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IN-PLANE/OUT-OF-PLANE DYNAMIC RACKING TESTS OF CURTAIN WALL GLASS ELEMENTS

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SUBMITTED TO:

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OURE GRANT PERSONNEL

ABSTRACT

This report describes a research project that was conducted to examine architectural glass behavior as curtain wall components subjected to earthquake-like dynamic motions. The project was an extension of an earlier pilot study conducted in 1991. The 1991 pilot study dealt only with dynamic racking of the curtain wall in its own plane.

The focus of this study was to investigate the effects of adding out-of-plane motions to the previous in-plane motions and to observe the resulting structural performance of various types of architectural glass. Thus, the curtain wall specimens in the current study were racked with motion components both perpendicular and parallel to the plane of the curtain wall. The current project, therefore, involved modification of the test facility to permit the coupled in-plane/out-of-plane dynamic motions.

After revision of the test facility, a series of experimental tests were conducted. The resulting data indicated that this new loading spectrum caused a substantially greater amount of glass breakage and subsequent glass fallout in most of the glass types that were found earlier to be prone to glass fallout.

INTRODUCTION

Glass elements in curtain wall systems are becoming an increasingly important feature in modern building design. A large number of tall buildings in the United States, especially those in large cities, have exterior walls and facades that are comprised predominantly of glass. These so-called "curtain wall systems" are generally considered to be non-load bearing, since they do not directly support the weight of the building. However, the notion that curtain walls are non-load bearing is misleading, since curtain walls must have the ability to resist loadings imposed by critical natural phenomena such as windstorms and earthquakes.

The current structural design practice for architectural glass, as specified in model building codes, is based on uniform lateral pressures meant to simulate wind effects, but little consideration is given to earthquake loadings. The current design practice is deficient when one considers the potentially devastating failures that earthquakes can induce in glass elements that compromise so much of the surface area of wall systems on multi-story buildings.

The goal of this research project was to investigate the structural behavior of various types of architectural glass elements in a common curtain wall system under a controlled set of dynamic motions. This research builds upon a previous pilot study conducted by James P. Deschenes during a 1991 Master of Science degree program in Civil Engineering at the University of Missouri-Rolla under the direction of Professor Richard A. Behr.

The dynamic motions applied to the glass in the 1991 pilot study and in this study were similar in character to seismic motions, but they were not intended to represent seismic motions in actual curtain wall systems on actual buildings. Determination of such seismic motions is highly site-specific and requires a complete dynamic structural analysis for each building frame and curtain wall design. Rather, the UMR pilot studies were designed to investigate the overall glass breakage and glass fallout effects that earthquake-like loadings could impose on different types of architectural glass.

The 1991 pilot study dealt only with dynamic racking of the curtain wall in its own plane. In other words, the curtain wall was racked back and forth in a motion that was parallel to the plane of the curtain wall. The focus of this study was to investigate the effects of adding out-of-plane motions to the previous in-plane motions and to observe the resulting structural performance of various types of architectural glass. Thus, the curtain wall specimens in the current study were racked with motion components both perpendicular and parallel to the plane of the curtain wall.

Evaluation of the structural behavior of architectural glass under dynamic racking motions is important because of the potentially serious safety hazards that would exist if glass were to fall from multi-story buildings in crowded metropolitan areas during a major earthquake. Glass fallout need not be extensive to pose life-threatening danger when it falls from the heights associated with multi-story buildings. The hazard potential due to falling glass in an earthquake is magnified by the fact that people tend to "take to the streets" during an earthquake, while they tend to remain indoors during a severe windstorm.

Safety considerations alone make the study of glass performance under dynamic motions important, but economic considerations are also highly relevant. For instance, after a building has been racked by an earthquake the repair efforts necessary to restore building serviceability could be extremely expensive. Necessary repairs could include replacing glass that has fallen out or has cracked, repositioning glass lites that have shifted within the curtain wall and are now allowing air infiltration and water leakage, and repairing other damage that has occurred to the curtain wall frame. These repairs are difficult, expensive, and time-consuming. Protracted repair times can also create inconvenience to building occupants, weakened building security, and weather damage to building contents if breaches in the building envelope occurred during the earthquake event. The resulting economic losses could be staggering.

Given the severity of the potential hazards and the expenses associated with architectural glass failure during an earthquake, it is important to advance the structural design procedures for architectural glass to include seismic effects. Model building codes should address in a realistic and safe manner the structural design of architectural glass and curtain wall systems in various earthquake regions. By so doing, personal injuries will be prevented and major economic losses will mitigated.

