CONSIDERATIONS FOR BLAST-RESISTANT GLAZING DESIGN

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ABSTRACT: When an explosive threat exists building owners should strongly consider using blast-resistant glazing in windows and curtain walls. Architects and engineers have no publicly available tools, procedures, or formal guidelines to aid in the design of blast-resistant glazing. This paper discusses factors pertinent to the design of blast-resistant glazing. It makes specific recommendations concerning window glass types and constructions suitable for use in blast-resistant glazing constructions. It addresses considerations in framing and attachment of blast-resistant glazing to its framing. Most significantly, the authors offer a relatively simple approach to facilitate blast-resistant glazing design in terms of traditional window glass design methodologies for laminated glass and insulating glass fabricated with laminated glass. Use of the blast-resistant glazing design procedure described herein eliminates the need for very expensive blast testing.

INTRODUCTION

When air blast pressure fractures window glass lites, flying and falling glass shards pose a major hazard to anyone in the proximity. The use of blast-resistant glazing in buildings subject to such an air blast pressure loading can greatly reduce, if not eliminate, this hazard. Blast-resistant glazing can also decrease the extent of damage to building interiors and the cleanup that an explosion entails.

At present, architects, engineers, and glazing designers for nongovernmental structures have no publicly available tools, procedures, or formal guidelines available to aid in designing blast-resistant glazing. Their only option consists of hiring blast consultants who can offer blast-resistant glazing designs accompanied by testing. This option significantly increases glazing costs for a building.

In this paper, the authors offer the architectural and engineering communities an approach that facilitates blast-resistant glazing design using readily available traditional window glass design methodologies. The design methodology relies on blast-resistant glazing constructions that employ laminated glass.

PURPOSE OF BLAST-RESISTANT GLAZING DESIGN

When explosions occur in populated areas, air blast pressure typically fractures windows, causing catastrophic results. In the worst scenarios, the shards flying and falling from fractured window glass injure and kill persons (Blocker and Blocker 1949; Brismar and Bregenwald 1982; *Misty* 1987; Norville et al. 1995, 1996), even in the absence of building collapse. At the same time, air blast pressure entering buildings can cause severe damage to ears that might cause diminished hearing ability, loss of balance, and headaches (Norville et al. 1999). Even relatively small explosions will cause significant window glass breakage, requiring as a minimum, window glass replacement and significant cleanup.

Ideally, properly designed blast-resistant glazing should minimize, if not eliminate, flying and falling glass shards in any explosion. In addition, under air blast pressure loading, properly designed blast-resistant glazing should maintain closure of its fenestration, reducing cleanup costs and reducing pressure-related injuries. Even with blast-resistant glazing, air blast pressure will fracture windows, necessitating replacement. However, blast-resistant glazing should remain in its openings and reduce the urgency for immediate replacement.

Unfortunately, explosive threats exist in the uncertain world today. Such threats necessitate architects and engineers to produce designs that afford protection from air blast pressure. To accomplish this, they must make a prediction of a potential blast threat to a building. They define the potential blast threat in terms of (1) an amount of high explosive; and (2) a standoff distance from a building. They design and install blast-resistant glazing based upon this predicted design threat. Should an explosion larger than the design threat occur, provided it does not cause building collapse, properly designed blast-resistant glazing should (1) minimize flying and falling glass shards and their associated lacerative hazard; and (2) maintain closure of most of the glazed openings.

The more probable scenario for blast-resistant glazing, properly designed for a potential threat, arises when no explosion occurs during the in-service life of the blast-resistant glazing. In this case, the blast-resistant glazing must perform the functions of standard glazing, i.e., providing a barrier between environments inside and outside a building while allowing light to enter the building and its occupants to observe the outside world. Blast-resistant glazing must perform the everyday glazing functions economically, without maintenance beyond that which standard glazing requires.

