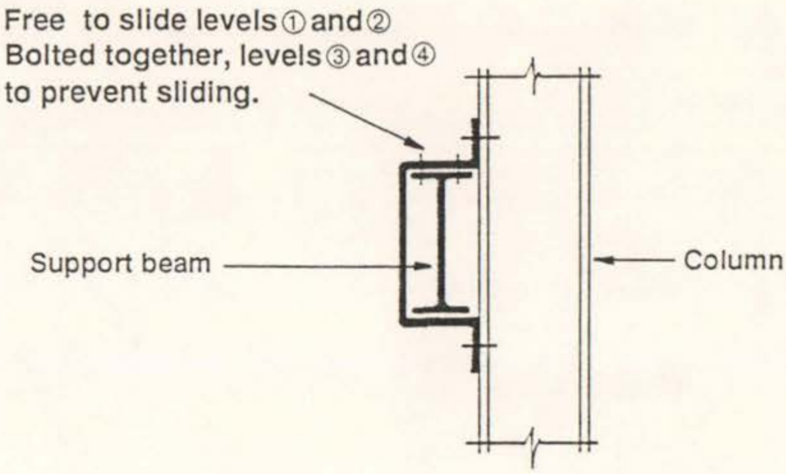
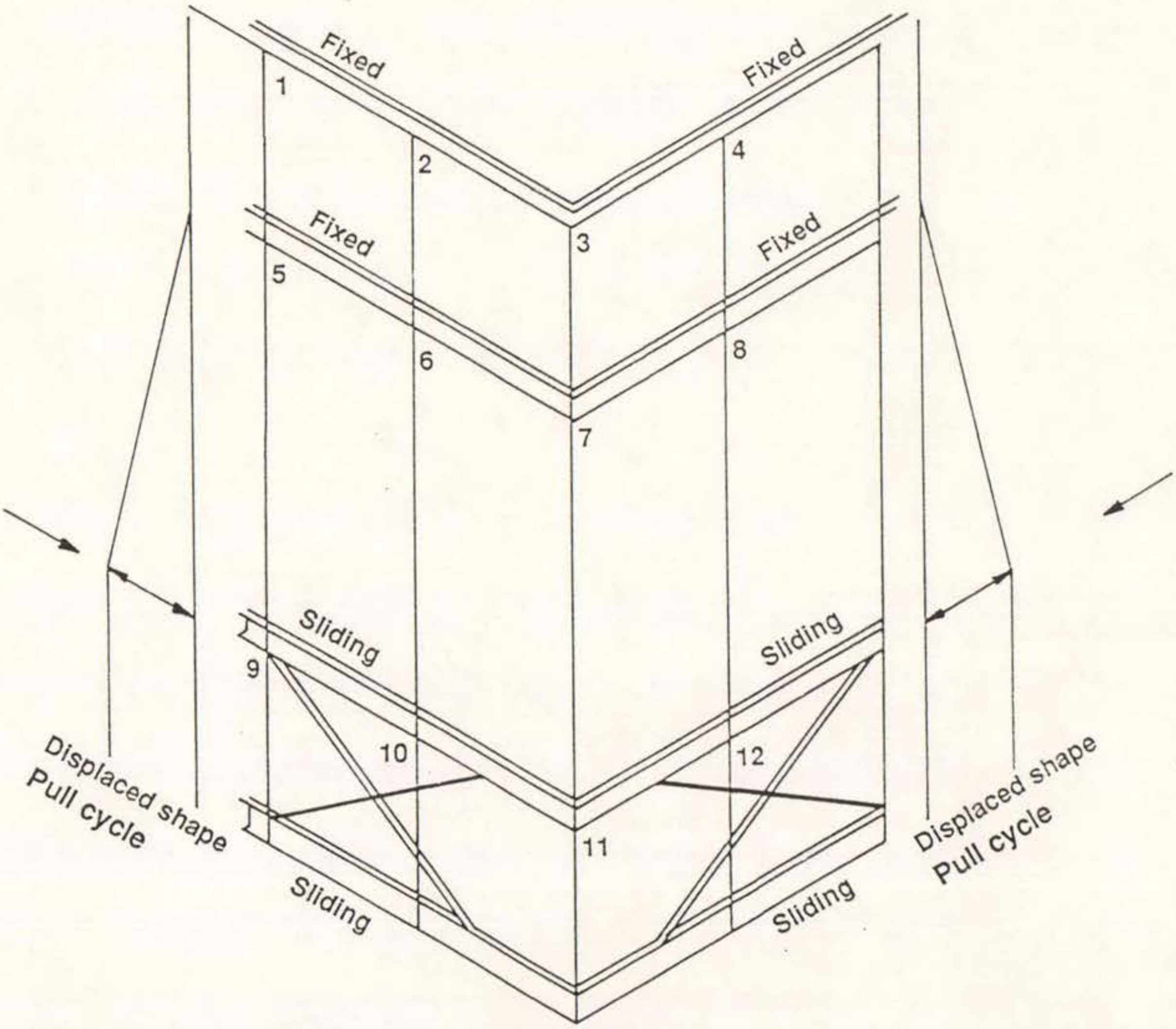


Figure 1 General test set-up.



Section B - B



Isometric View
Figure 1 Continued

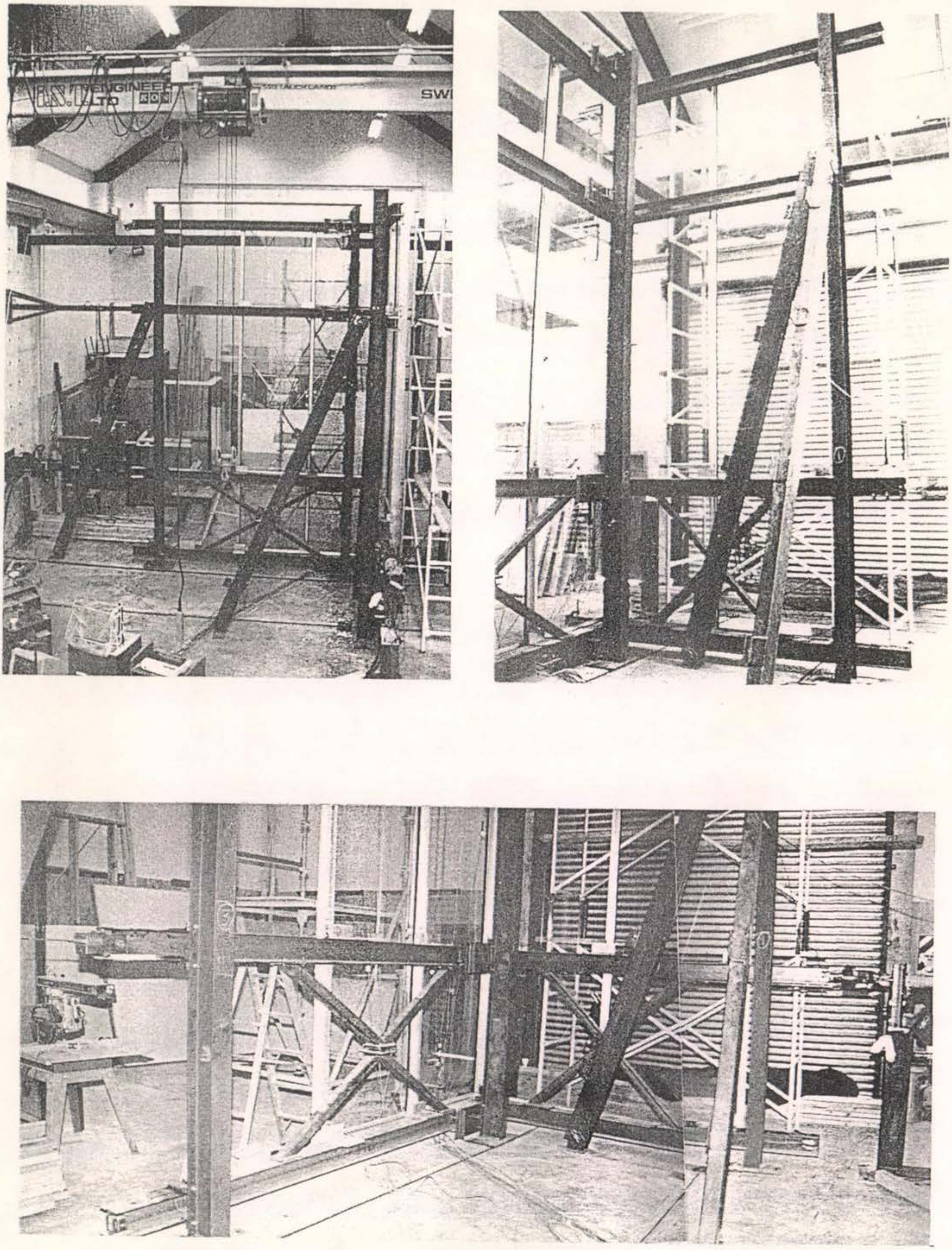
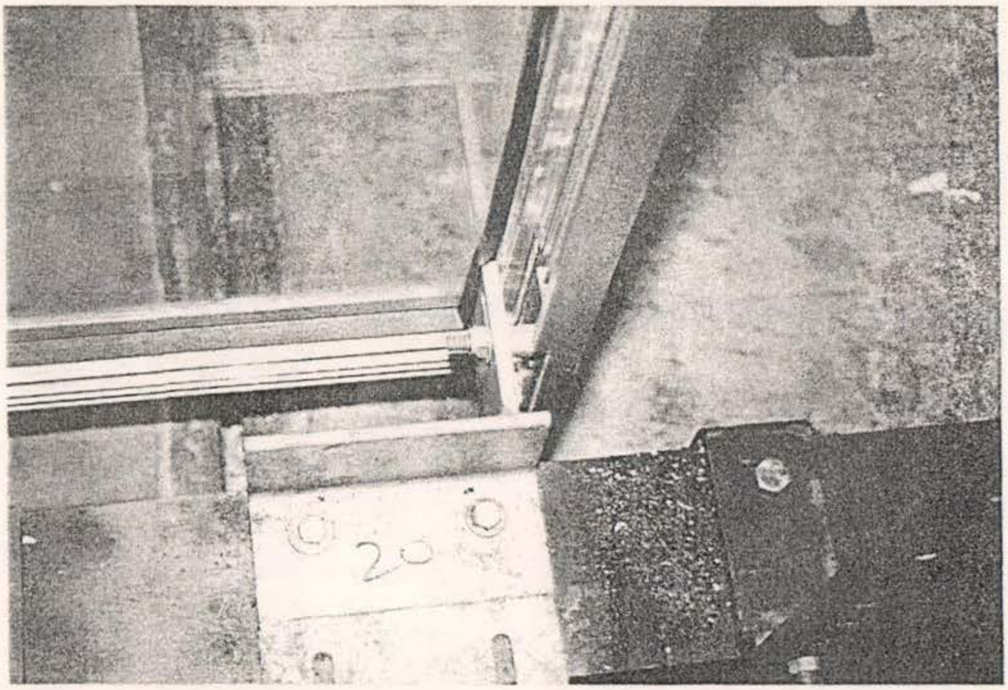
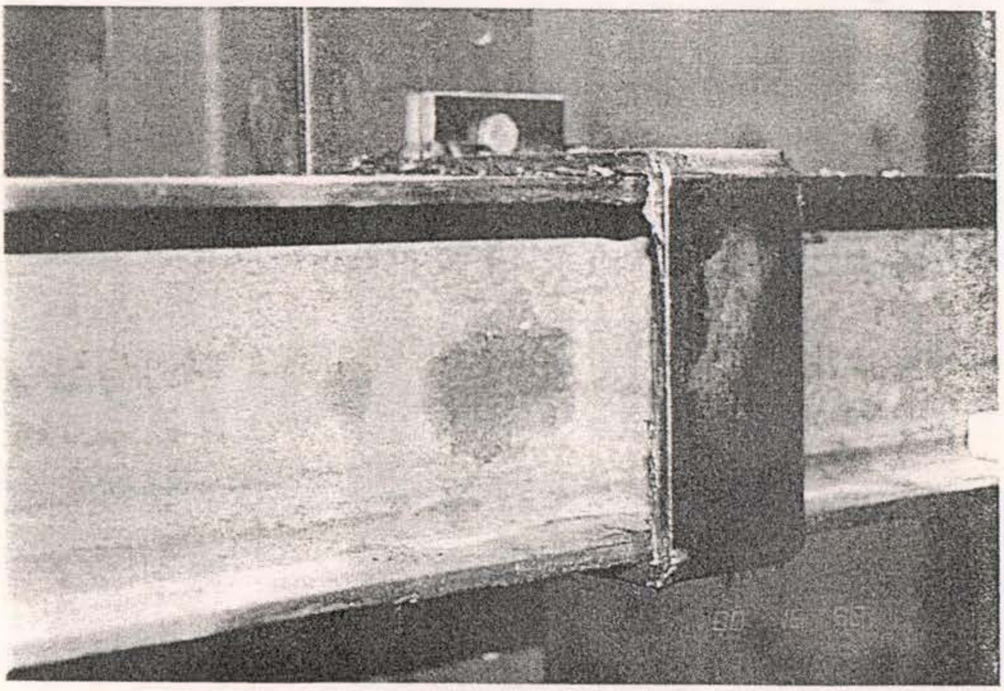


Figure 2 General view of test rig

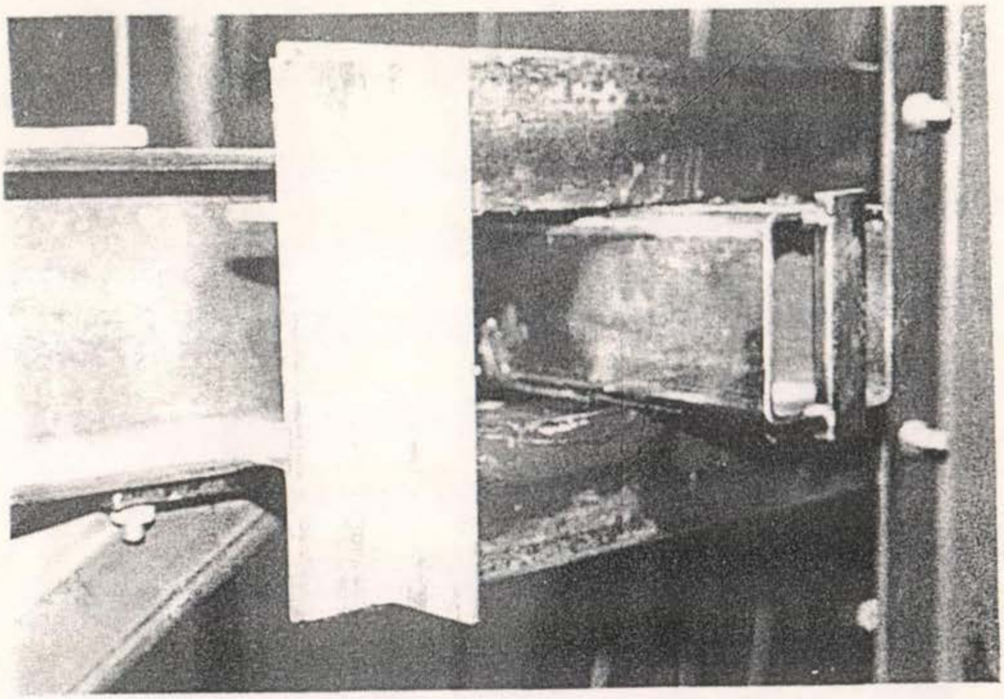


(a) Connection of glazing mullions to support beam

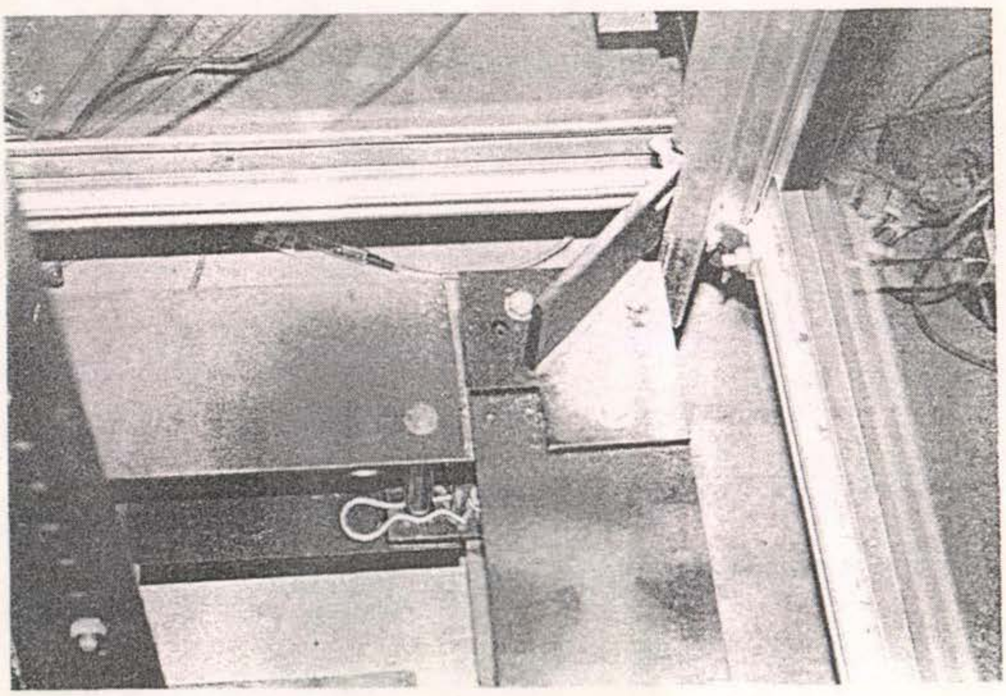


(b) Connection of support beam to columns at columns [1] and [3]

Figure 3 Details of test rig



(c) Connection of support beam to column 2



(d) Connection between support beams

Figure 3 Continued

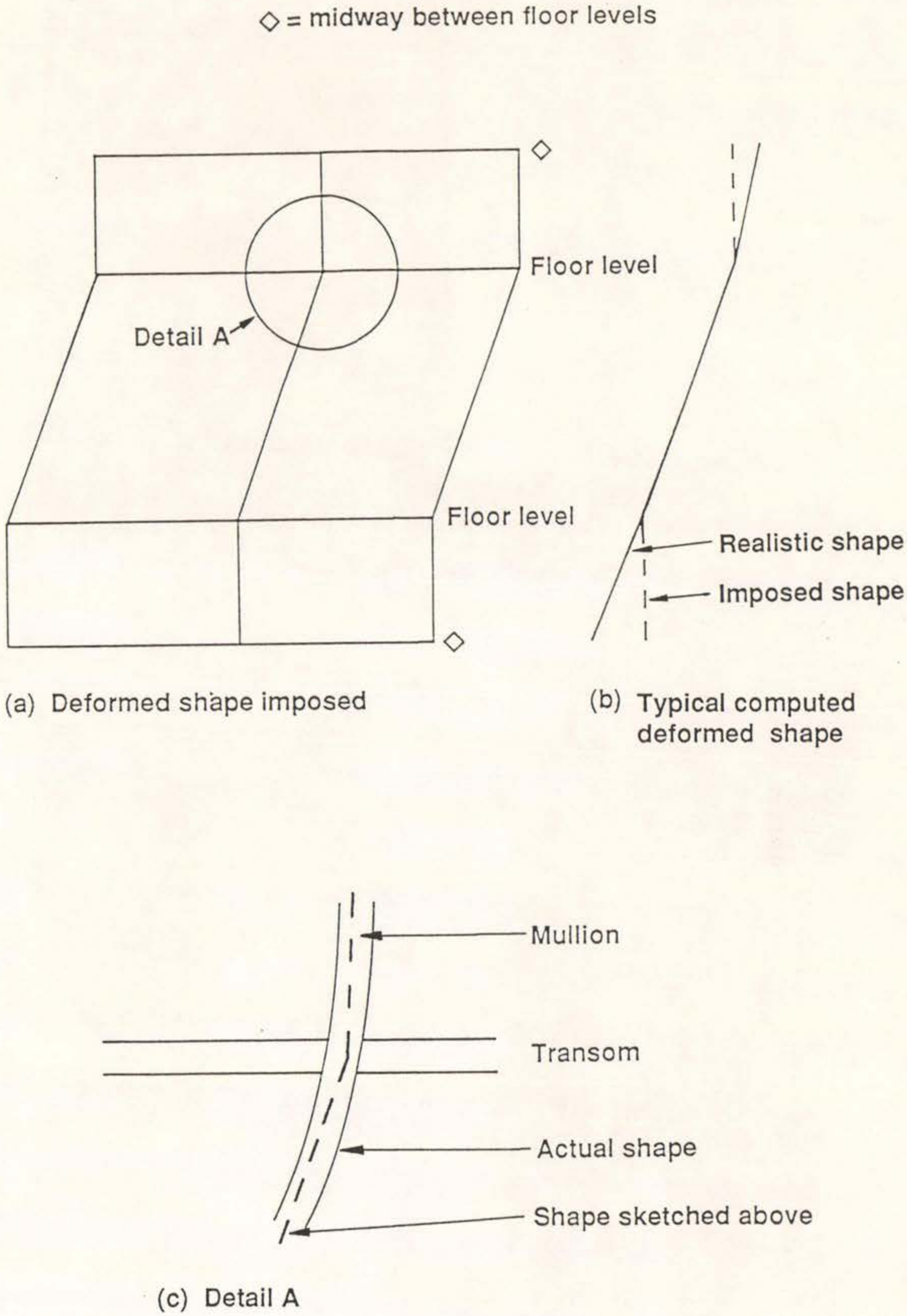
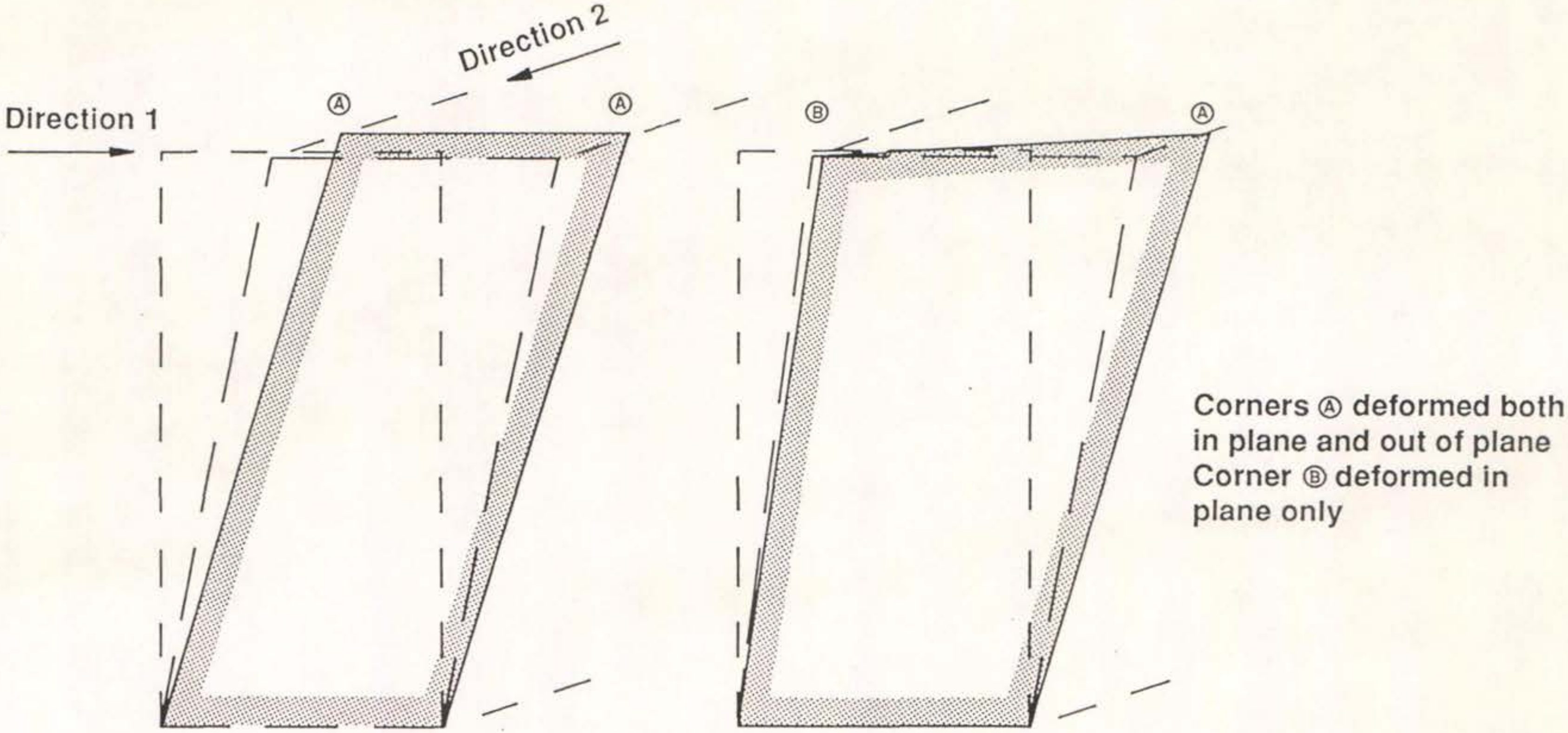