EXPERIMENTAL OVERVIEW

The facility used to perform this research project was a modification of the facility used in the 1991 UMR pilot study, in which only in-plane racking motions of the curtain wall assembly were tested. To allow curtain wall specimens to be tested with in-plane **and** out-of-plane motions, it was necessary to modify the UMR test facility.

Test Facility

A schematic of the test facility with the curtain wall assembly in place is shown in Figure 1. In previous tests, the sliding lower support tube in Figure 1 was restricted to moving only parallel to the plane of the curtain wall. In order to introduce both in-plane and out-of-plane motions, a substantial modification of the two roller mechanisms at the lower corners of the test facility was required.

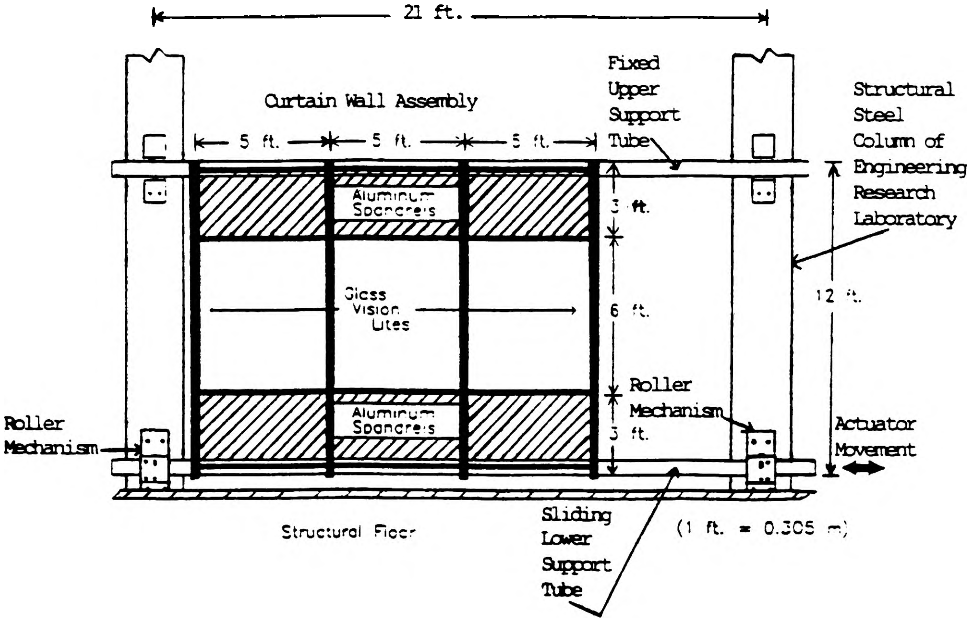

Figure 1. Test Facility with Curtain Wall in Place [adapted from Deschenes, 1991]

A new roller assembly was designed to enable the axial movement of the hydraulic actuator ram to produce mechanically coupled in-plane and out-of-plane motions on the sliding tube at the bottom of the curtain wall assembly. As depicted in Figure 2, the hydraulic actuator ram was connected to the sliding tube in Figure 1 by a universal-joint, a straight link, and a vertical pin. The modified roller mechanisms contained stationary rollers that guided the edges of the moving angled wedges, thereby permitting the tube to move both parallel and perpendicular to the plane of the curtain wall.

The angled wedges used in this project had sloped edges with an angle equal to 26.6 degrees relative to the longitudinal axis of the sliding support tube. This angle provided for an out-of-plane displacement equal to 50% of the in-plane displacement. Thus, as the hydraulic actuator ram moved forward, the sliding support tube had the resultant outward movement shown in Figure 2, with an in-plane movement component equal to the actuator ram movement and an out-of-plane movement component equal to 50% of the in-plane movement. As the sliding support tube moved, it remained parallel to its initial orientation, since the same angled wedges were used at both lower corners of the test facility.

Racking movements were induced with an MTS Systems DELTA-P Model 254.04 A-01 hydraulic actuator, with a load capacity of 22 kips (98 kN) and a maximum stroke of 3 in. (76 mm) in either direction about a neutral point. The actuator was interfaced with an MTS Model 406 analog controller in conjunction with an MTS Model 436 control panel. This control configuration allowed the desired actuator displacement amplitude, frequency, displacement wave form, and number of cycles to be programmed manually by the system operator.

