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The racking behaviour of curtain wall glazing during simulated earthquake

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ABSTRACT: This paper reviews a three year research programme which focused on assessing the behaviour of curtain wall glazing systems when subjected to simulated interstorey drift as may be expected to occur during the response of multi-storey buildings to earthquake attack. The paper reviews the laboratory testing programme undertaken which examined the behaviour of several different types of curtain wall glazing which were subjected to racking actions. Both planar specimens and two-dimensional (corner) specimens were tested. Recommendations are made as to laboratory test methods which could be used to assess the behaviour of curtain wall systems to be erected in earthquake prone areas.

1 BACKGROUND

This project evolved following public concern about the safety of four-sided silicone curtain wall glazing systems during earthquakes. The scope of the project was expanded to include various other types of curtain wall glazing for comparison.

The project has been undertaken in three phases. The first involved a review of overseas practices with regard to the behaviour of such systems during earthquakes and the formulation of a proposed method of test. The findings were published by Wright (1989). The second phase involved fabricating a full-scale mock exterior wall in the laboratory, cladding this with different types of curtain wall glazing, and subjecting each to interstorey displacements simulating the response of buildings to earthquake attack. The project was extended to a third phase with the fabrication of several mock "corner" specimens, with two sliding frames simulating in-plane distortion in two orthogonal directions.

A standard laboratory test method and evaluation procedure is being prepared based upon the findings from the research undertaken. This will enable the ability of specific curtain wall glazing systems to withstand given interstorey displacements to be assessed within the laboratory.

2 THE EXPERIMENTAL PROGRAMME

2.1 Glazing Systems Investigated

Four generic types of glazing systems were subjected to in-plane racking testing and are considered in this paper.

1. neoprene gasket dry-glazed systems

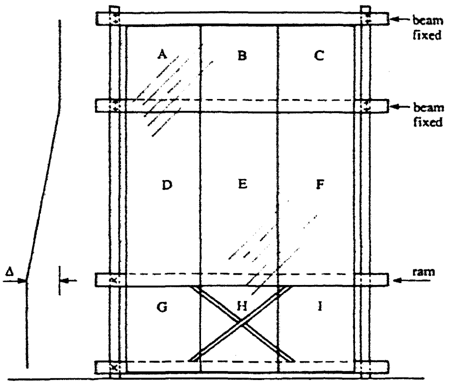

Figure 1: Single storey specimen with zero adjacent interstorey drift (configuration zs).

2. unitised 4-sided structural silicone glazed systems,
3. a two-sided silicone glazed system
4. mechanically fixed patch plate systems (with toughened glass)

2.2 Parameters Considered

1. Specimen Configuration: The planar test rig was able to accept specimens up to 3.6 m in length, having either a two storey configuration (identified as "d") or a single storey with two half storeys (identified as "s"). Corner specimens were 2.4 m in each wall plane, and of an "s" configuration.

2. Displacement Profiles: The test rig was designed to induce the nominated interstorey displacement over the height of the test panels and either zero displacement

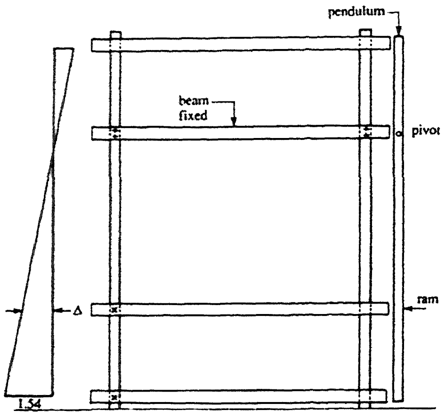

Figure 2: Single storey specimen with full adjacent interstorey drift (configuration fs).

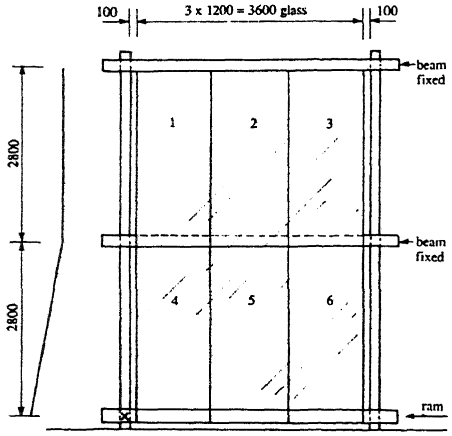

Figure 3: Double storey specimen with zero adjacent interstorey drift (configuration zd).