In summary, the primary goal of blast-resistant glazing design consists of protecting people inside or near a building subjected to air blast pressure loading. To afford this protection, blast-resistant glazing must not contribute to the hazards associated with the explosion. Blast-resistant glazing accomplishes this by remaining in its frame following fracture, and eliminating flying and falling glass shards. In the vast majority of its applications, blast-resistant glazing will never experience loading from air blast pressure. Consequently, blast-resistant glazing must economically perform the functions of standard glazing.

WINDOW GLASS DESIGN VERSUS BLAST-RESISTANT GLAZING DESIGN

The primary function of window glass consists of providing a transparent barrier between the inside and outside of a building, thus protecting the building occupants from the elements. To achieve this function, window glass must usually resist only wind loading. For sloped glazing, window glass must resist loading from snow, its own weight, and wind. Consequently, window glass design consists of determining the appropriate window glass type, construction, and thickness designation(s) to resist uniform loads from wind, snow, and its

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own weight, as appropriate. Designers assume these loads act in a quasi-static manner.

The failure prediction methodology (Beason 1980; Norville and Minor 1984; Beason and Norville 1990) provides the theoretical model that describes load resistance of window glass for U.S. design procedures. The failure prediction methodology addresses all factors known to affect window glass strength (Norville and Minor 1984). It relates a uniform load having constant magnitude over specified time duration to a probability of breakage. Under this theory, any uniform loading having finite time duration that acts on an annealed window glass lite induces a nonzero probability of breakage. Within traditional window glass design, any breakage occurring in a window glass lite (i.e., a crack or fracture), constitutes failure.

ASTM Standard E 1300 (ASTM 2000) formulates the failure prediction methodology into a design procedure. This document defines the load resistance (i.e., strength of a window glass lite) in terms of the magnitude of the uniform loading that acts over a time duration of 60 s to produce a nominal probability of breakage of eight lites per thousand ($P_B = 0.008$) at its first occurrence. Currently, U.S. model building codes [Building Officials and Code Administrators International (BOCA) 1999; Southern Building Codes Congress International (SBCCI) 1999; International Code Council (ICC) 2000] have adopted the ASTM Standard E 1300 methodology in some form to facilitate design to resist uniform loading.

ASTM Standard E 1300 presents load resistance for annealed glass—termed nonfactored load—in 12 charts, one for each nominal thickness designation. Fig. 1 shows a nonfactored load chart for window glass having nominal 6 mm (1/4 in.) thickness, similar to that contained in ASTM Standard E 1300.

ASTM Standard E 1300 uses glass-type factors that relate the strength of other monolithic window glass types (heat strengthened and fully tempered) and constructions (insulating glass and laminated glass) to that of monolithic annealed window glass. Current window glass theory does not precisely define the relationship between loading, time duration, and probabilities of breakage for window glass constructions and heat-treated monolithic window glass. When designed using ASTM Standard E 1300 (ASTM 2000), the probability of breakage for heat-treated monolithic window glass and window glass constructions with any glass types has nominal values ≤ 0.008 at the first occurrence of the design loading.

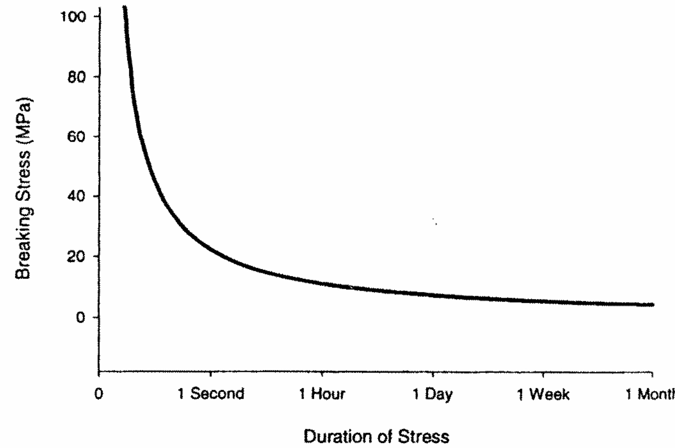

FIG. 2. Approximate Relation between Stress Duration and Stress Magnitude to Initiate Fracture

