Laminated Glass: Glazing Material for all Conditions

by H. Scott Norville, PE, Ph.D

Introduction

In most large-scale disasters such as hurricanes, earthquakes, and explosions, window glass fractures. In many instances, such as the Oklahoma City bombing, the Northridge earthquake, and Hurricane Andrew, news reports and damage investigations focus on window glass breakage and associated damage, frequently including injuries. One glazing material, laminated glass, can reduce damage and injuries in many types of disasters at a cost not significantly higher than that of normal window glass. Laminated glass provides these benefits because it prevents glass shards from falling and flying through the air while maintaining closure of its fenestration under the most severe loading conditions. In addition, laminated glass possesses strength equivalent to that of monolithic glass in resisting wind loadings.

A Brief Discussion of Window Glass

Glass design professionals use many terms, unfamiliar to architects and engineers, in discussing window glass. A brief review of some of this terminology will provide a basis for understanding laminated glass. Annealed, heat-strengthened, and fully tempered comprise the three basic monolithic window glass types. Annealed window glass forms the basis for all other window glass types and constructions.

Major glass manufacturers produce annealed window glass by melting its composite raw materials to produce molten glass and then pouring the melt onto a bed of molten tin where it cools and hardens. After it hardens on the molten tin, the glass then goes through an annealing lehr that heats it to temperatures near its softening point. After heating, the glass cools slowly in a controlled manner, eliminating undesirable residual stresses. Glass manufacturers term this procedure the float process. The end result, annealed window glass, commonly known as plate glass, appears optically clear and very smooth. Manufacturers produce annealed window glass in twelve nominal thicknesses ranging from 3/32-inch (2.5-mm) to 7/8-inch (22-mm).

Annealed window glass produced by the float process, though far superior to window glass produced by older methods, remains a brittle material that fractures at rather low magnitudes of load or load-induced tensile stresses (PPG, 1979; Kanabolo and Norville, 1984; Norville and Minor, 1985). When it fractures, annealed glass usually produces large, razor-sharp shards (GRTL, 1987). Because of its relatively low strength and the significant lacerative hazards associated with its shards, designers should never use annealed glass to resist loads other than wind loading.

Glass temperers produce the other two monolithic window glass types, heat-strengthened and fully tempered, by heating annealed window glass to high temperatures and then quenching it. Because heat-strengthened and fully tempered window glass fractures uncontrollably when cut, temperers first cut annealed window glass into the size and shape of the fenestration it will glaze. They heat the annealed window glass lite to temperatures near the glass softening point and then cool it rapidly. The outer surfaces cool first while the interior of the glass remains hot. As the interior cools more slowly, it contracts and pulls the outer surfaces into compression, producing residual compressive surface stresses of relatively high magnitudes. Figure 1 shows stress distribution through the thickness of fully tempered window glass.

The cooling rate in the heat-strengthening process controls the magnitudes of the residual

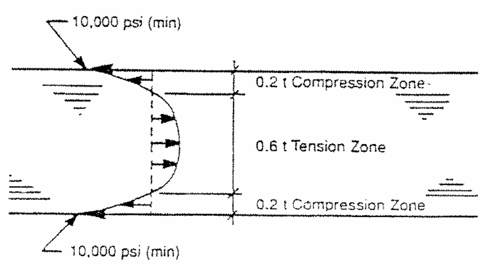

Figure 1: Residual stress distribution through fully tempered glass thickness

compressive surface stresses. Heat strengthened window glass has residual compressive surface stresses ranging from 24.1-MPa (3,500-psi) to 51.7-MPa (7,500-psi). Fully tempered window glass has residual compressive surface stresses with magnitudes of at least 69.0-Mpa (10,000-psi). ASTM C1048-97b, "Standard Specification for Heat-Treated Flat Glass—Kind Heat Strengthened, Kind Fully Tempered Coated and Uncoated Glass," spells out all the criteria for classification of window glass as either heat-strengthened or fully tempered. ASTM C1279-94, "Standard Test Method for Non-Destructive Photoelastic Measurement of Edge and Surface Stresses in Annealed, Heat-Strengthened, and Fully Tempered Flat Glass," provides non-destructive methods for estimating magnitudes of residual compressive surface stresses in heat-treated window glass.

Window glass almost always fractures when the net tensile stress at one point exceeds some critical value (Brown, 1974; PPG, 1979). Under uniform loading, fracture always originates on a window glass surface. Heat-strengthened and fully tempered window glass obtain their high strengths to resist uniform loading because the magnitudes of load-induced tensile stresses must significantly exceed the magnitudes of the residual compressive surface stresses before fracture can occur.

