Architectural Glass for Earthquake-resistant Buildings

Richard A. Behr
Professor and Department Head
Architectural Engineering Department
The Pennsylvania State University

Keywords

1 = seismic design 2 = curtain wall systems
3 = architectural glazing 4 = glass failure
5 = storefront systems 6 = drift limit data

Abstract

Significant differences exist in the performance of various architectural glass types subjected to simulated earthquake conditions. Controlled laboratory studies were conducted to investigate the cracking resistance and fallout resistance of different types of architectural glass installed in the same storefront and mid-rise wall systems. Quantitative data obtained from these studies are summarized, along with qualitative observations regarding the various failure modes exhibited by architectural glass under simulated seismic loadings. Effects of glass surface prestress, lamination, wall system type, and dry versus structural silicone glazing are discussed. Laboratory results revealed that distinct magnitudes of "drift" (i.e., differential horizontal movements between adjacent floors in a building frame) cause glass cracking and glass fallout in each glass type tested. Notable differences in seismic resistance exist between architectural glass types commonly used in contemporary building design, with annealed and heat-strengthened laminated glass units showing the highest levels of resistance to glass fallout. Annealed monolithic glass panels with 0.1 mm plastic (PET) film (unanchored to the wall system frame, as in retrofit film applications) are not as resistant to glass fallout as are annealed and heat-strengthened laminated glass units.

Introduction

It takes only a brief glance at any urban landscape to reveal the prominence of architectural glass in modern building design. Architectural glass can help orchestrate bold and brilliant aesthetic statements. Architectural glass components and the curtain wall systems within which they are glazed are normally considered "non-structural" elements of a building. However, curtain wall systems (and the glazing systems within them) must resist substantial structural loads during severe windstorms and earthquakes.

Design of architectural glazing systems to resist the effects of severe windstorms has received considerable attention in building codes and standards over the past few decades. Recent attention has focused on the design of architectural glazing systems to resist windborne debris impacts. Despite this activity in the wind engineering field, building codes contain only minimal information regarding the seismic design of architectural glazing systems.

This void in building envelope design practice is disturbing when one considers the potential life safety hazards of falling glass during a severe earthquake. In a less severe earthquake (or in regions farther away from the epicenter of a severe earthquake), life safety considerations can be eclipsed by the high costs associated with loss of building security, disruptions to building operations that can occur when glass breaks (and building envelopes are breached), and damage to building interiors during post-earthquake storms. Such costs, when accumulated over a widespread region, can be enormous. The insurance industry can attest to this.

Although standard test methods and codified design procedures for architectural glazing systems under earthquake loadings are not yet complete, significant data have been obtained on the performance of commonly specified architectural glass types under simulated earthquake conditions.

Test Facility and Experimental Plan

In-plane dynamic racking tests were performed by the author and his colleagues using the facility shown in Figure 1. Rectangular steel tubes at the top and bottom of the facility are supported on