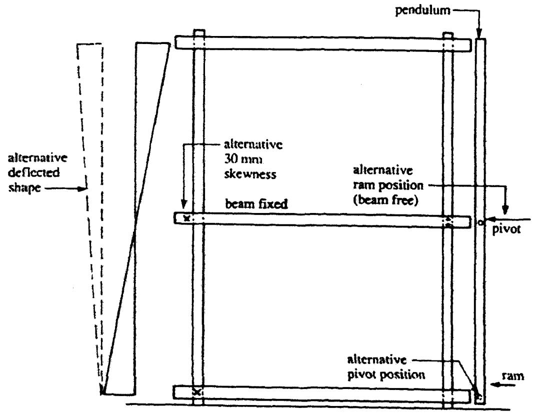

Figure 4: Double storey specimen with full adjacent interstorey drift (configuration zf).

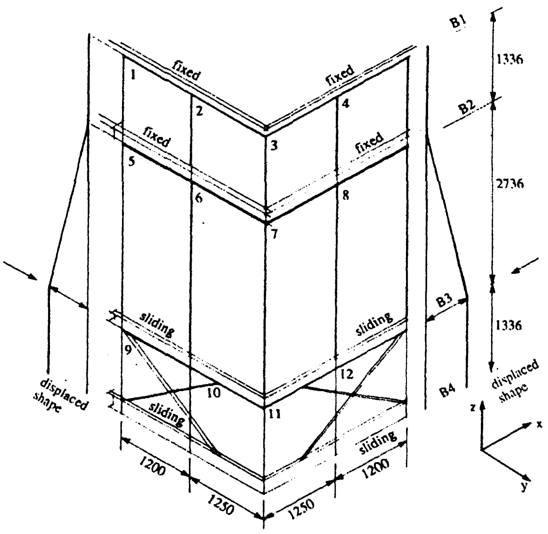

Figure 5: Corner specimen with zero adjacent interstorey drift (configuration cf).

over adjacent panels (identified as profile "z") or equal displacements in adjacent panels (i.e., a linear profile - identified as profile "f")

(Note: the displacement profile and specimen configuration are detailed in figures 1 to 5).

3. The effect of different rates of racking displacement
4. An indication of the effect of out-of-plane skewness.

2.3 Failure criterion

Failure was deemed to occur when in excess of 5% of the mass of glass supported in any frame fell from that frame. At this juncture it was considered that falling glass would significantly increase the risk of injury to people in and around the building.

2.4 Test Procedure

The procedure involved cyclically displacing the "floor" beam (sliding steel beams) to a designated displacement at a uniform displacement rate, and to repeatedly cycle to this nominated peak displacement as required. The peak displacement was increased by the appropriate increment, and the procedure repeated. Movement was initiated using hydraulic actuator operating under displacement control. A second actuator was introduced during testing of the corner specimens.

Both the dry glazed and the 4-sided silicone systems were tested in each configuration and subjected to both displacement profiles as planar specimens. They were also tested as corner elements.

Different two-sided silicone system was tested in configuration "s" with displacement profile "z" in the planar and the corner rig.

The patch plate system, glazed with 6 mm toughened glass, was tested in all configurations and subjected to both displacement profiles, but was limited to only the planar rig.

3 OBSERVATIONS AND RESULTS

3.1 General

All systems tested proved to be considerably more resilient to interstorey displacements than had been anticipated. One of two mechanisms developed in all cases; either pane rotation within skewed frames (sometimes accompanied by mullion twisting), or a slip plane developed enabling frames to slide relative to each other.

The results of the planar testing are published by Lim and King (2). A summary of these is listed in Table 1. The several instances where glass fracture did not occur are noted as "No failure".

3.2 Gasket Glazed System

Interstorey displacements in excess of 100 mm (0.04 H) were achieved without failure in all configurations. The panes were observed first to rotate within their frames (the glass was installed on neoprene packing blocks and had a clearance of 17mm clearance before coming into contact with the frame). The aspect ratio of the panes tested was approximately 2.3:1. It was calculated that, for this geometry and clearance, contact between glass and framed would occur at an interstorey drift of approximately 140 mm with the presence of the spacer blocks being ignored.