Monolithic window glass, regardless of type, comprises the most rudimentary window glass construction. Laminated glass and insulating glass comprise the other two major window glass constructions. Laminated glass consists of two or more glass plies bonded together by elastomeric interlayers. Although other interlayer materials exist, fabricators most commonly use polyvinyl butyral (PVB). The thickness of the PVB interlayer can range from 0.38-mm (0.015-inch) to 5.10-mm (0.200-inch). Fabricators can use any combination of glass thicknesses and types. Most laminated glass constructions consist of two symmetric glass plies with one interlayer bonding them (Figure

Continuing Education Series

If you are a registered architect and an AIA member, reading this supplement to *Texas Architect* can help you accumulate valuable learning units. Complete the questions on page 6, check your answers on page 7, and return the form on page 7 for two learning units.

Learning Objectives

After reading this article and completing the exercises, you will have:

1. learned the different types and properties of manufactured window glass;
2. understood the requirements for a safety glass rating;
3. differentiated the design considerations to be considered when specifying glazing; and
4. learned the effects of air blasts, hurricanes, and earthquakes on glazing materials.

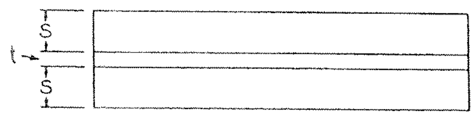

Figure 2: Symmetric laminated glass cross-section: glass ply thickness S, interlayer thickness t.

2). In the U.S., PVB thicknesses typically range from 0.76-mm (0.030-inch) with annealed glass plies to 1.50-mm (0.060-inch) with heat-treated, i.e., heat-strengthened or fully tempered, glass plies. ASTM C1172, "Standard Specification for Laminated Architectural Flat Glass," provides the definitions and constructions for laminated glass. ASTM E1300, "Standard Practice for Determining the Load Resistance of Glass in Buildings," presents a table of standard symmetric laminated glass constructions with nominal thicknesses ranging from five-mm (3/16 inch) to 19-mm (3/4 inch).

Insulating glass consists of two window glass lites with a sealed air space between them. As its name implies, insulating glass provides thermal insulation far superior to that of monolithic window glass. When fabricated using laminated glass, insulating glass provides excellent sound insulation, too.

At noted above, window glass behaves as a brittle material. In the event of fracture, both annealed window glass and heat-strengthened window glass produce large shards that can cause severe injuries. To reduce lacerative hazards, U.S. model building codes (SBCCI, 1997; ICBO, 1997) require the use of safety glazing materials in certain situations.

Model building codes recognize only two safety glazing materials: laminated glass and fully tempered glass. They earn their safety glazing rating for entirely different reasons. Fully tempered window glass displays extremely high strength in comparison to annealed window glass, but it earns its rating as a safety glazing material for another reason. When fully tempered window glass fractures, the residual compressive surface stresses, combined with the interior tensile stresses (refer to Figure 1) cause fully tempered window glass to dice into numerous, very small shards that reduce the lacerative hazards typically associated with fractured annealed or heat-strengthened window glass. Laminated glass earns its rating as a safety glazing material because when it fractures, glass shards, regardless of glass ply type, adhere to the interlayer, eliminating lacerative hazards to persons nearby.

Because glass shards adhere to the PVB interlayer should the plies fracture, laminated glass maintains a degree of stiffness after breakage, even when both plies fracture. The term "post breakage behavior" describes the ability of fractured laminated glass to remain in its frame. Its post breakage behavior makes laminated glass an ideal material for many glazing applications where monolithic glass would not provide safety. Such applications include any circumstances where maintaining closure of a fenestration following fracture and prevention of falling and flying glass shards constitute primary design considerations. Examples of design situations of this type include: glazing to provide blast resistance, glazing in hurricane-prone regions, glazing in earthquake prone regions, and glazing that interferes with burglars or other unwelcome intruders entering buildings.

Table 1
Type Factors for Window Glass Design

Window Glass Type or Construction	Type Factor
Annealed Monolithic	1.0
Heat-Strengthened Monolithic	2.0
Fully Tempered Monolithic	4.0
Laminated Annealed (under most conditions)	0.9
Laminated Annealed (all other conditions)	0.75
Insulating Glass (Annealed Symmetric Plies)	1.8

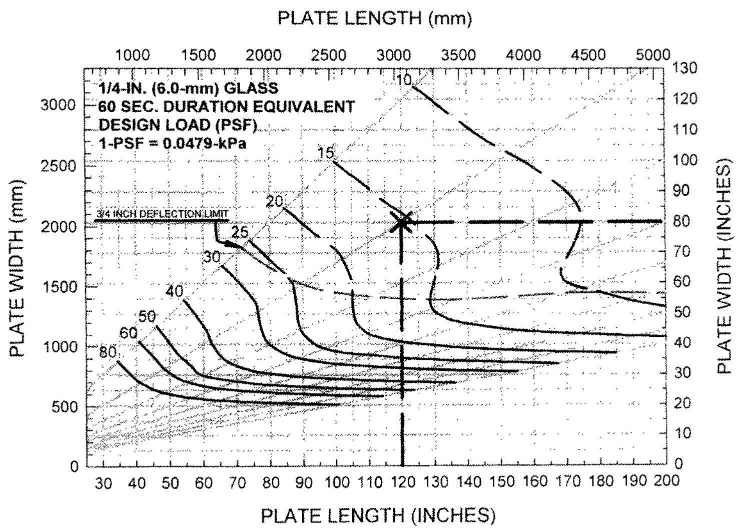

Figure 3: Basic annealed window glass strength chart [Example: A nominal 6-mm (1/4-inch) thick monolithic annealed lite with rectangular dimensions of 2030 mm (80 inches) x 3050 mm(120 inches) has a basic design strength of 0.75-kPa (15.4-psf).]