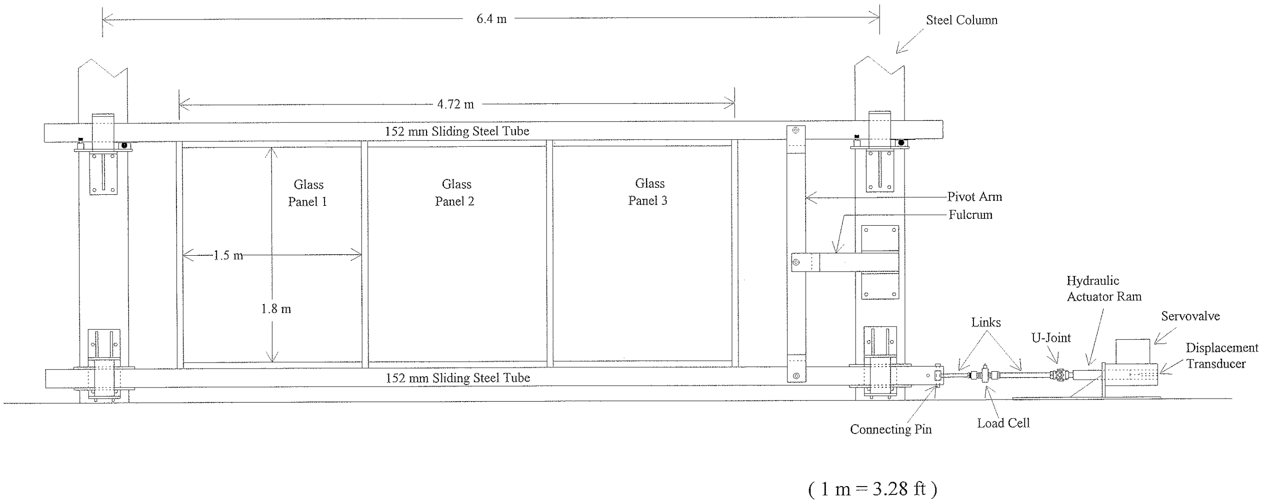


Figure 1. Dynamic racking test facility

roller assemblies, which permit only horizontal motion of the tubes. The bottom steel tube is driven by a computer-controlled hydraulic ram, while the top tube is attached to the bottom tube by means of a fulcrum and pivot arm assembly. This mechanism causes the upper steel tube to displace the same amount as the lower steel tube, but in the opposite direction, which doubles the amount of interstory drift that can be imposed on a test specimen from ± 75 mm to ± 150 mm (± 3 in. to ± 6 in.). The test facility accommodated up to three glass test panels, each 1.5 m (5 ft) wide x 1.8 m (6 ft) high.

Several types of architectural glass, shown in Table 1, were tested under simulated seismic conditions in the storefront and mid-rise dynamic racking tests. These glass types, along with the wall systems used in the tests, were selected after polling industry practitioners and wall system designers for their opinions regarding the most common glass and wall system types used in contemporary storefront and mid-rise wall constructions.

Storefront Wall System Tests

Tests were conducted in 1993 [1] on various glass types dry-glazed within wall systems

Table 1. Glass types included in storefront and mid-rise dynamic racking tests

Glass Type	Storefront Tests	Mid-Rise Tests
6 mm (1/4 in.) Annealed Monolithic	X	X
6 mm (1/4 in.) Heat-Strengthened Monolithic		X
6 mm (1/4 in.) Fully Tempered Monolithic	X	X
6 mm (1/4 in.) Annealed Monolithic with 0.1 mm PET Film (film not anchored to wall system frame)		X
6 mm (1/4 in.) Annealed Laminated	X	X
6 mm (1/4 in.) Heat-Strengthened Laminated		X
6 mm (1/4 in.) Heat-Strengthened Monolithic Spandrel		X
25 mm (1 in.) Annealed Insulating Glass Units	X	X
25 mm (1 in.) Heat-Strengthened Insulating Glass Units		X
25 mm (1 in.) Fully Tempered Insulating Glass Units	X	

commonly used in storefront applications. Loading histories for the storefront wall system tests were based on dynamic analyses performed on a "typical" storefront building that was not designed specifically for seismic resistance [2].

Two types of tests were conducted on the storefront wall systems: (1) serviceability tests, wherein the drift loading history of the glass simulated the response of a storefront building structure to a "maximum probable" earthquake event; and (2) ultimate tests, wherein drift amplitudes were twice those of the serviceability tests, which was a simplified means of approximating the loading history of a "maximum credible" earthquake event.

As Table 1 shows, five dry-glazed glass types were tested. Three glass panels were mounted side by side in the test facility, after which horizontal (in-plane) racking motions were applied. The serviceability test lasted approximately 55 seconds and incorporated drift amplitudes ranging from ± 6 mm to ± 44 mm (± 0.25 in. to ± 1.75 in.). As stated previously, the drift pattern in the ultimate test was formed by doubling each drift amplitude in the serviceability test. Both tests were performed at a nominal frequency of 0.8 Hz.