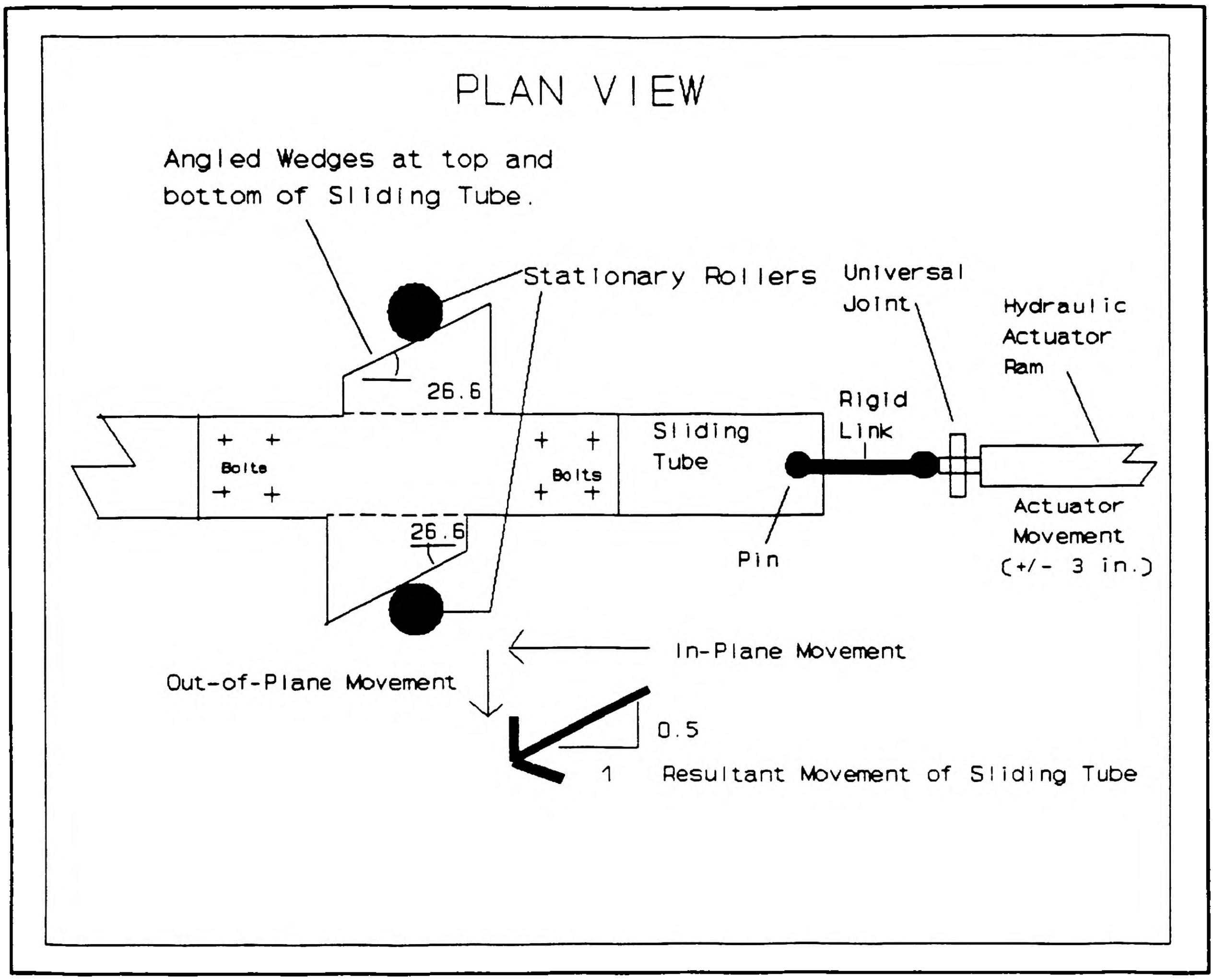

Figure 2. Mechanism Used to Produce Coupled In-Plane and Out-of-Plane Motions on a Curtain Wall Test Specimen

The curtain wall system that was used is the Robertson-Cupples "Horizon Wall" system, and it is the same system that was used in the 1991 in-plane pilot study. Horizon Wall is a popular, standard product from Robertson-Cupples, a world leader in curtain wall design, manufacture, and installation. The Horizon Wall system is a "wide mullion design" that allows glass to be installed from either the interior or exterior of the building, which makes this curtain wall system well-suited for high-rise building installations. Another attribute of the wide mullion design is a relatively spacious glazing pocket that allows a greater amount of curtain wall racking motion without glass-to-aluminum contact.