Window Glass Function and Design

The primary function of window glass consists of providing a transparent barrier between the environments inside and outside a building. To achieve its purpose, window glass frequently must simply resist wind loading. Typical window glass design, therefore, consists of selecting the appropriate thickness of window glass to resist a specified wind loading for a region given the geometry of the window. To facilitate thickness selection, U.S. model building codes and manufacturers' design recommendations assign design strengths (SBCCI, 1994; ICBO, 1996; ASTM E1300, 1996; LOF, 1980) to the various window glass types and constructions using charts and type factors.

ASTM E1300 provides the most comprehensive approach to window glass design available. ASTM E1300 presents twelve charts, one for each monolithic glass thickness. Each chart relates basic annealed window glass design strength in terms of a 60-second duration, uniformly distributed, constant magnitude loading as a function of area and aspect ratio (long dimension/short dimension). Figure 3 presents a chart similar to one found in ASTM E1300 that provides the basic strength for annealed window glass having nominal six-mm thickness. Once the designer determines the basic strength for an annealed window glass lite with specified rectangular dimensions, ASTM E1300 provides type factors that relate design strengths of window glass types and constructions to the basic window glass strength from the charts.

The designer multiplies the basic annealed glass strength by the appropriate type factor to determine the design strength for a particular glass type or construction. Table 1 presents an abbreviated list of type factors.

In general, the designer can combine type factors. For example, in designing laminated glass with fully tempered plies, the designer

Support provided by Solutia, Inc.

would multiply the type factors for fully tempered window glass and laminated glass to obtain: 4.0 x 0.9 = 3.6

To achieve an efficient design, the architectural window glass designer uses an iterative procedure that goes beyond this discussion.

Voluminous published research (Quenett, 1967; Pilkington, 1971; Behr, et al., 1993; Linden, et al., 1983; Linden, et al., 1984; Vallabhan, et al., 1985; Minor and Reznik, 1990; Norville, et al., 1993; Norville, et al., 1998) indicates that laminated glass displays strength and behavior equivalent to that of monolithic glass under wind load. As Table 1 indicates, building codes and design recommendations set laminated glass design strength at something less than that of monolithic window glass having the same nominal thickness and fabricated from the same window glass type. The conditions that allow the designer to use the laminated glass factor of 0.9 cover the vast majority of design situations.

For most glazing designs, the difference between laminated glass design strength and monolithic glass design strength is so small that the same thickness of either construction will suffice to resist a specified wind loading. If wind loading comprises the only consideration in achieving a particular window glass design, then the designer should opt for monolithic window glass. While laminated glass adequately resists wind load, its optimum use occurs when other considerations affect window glass design.

Competing Products

This section divides glazing applications into two areas: new construction and retrofit situations. In new construction, the designer can devise a system using appropriate glazing materials and framing to provide the desired strength and/or behavior for a given design situation. In retrofit applications, existing frames may significantly limit the designer's options. Laminated glass possesses qualities that make it highly suitable for new construction or retrofit applications.

The architectural window glass designer must never use monolithic window glass when factors other than wind load govern the design. Any type of window glass or window glass construction, due to glass' brittle nature, has a finite probability of fracturing under any air blast loading, any impact, or any contact with its frame. If fracture occurs, then the resultant glass shards pose significant lacerative hazard to nearby persons.

The optimum glazing materials for new and retrofit construction include laminated glass, polycarbonate, glass-clad polycarbonate, and insulating glass made with any of the above. The paragraphs below describe each of these glazing materials not described earlier. The closing paragraphs in this section address retrofit security film. Some engineers believe that retrofit security film, though not a glazing material in itself, provides post-breakage behavior for monolithic glass similar to that of laminated glass in the event of fracture.

All the glazing materials discussed below have significantly higher costs than laminated glass. Retrofit window films have initial costs ranging from slightly less to much higher than that of laminated glass, depending upon the thickness used and the application method. Retrofit window films also have a very high maintenance cost over the life of a building because they require replacement at intervals of 6 to 10 years as they degrade due to mechanical action such as abrasion and ultraviolet exposure.

Polycarbonate: Some designers frequently use polycarbonate, a plastic material involving no glass, to resist air blast loading. This material resists large magnitudes of loading through plastic deformation. Polycarbonate does not fracture and produces no shards. When used as blast-resistant glazing, polycarbonate sheets require special framing. To realize the full value of polycarbonate, the frame must either clamp the polycarbonate or have a deep rebate to prevent air blast pressure from propelling the entire sheet from the frame.