Experimental results indicated that for all glass types tested, serviceability limit states of glass edge damage and gasket seal degradation in the storefront wall system were exceeded during the moderate earthquake simulation (i.e., the serviceability test). Ultimate limit states of major cracking and glass fallout were reached for the most common storefront glass type, 6 mm (1/4 in.) annealed monolithic glass, during the severe earthquake simulation (i.e., the ultimate test). This observation is consistent with a reconnaissance report of damage resulting from the Northridge Earthquake [3]. In addition to the serviceability and ultimate tests, "crescendo tests," similar to those described below for the mid-rise tests, were performed at a frequency of 0.8 Hz on some storefront architectural glass types.

Mid-Rise Curtain Wall System Tests

A more recent series of tests, performed in 1996, focused on the behavior of glass panels in popular curtain wall systems for mid-rise buildings. All mid-rise glass types in Table 1 were tested using a dry-glazed wall system, which uses polymeric (rubber) gaskets wedged between the glass edges and the curtain wall frame to secure each glass panel perimeter. In addition, three glass types were tested with a bead of structural silicone sealant on the vertical glass edges and dry glazing gaskets on the horizontal edges (i.e., a two-sided structural silicone glazing system). Six specimens of each glass type were tested.

Figure 2 illustrates the drift history of the crescendo test performed on all mid-rise test specimens [4]. The crescendo test consisted of a series of alternating "ramp-up" and "constant amplitude" intervals, each containing four drift cycles.

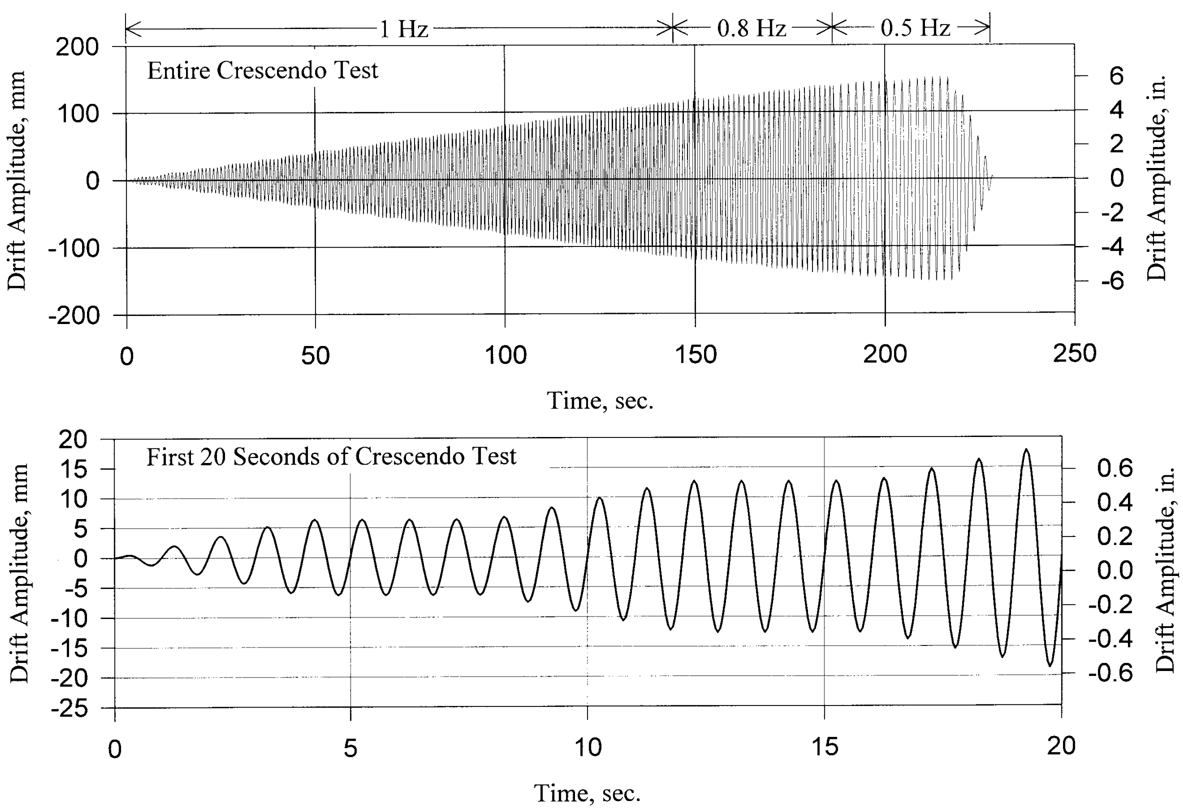


Figure 2. Drift time history in the crescendo test used for mid-rise architectural glass specimens