Traditional window glass design methodology assumes that loads act quasi-statically with durations measured in seconds or longer periods. When an explosion occurs, air blast pressure dynamically loads window glass lites over very short time durations. Fig. 2 shows the approximate relationship between stress duration and stress magnitude at which fracture occurs for annealed window glass (Minor 1990). Fig. 2 indicates that under short duration loading the stress at which fracture initiates, which correlates with window glass load resistance, increases dramatically.

On the other hand, the dynamic air blast pressure loading associated with an explosion excites higher mode shapes in a window glass lite causing much larger deflections and stresses than would a quasi-static loading having the same magnitude of pressure. Because of the excitation of higher modes, the stress distribution for a dynamically loaded window glass lite differs significantly from the stress distribution under quasi-static loading of the same magnitude in that stresses having high magnitudes occur over large regions of a window glass lite (Norville 1990). In addition to their dynamic nature, air blast pressure loadings tend to have much larger magnitudes

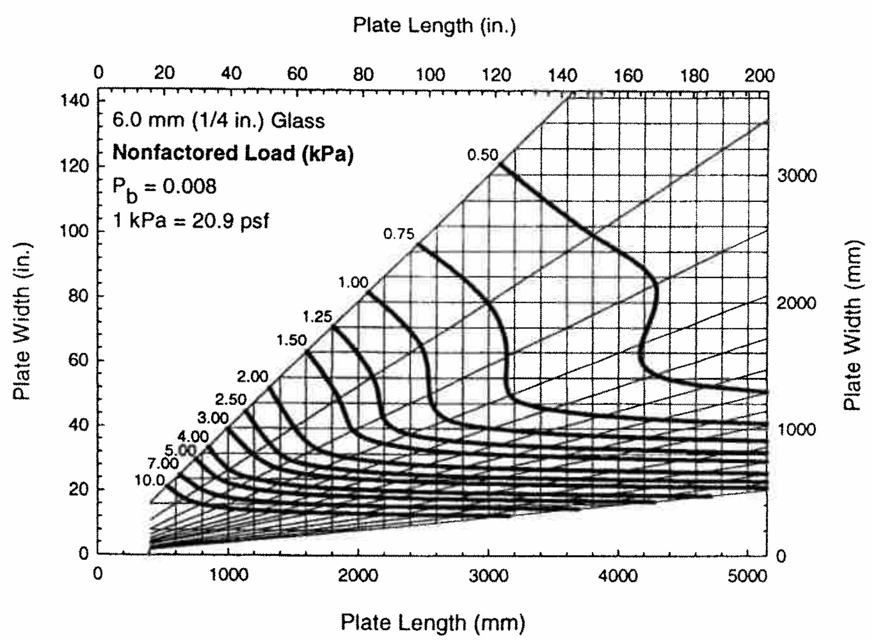

FIG. 1. Nonfactored Load Chart for Nominal 6 mm (1/4 in.) Glass Similar to Those Presented in ASTM Standard E 1300

than wind and snow loadings that typically govern window glass design. Incorporating these factors, the failure prediction methodology indicates that under air blast loadings, the probability of breakage for typical monolithic window glass lites or window glass constructions approaches one even for relatively small air blast pressure loadings (Norville 1990). In short, the distribution and severity of the load-induced tensile stresses in a window glass lite subjected to loading from air blast pressure typically overcome any increase in resistance resulting from the relatively short duration of the loading.