Figure 4 Curtain wall deformed shape

Note - BRANZ specimen is displaced at the base
rather than at the top as shown

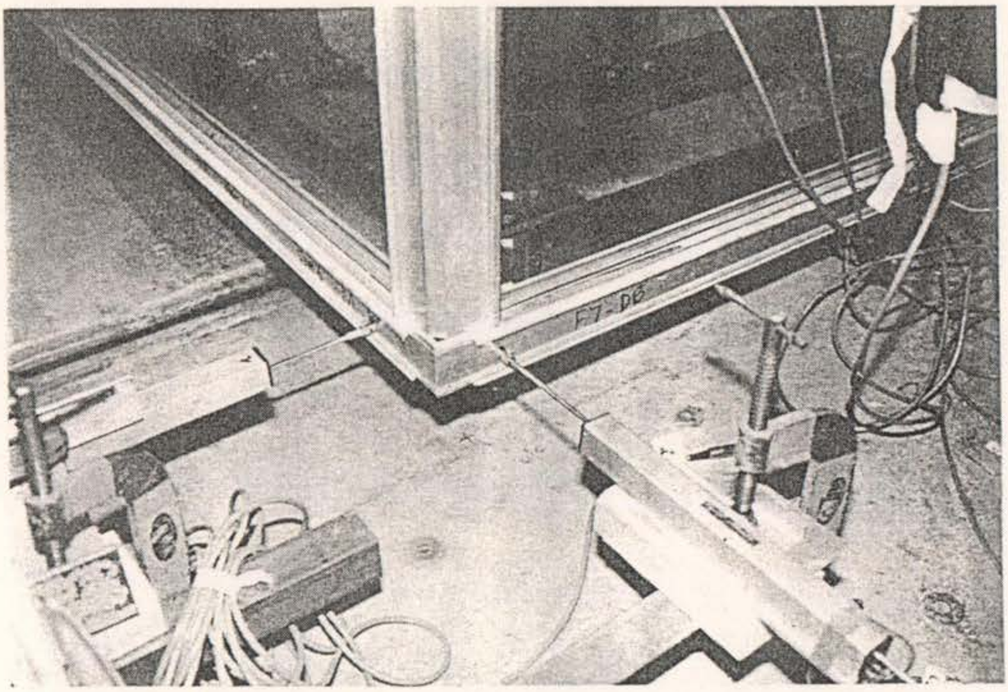


(a) Real building

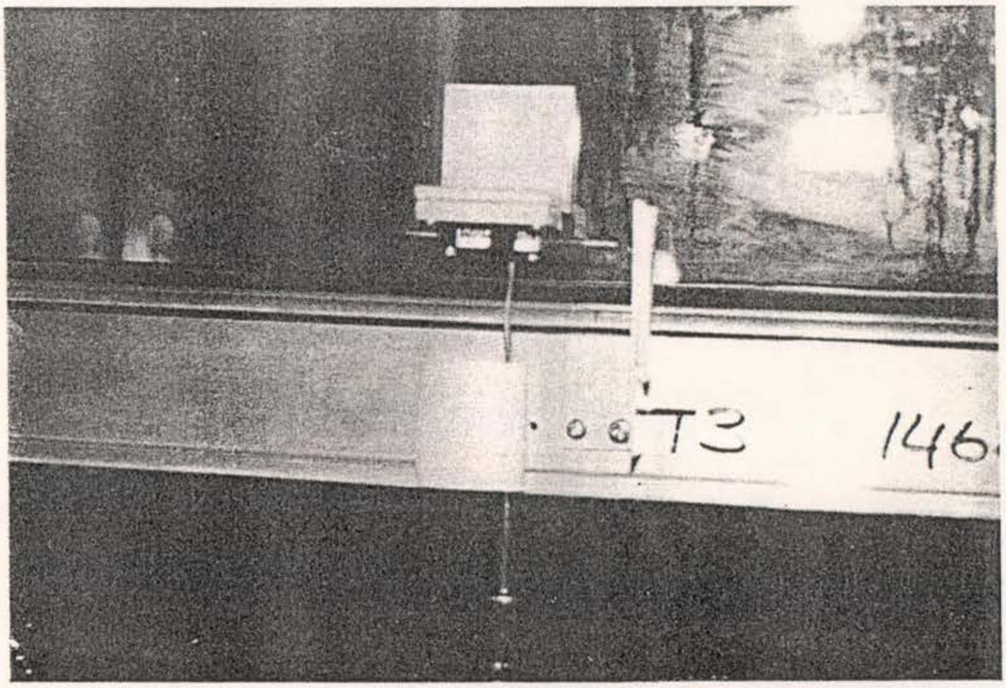
(b) BRANZ laboratory specimen (turned upside down)

Isometric Projection

Figure 5 Deformed shape of glazing racked in two directions

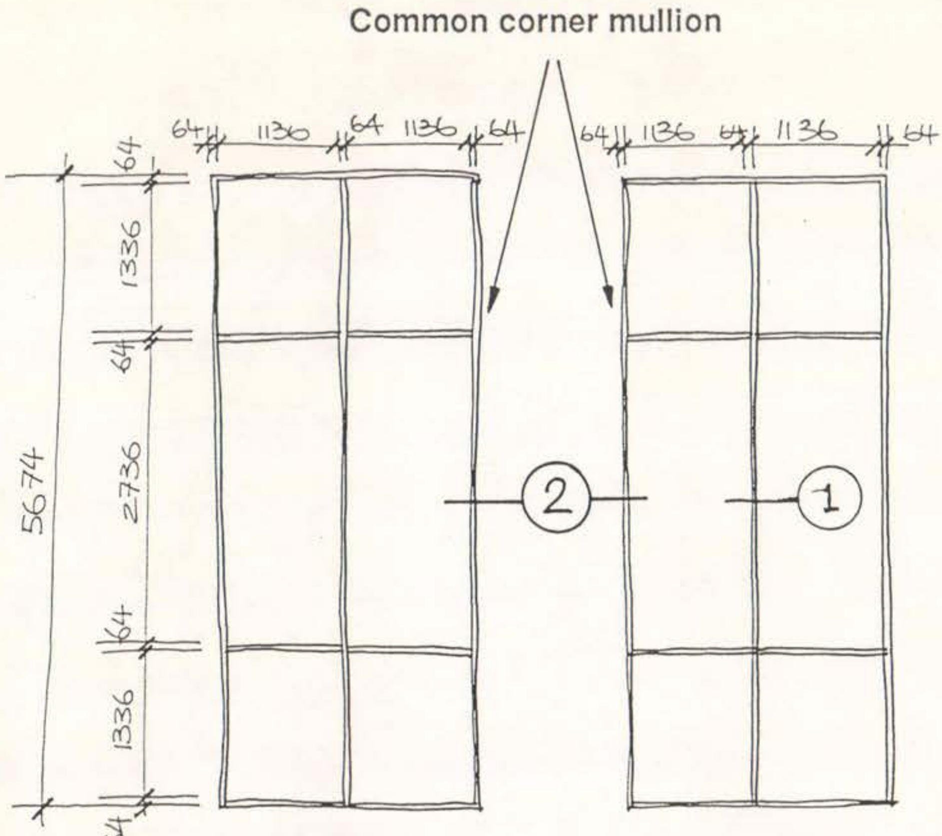


(a) Gross deflection of frame

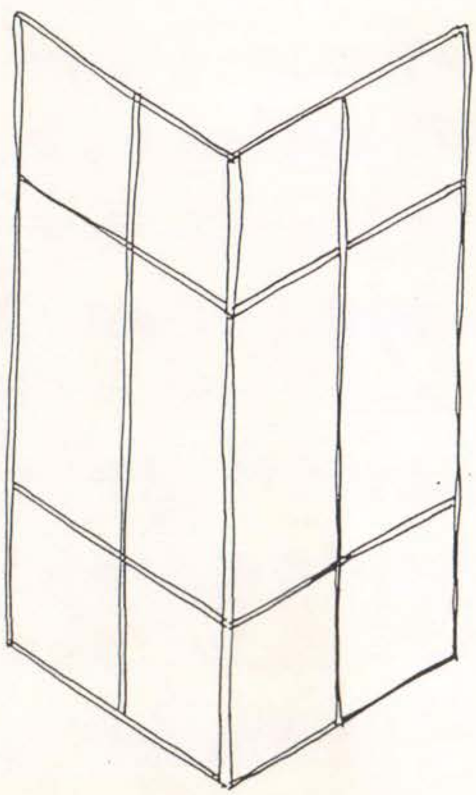


(b) Slip between glass and frame

Figure 6 Deflection measurements

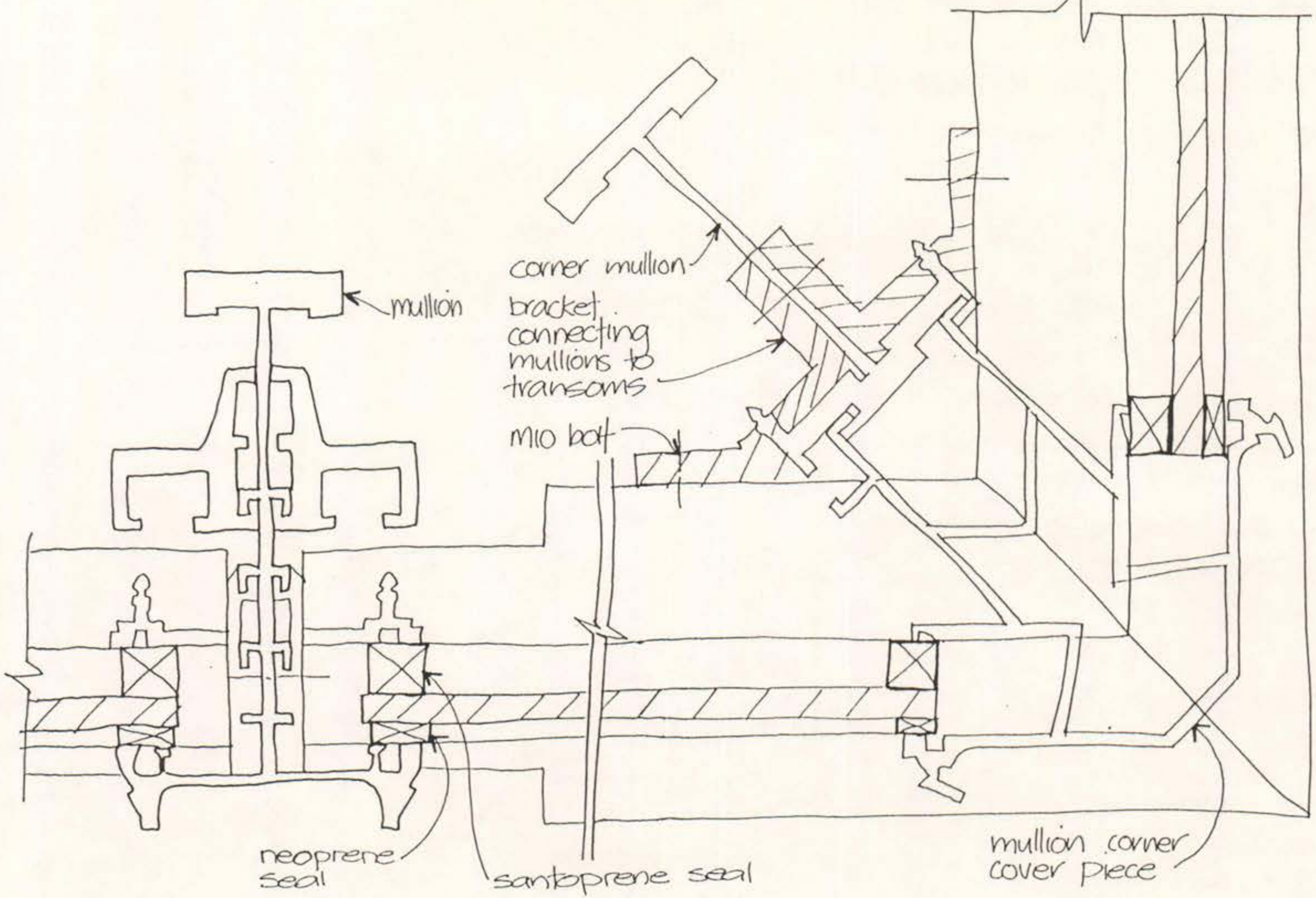


Face A 7a Face B



7b Isometric view

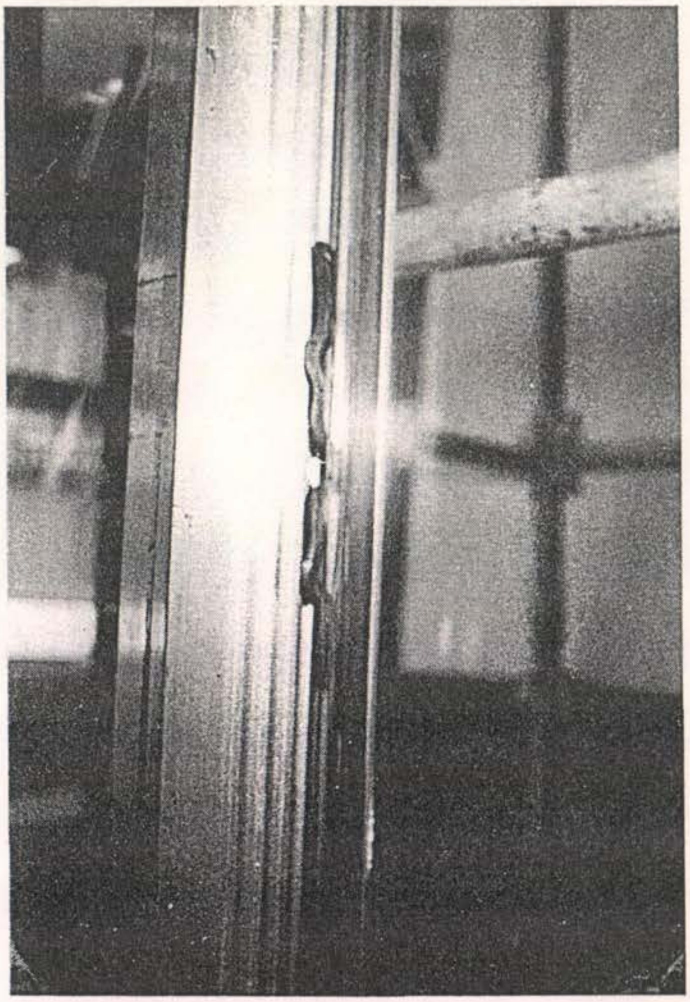
Figure 7 Details of gasket glazed system (Wall NG)



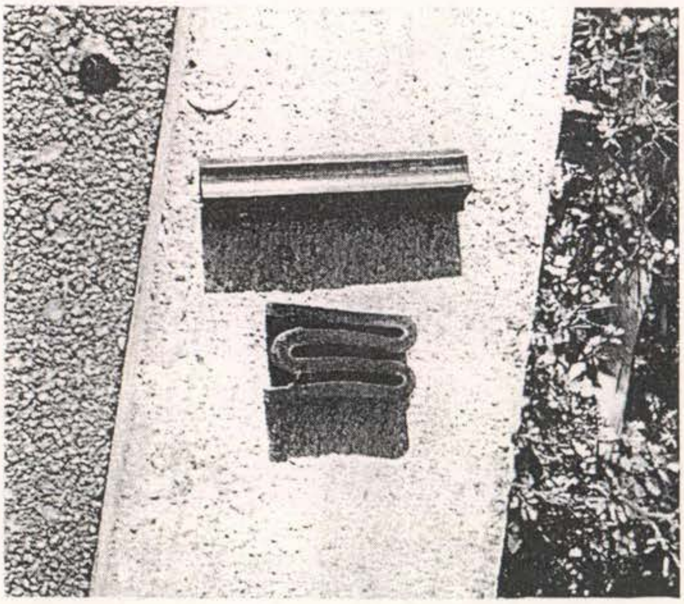
Detail 1

Detail 2

Figure 7c Detail 1 and 2



(a) Distortion of neoprene spacer (antiwalk blocks)



(b) Spacer and block

Figure 8 Neoprene spacer and setting blocks

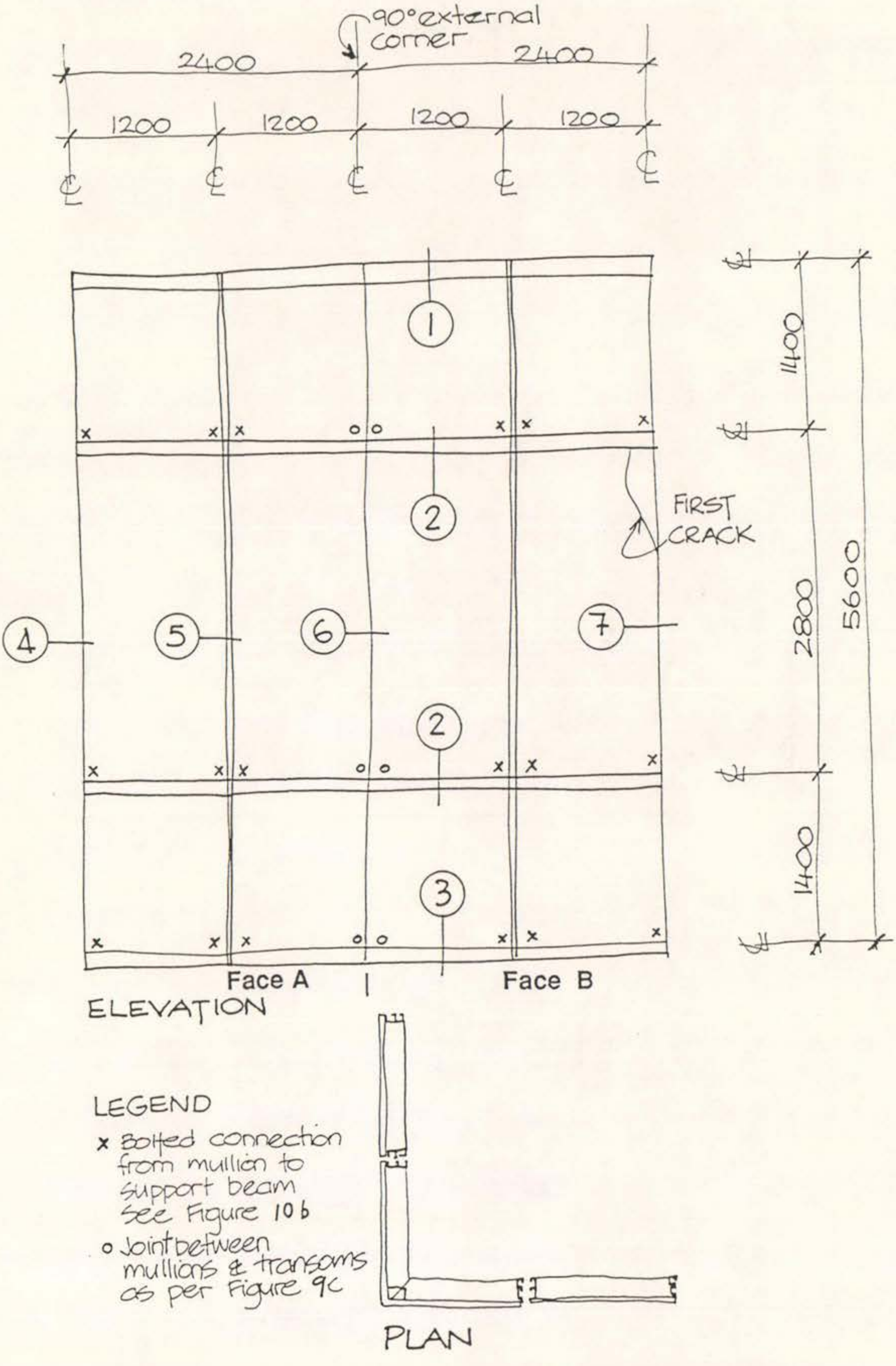


Figure 9a Dimensions of two sided silicone system (Wall S2) & location of first crack during testing