The gaskets were observed to work loose from the frame during repeated cycling in excess of 15 mm interstorey drift. The onset of such behaviour appeared to be a function of the number of displacement reversals. When this occurred during the early stages of the test, the test was stopped and the gaskets re-instated. Once displacements exceeded 60 mm, gasket extraction was ignored and the incremental displacement continued until failure.

Failure occurred during the 120 mm and 100 mm peak amplitude cycling for the single and double configurations respectively were achieved without failure. In each case it was preceded by the loss of the gasket and the subsequent clashing of the glass and mullion because of misalignment. The glass typically developed a "scallop shaped" crack in one corner, which rapidly developed into multiple cracks and eventual (typically after a further one to three displacement exertions) the glass fell from the frame.

The corner specimen demonstrated similar pane rotation. Failure occurred in the corner pane (pane 7 in figure 5) at an in-plane interstorey displacement of 85 mm. Prior to this, the corner mullion cover plate separated and fell from the system. This is a light component and its detachment was not considered to create significant additional hazard and therefore did not fulfil the failure criteria (indicated above). One significant difference observed between the planar and corner specimens, was that in the former tests, significant twisting along the axis of the mullion was noted. This was caused by eccentricities between the "floor" and the plane of the glass (over a distance of 125 mm). Such twisting was measured as amounting to up to 40 mm of the induced peak displacement. This action was not present in the corner specimen because of the connections of the framing members at the corner mullion.

3.3 Patch Fitting System

The patch plates tested were detailed to allow joint rotation in an attempt to alleviate localised stress concentrations anticipated at the connection points. The detail involved a combination of rotating and sliding mechanisms being incorporated into the patch fitting. While these mechanisms were observed, failure of the toughened glass occurred when the mechanism had displaced to but half of the available movement potential of the fixing. Furthermore, when constrained to distort in the "z" displacement profile, back plate rotation (which had been identified as one of the secondary displacement mechanisms) was prevented at the quadruple patch fitting. Failure occurred at an interstorey displacement of 40 mm (0.012 H). Scrutiny of slow-motion video replays of the failure, identified that failure was typically initiate at one fixing points. The toughened glass shatter pattern rapidly spread across the panel. The glass mass was observed to fall from the frame in coherent fragments assessed to measure 0.5 m by 0.9 m, which shattered onto small (10 x 10 mm) glass granules on impact with the floor.

3.4 Two-Sided Silicone System - Planar specimen

Different systems were used for the planar test specimen and the corner specimen. The planar system was factory assembled and involve structural silicone joints between each glass pane and the supporting mullion. The mullion was formed from an "I" shaped aluminium section on to which an aluminium box section "glazing bar" was fixed using stainless steel screws. Transom support was by conventional entrapment of the glass into a aluminium "T " section with support by dry- glazing (neoprene gasket) techniques.

At 25 mm, the glass was observed to distort the silicone joint relative to the mullions characteristic of vertical shear along this joint. The mullions were observed rotate about their splice points (at h/4 within the test panel).

At peak displacements of 60mm, the screws fastening the glazing bar to the mullion failed, some in shear and others by head pull-through after which the glazing panels were free to slide over the face of the mullion while remaining entrapped by the transom. Once screw fracture had occurred, the resistance to displacement dropped markedly and the glass slid within the transom. Glass failure could not be initiated.

Table 1. Summary of Planar Specimen Results

Test	Peak Load (kN)	Max. interstorey displacement (mm)	Failure mode
Gasket system Config "s" Profile "f"	16	120	Glass fracture Following pane rotation
Gasket system Config "s" Profile "f"	14	100	Glass fracture to Following pane rotation
Patch plates Config "s" Profile "z"	17.5	40	Toughened pane shattered
Patch plates Config "s" Profile "f"	11	60	Toughened pane shattered
2-sided silicone Config "s" Profile "f"	12	120	No failure; sub-mullion slip
4-sided silicone Config "s" Profile "f"	15	80	Glass cracked but did not fall Severe frame distortion at slip pane
4-sided silicone Config "d" Profile "f"	10	90	No failure; severe frame distortion at slip plane

3.5 Two-sided Silicone System - Corner Specimen

The corner specimen was unitised (factory installed into aluminium frames which mechanically interlocked on site). Structural silicone was used to adhere the glass to the mullions. The transom/glass connection maintained a mechanical entrapment with neoprene gasket seals. Both mullion and transom interlocked with their respective neighbours each with p.v.c. strip seals providing appropriate weather seals within the interlocking aluminium sections.