Glass specimens were placed in the curtain wall glazing pocket as shown in Figure 3. A 1/2 in. (13 mm) bite was provided on all glass edges, which left a 1 in. (25 mm) clearance between the glass edges and the top and sides of the aluminum glazing pocket, and a 3/4 in. (19 mm) clearance between the glass edge and the bottom of the glazing pocket. The lower edge of each glass panel was supported by two aluminum "setting blocks" with rubber contact pads, and the vertical edges of the glass were separated from the aluminum mullion glazing pocket with 1/2 in. (13 mm) W-shaped rubber "side blocks." Dimensions associated with glass placement in the curtain wall test assembly are shown in Figure 3.

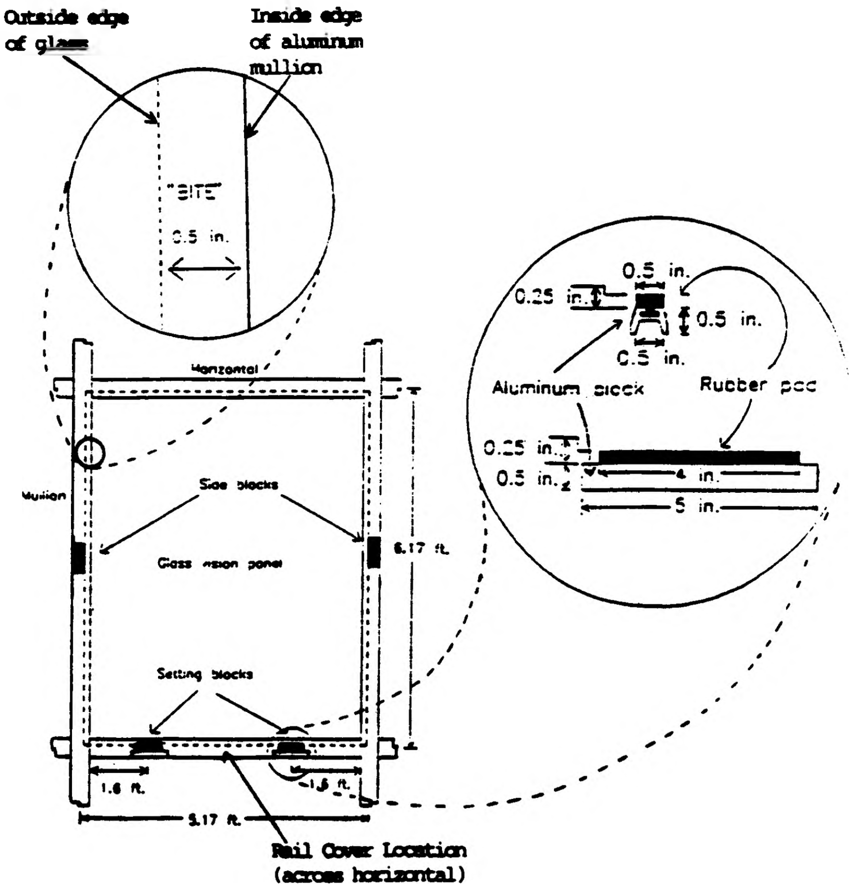

Figure 3. Glass Placement in Glazing Pocket
[adapted from Deschenes, 1991]

The glass was dry glazed, meaning that it was held in the glazing pocket by interior and exterior Santoprene gaskets. The gaskets act as rubber wedges that hold the glass within the aluminum glazing pocket. The glass was installed by completing the following steps. First, an interior gasket called "preset" was attached to the mullions and horizontals by pressing a flange in the preset into a groove on the inside of the glazing pocket. Second, the glass was lifted into place so that it was positioned within the frame as illustrated in Figure 3. Third, a rail cover was snapped into place on the exterior of the bottom horizontal member to complete the bottom horizontal glazing pocket. Fourth, the glazing procedure was completed by pressing or pounding a "wedge" gasket between the glass perimeter and the aluminum glazing pocket.

Loading Spectrum

Prior to installing the glass panels at the start of each test, a stiffness test of the frame was conducted with the aluminum spandrals shown in Figure 1 in place. This stiffness test was performed to determine if appreciable wear had occurred to the frame during the previous test sequence. The stiffness test was administered by racking the frame for 5 cycles with a 1 in. (25 mm) amplitude at a frequency of 1 Hz. While the frame was being racked, an X-Y plotter was used to record the actuator displacement versus the load resisting the actuator movement in the in-plane direction. The resistance caused by the frame was measured with a load cell attached to the hydraulic actuator ram. The graph produced by the plotter was then used to evaluate the frame condition in comparison to previous tests so that the frame could be declared suitable for another test sequence.