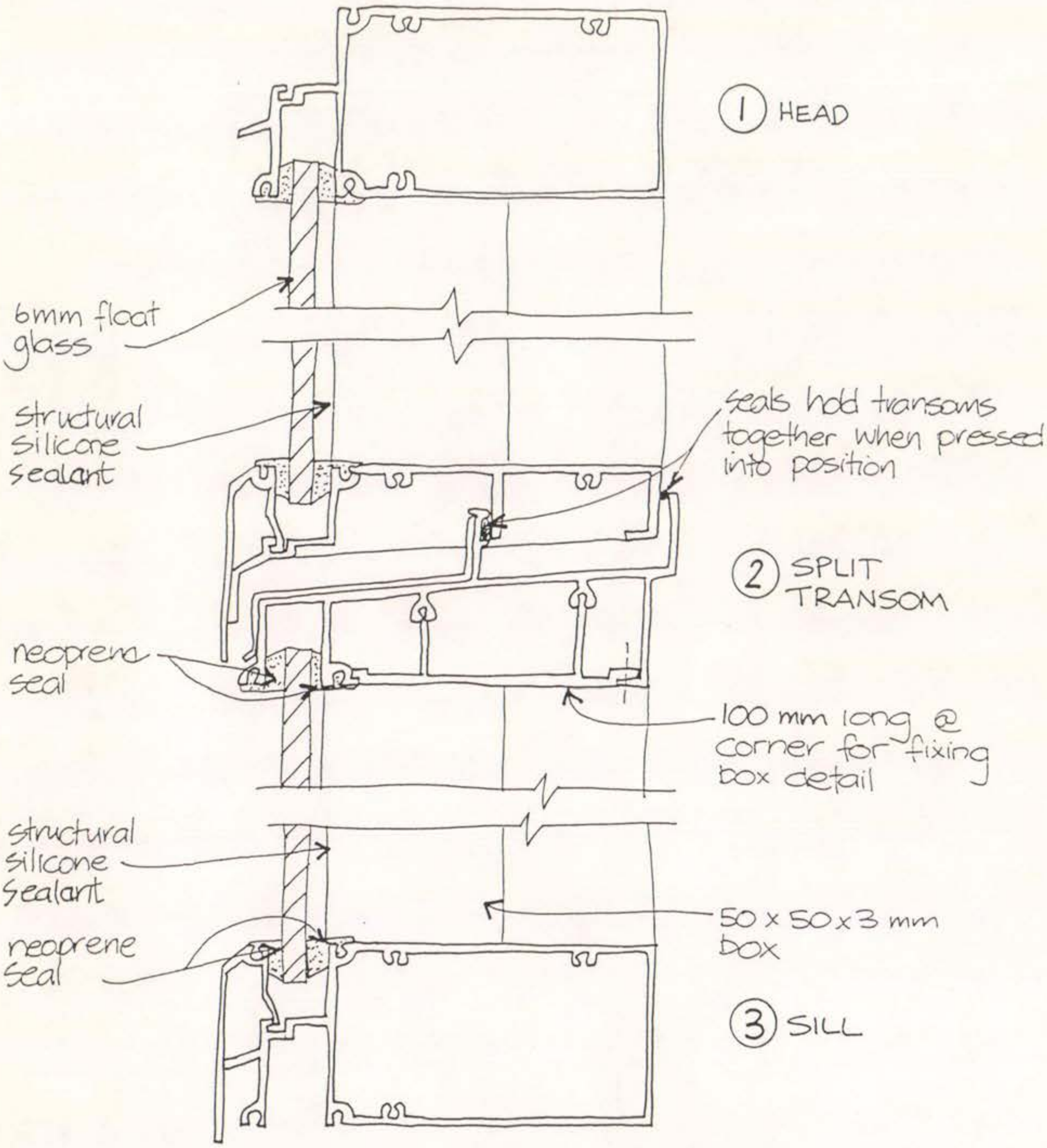
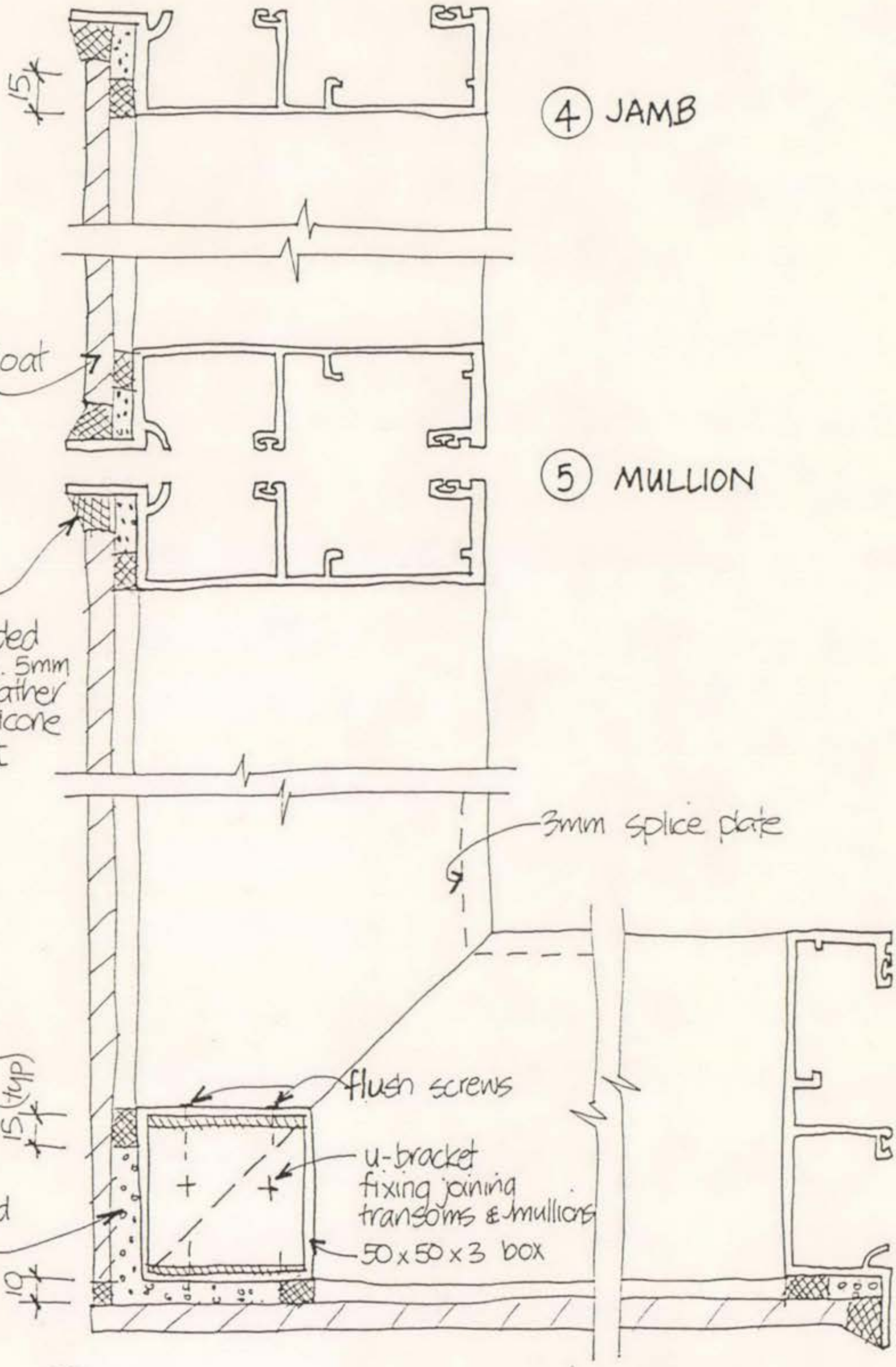


Figure 9b Cross-section though transoms (Wall S2)



6 90⁰ Ext. Corner

7 Jamb

Figure 9c Cross-section views though mullions (Wall S2)

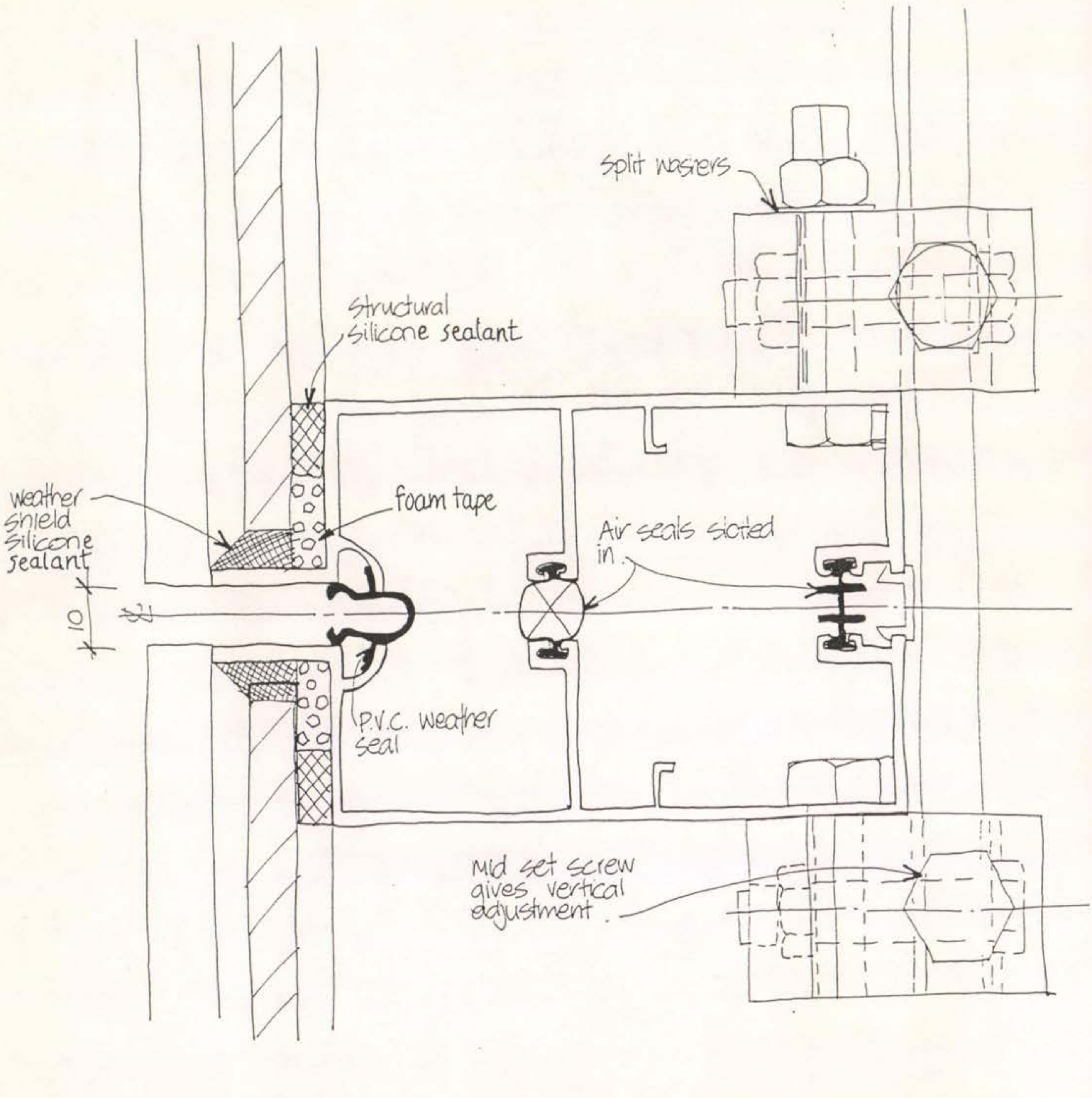
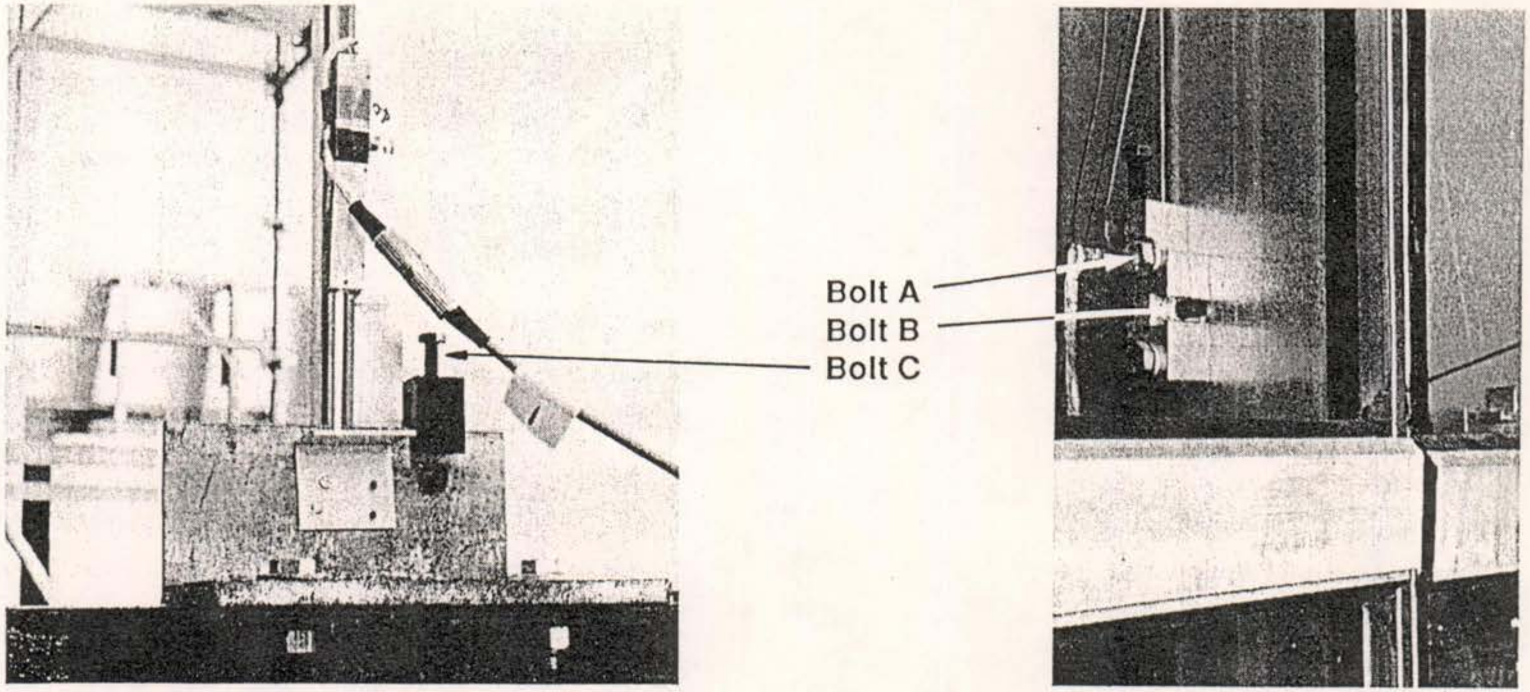


Figure 9d Detail 5 Cross-section though mullions showing connection details(Wall S2)



(a) Vertical movement of mullion relative to load beam

(b) Connection of mullion onto load beam

Figure 10 Wall S2 details

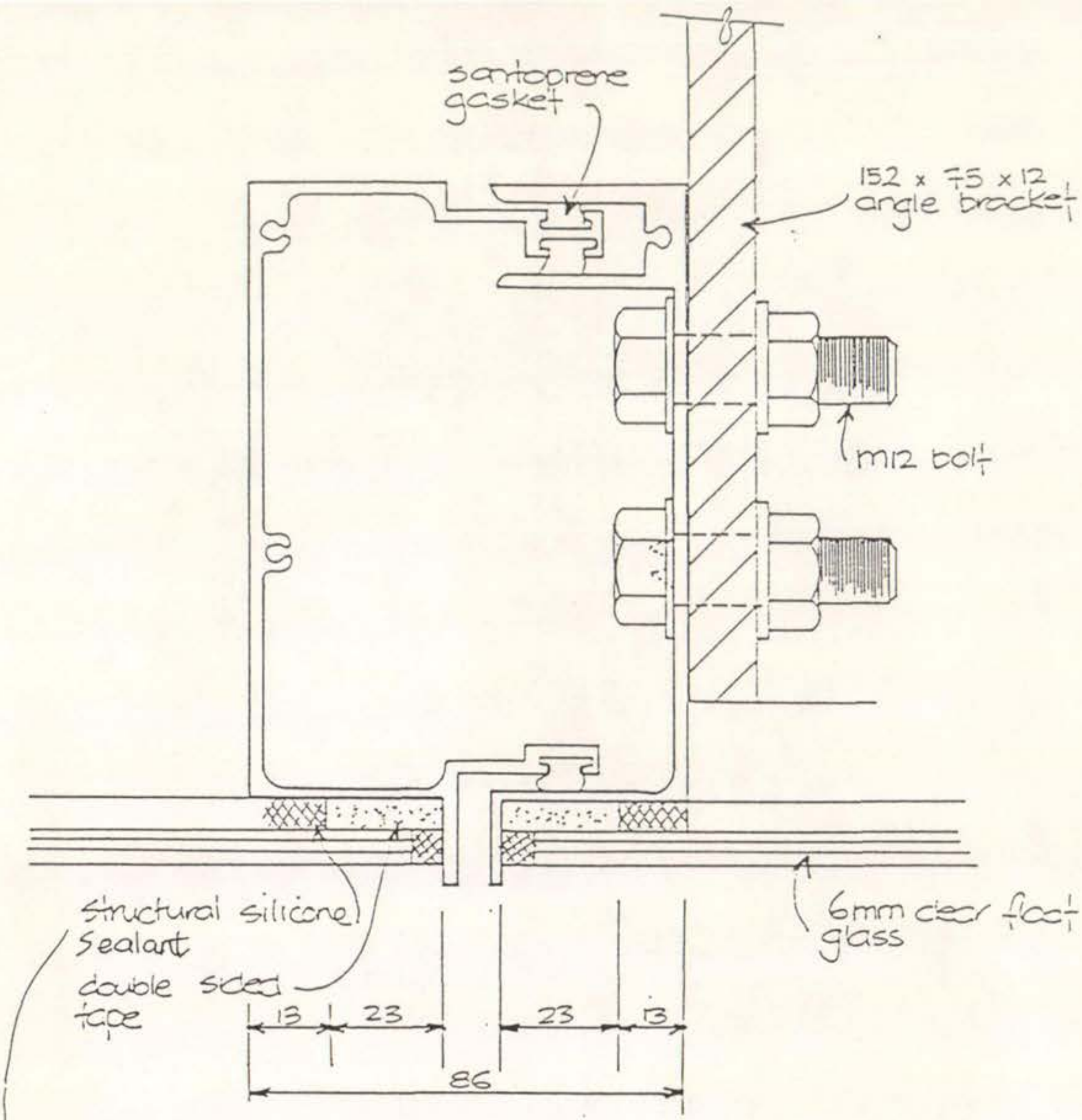
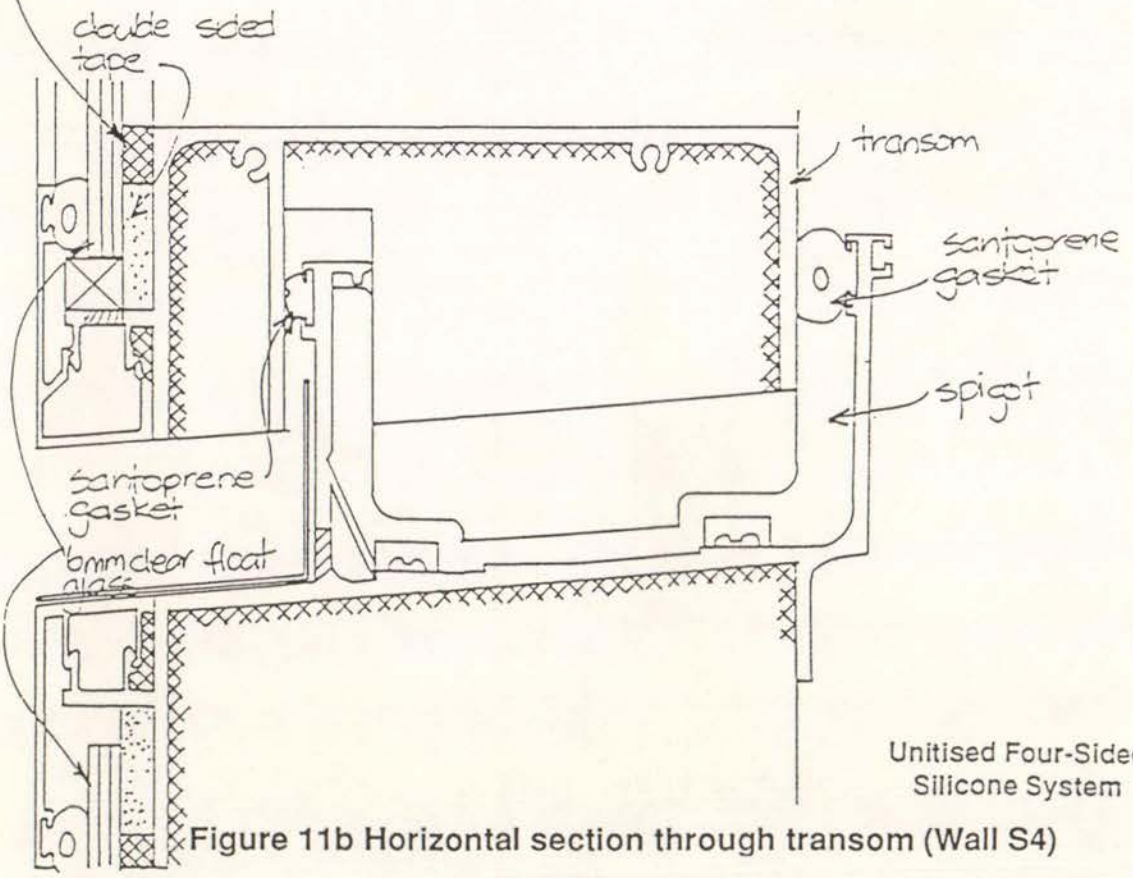


Figure 11a Vertical section through mullion (Wall S4)



Unitised Four-Sided Silicone System

Figure 11b Horizontal section through transom (Wall S4)

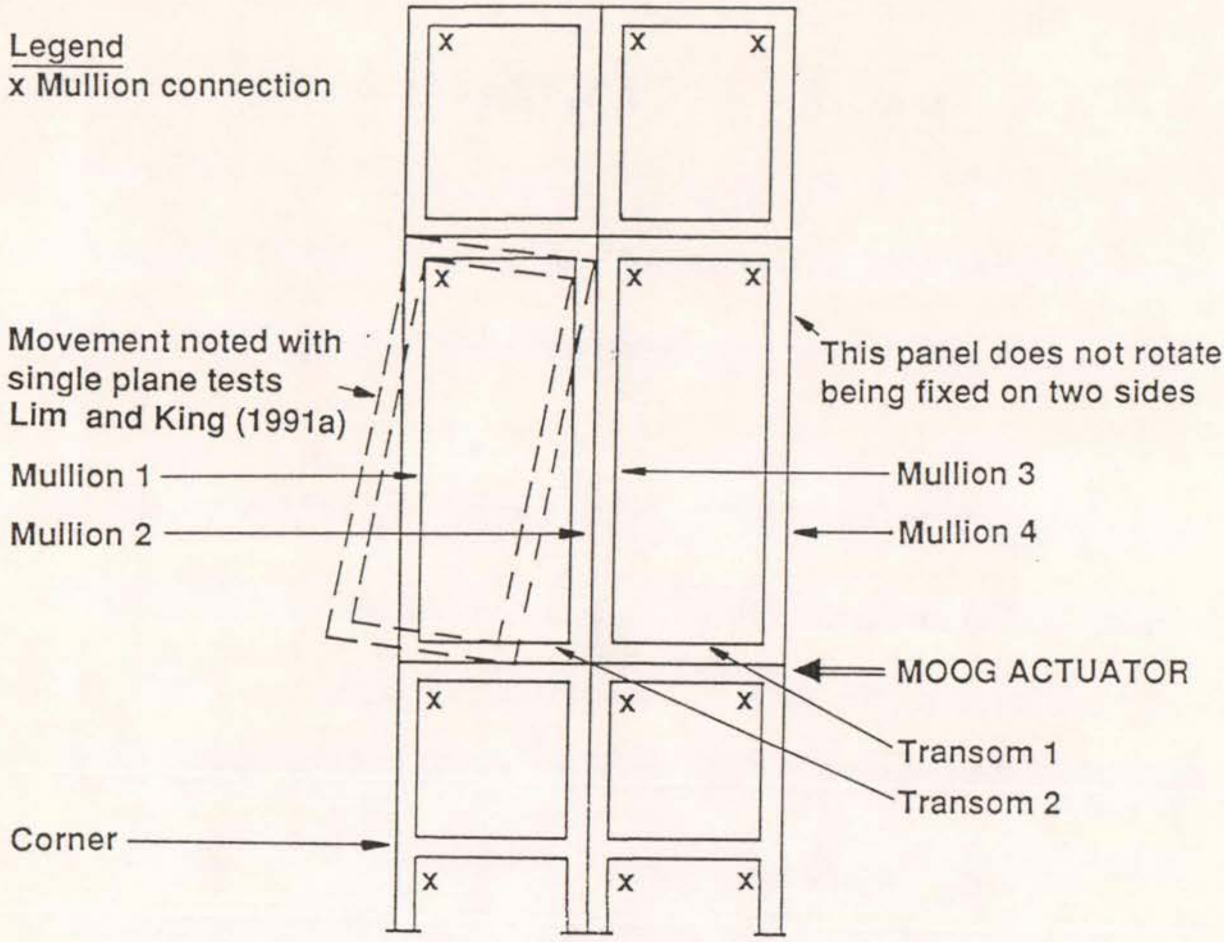


Figure 11c Location of mullion connections (wall S4)

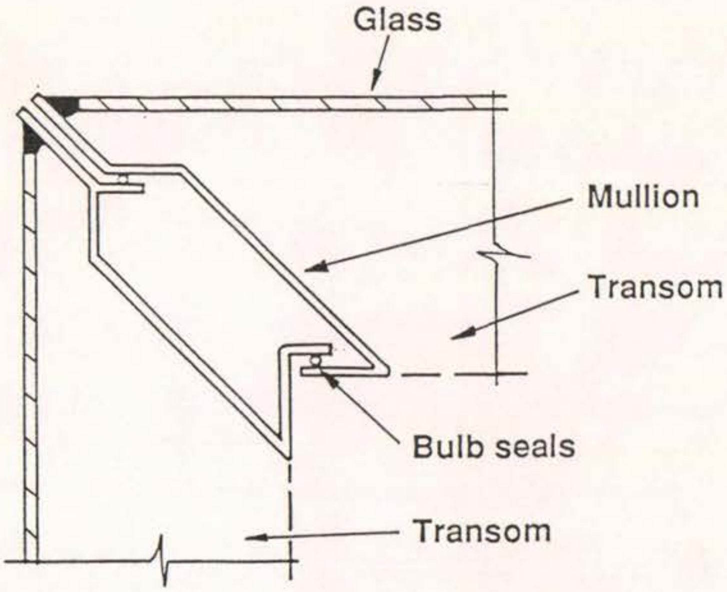


Figure 11d Plan - Preferred site corner detail using split mullion (Wall S4)