Each drift amplitude step was ± 6 mm (± 0.25 in.). The entire crescendo test sequence lasted approximately 230 seconds. Crescendo tests on mid-rise glass specimens were conducted at 1.0 Hz for dynamic racking amplitudes from 0 mm to 114 mm (0 in. to 4.5 in.), 0.8 Hz for amplitudes from 114 mm to 140 mm (4.5 in. to 5.5 in.), and 0.5 Hz for amplitudes from 140 to 152 mm (5.5 in. to 6 in.). These frequency reductions at higher racking amplitudes were necessary to avoid exceeding the capacity of the hydraulic actuator ram in the dynamic racking test facility.

The drift magnitude at which glass cracking was first observed was called the "serviceability drift limit," which corresponds to the drift magnitude at which glass damage would necessitate glass replacement. The drift magnitude at which glass fallout occurred was called the "ultimate drift limit," which corresponds to the drift magnitude at which glass damage could become a life-safety hazard.

In addition to recording the serviceability and ultimate drift limits for each glass test specimen, the drift magnitude at which contact between the glass panel and the aluminum frame first occurred was also recorded. To establish when this contact occurred, thin copper wires were attached to each corner of the glass panel and to an electronics box. If the copper wire came into contact with the aluminum frame, an indicator light on the electronics box was actuated.

Glass Failure Patterns

Glass failure patterns were recorded during each storefront and mid-rise test (see Figure 3). Annealed monolithic glass tended to fracture into sizeable shards, which then fell from the curtain wall frame. Heat-strengthened monolithic glass generally broke into smaller shards than annealed monolithic glass, with the average shard size being inversely proportional to the magnitude of surface compressive prestress in the glass. Fully tempered monolithic glass shattered into much smaller, cube-shaped fragments.

Annealed monolithic glass with unanchored 0.1 mm (4 mil) PET film also fractured into large shards, much like annealed monolithic glass without film, but the shards adhered to the film. However, when the weight of the glass shards became excessive, the entire shard/film conglomeration sometimes fell from the glazing pocket as a unit. Thus, unanchored 0.1 mm PET film was not observed to be totally effective in terms of preventing glass fallout under simulated seismic loadings, which agrees with field observations made by Gates and McGavin [5] in the aftermath of the 1994 Northridge earthquake.

In contrast, annealed and heat-strengthened laminated glass units experienced fracture on each glass ply separately, which permitted these laminated glass units to retain sufficient rigidity to