Little movement was observed between the glass and frame when compared to the dry-glazed system. Most movement was accommodated by rotation of the complete unitised frame, and by relaxation of the frame to "floor" connections. The frame rotation was particularly dominant in each corner pane (panes 6 and 7 of figure 5). Such rotational freedom is thought to have minimised internal stresses within these panes.

An initial crack was observed to develop in panel 8 (refer figure 5) at an interstorey displacement of 80 mm. A substantial portion of glass fell from this frame during the subsequent 100 mm interstorey displacement cycle.

3.6 Unitised Four-Sided Silicone System

The four-sided silicone panels were subjected to displacements in excess 80 mm (0.03H) without "failure". The shear distortion was accommodated by a combination of slip between the units, and relaxation of the support brackets. At high drift levels, the complete panels were observed to rotate (being eccentrically supported) at which stage the panels disengaged from each other (Figure 6). One of the glass panes developed a diagonal crack (within the upper half of the panel) as a result of out-of-plane distortion which occurred following this disengagement. The glass remained attached to the frame through the silicone and therefore did not fulfil the "failure" criteria.

4 DISCUSSION

4.1 Corner Effects

The behaviour of the corner specimens was consistent with that observed for compatible planar systems except that the development of slip lines was inhibited by the two-way action required at the corners. It is reasonable to limit the standard test regime to planar systems only, while intentionally restricting any such slip development.

4.2 *Specimen Configuration*

The single storey (with two half storey) configuration most appropriately simulated actual building response, and, when accompanied by the most severe limit of zero displacement of of adjacent storeys, resulted in the most severe distortion of the test panels. This configuration along will be sufficient for any standard laboratory test method.

4.3 *Displacement Rate*

The rate of loading was only significant when very slow. This was particularly significant a friction mechanism developed. Displacement rates greater than 5 mm/sec are sufficient to overcome this variation and gave consistent results.

4.4 *Effect of Skewness*

It was recognised that the use of a static skew, such as the packer used in this series of test, simplified the effect of out of plane motion to the extreme. Such simplicity was necessary because of the modelling constraints under which the systems was tested. Within these limitations however, it was predicted that out-of-plane distortion (twisting) had little effect on either the sustainable stress level or the behaviour of the panels. (Note further investigation into this issue is currently proceeding with the third phase of testing associated with the investigation into corner effects).

5 CONCLUSIONS

Some forms of curtain wall glazing systems are able to withstand very large interstorey in-plane shear displacements without damage.

This ability varies markedly with different types of systems. This ability may 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, require careful consideration.

Slow displacement rates should be avoided during racking tests of glass systems. However, provided the rate of displacement is moderate (> 10 mm/sec) the results are not sensitive to the rate of displacement.

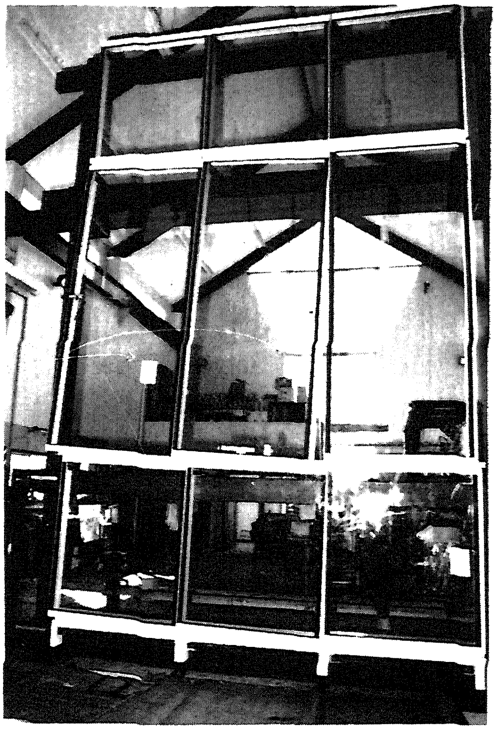

Figure 6: Four sided unitised panels.

6 ACKNOWLEDGEMENTS

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