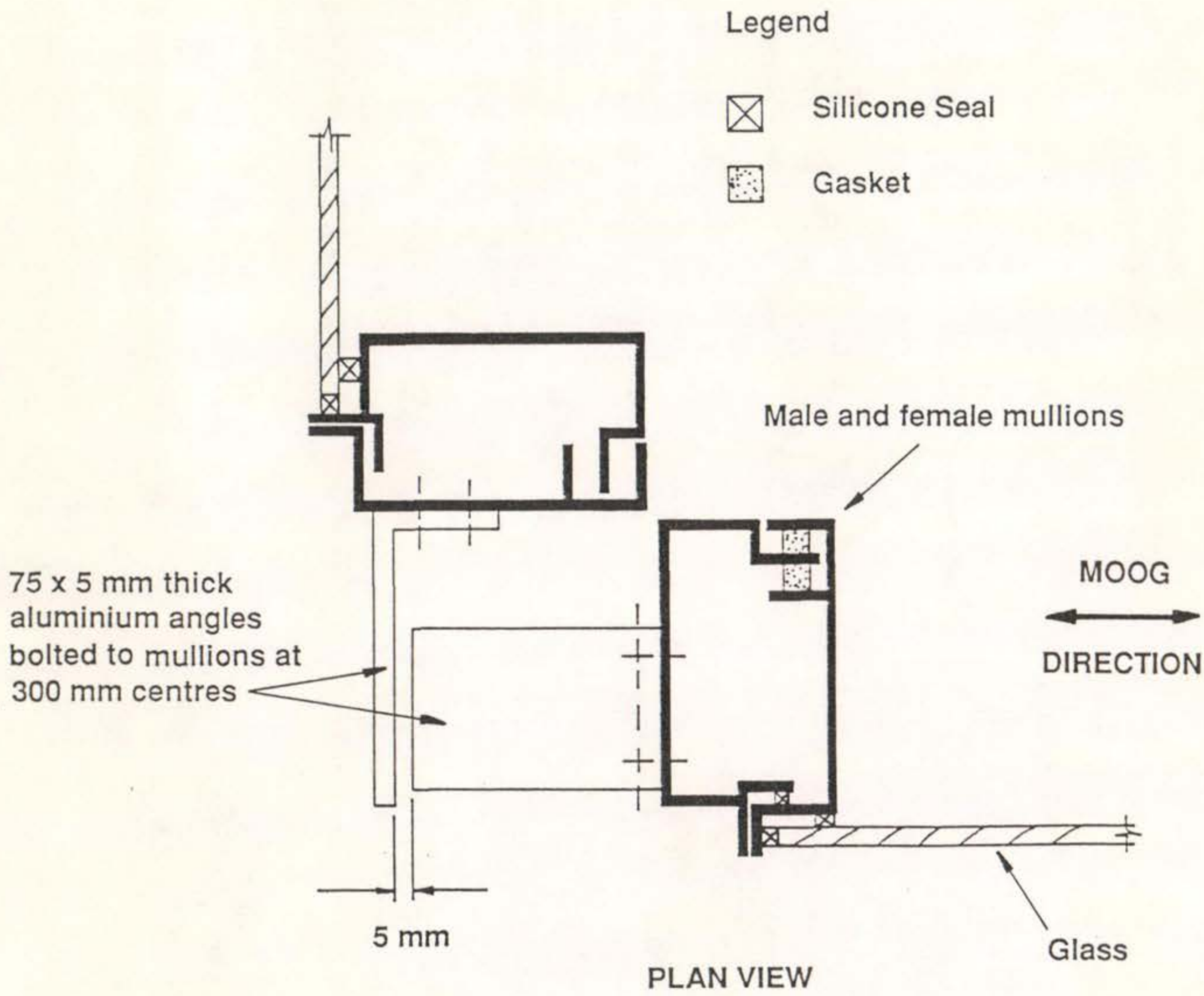


Figure 11e Corner detail used (Wall S4)

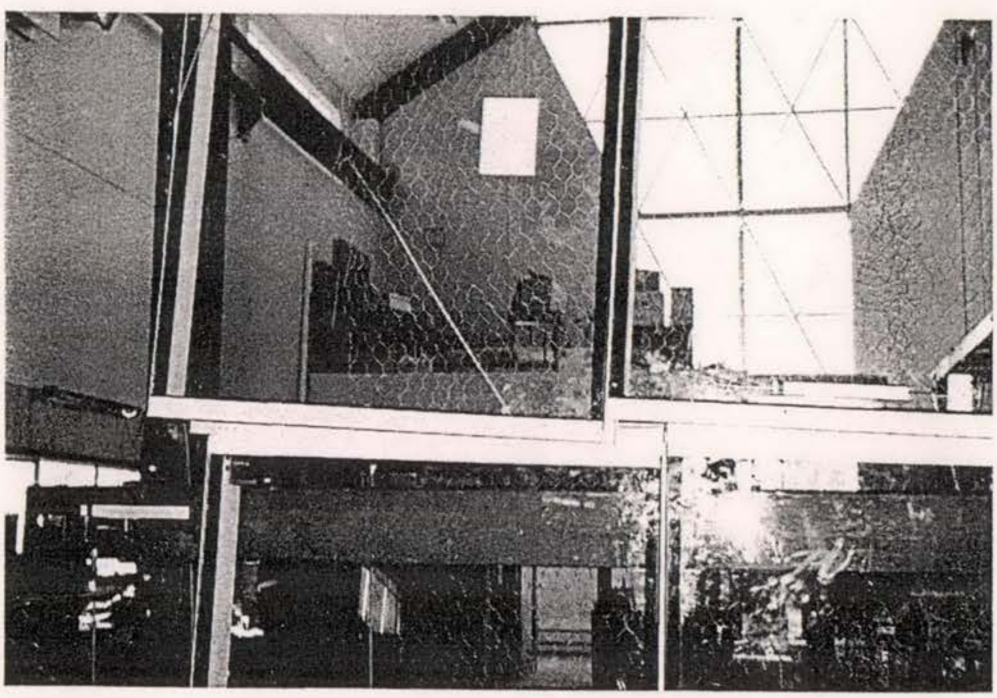
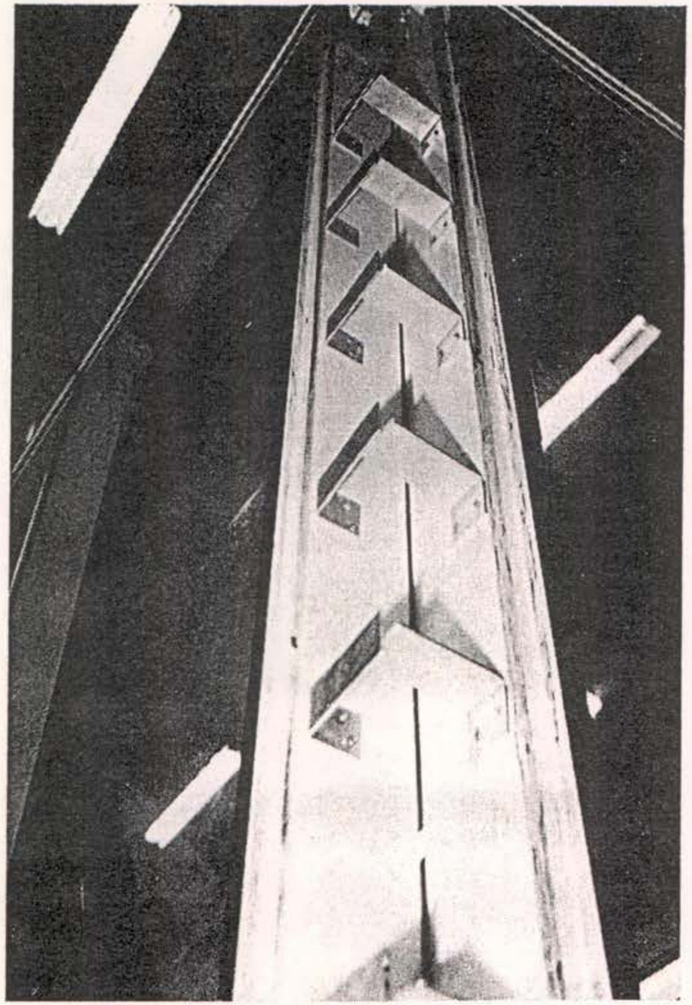
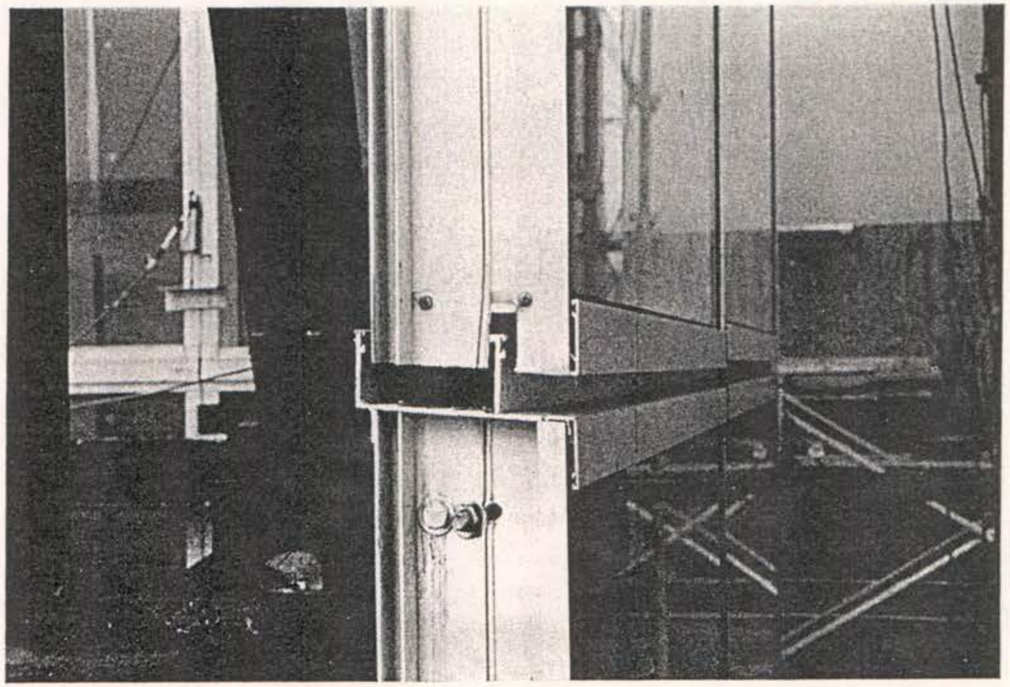


Figure 11f Distortion of planar wall four-sided silicone system. (From Lim & King 1991a)

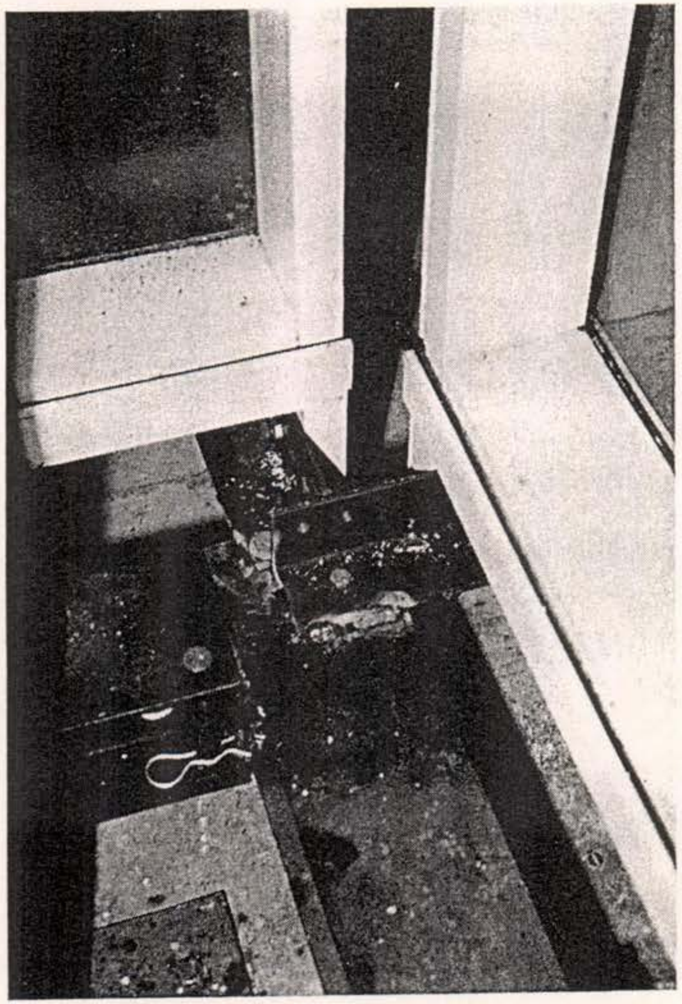


(a) Corner detail

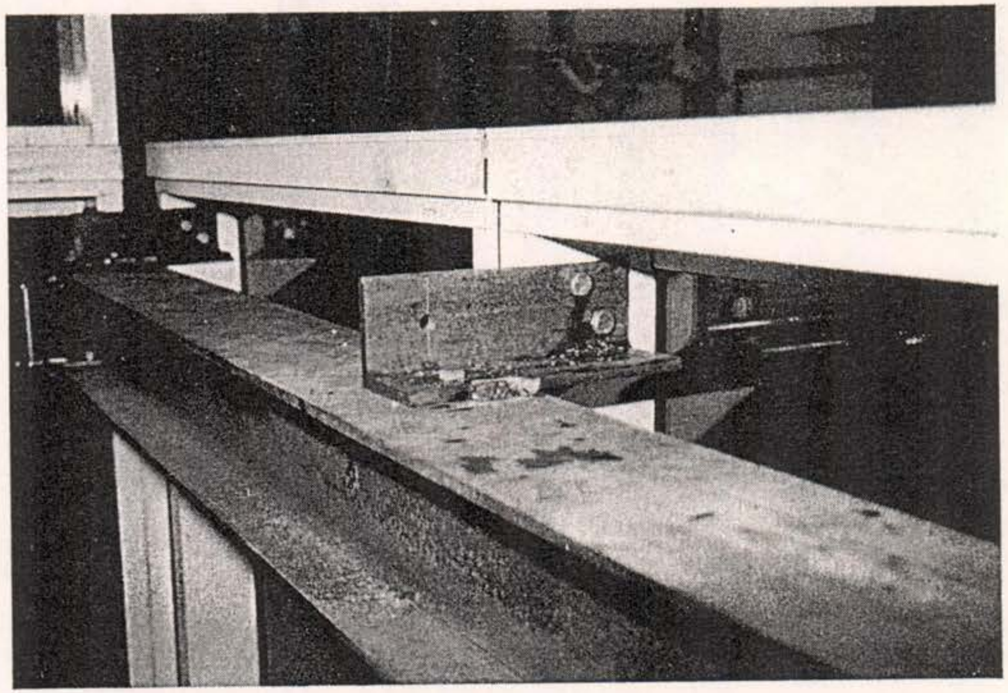


(b) Free end of panel 5 and 9 (see Figure 1)

Figure 11g Details Wall S4

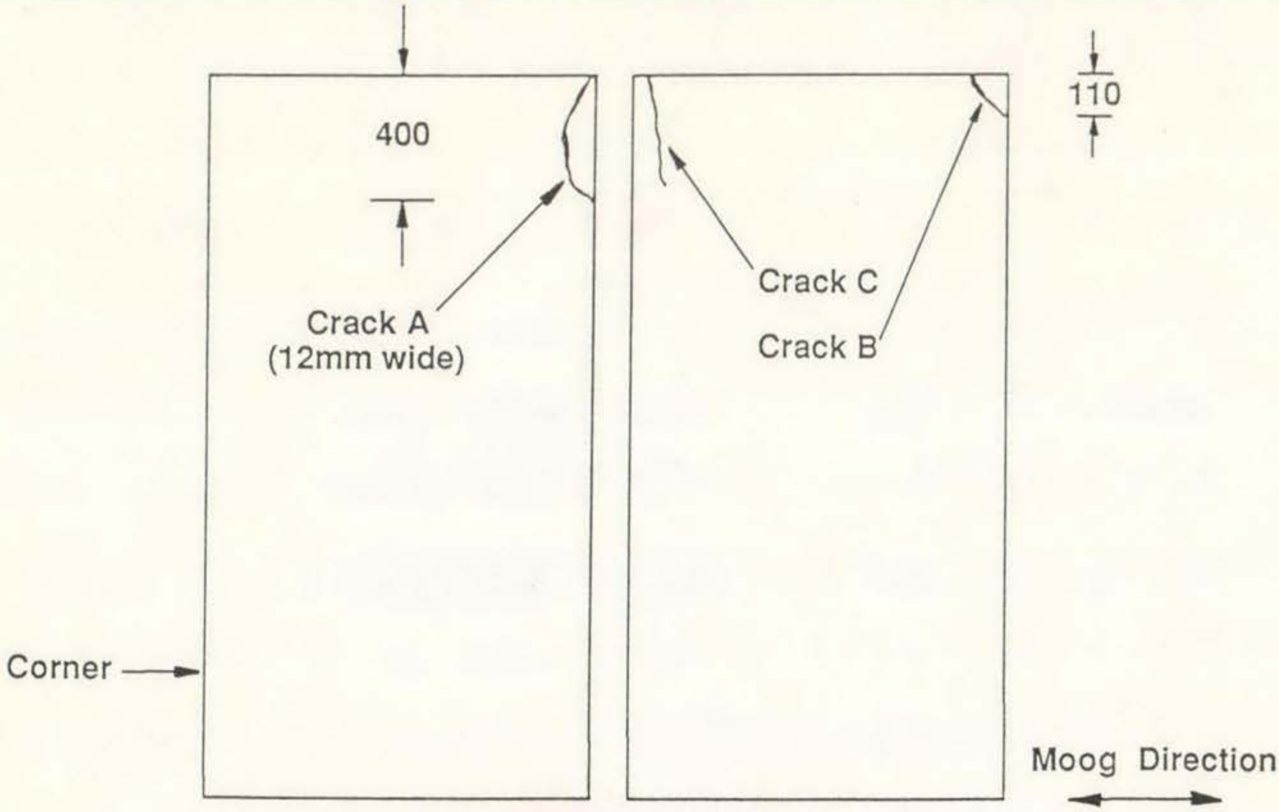


(a) At corner

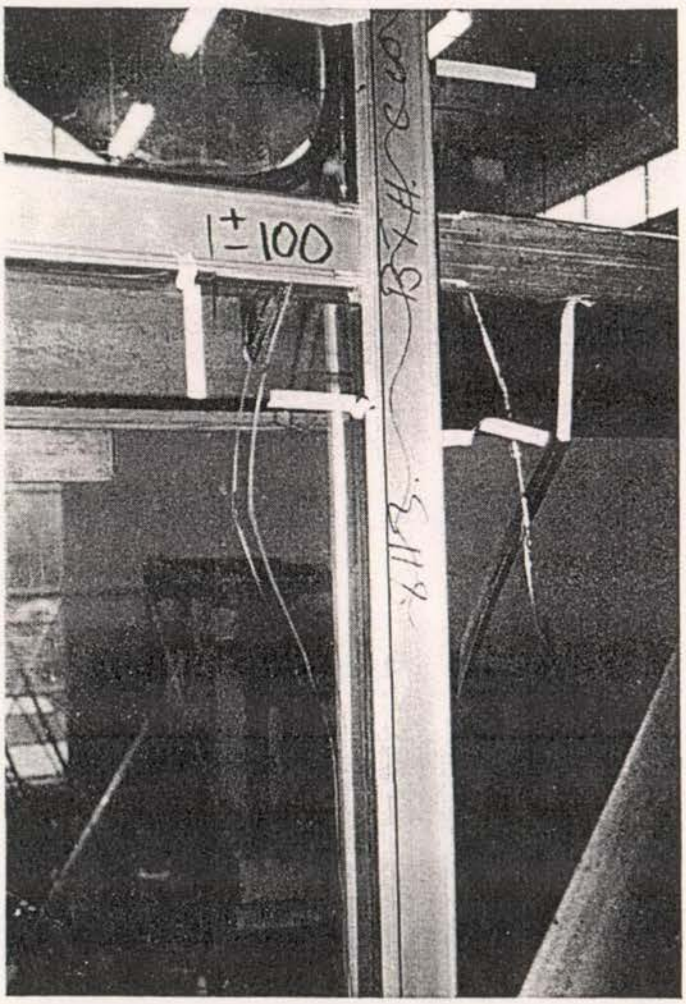


(b) On sides

Figure 11h Connection mullions to load beam Wall S4



(a) Sketch of cracks



(b) Crack A and C

Figure 12 Cracking in gasket glazed windows (Wall NG)

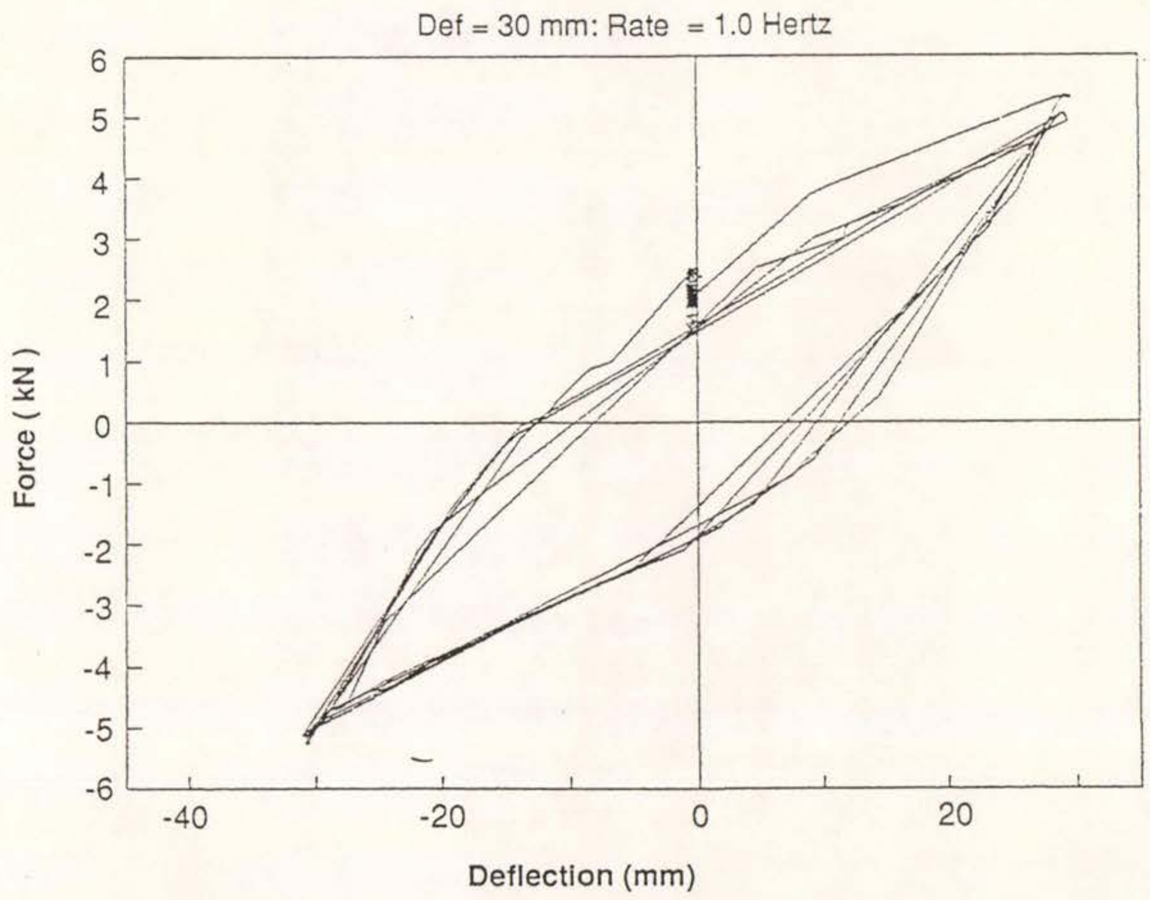


Figure 13 Force / Deflection Hysteresis Loops (Wall NG)