Stiffness tests were a necessary quality control measure that were used to insure that all tests were conducted on a frame of similar stiffness. The plotted graphs indicated that the frame stiffness changed a small amount, less than 5 percent, after the first test was run but remained uniform from that point on throughout the entire test sequence; therefore, a single Horizon Wall was re-used for all the tests that were conducted. However, minor repairs such as tek screw replacement were occasionally required. The tek screws securing the horizontal members were replaced with 1/4 in. (6 mm) bolts. These repairs were deemed necessary after it was visually noted that the horizontal members below the glass were observed to be experiencing excessive movement due to enlargement of the holes around the tek screws. The repairs were made without delay so that the condition of the frame would remain serviceable.

Each test used to evaluate the dynamic performance of the curtain wall glass elements consisted of two phases. "Phase I" approximated the inter-story drifts and associated frequencies that would be present in the response of a typical 15-story steel frame structure during a moderate earthquake. A FORTRAN program called SPECELC (developed by Dr. Chris Pantelides at UMR) was used in conjunction with the known physical limitations of the MTS hydraulic actuator to determine the motions prescribed for Phase I. "Phase II", which was conducted immediately after Phase I, included a more severe combination of amplitudes, frequencies, and number of cycles than those contained in Phase I. Phase II was purposely severe so that the post breakage fallout behavior of various glass types could be observed more fully. The maximum amplitude/frequency combinations in Phase II approached the physical limits of the UMR hydraulic actuator. The test sequences for both Phases I and II are outlined in Table I.

TABLE I. TEST SEQUENCES FOR DYNAMIC IN-PLANE/ OUT-OF-PLANE RACKING TESTS

PHASE I

1 HZ 5 CYCLES PER AMPLITUDE

In-Plane Amplitude (in.)	Out-of-Plane Amplitude (in.)
0.19	0.10
0.39	0.20
0.59	0.30
0.79	0.40
0.98	0.49
1.18	0.59
1.38	0.69
1.57	0.79

0.5 HZ 5 CYCLES PER AMPLITUDE

In-Plane Amplitude (in.)	Out-of-Plane Amplitude (in.)
1.77	0.89
1.97	0.99
2.16	1.08
2.36	1.18
2.56	1.28
2.75	1.38
2.95	1.48

PHASE II (Repeated 10 times)

60 CYCLES PER AMPLITUDE

Frequency	In-Plane Amplitude (in.)	Out-of-Plane Amplitude (in.)
4 HZ	0.40	0.20
3 HZ	0.60	0.30
2 HZ	1.00	0.50
1 HZ	2.50	1.25

(1 in. = 25.4 mm)

Experimental Plan

Six test series were conducted as listed in Table II. Each test series consisted of three tests, and each test consisted of the two phases outlined in Table I.

TABLE II. GLASS TYPES IN THE IN-PLANE/OUT-OF-PLANE DYNAMIC TEST PROGRAM

TEST SERIES	TYPE OF GLASS
1	1/4 in. (6 mm) Annealed Laminated
2	1/4 in. (6 mm) Annealed Monolithic
3	1/4 in. (6 mm) Annealed Monolithic with a 0.004 in. (0.1 mm) PET Film (film not anchored to framing members)
4	3/8 in. (10 mm) Annealed Monolithic
5	7/16 in. (11 mm) Fully Tempered Laminated
6	7/16 in. (11 mm) Heat-Strengthened Laminated

In the 1991 UMR in-plane racking tests, 1/4 in. (6 mm) annealed laminated glass and 7/16 in. (11 mm) heat strengthened laminated glass experienced no glass fallout (Deschenes, 1991). Therefore, these types of glass were included in the current test program to determine if they could also withstand in-plane/out-of-plane motions without glass fallout. The 1/4 in. (6 mm) annealed monolithic glass (with and without PET film) and the 7/16 in. (11 mm) fully tempered laminated glass were included in the latest experimental plan to determine how glass performance would compare with that observed in the previous in-plane tests. This comparison was intended to determine if the in-plane/out-of-plane tests were more detrimental to glass performance than were the in-plane only tests -- as intuition might suggest. The 3/8 in. (10 mm) annealed monolithic glass was included to determine if glass thickness had a notable effect on performance, since 1/4 in. (6 mm) annealed monolithic glass was the only thickness tested in the previous in-plane tests.