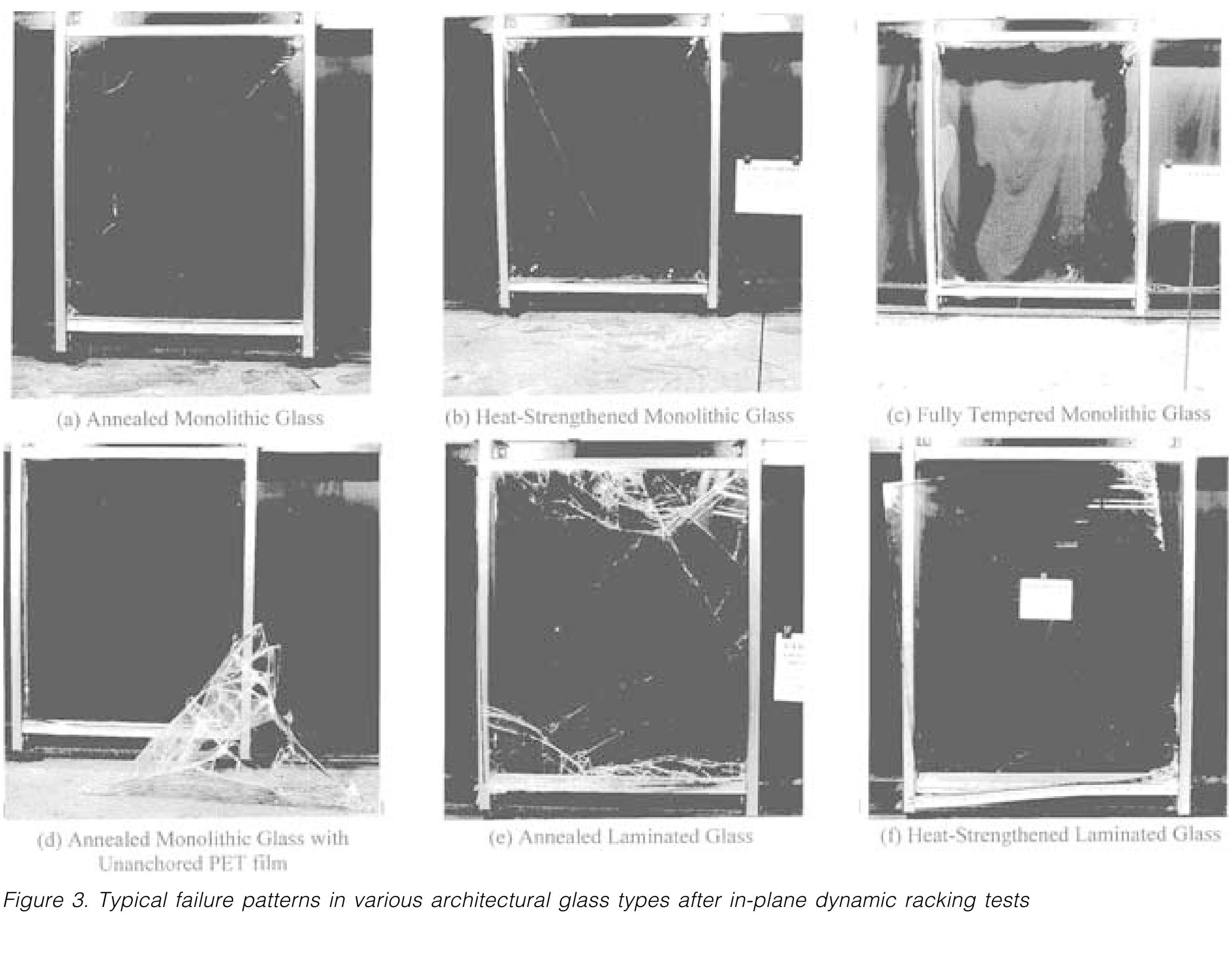


Figure 3. Typical failure patterns in various architectural glass types after in-plane dynamic racking tests

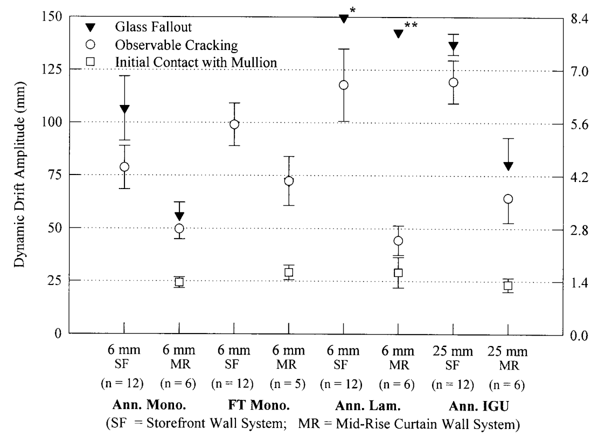
remain in the glazing pocket after one glass ply (or even both) had fractured due to glass-to-aluminum contacts. Annealed and heat-strengthened laminated glass units exhibited very high resistance to glass fallout during the dynamic racking tests.