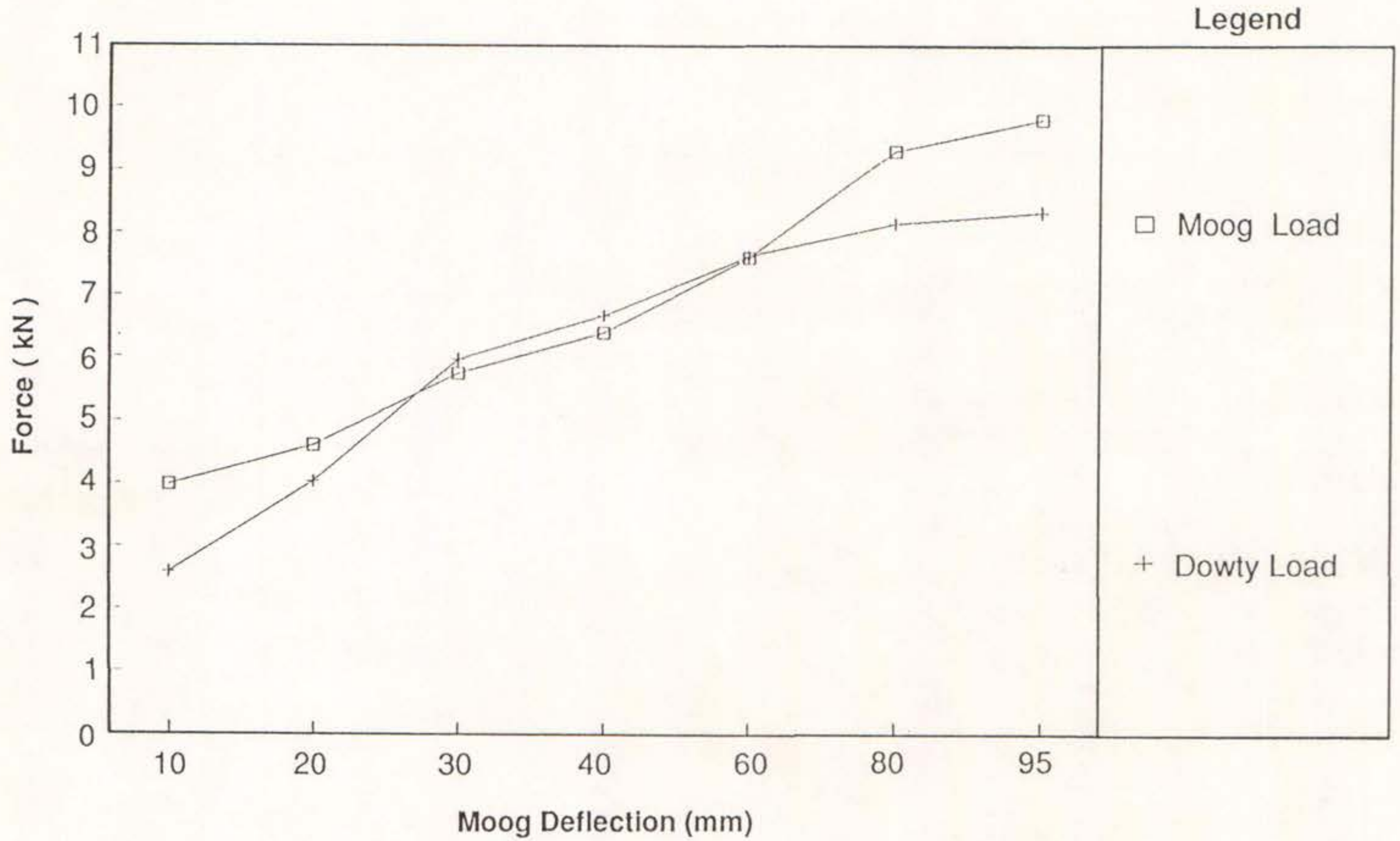


Figure 14 Peak actuator loads versus Moog deflection (Wall NG)

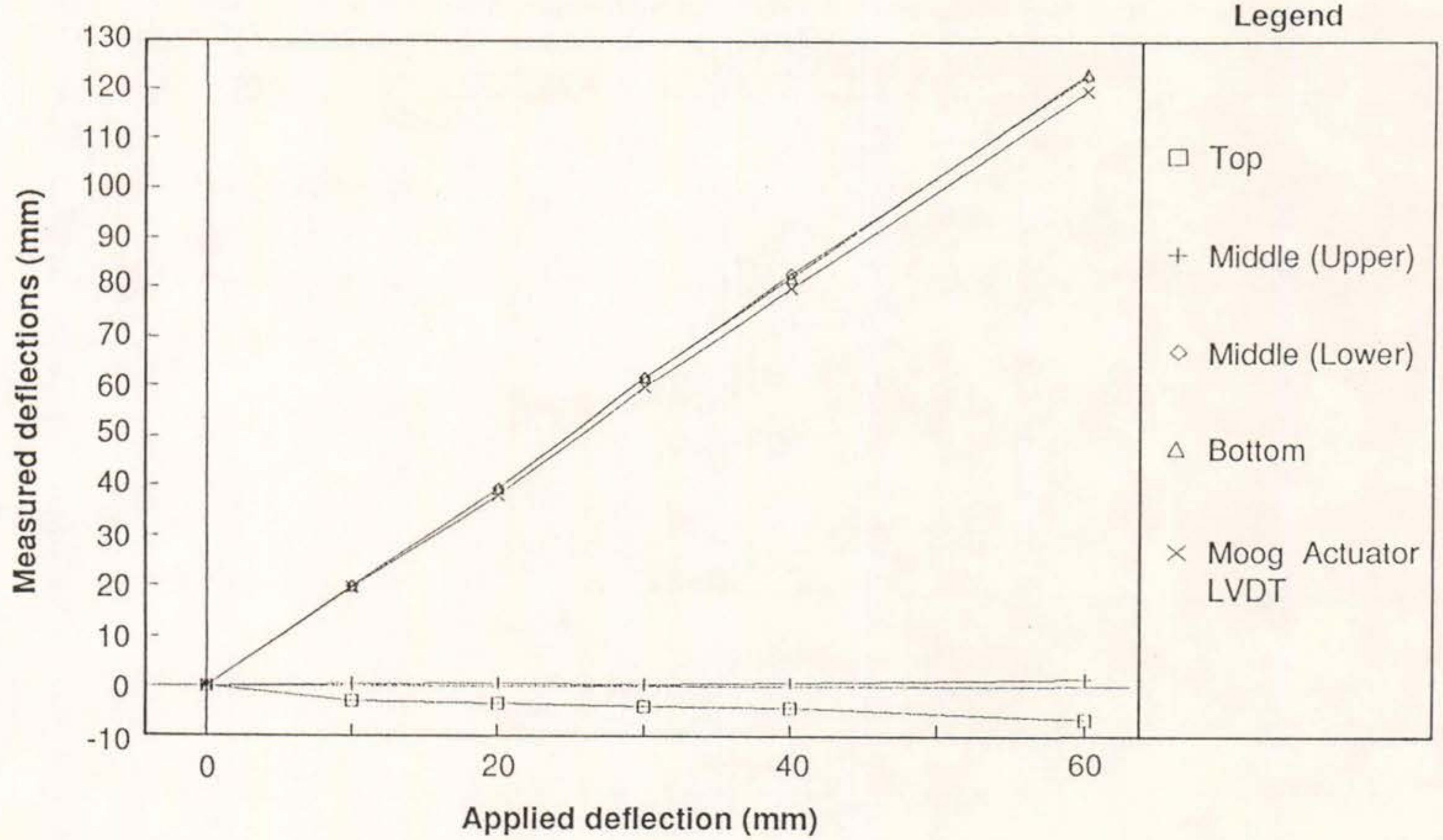


Figure 15 Gross deflection Moog direction (Wall NG)

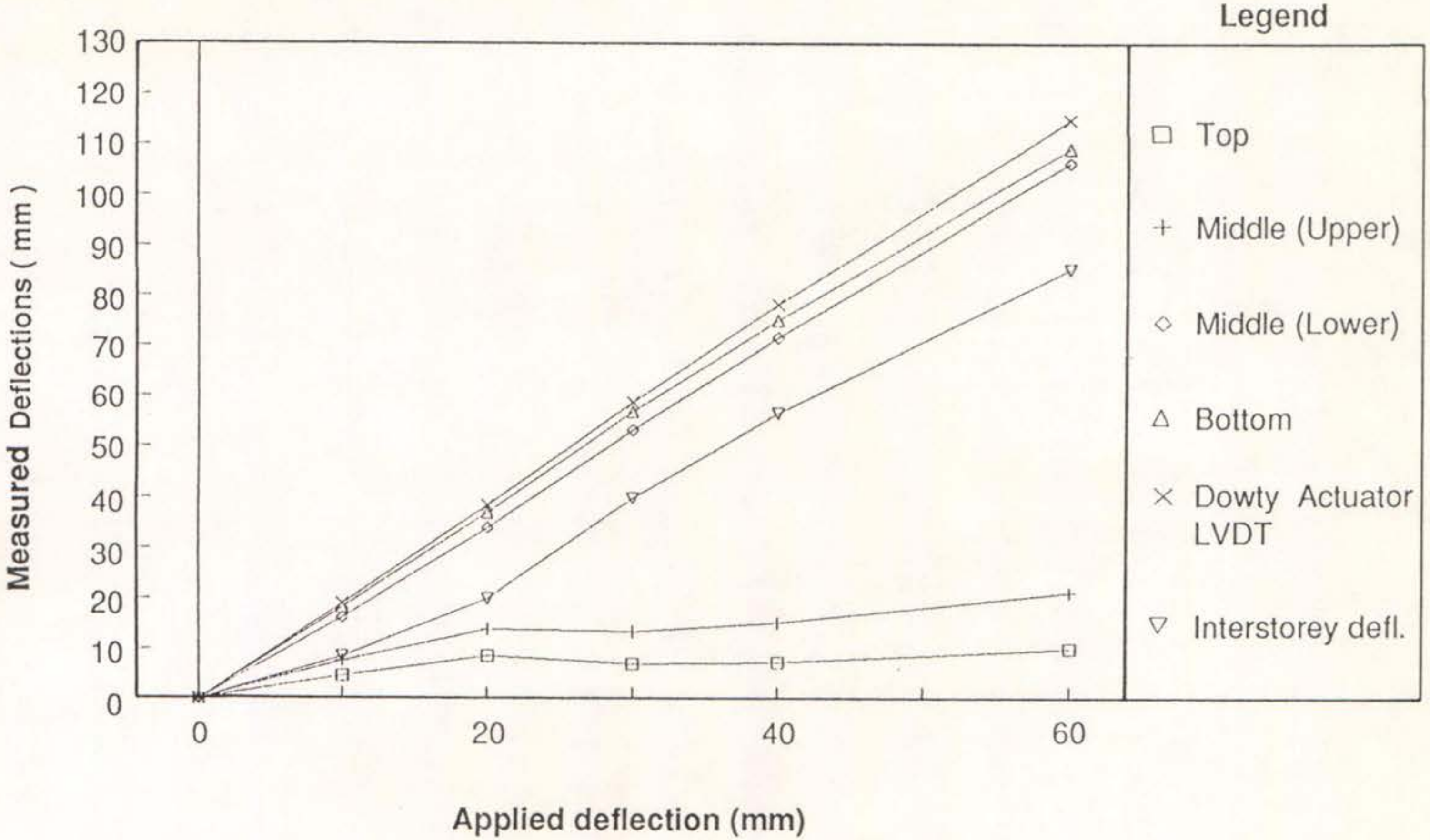


Figure 16 Gross deflection Dowty direction (Wall NG)

Frame deflection = a + c + (b + d) * aspect ratio

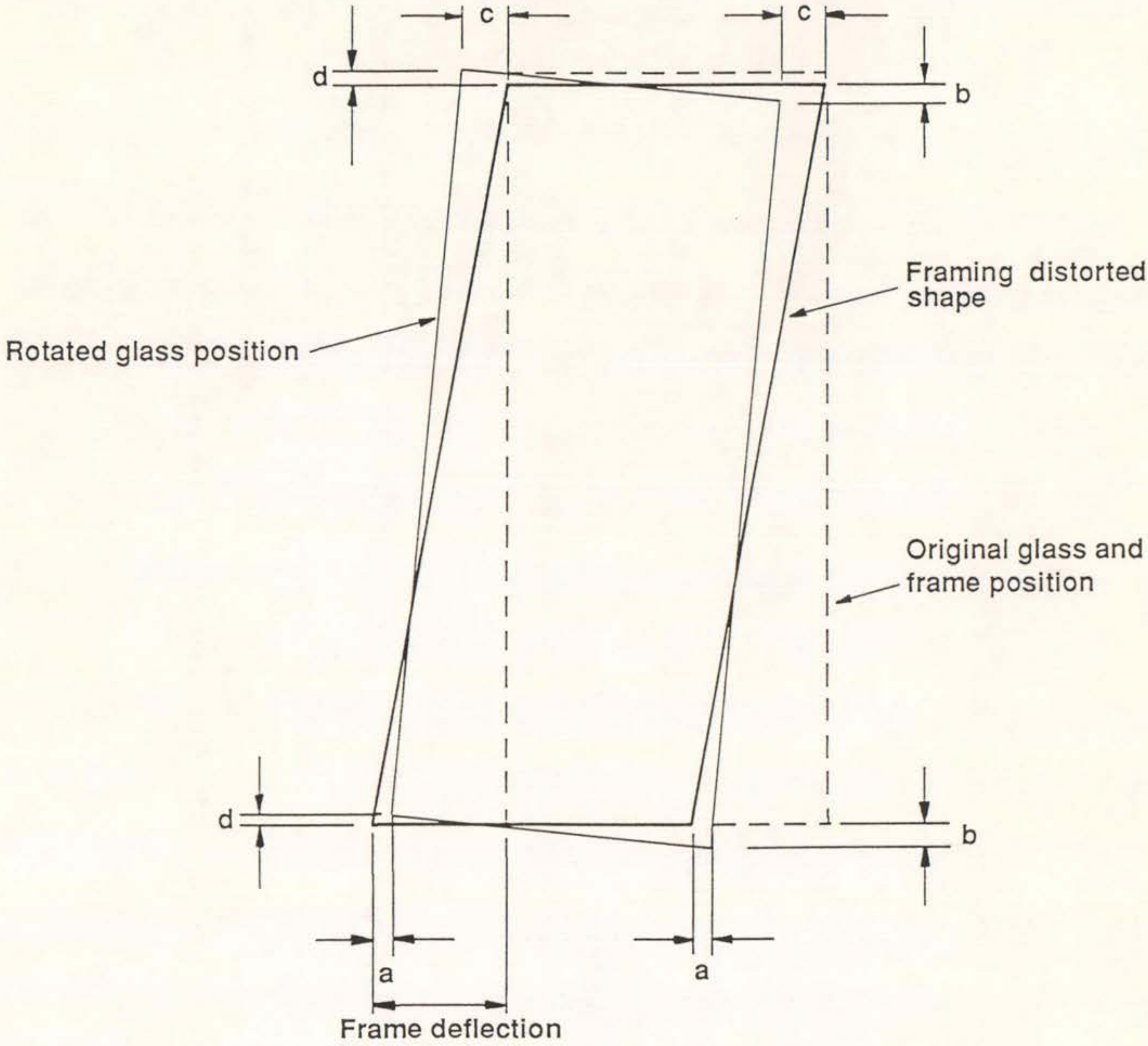


Figure 17 Deflections measured (Wall NG)

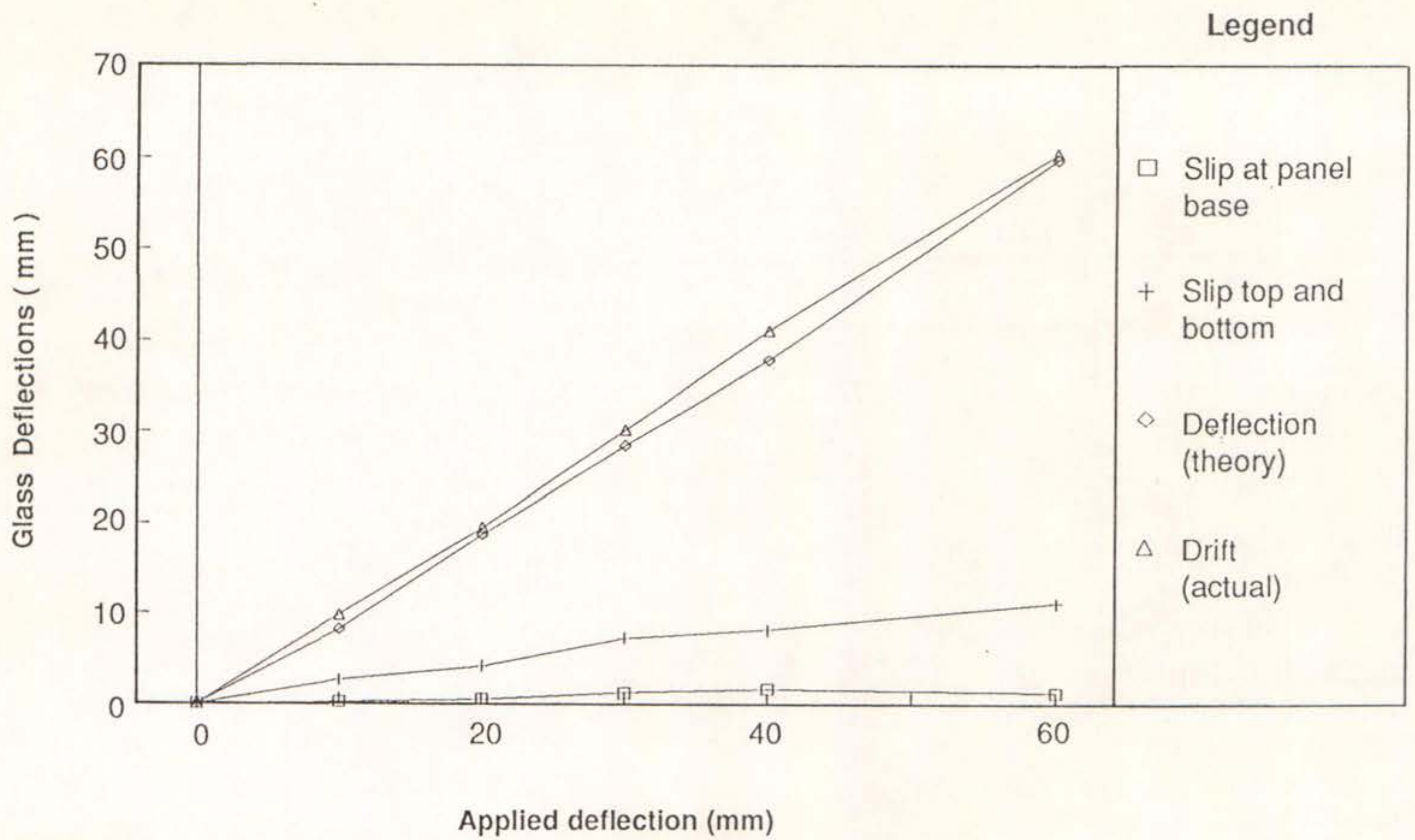


Figure 18 Components of Inter-storey deflection (First Panel) (Wall NG)

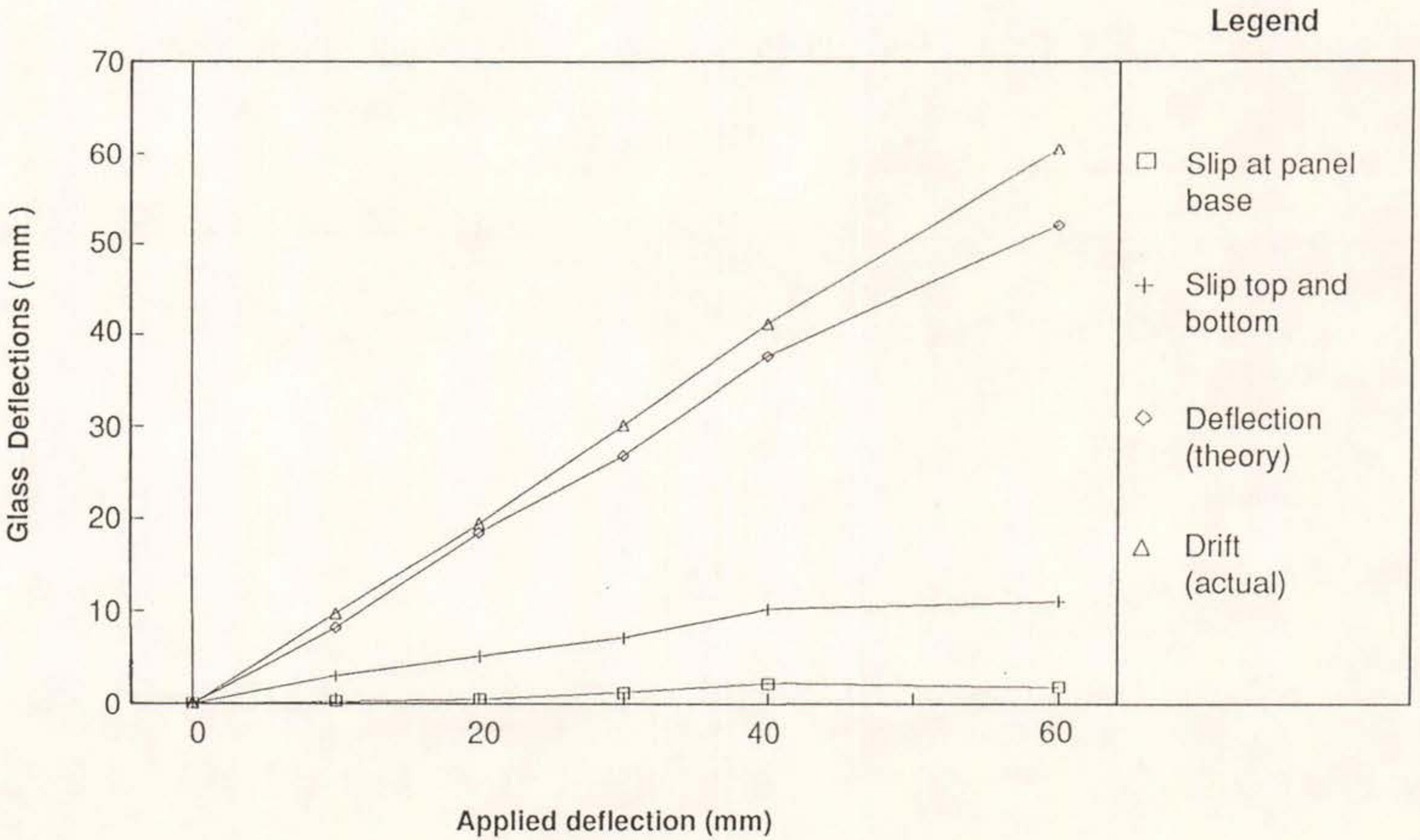
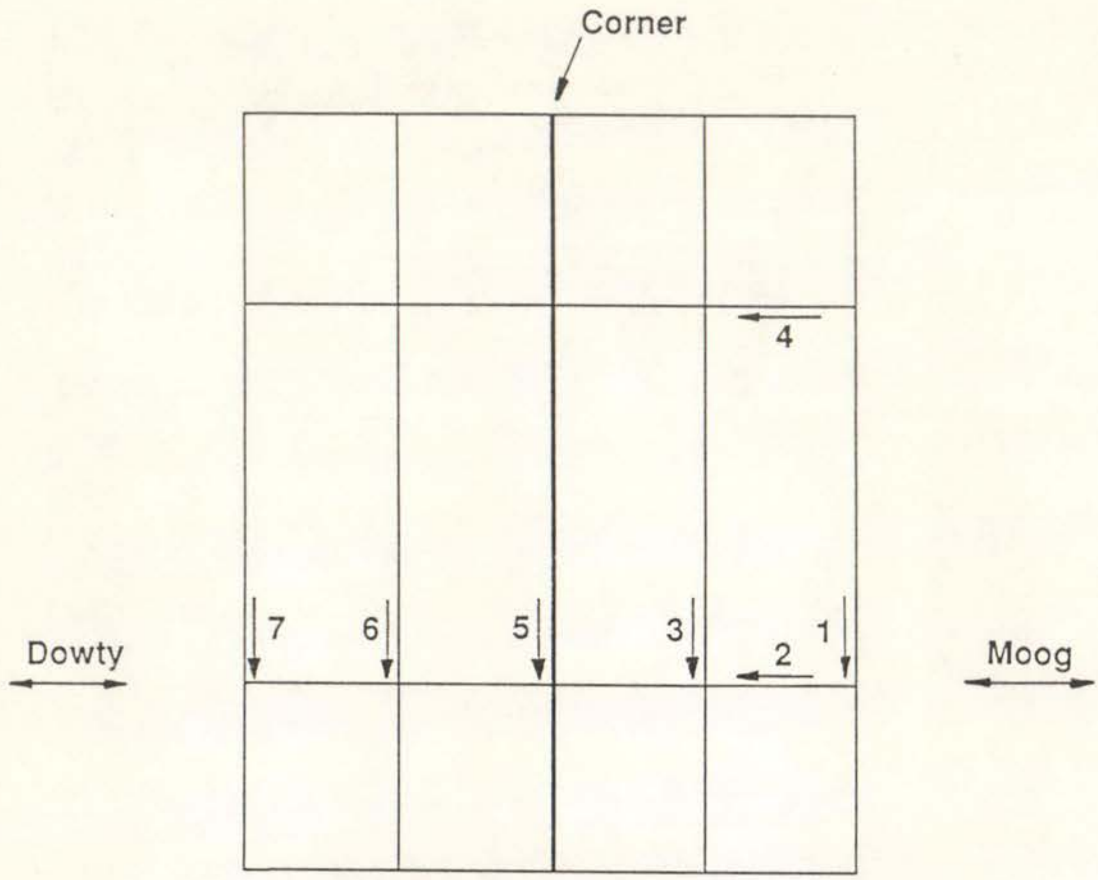