Since polycarbonate glazing resists the entire air blast loading without fracture, its supporting frame must have sufficient anchorage to transfer the air blast loading to the structural frame. Polycarbonate possesses ideal blast-resistant qualities, provided the structural frame of the building it glazes can withstand the air blast loading forces. Polycarbonate has a very high initial cost and relatively high maintenance costs. Unlike glass, polycarbonate discolors after prolonged exposure to ultraviolet light and it scratches easily, requiring periodic replacement to provide visual acuity. Polycarbonate has suitability for both new construction and retrofit applications. Retrofit applications may require new frames if the polycarbonate replaces existing glass.

Glass-clad polycarbonate: Glass-clad polycarbonate consists of two glass plies bonded with elastomeric interlayers to a middle layer of polycarbonate. Glass-clad polycarbonate, therefore, is a special type of laminated glass that provides the same blast-resistant qualities. In addition, the polycarbonate layer provides additional stiffness that enhances the lite's ability to remain in the frame following fracture of the glass plies under air blast and impact loadings. If the designer uses a frame that prevents glass-clad polycarbonate from pulling out, it will maintain closure of the fenestration under more extreme loading than will standard laminated glass.

Like laminated glass, glass-clad polycarbonate provides very good sound insulation. The outer glass plies protect the polycarbonate from ultraviolet degradation and scratching, thus providing superior performance to polycarbonate sheet. Glass-clad polycarbonate tends to fail from delamination after it undergoes numerous cycles of temperature variation. Glass clad polycarbonate has high initial cost but remains optically clear over much longer periods than polycarbonate sheets, thus reducing replacement costs. Glass-clad polycarbonate is suitable for new construction and retrofit applications. As for polycarbonate, retrofit applications may require new frames if the glass-clad polycarbonate replaces existing glass.

Insulating glass units fabricated with laminated glass: A sealed insulating glass unit consists of two or more window glass lites with an air space between them. The lites may be monolithic window glass, glass-clad polycarbonate, or laminated glass. Any glass type of the monolithic or laminated glass lites suffices in comprising an insulating glass unit.

For blast- and hurricane-resistant glazing, an insulating glass unit fabricated with a monolithic lite facing the outside of the building and a laminated glass lite facing the inside of the building provides excellent protection to personnel inside the building. Under air blast or impact loading, the monolithic (sacrificial) lite will fracture first, thus greatly reducing the load that the laminated glass lite must resist. On the other hand, shards will fall from the sacrificial monolithic lite, creating lacerative hazards for persons outside the building. The designer can overcome such hazard by using laminated glass for the outboard lite. As their name implies, insulating glass units provide both thermal and sound insulation to a wall system. Because insulating glass is much thicker than monolithic window glass, it finds most use in new construction.

Retrofit security window film: Retrofit security window film is not a glazing material. Installers apply retrofit security window film to extant monolithic window glass using water-based or pressure sensitive adhesives, in an attempt to provide post-breakage behavior similar to that of laminated glass. Retrofit security window film consists primarily of polyethylene terephthalate (PET), commonly referred to under its trade name of Mylar™. Retrofit security window film manufacturers market films with a minimum thickness of 0.10-mm (4-mil) claiming that they provide blast resistance. They also market films with thickness in excess of 0.71-mm (28-mil), claiming the greater thickness enhances blast resistance.

Installers use one of three methods to apply retrofit security window film to existing window glass: a daylight application, an edge-to-edge application, or an anchored application.

In a daylight application, which is the most common retrofit security window film installation method, the installer applies the security film only to the vision portion of the window. The window frame does not capture the film in the frame bite. Until recently, installers applied water-based adhesive to the glass surface, placed the film on the adhesive, and then trimmed the film by running a razor knife along the edge of the vision portion of the glass. Retrofit security window film manufacturers now profess that their installers trim the film before adhering it to the window glass surface, since trimming against the glass surface weakens window glass significantly.

When air blast pressure or impact fractures a monolithic glass lite with a daylight application of security film, it almost always propels the entire lite from the frame. The distance the lite travels from the frame and the amount of shards it retains against it depend upon the intensity of the loading and the age and condition of the film and its adhesive. Building owners should never consider using a daylight application of security film to maintain monolithic glazing in its frame following fracture resulting from impact or air blast pressure.

In an edge-to-edge application, installers remove the window from the frame and then apply the retrofit security window film to the entire window glass surface. They then reinstall the window in the frame, capturing the film in the bite. This provides slightly better post-breakage behavior characteristics than does a daylight application of security film. The cost of applying retrofit security window film in an edge-to-edge application exceeds the cost of installing it in a daylight application simply due to the additional labor required.

The Glass Research and Testing Laboratory conducted blast tests in which new 0.10-mm (4-mil), 0.18-mm (7-mil), and 0.25-mm (10-mil) retrofit security window films in edge-to-edge applications failed to maintain window glass lites in the frame when air blast pressure fractured them. Between 30 percent and 70 percent, by weight, of the glass shards adhered to the films after blast loadings propelled them from their frames. In these tests, certified installers applied the retrofit security window film to the window glass test specimens.