Quantitative Drift Limit Data

Serviceability and ultimate drift limit data obtained during the crescendo tests are presented in Figures 4 through 7. Figure 4 shows the effects of glass surface prestress (i.e., annealed, heat-strengthened and fully tempered glass) on seismic drift limits; Figure 5 shows the effects of lamination (i.e., monolithic glass, monolithic glass with unanchored 0.1 mm PET film, and laminated glass); Figure 6 shows the effects of wall system type (i.e., lighter, more flexible, storefront wall system versus the same glass types tested in a heavier, stiffer, mid-rise wall system). And Figure 7 shows the effects of structural silicone glazing (i.e., dry glazing versus two-side structural silicone glazing).

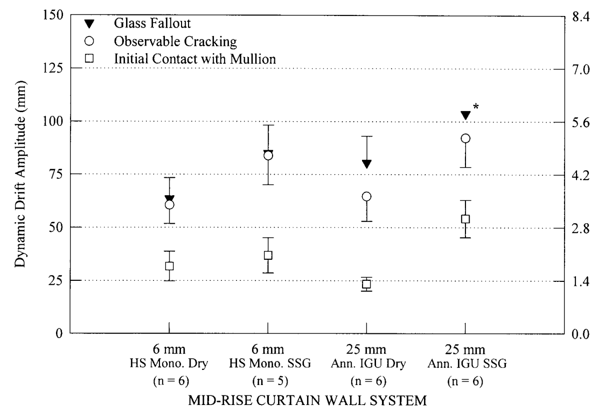
Each symbol plotted in Figures 4 through 7 is the mean value for specimens of a given glass type, along with ± 1 standard deviation error bars. In cases where error bars for a particular glass type overlap, only one side of the error bar is plotted. In cases where the glass panel did not experience fallout by the end of the crescendo test, a conservative ultimate drift limit magnitude of 152 mm (the racking limit of the test facility) is assigned for plotting purposes. No error bars are plotted for these "pseudo data points" because the actual drift magnitude at which the glass panel would have experienced fallout could not be observed; certainly, the actual ultimate drift limits for these specimens is greater than ±152 mm (± 6 in.).

The ±152 mm racking limit of the test facility, when applied over the 1829 mm (72 in.) height of glazing panel specimens in Figure 3, represents a severe interstory drift index of over 8 percent. This 8 percent drift index exceeds, by a significant margin, provisions in the 1997 Uniform Building Code (UBC) that limit calculated inelastic interstory drifts to 2.5 percent of the story height for structures having a fundamental period of less than 0.7 of a second. For structures having a fundamental period of 0.7 of a second or greater, UBC limits the calculated inelastic interstory drift to 2.0 percent of the story height. Thus, code-specified drift limits are considerably lower than the racking limits of the laboratory facility used for the crescendo tests.



*8 of 12 specimens did not fall out. **5 of 6 specimens did not fall out.

Figure 6. Effects of wall system type



*1 of 6 specimens did not fall out.

Figure 7. Effects of structural silicone glazing

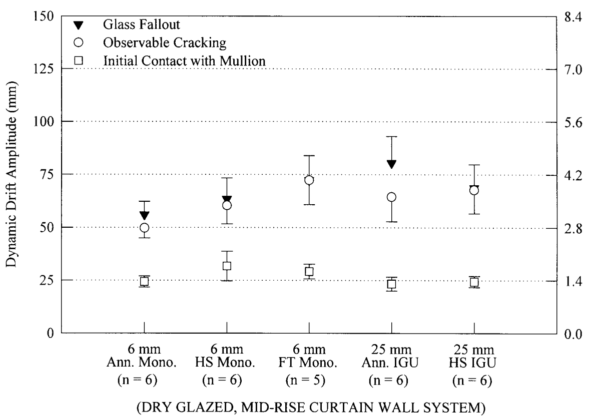
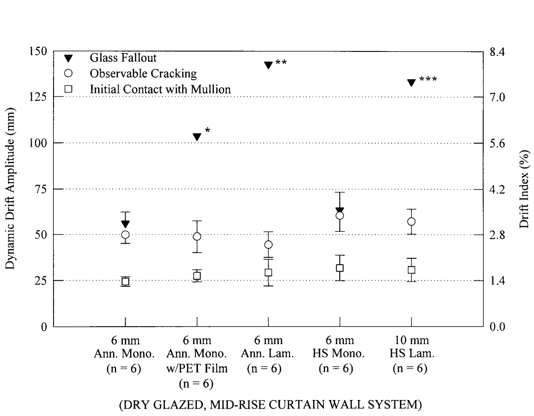