The film applied to the 1/4 in. (6 mm) annealed monolithic glass was a 0.004 in. (0.1 mm) polyethylene terephthalate (PET) adhesive film made by Madico, Inc. of Woburn, Massachussets. The PET film was applied by experienced personnel from Miller Glass Company of Rolla, Missouri. The film was applied to the glass with a 5/8 in. (16 mm) wide unfilmed border around the edge of the glass. The film was not anchored mechanically to the curtain wall framing members, because unanchored film installations prevail in retrofit applications on existing buildings. Thus, the PET film was tested in accordance with the manner in which it is normally applied to architectural glass.

The interlayer used for the laminated glass units was Saflex polyvinyl butyral (PVB) from the Monsanto Chemical Company in St. Louis, Missouri. The interlayer thickness in the 1/4 in. (6 mm) laminated glass units was 0.030 in. (0.76 mm), while that in the 7/16 in. (11 mm) laminated glass units was 0.060 in. (1.52 mm).

EXPERIMENTAL RESULTS

All dynamic curtain wall tests were performed from the perspective of observing both the serviceability limit state performance and the ultimate limit state performance of the various types of architectural glass. Serviceability limit state failures were taken to include gasket fallout, glass crushing and cracking, setting block movement, and glass lite shifting. These serviceability failure types would not pose safety hazards in themselves, but they would certainly necessitate building repairs. Ultimate limit state failure was considered to be actual glass fallout. Such failures would not only necessitate building repairs, but they would also pose significant threats to life safety.

Serviceability Limit State Performance

Indications of serviceability limit state failures often began early in Phase I. This is important to note, since Phase I motions were in the range of building responses that could actually occur during only a moderate earthquake. The most noticeable early serviceability problem was sideways (in-plane) shifting of entire glass lites within the glazing pockets of the curtain wall frame. Normally, fallout of the Santoprene gaskets occurred along with glass shifting; however, all gasket fallout could not be attributed to glass shifting alone.

Some gasket fallout appeared to be caused by the dynamic movements of the glass panels, which sometimes caused gaskets to loosen and detach from the glazing pocket. Both the preset and the wedge gaskets experienced fallout; however, the wedge gaskets on the exterior side of the glass were affected to a larger extent. The preset gaskets had a tendency to roll up under the glass and become pinched, which prevented them from falling out of the frame. Often, gaskets began to pull out during Phase I, but they did not actually fall out until later in Phase II. As a rough estimate, less than 10% of the actual gasket fallout occurred during Phase I. Over 40% of the glass lites that experienced cracking or crushing had this serviceability problem originate in Phase I. Cracks and crushing usually began at the setting block regions where the glass weight was concentrated, or in the corner regions where glass-to-aluminum edge clearances became tight as the curtain wall system racked. Crack formation was usually preceded by minor chipping or crushing of the glass in the region of the crack origin.

During tests, the setting blocks had a tendency to shift horizontally or even move out from under the glass totally. This setting block migration caused significant changes in support conditions at the lower edge of the glass. Occasionally, glass weight was concentrated heavily on a displaced setting block. On other occasions, setting blocks also lost their top rubber pads, which caused the glass to bear directly on the aluminum base of the setting block. For these reasons, crack origination and crack propagation were often observed to be associated with the setting blocks.

As the glass shifted within the curtain wall frame, corner clearances were sometimes eliminated, causing undesirable contact between glass and aluminum. This situation contributed substantially to cracking, chipping, and crushing in the corners of the glass lites.

All of these serviceability limit state failures began in Phase I. This observation is crucial, since it seems to indicate that massive repair efforts would be necessary restore building serviceability after a building had been exposed to a moderate earthquake. The serviceability problems in Phase II were primarily a continuation of those initiated in Phase I; however, many new cracks and additional glass crushing occurred during Phase II.

Ultimate Limit State Performance

Glass fallout occurred in four of the six types of glass that were tested, and all of this fallout occurred during Phase II. The amount of glass fallout by percentage of total original face area for each type of glass tested is listed in Table III, along with the percentage of glass fallout observed for the same glass type during the 1991 in-plane study.

The amount of fallout that occurred during this in-plane/out-of-plane study was generally greater than that observed during the 1991 in-plane study. The only exception was the 1/4 in. (6 mm) annealed monolithic glass with the 4 mil, unanchored PET film, where the observed fallout was actually less during the in-plane/out-of-plane study than it was during the in-plane only study -- 34% versus 44% respectively. This slight decrease in fallout is not nearly as major as the increases in fallout that were observed. The 1/4 in. (6 mm) annealed monolithic glass and the 7/16 in. (11 mm) fully tempered laminated glass had over three times as much fallout during the current in-plane/out-of-plane study as was observed during the in-plane only study.