To achieve an anchored retrofit security window film application, installers apply the film to the glass surface with a portion of the film overhanging the daylight opening. They then mechanically attach the overhanging film to the window frame. While this method achieves the highest level of post-breakage behavior available from security film, it has serious problems. First, this application is very labor intensive and, hence, costly. Second, the level of post-breakage behavior achieved in an application depends upon the anchorage. In a blast loading, for example, if the security film is anchored to a window frame not designed to provide blast resistance, then the anchorage achieves little, if any, increase in blast resistance over other security film application methods. Finally, to date, the author remains unaware of aesthetically pleasing anchors for retrofit security window film.

As mentioned at the beginning of this section, the initial cost of installed retrofit security window film having 0.10-mm (4-mil) thickness in a daylight application starts at slightly below that of laminated glass. The initial cost significantly increases with thickness. Due to the labor required, the initial cost of retrofit security window film in an edge-to-edge application or an anchored application exceeds significantly that of laminated glass.

Once installed, retrofit security window film becomes exposed to the environment inside the building and subject to mechanical degradation from window washing and vandalism. It scratches easily. Although manufacturers have made significant improvements, retrofit security window film also degrades and yellows under ultraviolet exposure from sunlight coming through the window glass. Hence, building owners must replace retrofit security window film at regular intervals of six to ten years to maintain visual acuity as well as any blast resistance retrofit security window film might provide. According to Beers (1992), the life cycle of maintaining retrofit security window film can be as high as four to eight times the cost of reglazing with laminated glass.

Laminated Glass Under Extraordinary Loadings

As MENTIONED PREVIOUSLY, laminated glass provides advantages over monolithic glass that make laminated glass advantageous in certain design situations. The following paragraphs will discuss each of these in more detail and explain the advantage of laminated glass in each situation.

Laminated glass for blast resistance: In Oklahoma City on April 19, 1995, a terrorist bomb killed 168 people and injured numerous others (Conrath and Walton, 1995; Norville, et al., 1995). A study of injuries in the Oklahoma City bombing (Norville, et al., in press) indicated that approximately 500 people suffered injuries outside of the Alfred P. Murrah Federal Building. Of these 500 injury victims, approximately 200, or about 40 percent, suffered lacerations, abrasions, and contusions, as a direct result of flying or falling glass shards. Some victims still suffer from glass shards embedded in their skin. Several other victims, in buildings near the bomb's detonation point, suffered hearing damage and other injuries because fractured monolithic window glass allowed blast pressure into buildings. Figure 4 shows the distribution of glass related injuries for buildings in proximity to the bomb's detonation point.

Building designers could not anticipate a large bomb being placed on the streets of Oklahoma City. Had they done so and designed windows that maintained closure of their fenestrations following fracture, such windows would have eliminated the vast majority of the 200 direct glass-related injuries to persons outside the Alfred P. Murrah Federal Building (Norville and Conrath, in preparation; Norville, et al., in press). On the other hand, no commercially available glazing material could have protected the Alfred P. Murrah Federal Building itself.

No widely recognized method currently exists in the U.S. for designing blast-resistant

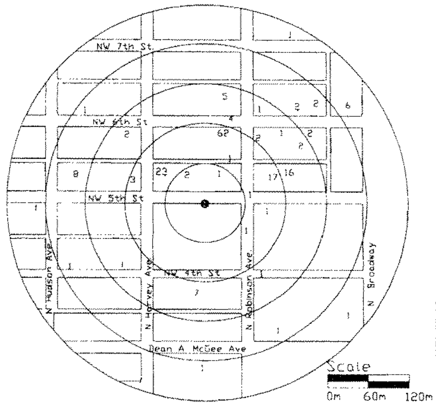

Figure 4: Glass-related injury victim distribution in proximity to bomb detonation point in Oklahoma City [Numbers indicate injuries at a particular location. The black dot indicates detonation point on the north side of the Alfred P. Murrah Federal Building.

glazing. Instead, blast-resistant windows achieve a rating by passing a test method given by F1642-96, "Standard Test Method for Glazing and Glazing Systems Subject to Airblast Loadings." To date, all glazing systems tested under this method involve laminated glass (Norville, 1995).

Laminated glass installed using standard dry glaze framing significantly enhances blast resistance. Certification under ASTM F1642 merely determines a level of blast-resistant performance. Architects and engineers should consider installing laminated glass whenever a risk of accidental or terrorist explosions exists (Norville and Beers, 1994; Norville and Conrath, in preparation).

Laminated glass for hurricane prone regions: Hurricane winds blow with very high velocity and exert some of the highest wind pressures that any architectural window glass experiences (Minor, 1974; Minor and Beason, 1976; Minor, et al., 1976; Minor and Mehta, 1979; Minor, 1981; Minor and Norville, in press). These high winds rarely fracture window glass simply because of the wind pressure loadings they generate. Instead the highly turbulent hurricane winds carry debris that impacts windows, causing fracture.