Figure 4. Effects of glass surface prestress



*1of 6 specimens did not fall out. **5 of 6 specimens did not fall out. ***2 of 6 specimens did not fall out.

Figure 5. Effects of Lamination

Figure 4 illustrates the effects of glass surface prestress on observed seismic drift limits. To eliminate all variables except glass surface prestress, data from only the mid-rise curtain wall tests are plotted. Slight increases in cracking and fallout drift limits can be seen for 6 mm (0.25 in.) monolithic glass as the level of glass surface prestress increases from annealed to heat-strengthened to fully tempered glass. However, effects of glass surface prestress on observed seismic drift limits were statistically significant only when comparing 6 mm fully tempered monolithic glass to 6 mm annealed monolithic glass.

All six of the 6 mm fully tempered monolithic glass specimens shattered when initial cracking occurred, causing the entire glass panels to fall out. Similar behavior was observed in four of the six 6 mm heat-strengthened monolithic glass specimens. No appreciable differences in seismic drift limits existed between annealed and heat-strengthened 25 mm (1 in.) insulating glass units.

Figure 5 shows the effects of lamination configuration on seismic drift limits. Lamination had no appreciable effect on the drift magnitudes associated with first observable glass cracking. In a dry-glazed system, the base glass type (and not the lamination configuration) appeared to control the drift magnitude associated with glass cracking.

However, lamination configuration had a pronounced effect on glass fallout resistance. Specifically, monolithic glass types were more prone to glass fallout than annealed monolithic glass with unanchored 0.1 mm PET film or annealed laminated glass. All six annealed monolithic glass panels experienced glass fallout during the tests; five of six annealed monolithic glass specimens with unanchored 0.1 mm PET film experienced fallout; and only one of six annealed laminated glass panels experienced fallout. In terms of resistance to glass fallout, annealed laminated glass was superior to annealed monolithic glass – with or without unanchored 0.1 mm PET film.

Laboratory tests also showed that heat-strengthened laminated glass had higher fallout resistance than heat-strengthened monolithic glass. All six heat-strengthened monolithic glass panels experienced fallout, while only four of six heat-strengthened laminated glass specimens fell out. However, heat-strengthened monolithic glass panels fell out at significantly lower drift magnitudes than did heat-strengthened laminated glass units. Heat-strengthened laminated glass units tended to fall out in one large piece, instead of smaller shards like heat-strengthened monolithic glass.

Figure 6 illustrates the effects of wall system type on observed seismic drift limits. To investigate this parameter, results from the storefront wall system crescendo tests performed in 1993 were compared to results from the mid-rise curtain wall crescendo tests performed in 1996. For all four glass types tested in both wall system types, the lighter, more flexible storefront frames allowed larger drift magnitudes before glass cracking or glass fallout than did the heavier, stiffer, mid-rise curtain wall frames. This observation held true for all glass types tested in both wall system types.

As shown in Figure 7, use of a two-side structural silicone glazing system increased the dynamic drift magnitudes associated with first observable glass cracking in both heat-strengthened monolithic glass and annealed insulating glass units. During the crescendo tests, glass panels were observed to "walk" horizontally across the frame after the beads of structural silicone sealant had sheared. Because the mid-rise curtain wall crescendo tests were performed on single glass panels, the glass specimen was unobstructed as it walked horizontally within the frame. In a multi-panel curtain wall assembly on an actual building, adjacent glass panels could collide, which could induce glass cracking at lower drift magnitudes than those observed in the single-panel tests performed in this study.