A designer can attempt to devise "strong" monolithic window glass lites or window glass constructions to resist a design air blast pressure without fracture. Many factors tend to make this approach undesirable. First, any window glass construction designed to withstand even an air blast pressure loading of low magnitude would be very thick and would most probably involve heat-treated window glass. Such window glass constructions would have prohibitive costs. Furthermore, a window glass construction with sufficient strength to resist without fracture, an air blast pressure loading, would transfer a large portion of the loading into the structural frame. This load transfer would require a frame design that could resist such loading without collapse. Finally, if the design employs window glass, regardless of its load resistance, it would have a finite probability of breakage when air blast pressure loads it. If monolithic glass fractures under air blast pressure, dire consequences ensue.

The authors recommend that blast-resistant glazing constructions using glass should fracture under air blast pressure loading. Following fracture, they should rely on postbreakage behavior characteristics to eliminate flying and falling glass shards and maintain closure of fenestrations. Because window glass constructions that fracture transfer much less load into the structural frame, the designer should find this approach desirable when considering the effect of air blast pressure on an entire building.

The designer must base blast-resistant glazing designs on maintaining closure of fenestrations and eliminating flying and falling glass shards to the greatest extent possible. Blast-resistant glazing that performs these functions will minimize damage to building contents and maximize safety to building inhabitants. For these reasons, laminated glass or glass-clad polycarbonate make excellent blast-resistant glazing materials. The following section discusses window glass types and constructions and assesses their suitability for use as blast-resistant glazing.

BLAST-RESISTANT GLAZING CONSTRUCTIONS

This section briefly discusses properties of polycarbonate sheet—a purely plastic material—and then continues with discussions of monolithic glass, laminated glass, glass-clad polycarbonate, and insulating glass. It concludes with a mention of retrofit window film even though it is not a glazing material. The combination of glass and plastic in laminated glass and glass-clad polycarbonate produces postbreakage behavior characteristics in blast scenarios that afford significant protection to buildings and their inhabitants.

Polycarbonate Sheet

Before beginning the discussion on glass, the authors remark that some plastic products such as polycarbonate sheet serve effectively in blast-resistant glazing applications. Polycarbonate and other plastic materials tend to have a shorter in-service life and cost much more than blast-resistant glazing materials that employ glass. For example, polycarbonate sheet degrades under ultraviolet radiation and scratches easily. On the other hand, polycarbonate sheet and many other plastic materials do not typically fracture under air blast pressure loading.

Monolithic Window Glass

Window glass has three basic constructions: monolithic glass, laminated glass, and insulating glass. The following paragraphs discuss these constructions along with glass-clad polycarbonate—a special form of laminated glass—and provide comments concerning their suitability for use as blast-resistant glazing.

With regard to the discussion of designing strong window glass constructions to resist air blast pressure loadings, the authors strongly recommend against using any type of monolithic window glass as blast-resistant glazing. In addition to the aforementioned economic and structural considerations, the authors note that should monolithic window glass lites fracture under air blast pressure loading, they will produce shards that will fly and fall from the window at very high velocities. Such shards place any people near the window glass lites in significant danger if an explosion occurs. Figs. 3 and 4 show shards from monolithic window glass embedded in distant walls following their fracture in the Oklahoma City bombing (Norville et al. 1995, 1996). Approximately 200 injuries, consisting of lacerations, contusions, and abrasions, resulted directly from flying and falling window glass shards in that incident (Norville et al. 1999). The authors include this discussion because current design methodologies for window