Figure 19 Components of Inter-storey deflection (Second Panel) (Wall NG)

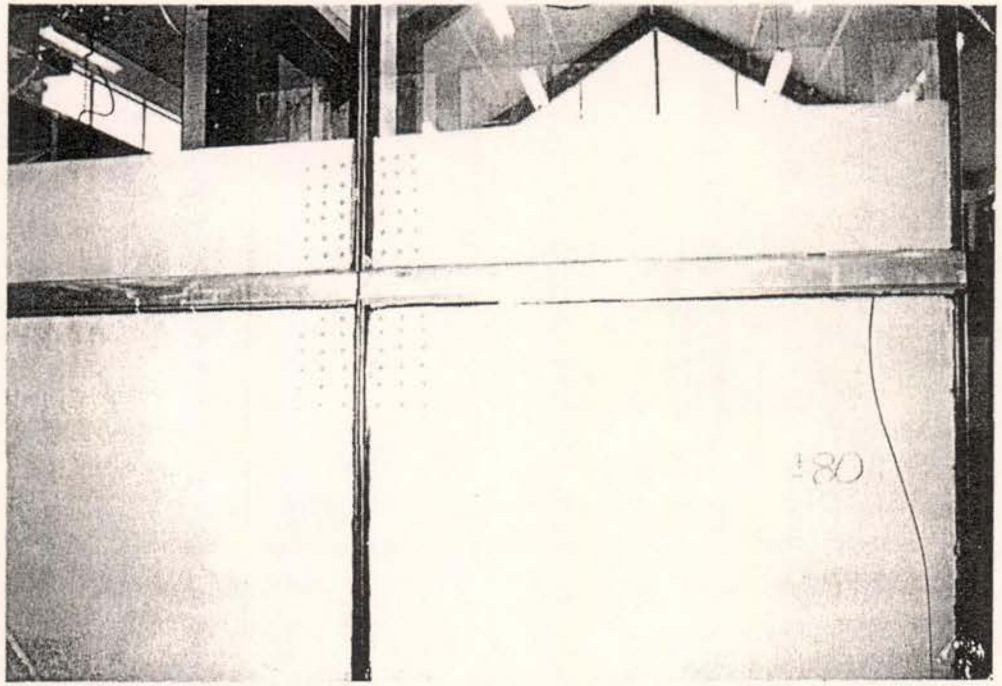


Unfolded elevation

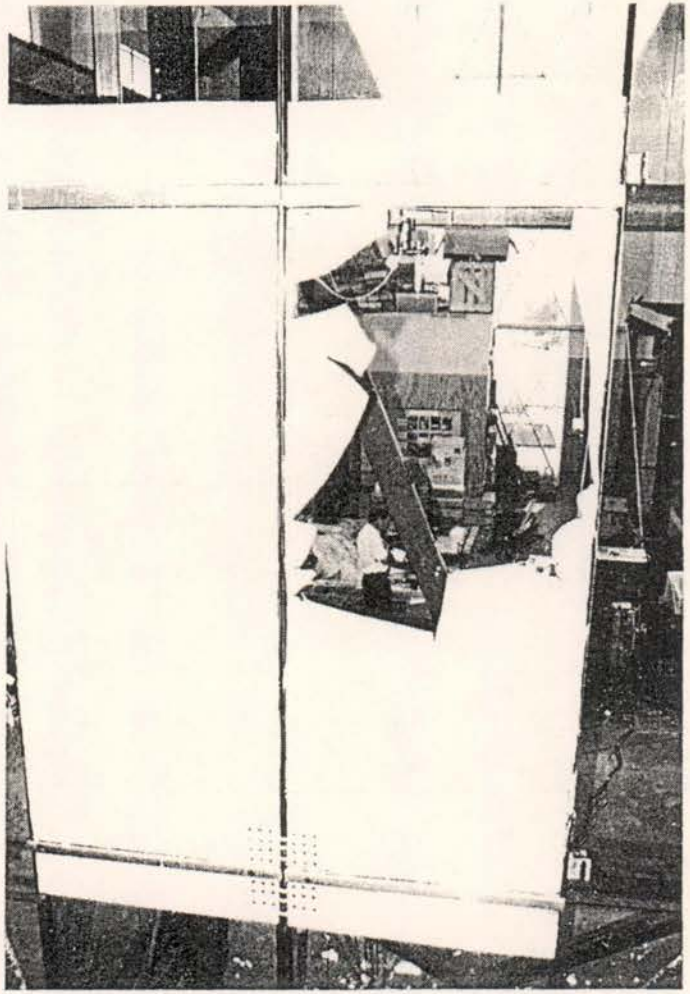
Gauges 1,3,7	Vertical movement of mullion relative to UB
Gauges 2,4	Horizontal slip of transom relative to UB
Gauges 6	Vertical slip between transom
Gauges 5	Vertical movement of mullion relative to sill for applied 10,20,30 mm. Subsequently relative to UB.

UB: Steel support beam shown in figure 3b

Figure 20 Type 3 Instrumentation (Wall S2)



(a) Cracking of glass after 3 cycles to ± 80mm



(b) Glass after 3 cycles to ± 100mm

Figure 21 Failure mechanism S2 Curtain wall

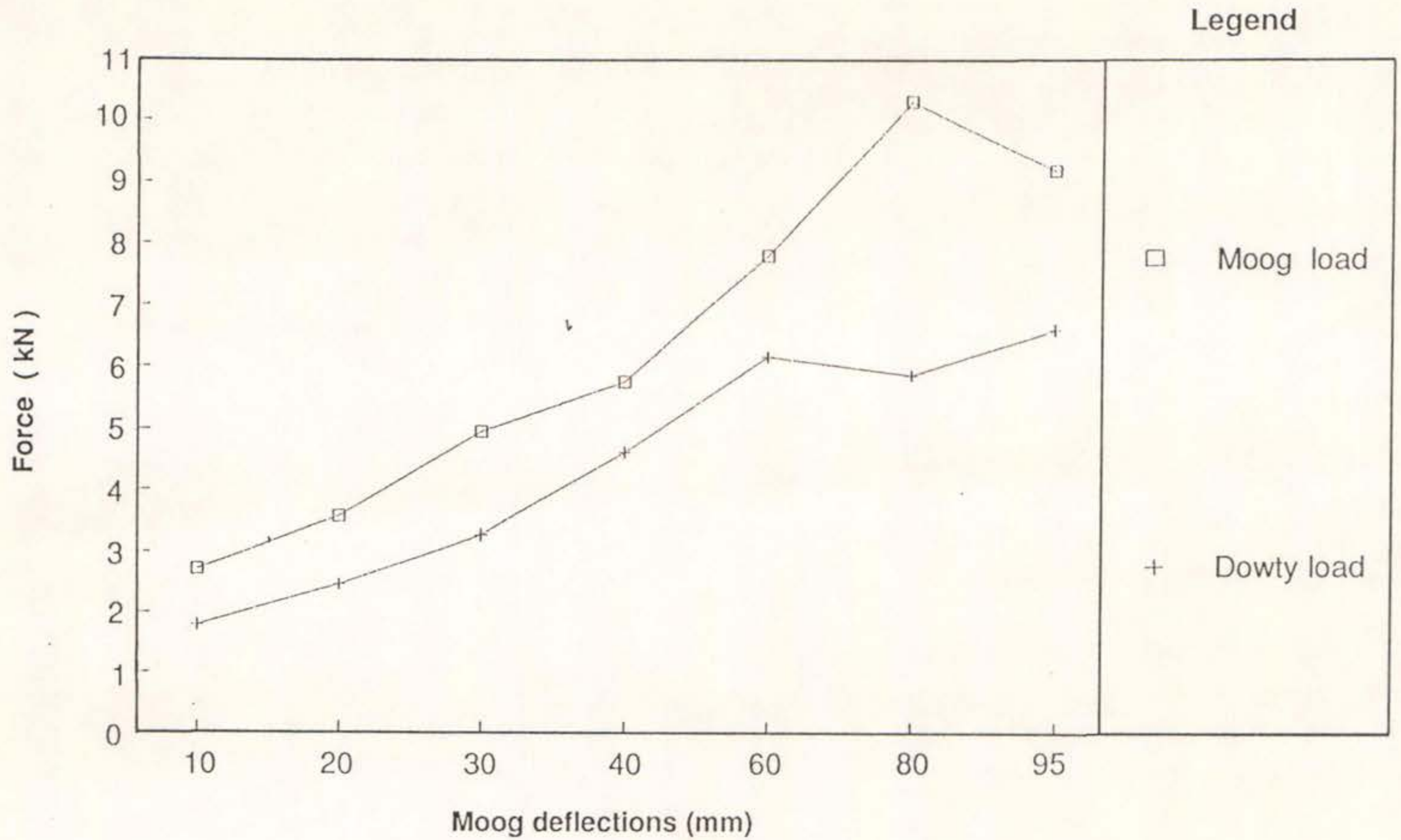


Figure 22 Peak actuator loads versus Moog deflection (Wall S2)

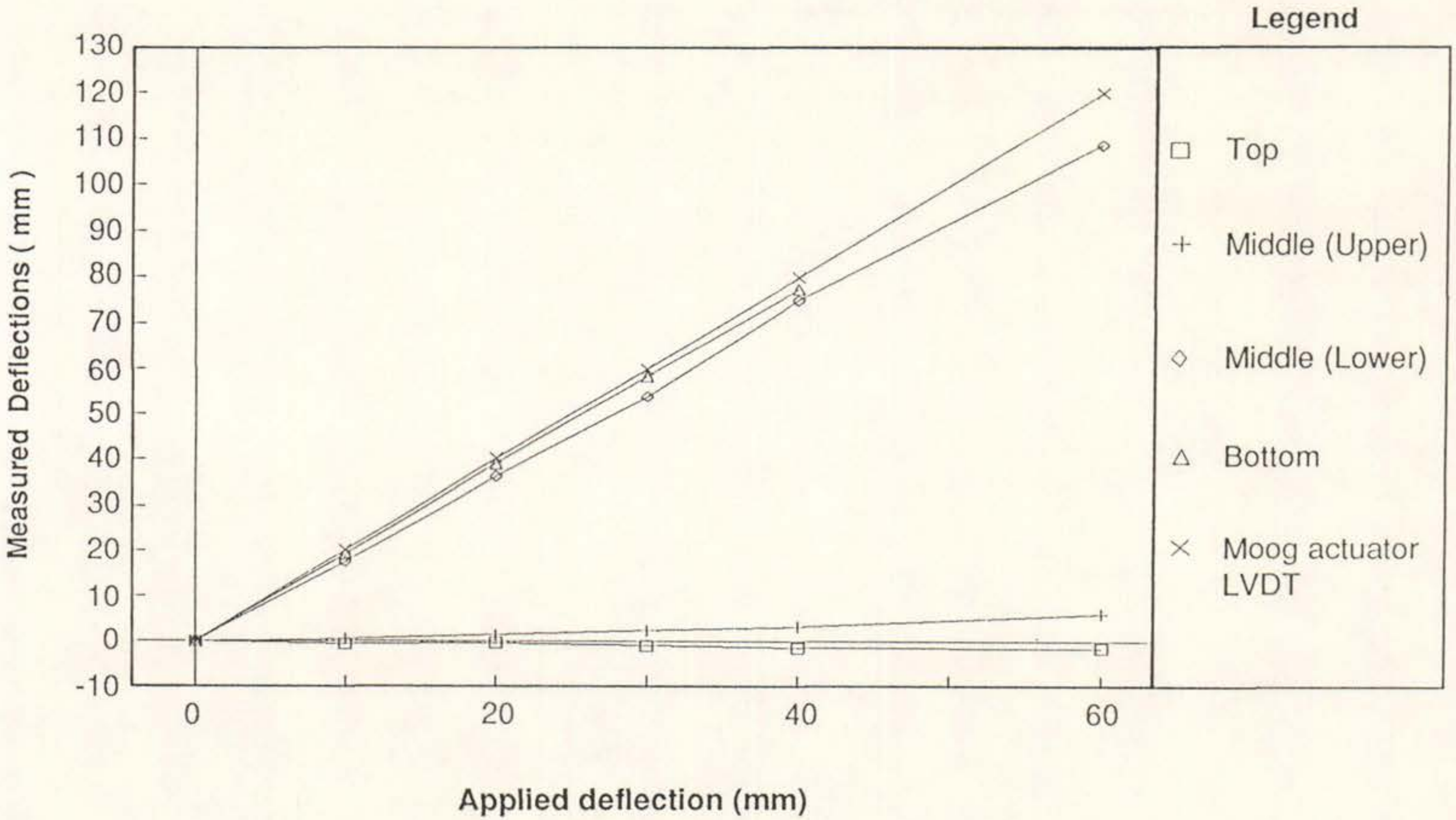


Figure 23 Gross deflection Moog direction (Wall S2)

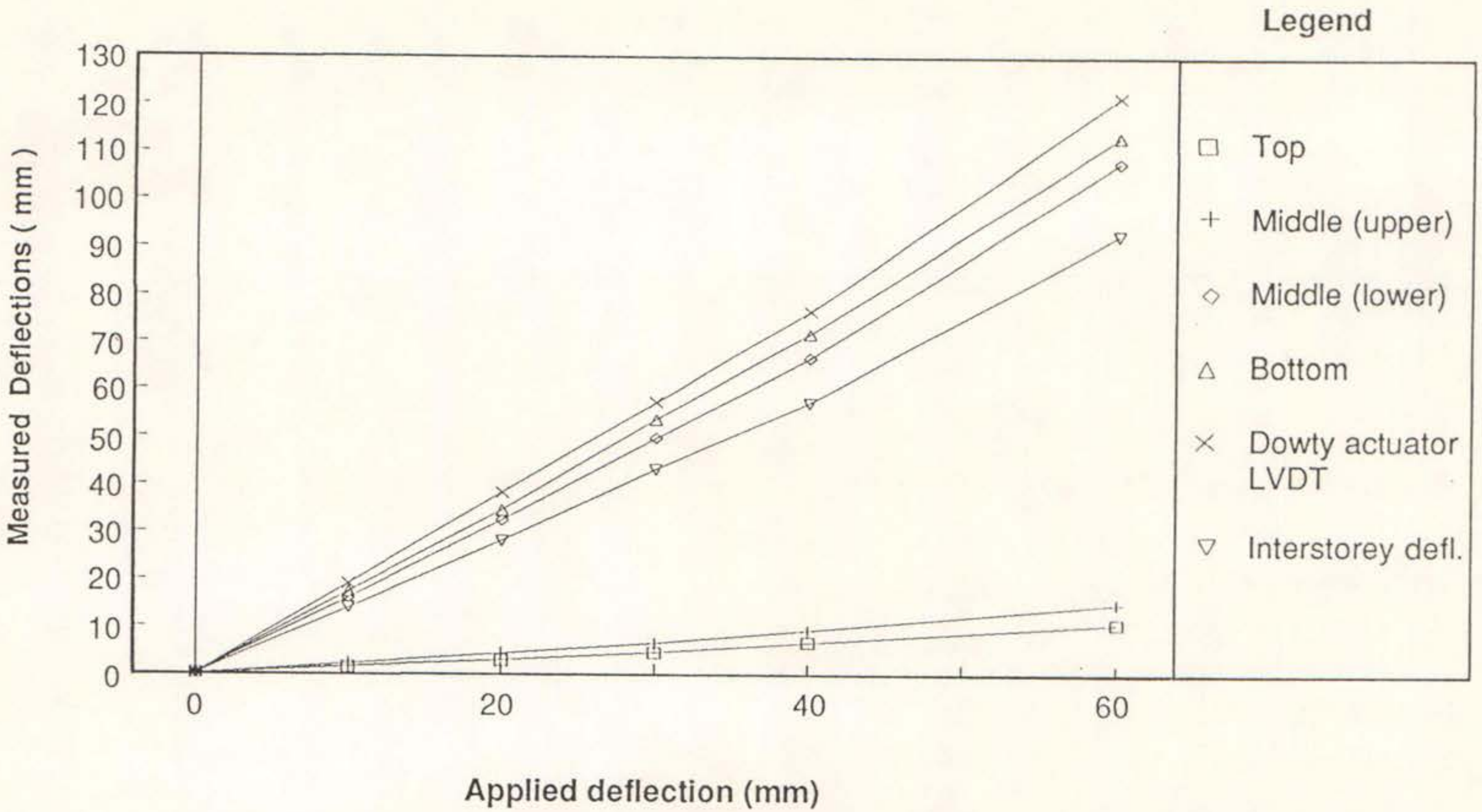


Figure 24 Gross deflection Dowty direction (Wall S2)

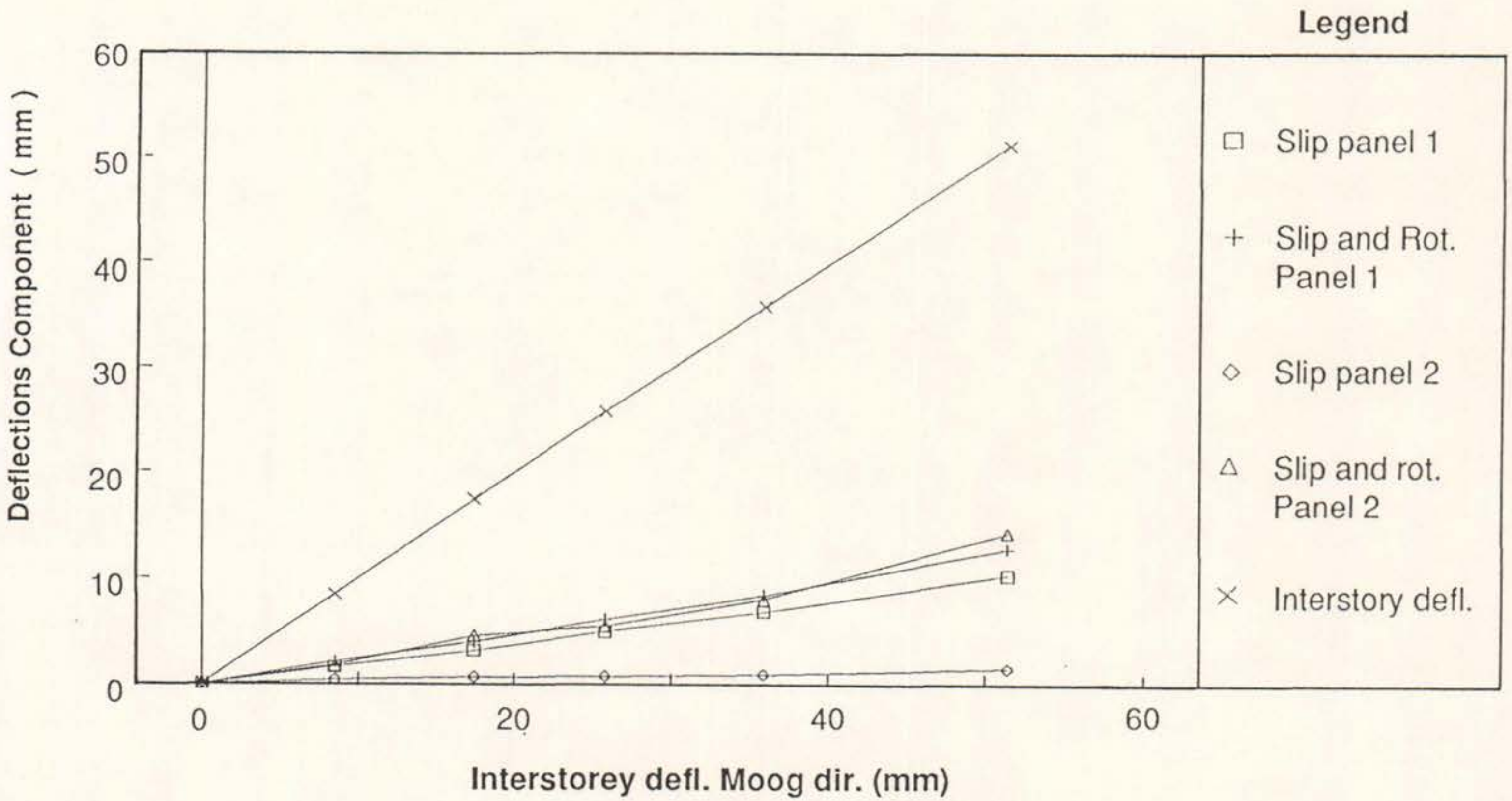


Figure 25 Deflection due to glass movement in silicone sealant (Wall S2)