Most architects in Texas recall the extensive window breakage that occurred in downtown Houston during Hurricane Alicia in 1983. This breakage occurred even though Alicia's winds blew below the design wind speed for Houston. The breakage resulted from hurricane winds picking up gravel from the roofs of one or two tall buildings and propelling it into windows of adjacent buildings.

Hurricane Andrew, in 1992, caused the collapse of a tremendous number of buildings in Homestead, Fla. Damage investigations attributed the majority of these collapses to internal pressurization of the buildings following fractures of windows caused by impact from windborne debris. Studies funded by the insurance industry indicate that insurance losses rise by 30 percent to 40 percent if a window vacates a fenestration and allows rain and wind into the building, even if no structural damage occurs.

In view of these observations, the South Florida Building Code (1994) instituted a test procedure to certify hurricane-resistant glazing. This method involves subjecting windows to approximately 9,000 pressure cycles subsequent to impacting them with missiles. The pressure spectrum found its basis in a paper by Letchford and Norville (1994). Depending upon the location of the proposed windows in the buildings, the missile impacts come from nine-pound, 2 x 4-inch timber missiles hitting end on at a speed of 15 m/s (50 feet/s), roof gravel, or steel balls traveling at much higher speeds.

The magnitudes of the pressure cycles depend upon design wind pressures for the geographic locations of the buildings the windows will glaze and the windows' positions in the building envelope. To obtain certification as a hurricane-resistant glazing material or system, a window tested under these methods must maintain closure of it fenestration throughout the impacts and the pressure cycles. This test method is rigorous. Other organizations, notably the Standard Building Code (SBCCI, 1997), ASTM, the International Building Code, and the Texas Department of Insurance, are codifying or have codified similar test methods for implementation in hurricane-prone regions.

Dade County, Fla., at its web site, maintains a list of hurricane-resistant window systems that have achieved certification under its version of this test method. The vast majority of hurricane-resistant windows use laminated glass because of its ability to hold together and maintain closure of its fenestration after fracture. As in blast-resistant glazing, most hurricane-resistant windows require special framing considerations to hold the laminated glass in the frame following fracture.

Laminated glass for earthquakes: When earthquake ground motions shake large buildings, they sway. During the swaying, glass frames deform out of the original shapes, both in and out of the plane of the glass. Glass in the frames may fracture, either due to stresses induced by large magnitude accelerations out of plane or as the result of contact with window frames due to large deformations in the plane of the glass.

When monolithic window glass fractures during an earthquake, the resulting shards fall from the fenestrations presenting severe lacerative hazards both to pedestrians on the street and persons in buildings. The Civil Engineering Department at the University of Missouri-Rolla conducted tests in which researchers forced cyclic deformation of glazed window frames both in and out of the plane of the glass. Their published research (Behr et al., 1995; Behr and Belarbi, 1996) indicates that laminated glass can remain in the frame under relatively large magnitude motions for many cycles even though it fractures. In the case of earthquake motions, laminated glass tends to remain in its frame even without special framing.

Laminated glass for forced entry: Intruders can easily fracture monolithic glass of any type and gain entry through the window. A fenestration glazed with laminated glass with no special framing keeps the fenestration closed and requires significant additional effort to gain entry following fracture. If the frame has a positive attachment to the laminated glass glazing it, then forced entry becomes nearly impossible in a short period of time. ASTM F1233-95, "Standard Test Method for Security Glazing Materials and Systems," provides test methods to assess levels of protection that security glazing materials afford.

Conclusions

LAMINATED GLASS PERFORMS all of the functions of monolithic glazing. Laminated glass costs more than monolithic glass of the same glass type. In comparison to other glazing materials suitable for extraordinary loading conditions, laminated glass has significantly lower cost, especially if the designer considers total costs associated with glazing over the life of a building.

In addition, laminated glass possesses post-breakage behavior characteristics that make it an ideal glazing material when extraordinary loadings occur. Under air blast loading, laminated glass nearly eliminates flying and falling glass shards and maintains closure of its fenestration, thereby significantlyreducing injuries and interior building damage. In hurricanes, laminated glass maintains closure of the fenestration under wind pressure following impacts by windborne debris, thus preventing building collapse from internal pressurization and reducing insurance losses from wind and water damage. Its post-breakage characteristics also make it an ideal material for retarding forced entry. In short, whenever considerations other than wind loading govern design of windows, the designer should seriously consider glazing systems employing laminated glass. ***H. Scott Norville***

H. Scott Norville, P.E., Ph.D., is the Director of the Glass Research and Testing Laboratory and a Professor in the Department of Civil Engineering at Texas Tech University.

References

Beers, P.E., (1992). "Remedial window film applications," Glazing Consultants, Inc., North Palm Beach, Fla.

Behr, R., and Belarbi, A.(1996). "Seismic test methods for architectural glazing systems," *Earthquake Spectra*, Vol. 12, No. 1, 129-143.