The 1/4 in. (6 mm) annealed laminated glass and the 7/16 in. (11 mm) heat strengthened laminated glass exhibited no fallout during either the in-plane tests or the in-plane/out-of-plane tests. The 3/8 in. (10 mm) annealed monolithic glass had very little fallout (1%) but could not be compared to previous results, because this type of glass was not included in the 1991 in-plane experimental plan.

TABLE III. GLASS FALLOUT AS A PERCENTAGE OF ORIGINAL GLASS SURFACE

	In-Plane/ Out-of-Plane Tests (1992)	In-Plane Tests (1991)
Glass Types	% Fallout	% Fallout
1/4 in. (6 mm) Annealed Laminated	0	0
1/4 in. (6 mm) Annealed Monolithic	87	23
1/4 in. (6 mm) Annealed Monolithic with a 0.004 in. (0.1 mm) unanchored PET Film	34	44
3/8 in. (10 mm) Annealed Monolithic	1	Not Tested
7/16 in. (11 mm) Fully Tempered Laminated (Surface Prestress = 13,000 psi.)	33	11
7/16 in. (11 mm) Heat-Strengthened Laminated (Surface Prestress = 11,400 psi.)	0	0

The in-plane/out-of-plane tests proved, for the most part, to cause no surprises with regard to observed fallout percentages and glass types escaping fallout. The observed fallout rates were generally higher, as was expected, in the in-plane/out-of-plane tests than in the in-plane only tests. The 1/4 in. (6 mm) annealed laminated glass and the 7/16 in. (11 mm) heat strengthened laminated glass both survived the in-plane/out-of-plane tests with no fallout, as they did the in-plane only tests. Both of these patterns of behavior seemed to provide some verification of consistent testing procedures.

Characteristics of Glass Fallout

Racking amplitude was definitely observed to be related strongly to the amount of observed glass fallout. As indicated in Figure 4, it is clear that most glass fallout occurred at higher racking amplitudes. The 7/16 in. (11 mm) fully tempered laminated glass experienced 100% of its observed glass fallout at a racking amplitude of 2.5 in. (64 mm). The 3/8 in. (11 mm) annealed monolithic glass also experienced 96% of its fallout at the 2.5 in. (64 mm) amplitude. This 2.5 in. (64 mm) racking was the maximum actuator amplitude applied in Phase II. The other two glass types experiencing fallout [i.e., 1/4 in. (6 mm) annealed monolithic and 1/4 in. (6 mm) annealed monolithic with film], had fallout patterns that were more evenly distributed with respect to Phase II racking amplitudes.

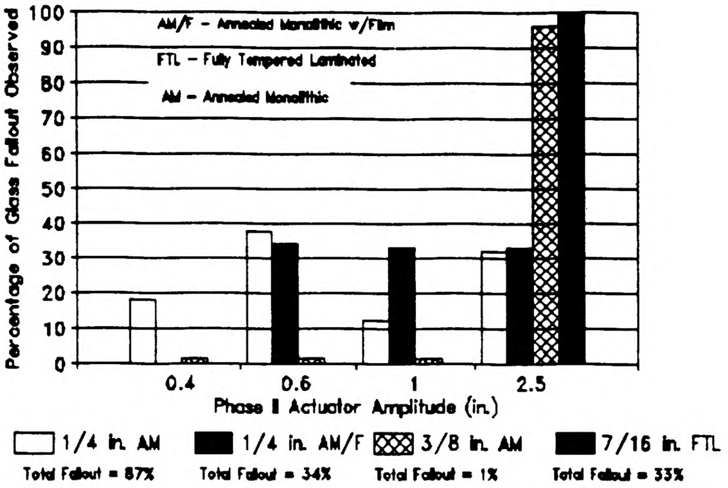

Figure 4. Observed Glass Fallout vs. Actuator Amplitude

Glass fallout observed during Phase II occurred rather randomly with fallout fairly evenly distributed over the whole spectrum of the 10 repetitions that were applied during Phase II. This distribution of observed glass fallout is shown in Figure 5, and it indicates that the fallout occurring during Phase II did not just occur during the first couple of repetitions as might be expected.