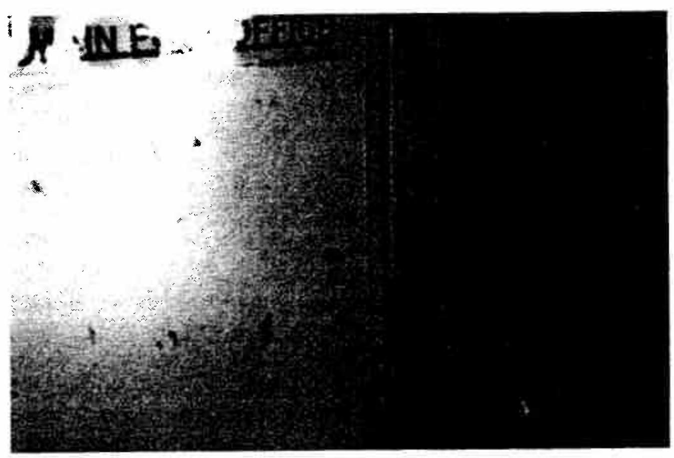

FIG. 3. Monolithic Fully Tempered Glass Shards Embedded in Wall of Durham Post Office from Lite Fractured by Air Blast Pressure in Oklahoma City Bombing (Norville et al. 1995, 1996)

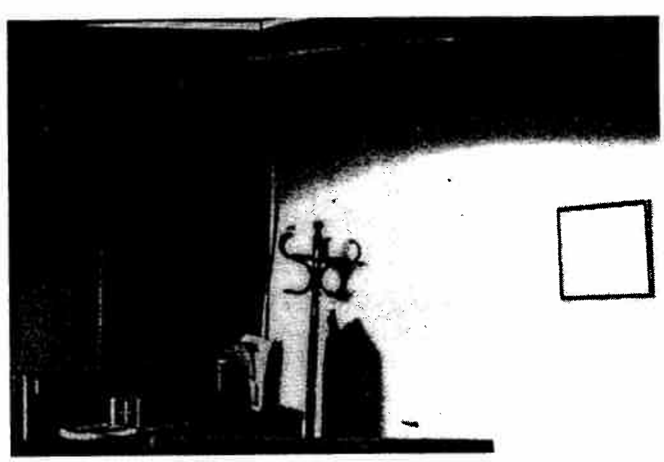

FIG. 4. Monolithic Annealed Glass Shards Embedded in Wall of State Office Building from Lite Fractured by Air Blast Pressure in Oklahoma City Bombing (Norville et al. 1995, 1996)

glass constructions center on the load resistance of monolithic annealed window glass.

Flat glass manufacturers produce monolithic annealed window glass in 12 discrete nominal thickness designations ranging from 2.5 mm (3/32 in.) to 22 mm (7/8 in.). In the production process, manufacturers pour molten glass over a weir from the oven, where it floats on a bed of molten tin in a continuous ribbon. As the ribbon moves along the molten tin, it cools and hardens. When hard, the glass ribbon moves into an annealing lehr that reheats it to a temperature near its softening point. Following reheating the glass cools in a carefully controlled manner to eliminate undesirable residual stresses in the final product, annealed window glass.

Further heat treatment processes produce two additional monolithic window glass types: heat strengthened and fully tempered. To form either, fabricators cut annealed window glass into its final size. The precut annealed window glass lite then passes through a tempering oven on rollers. The oven heats the glass lite to a temperature near its softening point. Quenching air jets cool the outer surfaces rapidly while letting the inside cool more slowly. As the interior cools slowly it contracts. The contraction induces compressive stresses in outer glass fibers and tensile stresses in inner glass fibers.

The magnitude of the compressive stresses in the outer fibers depends upon the quenching rate. Heat strengthened window glass has surface compressive stresses ranging between 25 MPa (3,500 psi) and 52 MPa (7,500 psi). Fully tempered window glass has surface compressive stresses in excess of 69 MPa (10,000 psi). Because window glass under load nearly always fails in tension, heat strengthened and fully tempered glass have nominal load resistances for design purposes of two and four times, respectively, that of annealed window glass. The complex stress distribution through the thickness of heat strengthened and fully tempered window glass make cutting it impossible, explaining why fabricators cut annealed glass to its final size before heat treating it.

The heat treatment process frequently causes distortions including surface (roller) waves and warping. Roller waves tend to cause only aesthetic problems. Warping of heat treated glass can lead to severe problems, both aesthetic and structural, in laminated glass and insulating glass units.