Behr, R., Belarbi, A., and Culp, J. (1995). "Dynamic racking tests of curtain wall glass elements with in-plane and out-of-plane motions." *Earthquake Engineering and Structural Dynamics*, Vol. 24, 1-14.

Behr, R.A., Minor, J.E., and Norville, H.S. (1993). "The structural behavior of architectural laminated glass," *Journal of Structural Engineering*, ASCE, Vol. 119, No. 1, pp. 202-222.

Brown, W.G. (1974). "A practicable formulation for the strength of glass and its special application to large plates." *Publ. No. NRC 14372*, Nat. Res. Council of Canada, Ottawa, Ontario, Canada.

Conrath, E.J., and Walton, B. (1995). "Terror strikes Oklahoma City." *Security Engineering Update Newsletter*, Missouri River Division, Omaha District, U.S. Army Corps of Engineers.

GRTL, (1987). "Evaluations of window glass response to low-level blast waves, final test report," Glass Research and Testing Laboratory, Texas Tech University, Lubbock, Tex.

Kanabolo, D.C., and Norville, H.S. (1984). "The strength of new window glass plates using surface characteristics," Institute for Disaster Research, Texas Tech University, Lubbock.

Letchford, C.W., and Norville, H.S. (1994). "Wind pressure loading cycles for wall cladding during hurricanes," *Journal of Industrial Aerodynamics and Wind Engineering*, Vol. 53, pp. 189-206.

Libbey-Owens-Ford Company (LOF). (1980). "Strength of glass under wind loads." File No. 1-Strength of Glass, ATS-109, Toledo, Ohio.

Linden, M.P., Minor, J.E., Behr, R.A., and Vallabhan, C.V.G. (1983). "Evaluation of laterally loaded glass units by theory and experiment." NTIS Accession No. PB84-216423, Glass Res. And Testing Laboratory, Texas Tech University, Lubbock.

Linden, M.P., Minor, J.E., and Vallabhan, C.V.G. (1984). "Evaluation of laterally loaded glass units by theory and experiment, supplemental report No. 1." NTIS Accession No. PB85-111532, Glass Research and Testing Laboratory, Texas Tech University, Lubbock.

Minor, J.E. (1974). "Window glass in windstorms," NTIS Accession No. PB232-258/AS, Civil Engineering Report CE 74-01, Texas Tech University, Lubbock.

Minor, J.E. (1981): "Window glass design practice: a review." *Journal of Structural Engineering*, ASCE, Vol. 107, No. 1, pp. 1-12.

Minor, J.E., and Beason, W.L. (1976). "Window glass failures in windstorms." *Journal of Structural Engineering*, ASCE, Vol. 102, No. 1, pp. 147-160.

Minor, J.E., Beason, W.L., and Harris, P.L. (1976). "Designing for windborne missiles in urban areas." *Journal of Structural Engineering*, ASCE, Vol. 104, No. 11, pp.1749-1759.

Minor, J.E., and Mehta, K.C. (1979). "Wind damage observations and implications." *Journal of Structural Engineering*, ASCE, Vol. 105, No. 11, pp. 2279-2291.

Minor, J.E. and Norville, H.S. (in press). "Securing the building envelope for tropical cyclones," accepted for publication in *Journal of Wind Engineering and Industrial Aerodynamics*.

Self-Test Questions

1. Which of the following are safety glazing materials: wired glass; fully tempered window glass; insulating glass; laminated glass; annealed monolithic window glass with an anchored application of retrofit security window film. ______

2. True or False: Building codes specify fully tempered window glass as a safety glazing material because of its high strength relative to annealed window glass. ______

3. True or False: Laminated glass fabricated with heat-strengthened glass plies has a higher design strength that is 3.6 times greater than that of annealed monolithic window glass. ______

4. True or False: Laminated glass fabricated using heat-strengthened glass plies is a safety glazing material. ______

5. True or False: In a hurricane, window glass fractures primarily as the result of the huge pressures induced by high wind speeds. ______

6. True or False: Laminated glass requires special framing considerations when designed to resist wind loading. ______

7. True or False: Retrofit security window film in a daylight application provides the best available means of maintaining closure of a fenestration under air blast loading. ______

8. Considering initial installation and life-cycle maintenance, which of the following materials has the lowest total cost? polycarbonate sheet; annealed monolithic glass with a daylight application of retrofit security window film; annealed monolithic glass with an anchored application of retrofit security window film; laminated glass fabricated using annealed glass plies; insulating glass fabricated using glass-clad polycarbonate lites ______

9. True or False: A designer should always use heat-strengthened or fully tempered window glass in earthquake resistant designs. ______

10. Referring to Figure 3, determine the basic annealed glass strength of a window glass lite with rectangular dimensions of 1,500 mm (59 inches) by 3,000 mm (118 inches) and 6-mm (1/4-inch) nominal thickness. ______

Support provided by Solutia, Inc.