It is also clear from Figure 7 that architectural glass specimens with two-side structural silicone glazing exhibited higher resistance to glass fallout than comparable glass specimens that were dry-glazed.

Conclusion

Dynamic racking tests showed that distinct and repeatable dynamic drift magnitudes were associated with glass cracking and fallout in various types of architectural glass tested in storefront and mid-rise wall systems. Seismic resistances varied widely between architectural glass types commonly used in contemporary building design. Annealed and heat-strengthened laminated glass exhibited higher resistance to glass fallout than monolithic glass. Annealed monolithic glass with unanchored 0.1 mm PET film exhibited total fallout of the glass shard/adhesive film conglomeration in five out of six of the crescendo tests performed.

Glass panels glazed within stiffer aluminum frames were less tolerant of glass-to-aluminum collisions and were associated with glass fallout at lower drift magnitudes than were the same glass types tested in a more flexible aluminum frame. Glazing details were also found to have significant effects on the seismic performance of architectural glass. Specifically, architectural glass within a wall system using a structural silicone glaze on two sides exhibited higher seismic resistance than did identical glass specimens dry-glazed on all four sides within a comparable wall framing system.

Observations and conclusions derived from only a limited number of laboratory tests cannot produce generic guidelines for designing and specifying seismic-resistant architectural glazing systems. Test data and laboratory observations can, however, provide designers and specifiers with meaningful insights regarding factors that can affect the safety and serviceability of architectural glass subjected to seismic loading conditions. These insights could assist in providing of safe and cost-effective architectural glazing systems in earthquake-prone regions.

From the dual perspectives of (1) protecting life safety and (2) maintaining building envelope integrity and serviceability, annealed or heat-strengthened laminated glass units are wise choices for either new or retrofit building envelope systems. Not only do these laminated glass units help protect building occupants and pedestrians from falling glass during a severe earthquake, but they also help maintain building envelope integrity after earthquake-induced building motions that could cause other glass types to fall from their glazed openings. By helping maintain building envelope integrity, laminated glass units can help keep a building secure and weathertight in the prolonged periods of cleanup and rebuilding following a major earthquake.

Acknowledgments

The author is grateful to the National Science Foundation (Grant No. CMS 9213172) for major funding of this project. Matching funds from the Monsanto Chemical Company and test specimen contributions from the Primary Glass Manufacturers Council and the Kawneer Company are also gratefully acknowledged.

A similar version of this article appeared in the May 1999 issue of The Construction Specifier. This article is distributed with permission of The Construction Specifications Institute, 99 Canal Center Plaza, Suite 300 Alexandria, Virginia 22314, U.S.A.

References

[1] Behr, R.A., A. Belarbi and A.T. Brown. “Seismic Performance of Architectural Glass in a Storefront Wall System.” Earthquake Spectra. Vol. 11. No. 3. (1995): 367–391.

[2] Pantelides, C.P., K.Z. Truman, R.A. Behr and A. Belarbi. “Development of a Loading History for Seismic Testing of Architectural Glass in a Shop-Front Wall System.” Engineering Structures. Vol. 18. No. 12. (1996): 917–935.

[3] Earthquake Engineering Research Institute (EERI). “Northridge Earthquake January 17, 1994: Preliminary Reconnaissance Report.” ed. John F. Hall. (Oakland, California, 1994): 56–57.

[4] Behr, R.A. and A. Belarbi. “Seismic Tests Methods for Architectural Glazing Systems.” Earthquake Spectra. Vol. 12. No. 1. (1996): 129–143.

[5] Gates, W.E. and G. McGavin. “Lessons Learned from the 1994 Northridge Earthquake on the Vulnerability of Nonstructural Systems.” Proceedings, Seminar on Seismic Design, Retrofit, and Performance of Nonstructural Components. ATC-29-1. January 22–23, 1998. San Francisco, California (Applied Technology Council, Redwood City, California): 93–101.