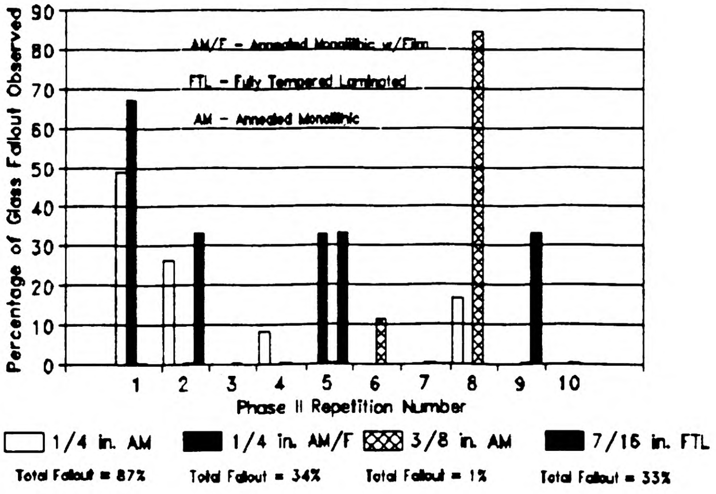

Figure 5. Observed Glass Fallout vs. Phase II Repetition Number

CONCLUSIONS

The following conclusions are based upon characteristics of ultimate limit state failure modes of the different types of glass that were tested. All of the tested glass types exhibited different patterns of failure, and the results also differed in the amount of fallout or cracking that was observed. These conclusions seek to summarize the different modes of failure associated with the in-plane/out-of-plane dynamic racking tests.

1. The 1/4 in. (6 mm) annealed monolithic glass experienced a large amount of fragmentary fallout (87%), while the 3/8 in. (10 mm) annealed monolithic glass experienced only a minimal amount of edge or corner chipping and cracking fallout (1%). The increase in thickness from 1/4 in. to 3/8 in. (6 mm to 10 mm) had a pronounced effect on glass fallout for annealed monolithic glass.

2. Addition of a 0.004 in. (0.1 mm) PET film (not anchored to curtain wall framing members) on the 1/4 in. (6 mm) annealed monolithic glass prevented fallout of small glass fragments; however, one triangular-shaped glass fragment with an area of about one square foot (0.09 square meters) did detach from the film and fall to the ground during one test. More importantly, the film was also observed to actually contribute to entire lite fallout, since the film held all the glass fragments together as a flexible plastic sheet with glass fragments adhered to it. The large, heavy PET/glass fragment sheet would sometimes drag itself out of the curtain wall glazing pocket as an entire unit.

3. The 7/16 in. (11 mm) fully tempered laminated glass experienced fallout as entire units. The laminated glass units fell out only after both glass plies had fractured into a closely spaced crack pattern that is characteristic of fully tempered glass. After both fully tempered glass plies fractured, the unit lost rigidity and its self weight caused it to pull itself out of the glazing pocket, a phenomenon that is sometimes likened to a "wet carpet."

4. All 1/4 in. (6 mm) annealed laminated glass units remained in the frame with no glass fallout, but cracking was observed in all nine units tested. All 7/16 in. (11 mm) heat strengthened laminated glass units also exhibited no fallout, and four of the nine laminated glass units survived the entire test regime without any glass cracking whatsoever. These laminated glass units were the only two types of architectural glass that completely resisted glass fallout, which is a strongly positive indication of their ability to safely resist dynamic motions in curtain wall systems. Heat strengthened laminated glass units also appear to have serviceability advantages in terms of their observed resistance to glass cracking during some rather severe dynamic motions with in-plane and out-of-plane components.

This series of in-plane/out-of-plane dynamic racking tests of curtain wall architectural glass elements proved to be very successful. The test facility that previously allowed only in-plane motions was modified to incorporate motions having both in-plane and out-of-plane components, and a new series of tests were conducted.

The fallout rates, as illustrated in Table III, were generally higher, as was intuitively expected, during the in-plane/out-of-plane tests than they were during the in-plane only tests. The 1/4 in. (6 mm) glass and the 7/16 in. (11 mm) heat strengthened glass were once again able to fully survive the dynamic tests as they were in 1991 with the in-plane only tests. All of the glass fallout occurred during Phase II and was somewhat evenly distributed over the 10 repetitions of the phase, as shown in Figure 5, while the fallout generally occurred at the highest actuator amplitude of 2.5 in. (64 mm), as shown in Figure 4.

All of these fallout characteristics were representative of fallout patterns that were observed in the in-plane study, or they were consistent with what was intuitively expected. The validity of the testing consistency, therefore, seems to be vindicated.

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REFERENCE

James P. Deschenes, Dynamic Racking Performance of Curtain Wall Glass Elements, 1991.