Minor J.E., and Reznik, P.L. (1990). "Failure strengths of laminated glass." *Journal of Structural Engineering*, ASCE, Vol. 116, No. 4, pp. 1030-1039.

Norville, H.S. (1995). "Tests of blast resistant windows with DuPont SpallShield™ composite," Glass Research and Testing Laboratory, Texas Tech University, Lubbock.

Norville, H.S., and Beers, P.E. "Wind does not break window glass," *Progressive Architecture*, April 1994.

Norville, H.S., Bove, P.M., and Massa, Ronald (1991). "The resistance of architectural glazing to small bomb blasts," Proceedings, Ninth ASCE Structures Congress, Indianapolis, Ind., pp. 354-357.

Norville, H.S., Bove, P.M., Sheridan, D., and Lawrence, S. (1993). "The strength of new heat treated window glass lites and laminated glass units," *Journal of Structural Engineering*, ASCE, Vol. 119, pp. 891-901.

Norville, H.S., Smith, M.L., and King, K.W. (1995). "Survey of window glass broken by the Oklahoma City bomb on April 19, 1995," Glass Research and Testing Laboratory, Texas Tech University, Lubbock.

Norville, H.S., King, K.W., and Swofford, J.L. (1998). "Behavior and strength of laminated glass," *Journal of Engineering Mechanics*, Vol. 124, No. 1, pp. 46-53.

Norville, H.S. and Minor, J.E., (1985). "The strength of weathered window glass," *Bulletin of the American Ceramic Society*, Vol. 64, No. 11, pp. 1467-1470.

Norville, H.S., Harvill, N., Conrath, E.J., Shariat, S., and Mallonnee, S. (in press): "Glass-related injuries in the Oklahoma City bombing," *Journal of Performance of Constructed Facilities*, ASCE.

Norville, H.S., and Conrath, E.J. (in preparation). "Considerations for blast resistant design," *Journal of Architectural Engineering*, ASCE.

Pilkington ACI (1971). "A practical and theoretical investigation into the strength of laminated glasses under uniformly distributed loading." Lab. Rep. and Discussion, Pilkington ACI Operations Pty., Ltd., Dandenong, Australia.

PPG Industries, Inc. (1979). PPG glass thickness recommendations to meet architects 1-minute wind load. Technical Services/Flat Glass Division, PPG Industries, Inc., Pittsburgh, Penn.

Quenett, R. (1967). "The mechanical behavior of laminated safety glass under bending and impact stresses." *Forgetragen auf dem DVM-Tag, Wurzburg* (Germany), Manuskript-Eing. 14, August (in German).

South Florida building code (1994). Miami-Dade County Protocol PA 210: Impact Test Procedures.

Standard Building Code (SBCCI). (1997). Southern Building Code Congress International (SBCCI), Inc., Birmingham, Al.

Standard practice for determining the load resistance of glass in buildings: E1300-96. (1996). ASTM. W. Conshohocken, Penn.

Standard specification for heat-treated flat glass-kind heat strengthened, kind fully tempered coated and uncoated glass: ASTM C1048-97b. (1997), ASTM. W. Conshohocken, Penn.

Standard specification for laminated architectural flat glass: ASTM C1172. (1996). ASTM. W. Conshohocken, Penn.

Standard test method for glazing and glazing systems subject to airblast loadings: F1642-96. (1996). ASTM. W. Conshohocken, Penn.

Standard test method for non-destructive photoelastic measurement of edge and surface stresses in annealed, heat-strengthened, and fully tempered flat glass: ASTM C1279-94. (1996) ASTM. W. Conshohocken, Penn.

Standard test method for security glazing materials and systems: ASTM F1233-95. (1997). ASTM. W. Conshohocken, Penn.

Uniform building code (1985). International Conference of Building Officials (ICBO), Whittier, Calif.

Vallabhan, C.V.G., Minor, J.E., and Nagalla, S. (1985). "Stresses in layered glass units and monolithic glass plates." *Journal of Structural Engineering*, ASCE Vol. 111, No. 11, pp. 2416-2426.

Answers to Self-Test Questions

1. Laminated glass
2. True
3. True
4. True
5. False.
6. False
7. False
8. Insulating glass fabricated using glass-clad polycarbonate lites.
9. True
10. 17 psf or .8kPa

TEXAS ARCHITECT
Continuing Education Report Form • November/December 1998

☐ I have read the article "Laminated Glass: Glazing Material for All Conditions," and I have taken the self-test.

☐ I will receive one learning unit at quality level two for a total of two learning units.

Name ____________________

Firm ____________________

Address ____________________

City, State, Zip ____________________

AIA Member number ____________________

Signature ____________________

Note: You MUST include your AIA member number and your signature to qualify for credit.

Please return the completed form to: *TA* Continuing Education • TEXAS ARCHITECT • 816 Congress Ave., Suite 970 • Austin, TX 78701

DO NOT SUBMIT THIS FORM DIRECTLY TO AIA.

TEXAS ARCHITECT must forward your form on your behalf.

Support provided by Solutia, Inc.