Laminated Glass

Laminated glass consists of two or more plies of monolithic glass bonded together using an elastomeric interlayer. Laminators use polyvinyl butyral (PVB) most commonly as the interlayer material in fabricating laminated glass. The glass plies can consist of annealed, heat strengthened, fully tempered window glass, or a combination. Also, a single laminated glass lite can consist of glass plies having different thicknesses. Aesthetically, annealed plies make the best, distortion-free laminated glass.

Because of its postbreakage behavior characteristic, laminated glass provides excellent protection under air blast pressure loading. When laminated glass fractures, the majority of glass shards adhere to the PVB interlayer (Fig. 5). Small shards spall from laminated glass in a blast, especially if the PVB tears. If the blast-resistant glazing must completely hold all shards, no matter how small, the designer should consider using a plastic film over the inner glass ply. Manufacturers provide commercially available laminated glass constructions with a layer of poly(ethylene terephthalate) (PET) laminated to the inside glass ply using PVB. PET scratches easily although it does not degrade from ultraviolet exposure in these constructions nearly as rapidly as does retrofit window film.

In properly designed blast-resistant laminated glass, the interlayer material should not tear under loading from air blast pressure. In addition, laminated glass should remain in its frame after fracture. The designer should strive to ensure that blast-resistant laminated glass behaves in this manner.

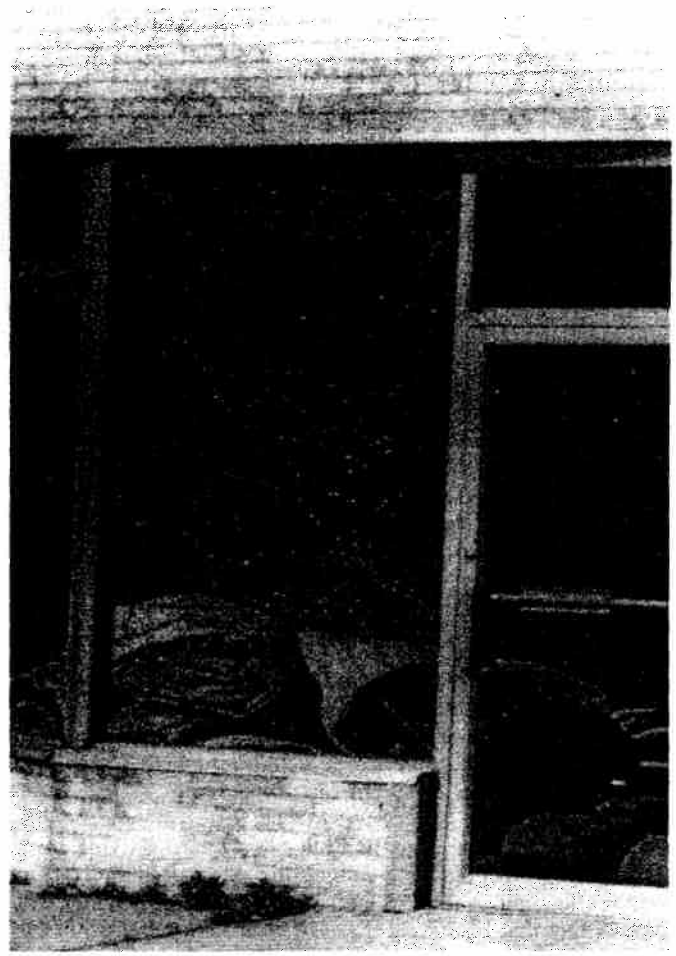

FIG. 5. Annealed Laminated Glass Storefront Window and Door Fractured by Air Blast Pressure in Oklahoma City Bombing (Norville et al. 1995, 1996)

Glass-Clad Polycarbonate

Glass-clad polycarbonate consists of two glass plies sandwiching a thin polycarbonate ply. Epoxy usually bonds the glass to the polycarbonate. Glass-clad polycarbonate is simply a special form of laminated glass that utilizes the excellent strength of the polycarbonate interlayer to provide blast resistance while the glass plies protect the polycarbonate from scratching and ultraviolet degradation. Unless noted otherwise, references concerning the design of laminated glass in subsequent sections apply to glass-clad polycarbonate.