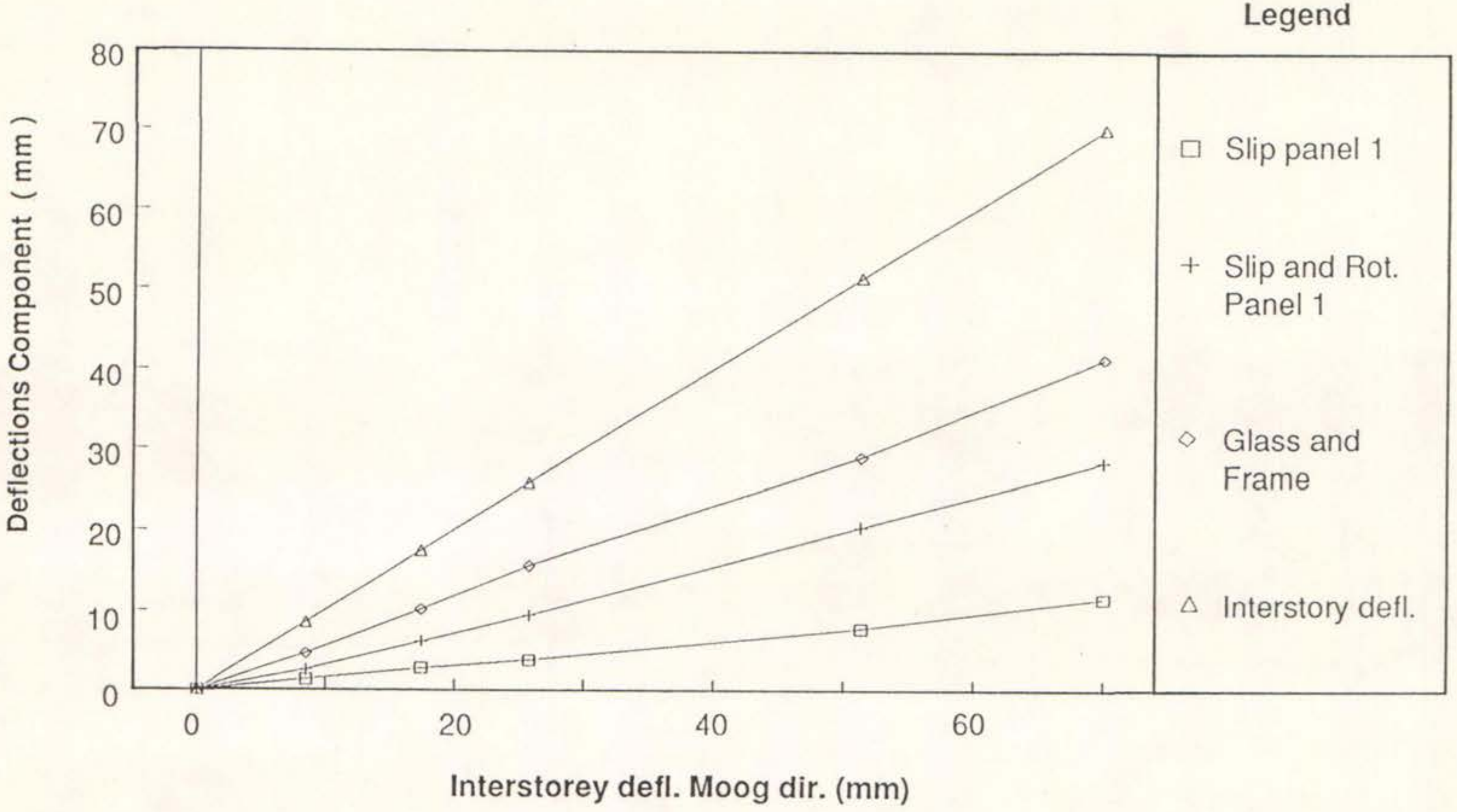
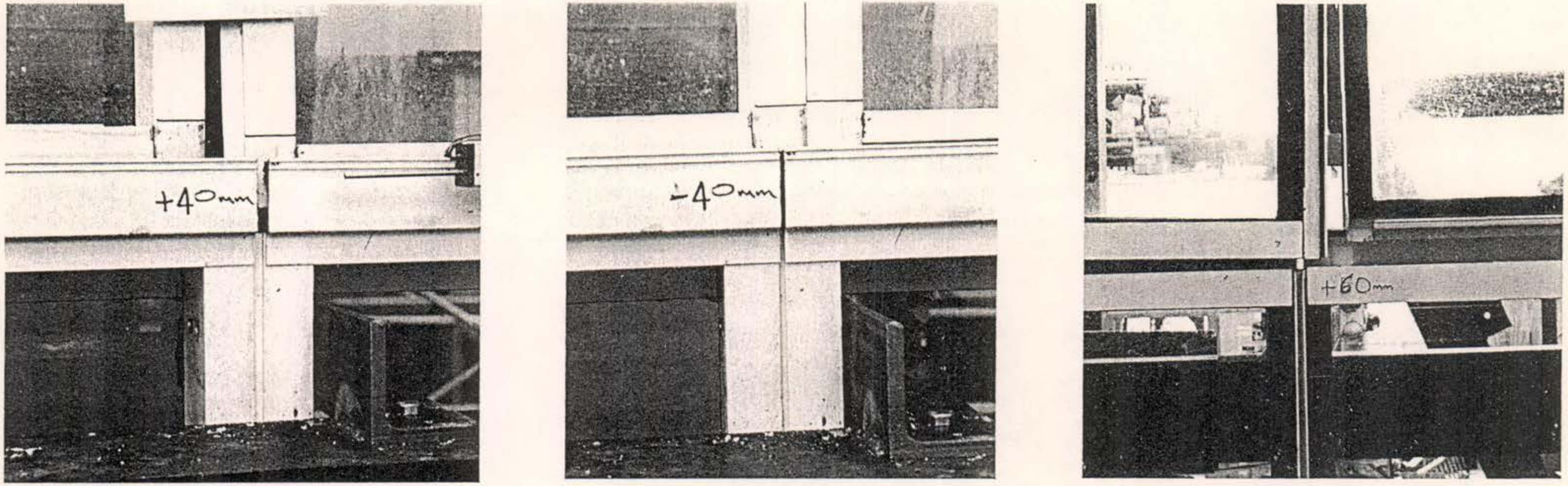


Figure 26 Deflection due to glass movement and frame movement (Wall S2)

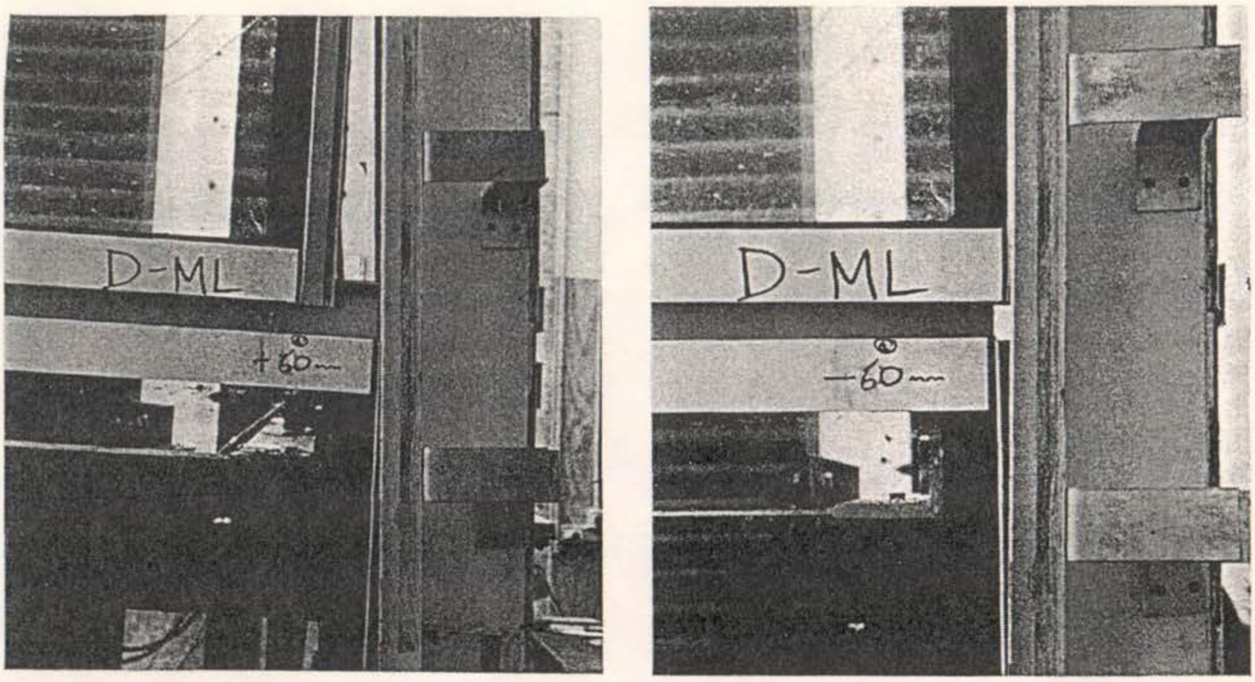


(a) Inside view - push

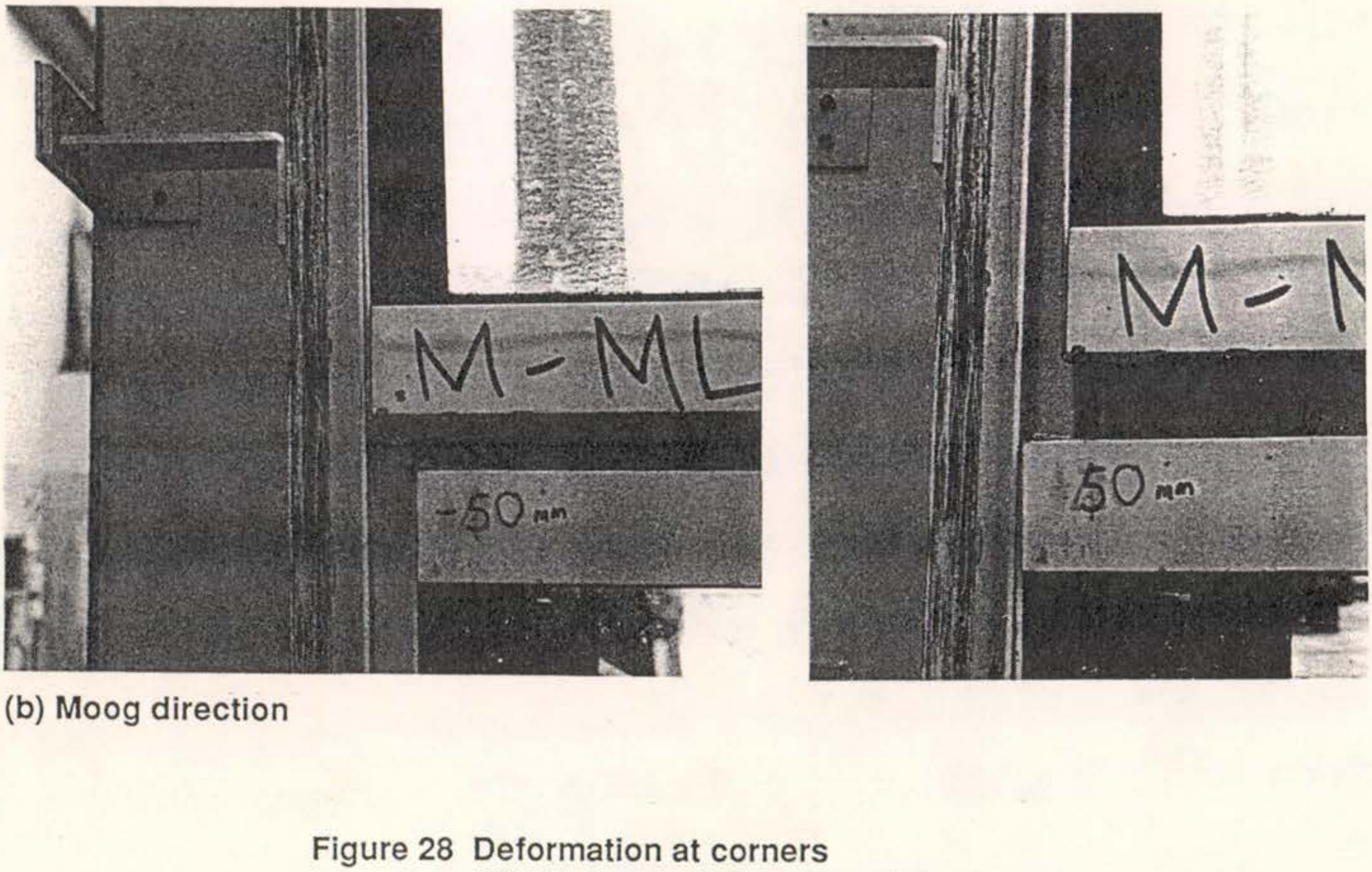
(b) Inside view - pull

(c) Outside view - push

Figure 27 Distortion at junction of panels (Wall S4)
7,8,11,12 (see figure 1)

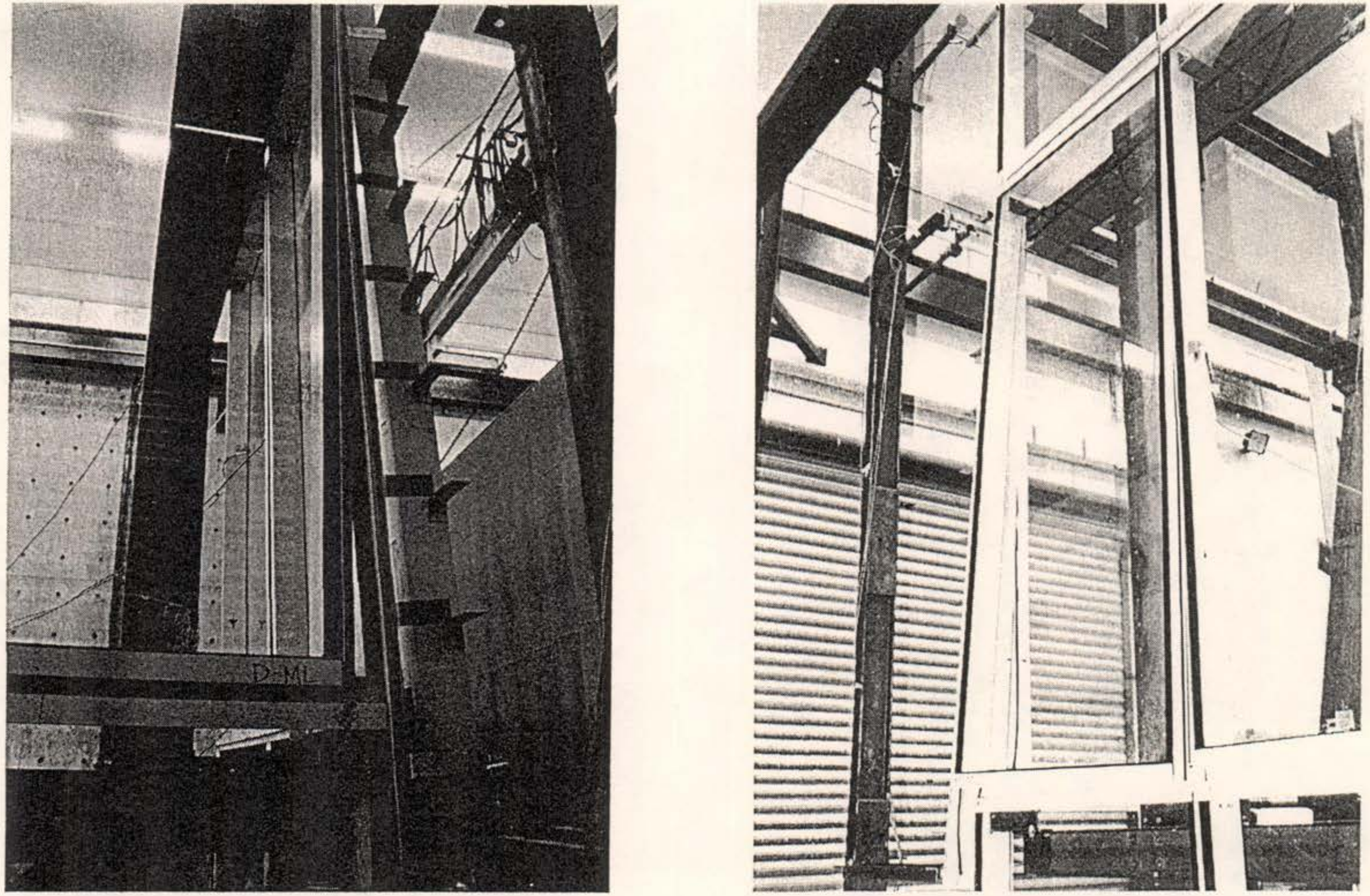


(a) Dowty direction



(b) Moog direction

Figure 28 Deformation at corners
(Photographs taken at peak push and pull direction Wall S4))

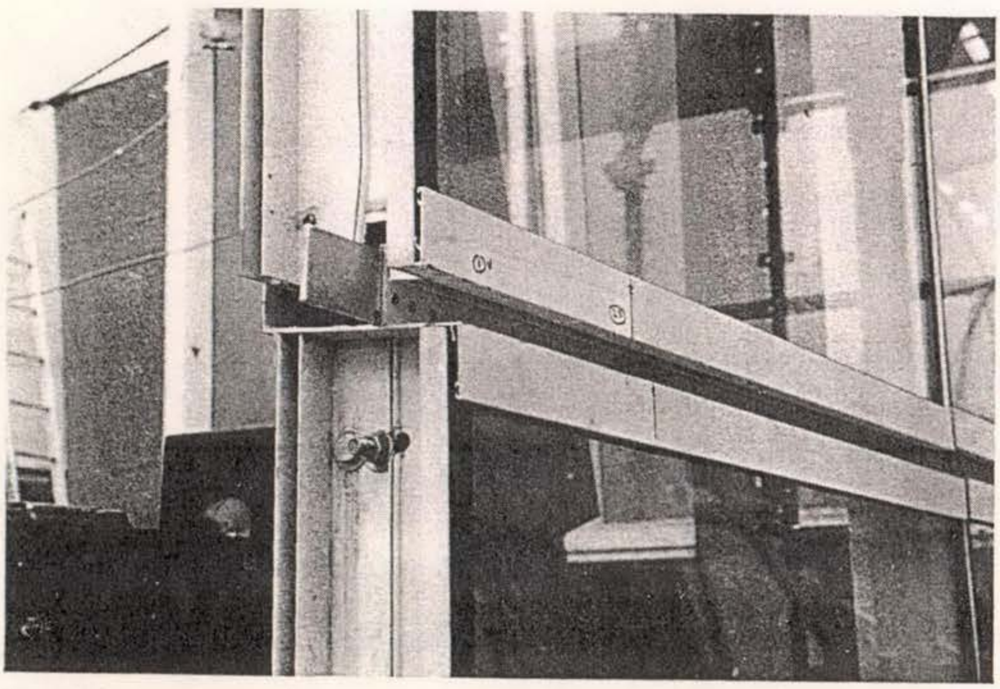


(a) Moog direction (100mm)

(b) Dowty direction (80mm)

Figure 29 General view of deformation mechanism (Wall S4)

(a) Panel 7 and 11 Wedged apart at the corner, as slotted mullion becomes misaligned with transom runners



(b) Runners extension

Figure 30 Potential for mis-alignment, transom runners and slotted mullions

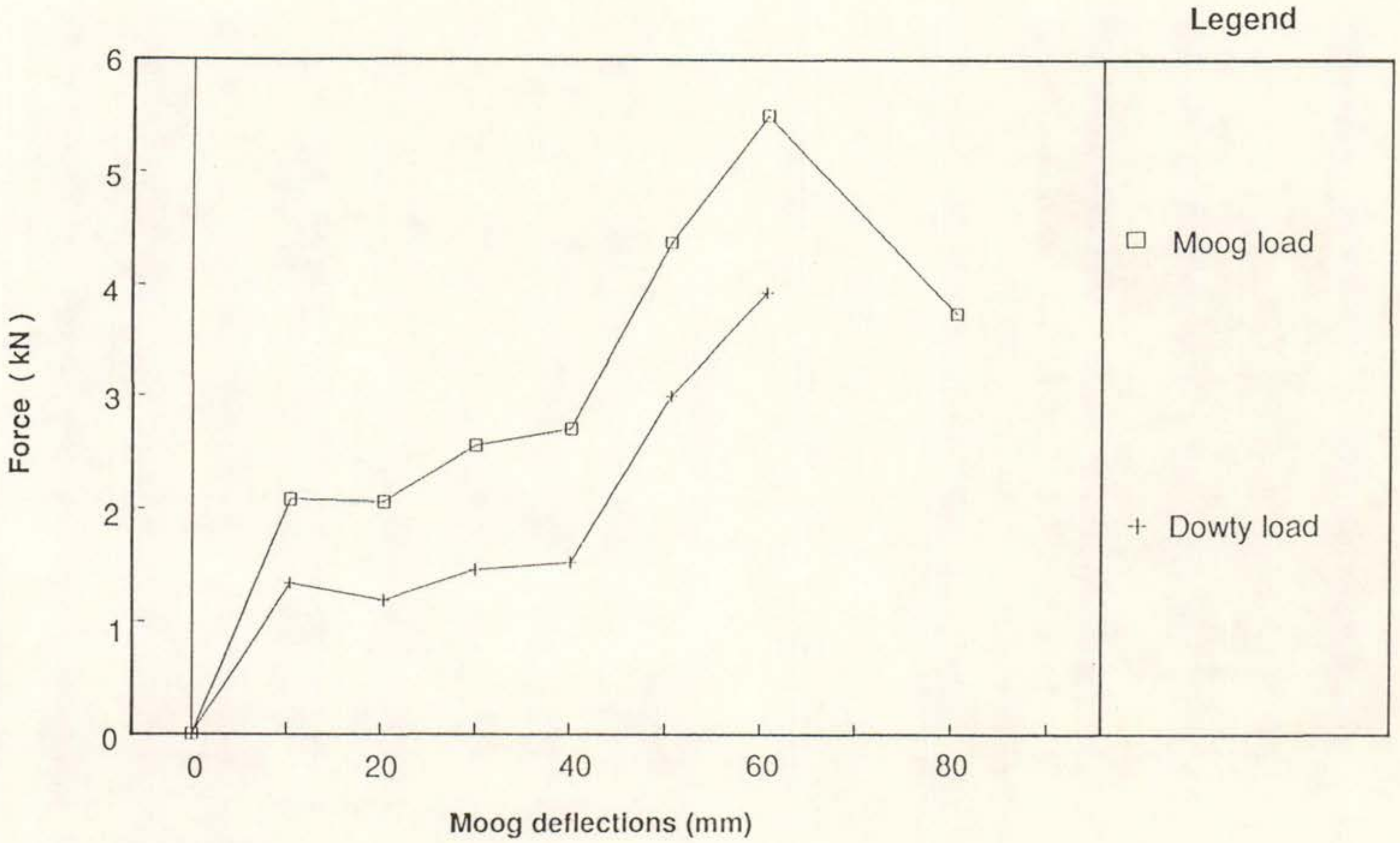


Figure 31 Peak actuator loads versus Moog deflection (WallS4)

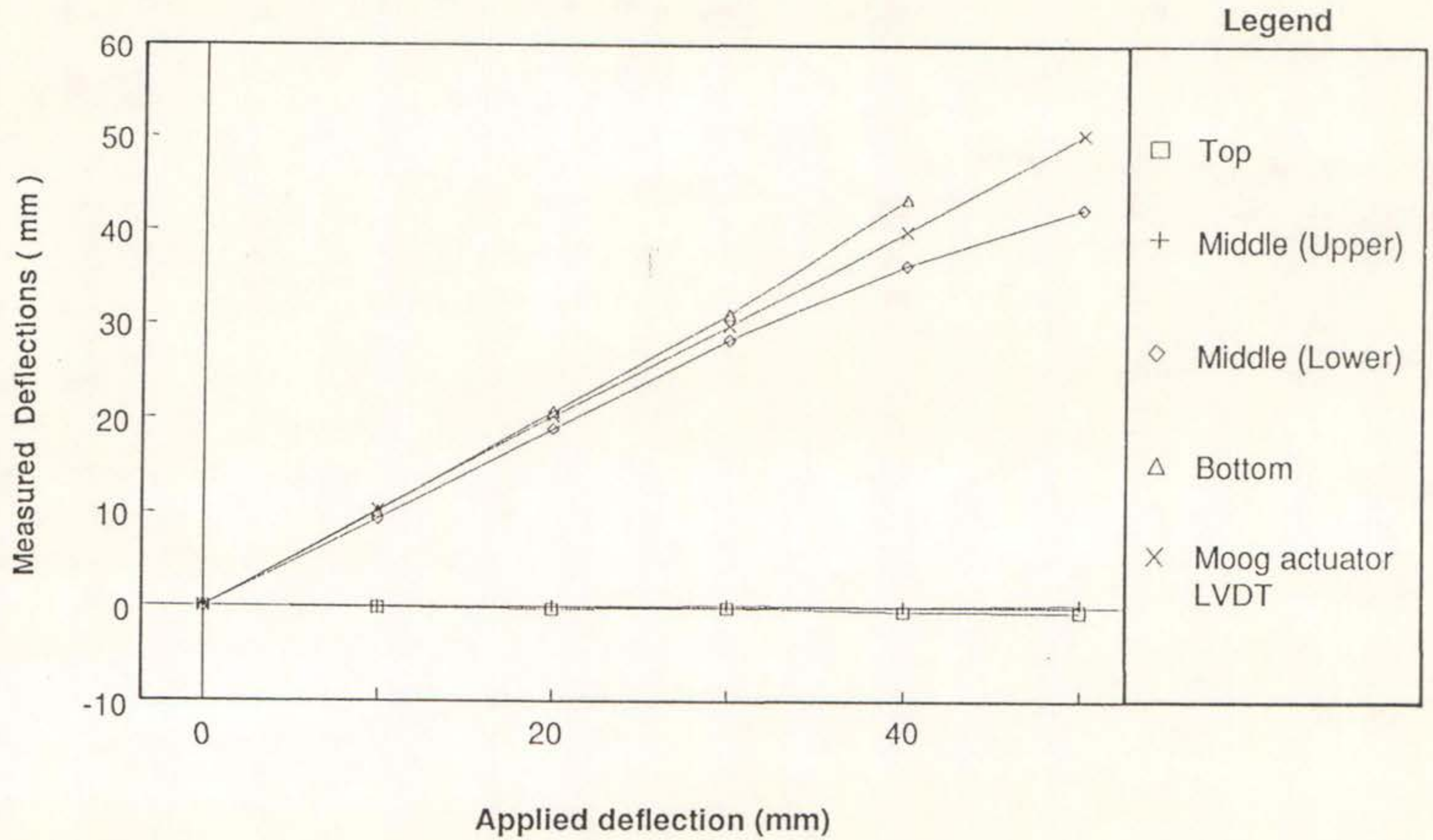


Figure 32 Gross deflection Moog direction (Wall S4)