Glass-clad polycarbonate offers all the benefits of laminated glass with the added benefit that the polycarbonate material will not tear. Glass-clad polycarbonate has some disadvantages associated with its use. First, glass-clad polycarbonate costs much more than laminated glass fabricated with PVB. Second, polycarbonate has a coefficient of thermal expansion roughly 10 times that of glass. Under normal diurnal temperature variations, the material that bonds the glass and polycarbonate plies tends to degrade over time, leading to delamination because of the different rates of thermal expansion. Delamination adversely affects the clarity of the glass-clad polycarbonate as well as its postbreakage behavior. Because polycarbonate undergoes little inelastic deformation under dynamic loading, the designer might need extraordinary measures to maintain attachment between glass-clad polycarbonate and its frame under air blast pressure loading.

REFERENCES

ASTM. (1998). "Standard practice for determining the load resistance of glass in buildings." *E 1300-98*, West Conshohocken, Pa.

Beason, W. L. (1980). "A failure prediction model for window glass." NTIS Accession Number PB81-148421, Institute For Disaster Research, Texas Tech University, Lubbock, Tex.

Beason, W. L., and Norville, H. S. (1990). "Development of a new glass thickness selection procedure." *J. Wind Engrg. and Industrial Aerodynamics*, Elsevier Science Amsterdam, 36, 1135–1144.

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

Blocker, V., and Blocker, T. G., Jr. (1949). "The Texas City disaster: A survey of 3000 casualties." *Am. J. Surgery*, 78, 756–771.

Brismar, B., and Bregenwald, L. (1982). "The terrorist bomb explosion in Bologna, Italy, 1980: An analysis of the effects and injuries sustained." *J. Trauma*, 22(3), 215–220.

Building Officials and Code Administrators International (BOCA). (1999). *The BOCA national building code*, Country Club Hills, Ill.

International Code Council (ICC). (2000). *International building code*, Falls Church, Va.

Minor, J. E. (1990). "Basic glass strength factors." *Glass Digest*, 69(9).

Misty picture data: Window glass experiment, final data report. (1987). Glass Research and Testing Laboratory, Texas Tech University Press, Lubbock, Tex.

Norville, H. S. (1990). *Dynamic Failure Prediction for Annealed Window Glass Lites*, Glass Research and Testing Laboratory, Texas Tech University Press, Lubbock, Tex.

Norville, H. S., Harvill, N., Conrath, E. J., Shariat, S., and Mallonee, S. (1999). "Glass-related injuries in the Oklahoma City bombing." *J. Perf. Constr. Fac.*, ASCE, 13(2), 50–56.

Norville, H. S., and Minor, J. E. (1984). "The strength of weathered window glass." *Bull. Am. Ceramic Soc.*, 64(11), 1467–1470.

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 Press, Lubbock, Tex.

Norville, H. S., Swofford, J. L., Smith, M. L., and King, K. W. (1996). *Survey of window glass broken by the Oklahoma City bomb on April 19, 1995, revised*, Glass Research and Testing Laboratory, Texas Tech University Press, Lubbock, Tex.

Smilowitz, R., Tennant, D., Rubin, D., and Lawver, D. (1999). "Las Vegas courthouse curtain wall project; blast prediction, test planning, and post-shot analysis." *Rep. No. WANY 99-01*, Weidlinger Associates, Inc., New York.

Southern Building Codes Congress International (SBCCI). (1999). *Standard building code*, Birmingham, Ala.

WinDAS. (2000). Protective Design Center, Omaha District Corps of Engineers, Omaha, Neb.