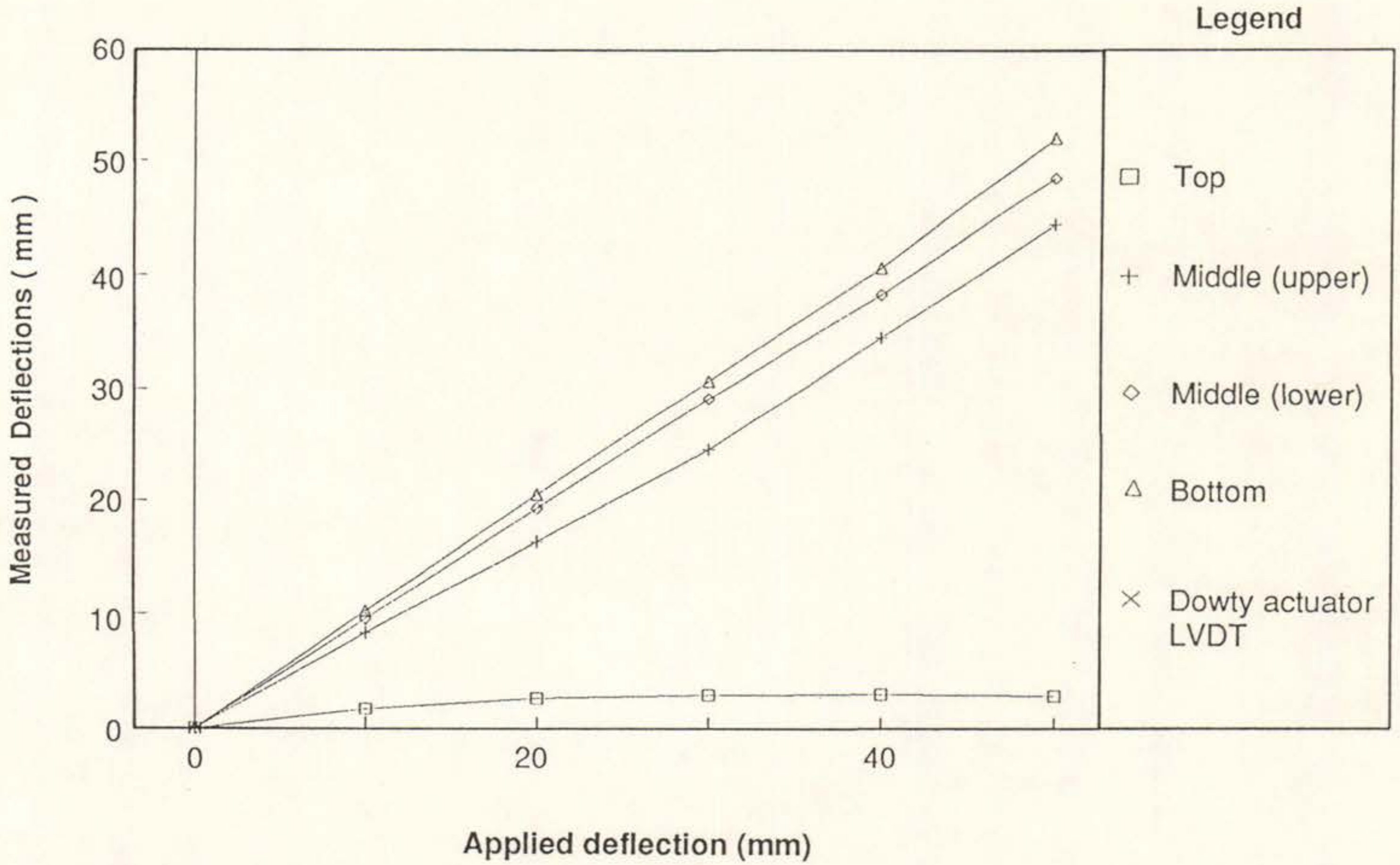


Figure 33 Gross deflection Dowty direction (Wall S4)

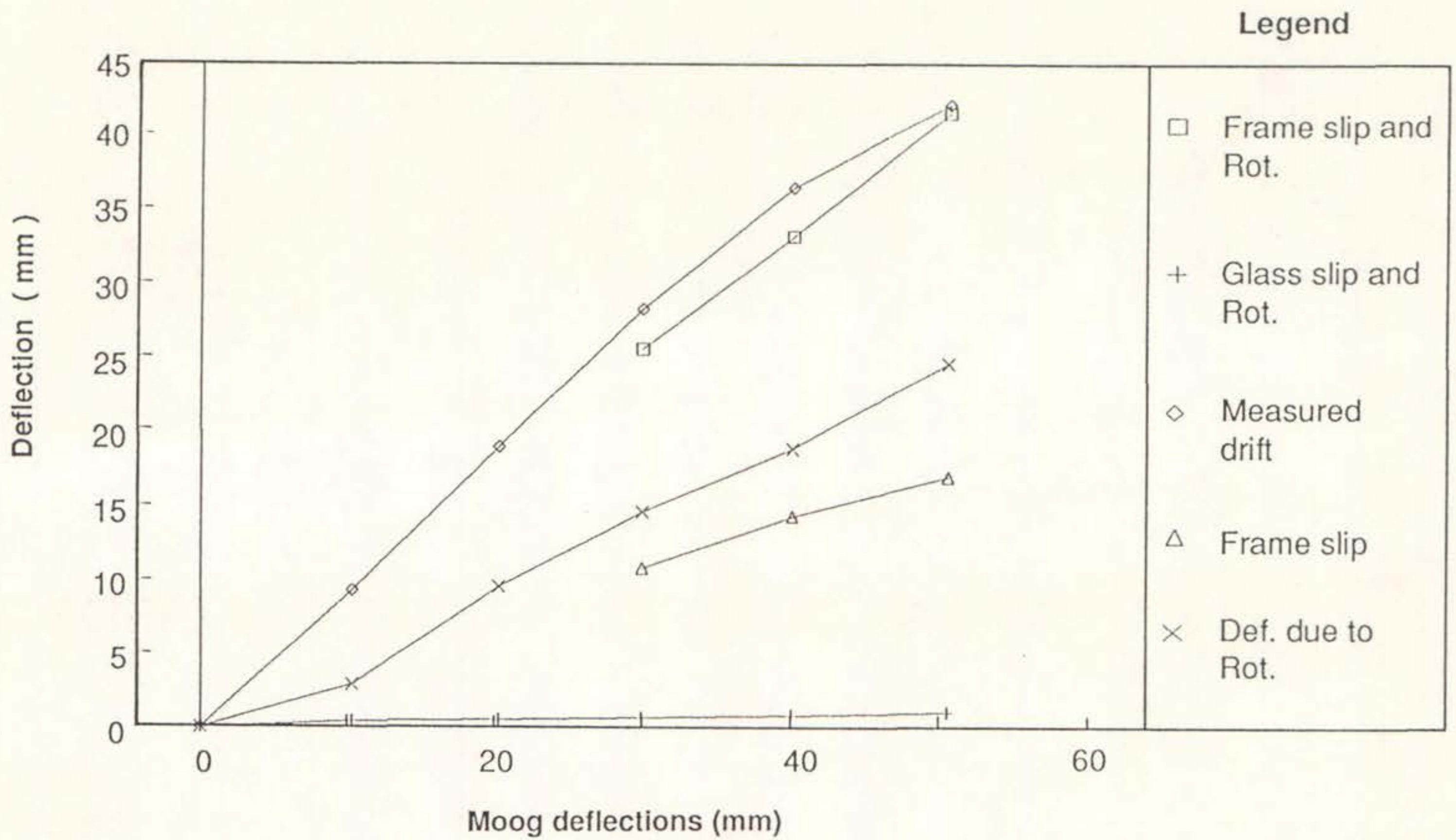


Figure 34 Components of applied deflection (WallS4)

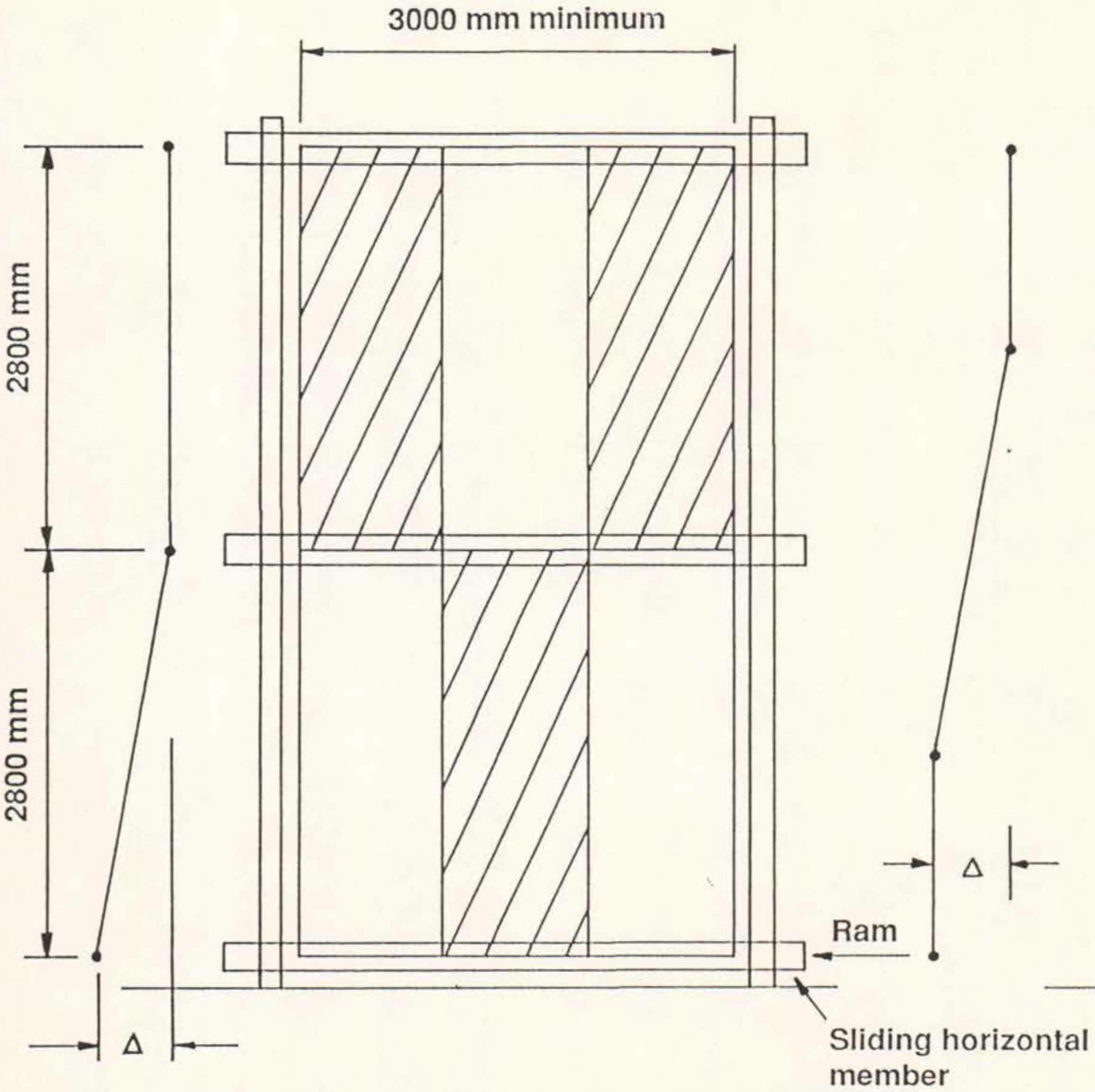


Figure A1 Double storey configuration (configuration "d")

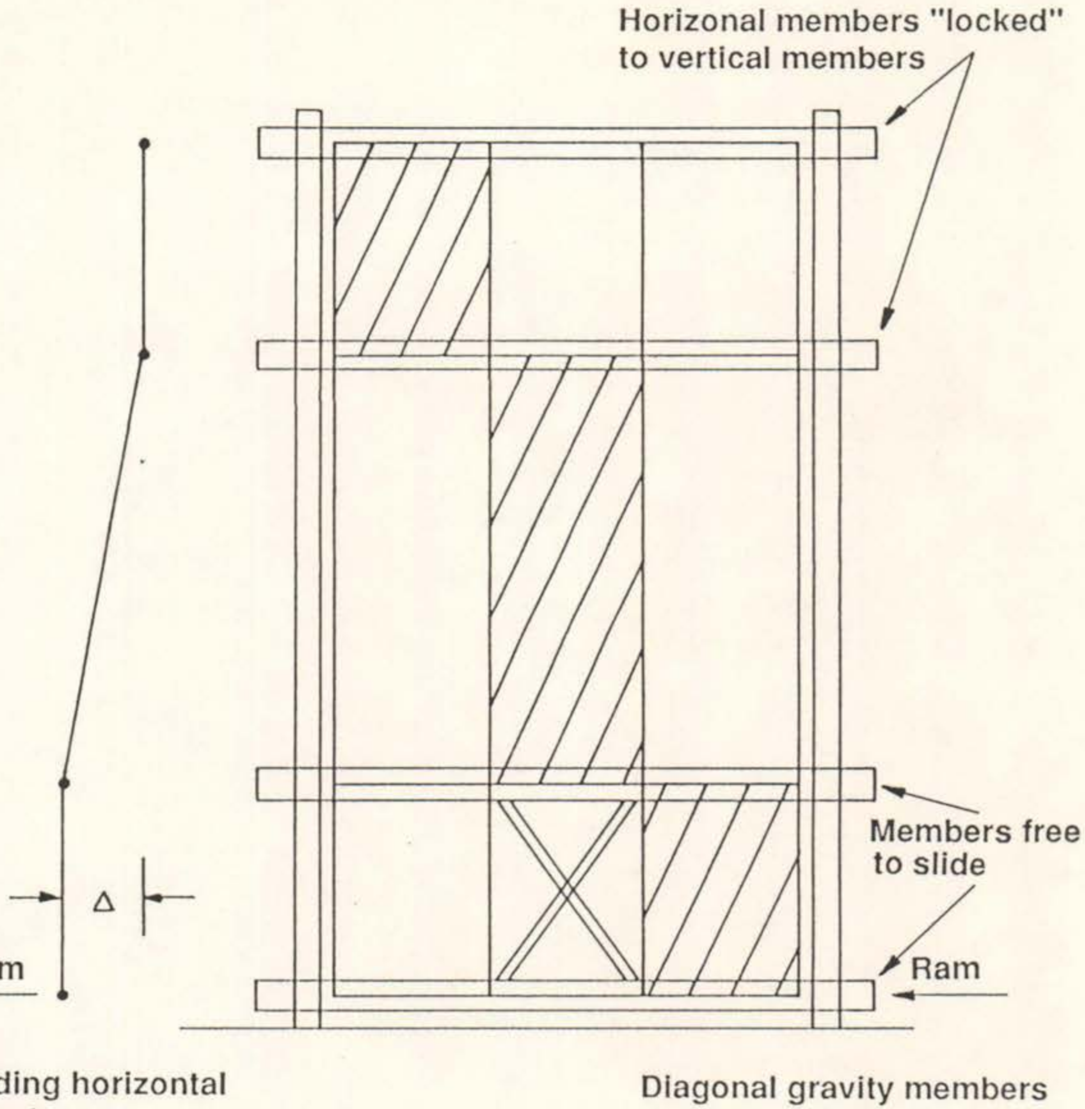


Figure A2 Single storey plus two half storeys configuration (configuration "s")

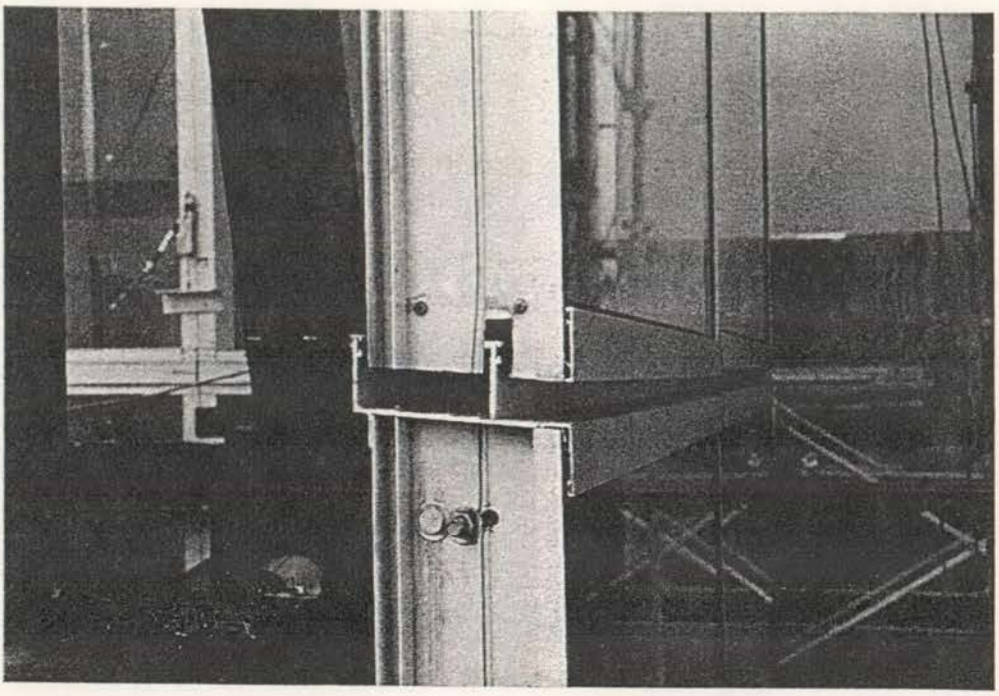


Figure A3 Typical free end of panel

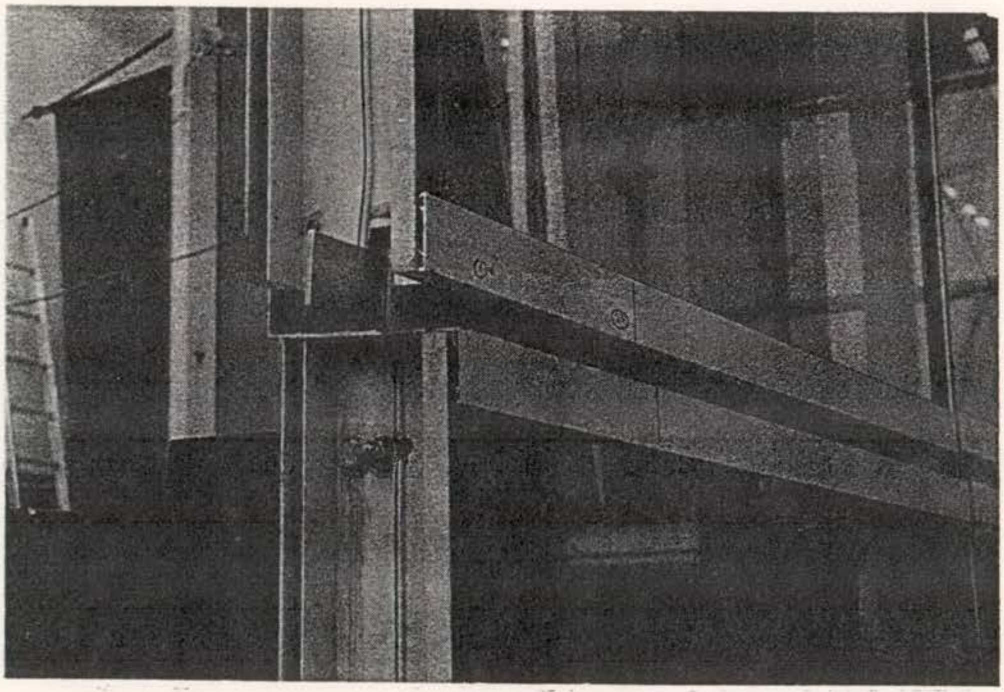


Figure A4 Method for preventing panel misalignment

TABLE 1: Gaps Between Glass and Framing at Large Window Nearest Column 1

Location	After 40 mm cycling (mm)	After resetting (mm)
a	15.5	17.5
b	26	20
c	11	11
d	14	10
e	13	19.5
f	25.5	23
g	28	26
h	30	28

Gauge Locations

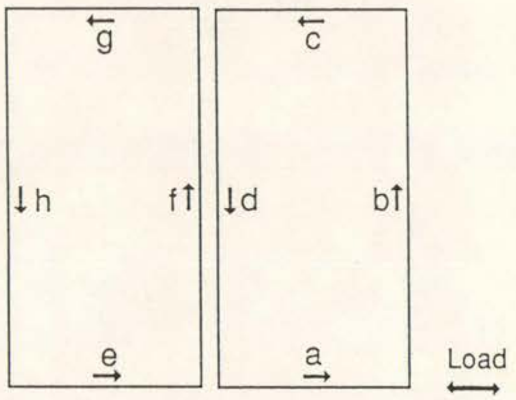


TABLE 2: Monitored Deflections From Gauges S2 Glazing Wall (Refer to Table 1 and Figure 20)

Gauge label	Dialled-up Moog Deflection (mm)						
	10	20	30	40	60	80	100
a	0.70	1.34	2.17	2.91	4.43		
b	0.12	0.19	0.26	0.36	0.56		
c	0.89	1.84	2.83	4.05	5.96		
d	0.09	0.15	0.23	0.29	0.45		
e	0.41	0.83	0.77	1.06	2.05		
f	0.31	0.57	0.55	0.69	1.16		
g	0.15	0.79	1.21	1.93	3.26		
h	0.24	0.42	0.45	0.59	0.99		
1	0.29	1.09	2.05		4.53	5.76	2.31*
2	0.16	0.24	0.15		0.34	0.70	1.30*
3	0.95	1.20	1.60		3.26	4.07	0.82*
4	1.13	2.45	3.58		7.47	10.87	5.71*
5	0.98	1.90	2.85		10.03	11.41	12.33
6	0.32	0.60	0.99		2.97	2.74	2.59
7	0.46	1.14	1.90		3.82		

* = Non-sinusoidal trace output. Value unreliable

TABLE 3: **Test Regime Wall S4**

Loading No.	MOOG displacement (mm)	DOWTY displacement (mm)	Frequency (Hertz)	Number of cycles
1	±10	±10	1.0	6
2	±10	±20	1.0	3
3	±30	±30	1.0	3
4	±40	±40	1.0	3
5	±40	40*	1.0	3
6	±50	±50	0.5	3
7	±50	50*	0.5	3
8	±60	±60	0.5	3
9	±60	60*	0.5	3
10	±80	80*	0.5	6
11	±100	80*	0.5	30

* = statically pushed and held at this displacement.

THE RESOURCE CENTRE FOR BUILDING EXCELLENCE

BRANZ MISSION

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