Simplified Design Procedure for Blast Resistant Glazing

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3 = Damage Prevention 4 = Design Criteria
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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. 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.

Introduction

When air blast pressure fractures window glass lites, shards flying and falling from these window glass lites pose a major hazard to anyone in 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 non-governmental 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.

The 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 [1,2,3,4,5], 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 [2]. 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.

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

The failure prediction methodology [6,7,8] provides the theoretical model that describes load resistance of window glass for US design procedures. The failure prediction methodology addresses all factors known to affect window glass strength [7]. It relates a uniform load having constant magnitude over specified time duration to a 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 E1300 [9] 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 which acts over a time duration of 60 seconds to produce a nominal probability of breakage, P_f = 0.008, at its first occurrence.

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 loads window glass lites dynamically over very short time durations. Figure 1 shows the approximate relationship between stress duration and stress magnitude at which fracture occurs for annealed window glass [10]. Figure 1 indicates that under short duration loading the stress at which fracture initiates, which correlates with window glass load resistance, increases dramatically.

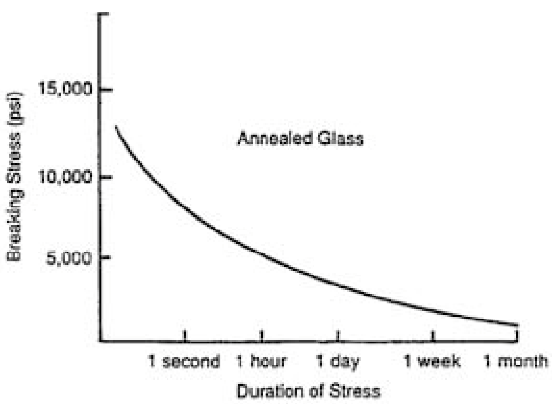

Figure 1. Breaking Stress versus Stress Duration for Annealed Window Glass.

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 [11]. In addition to their dynamic nature, air blast pressure loadings tend to have much larger magnitudes 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 monolithic typical window glass lites or window glass constructions approaches one even for relatively small air blast pressure loading [11]. 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.

The authors recommend that blast resistant glazing constructions using glass should fracture under air blast pressure loading. Following fracture, they should rely on post breakage 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.

Window Glass Type and Construction

As indicated above, the authors feel that laminated glass and insulating glass fabricated with laminated glass comprise the most effective and economical blast resistant glazing materials. The authors offer, *a priori*, a simple empirically derived chart (Figure 2) that provides an approximate relationship between the weight of a hemispherical TNT charge detonated on the ground surface and its standoff distance from a window glass lite to a 60-second duration static design load. In developing this chart the authors considered magnitude of reflected air blast pressure, magnitude of positive phase impulse, and experimental results [12] from blast tests involving laminated glass and insulating glass fabricated using laminated glass.

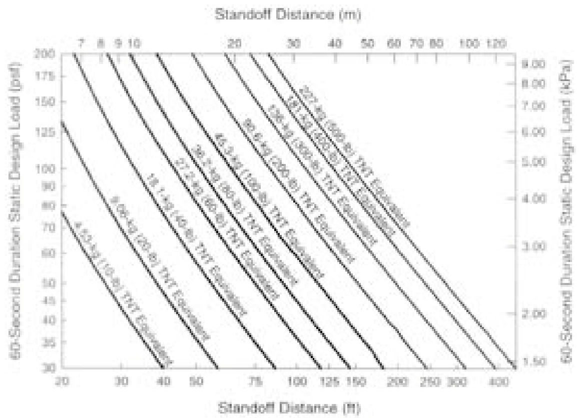

Figure 2. Relationship Between TNT Charge Size, Standoff Distance, and Design Load.

Designers should use this chart only to obtain 60-second duration static design loads for laminated glass and insulating glass fabricated using laminated glass or glass-clad polycarbonate. The values in the chart do not apply to any monolithic glass type or insulating glass fabricated with monolithic glass lites. In comparing designs obtained using values from this chart, the authors observe that nominal laminated glass thickness designations achieved will be slightly larger than those obtained using more esoteric procedures.

To use the chart, the designer defines the design threat explosion in terms of an equivalent weight of a hemispherical TNT charge and a standoff distance. The procedure for defining the design threat goes beyond the scope of this discussion. The designer enters the chart in Figure 2 by projecting a vertical line from the horizontal axes that represent standoff distance to the sloping line that represents the charge weight. From the intersection of the vertical projection and the sloping line, the designer projects a horizontal line to the vertical axes and reads the equivalent 60-second duration static design load. For charge sizes other than those shown, but less than 231 kg (500 lb), the designer can interpolate between the sloping lines. The designer then uses standard design procedures [9] to select the laminated window glass type(s) (annealed, heat strengthened, or fully tempered) and to determine the required thickness designation(s) to resist the 60-second duration static design load. If the wind load for a given design exceeds the magnitude of the 60-second duration static design loading determined from the chart in Figure 2, then the designer should use wind load to design the laminated glass or insulating glass fabricated using laminated glass.

The authors recommend that for laminated glass fabricated with PVB interlayer, the PVB should have at least 1.58 mm (0.060 in.) thickness in blast resistant glazing. The authors also recommend using either annealed or heat strengthened glass plies in the laminated glass. Upon fracture, annealed and heat strengthened glass plies tend to produce larger shards than do fully tempered glass plies. The larger shards facilitate their adhesion to the PVB thus reducing flying and falling glass shards and giving the laminated glass some stiffness following fracture, helping to maintain it in its frame.

Should air blast pressure load blast resistant glazing designed using values obtained from this chart, glass will fracture and require replacement. Laminated glass and insulating glass fabricated with laminated glass and designed using values from this chart will significantly reduce or eliminate the problems that a blast entails provided that it is adequately anchored in framing designed to withstand the blast loading.

The chart in Figure 2 coupled with traditional US design procedures provides a means to arrive at a laminated glass design suitable to resist the specified design threat explosion. The chart in Figure 2 also indicates that the best protection from a bomb is standoff distance, i.e., the loading associated with a given bomb goes down rapidly with increasing standoff distance.

Framing System

Under air blast pressure loading, the designer should design the framing system and its anchorage to the structural frame to resist the dynamic load that the window glass lite would transfer to it under the air blast pressure loading if the glass did not fracture. The architect or engineer can determine the loading transferred to the frame using dynamic analysis techniques. The authors note that design procedures in ASTM Standard E1300 [9] present load resistance values based on maximum nominal non-dimensional frame deflections of L/175. The authors also recognize that blast tests on curtain walls indicate that additional frame flexibility tends to somewhat retard fracture [13].

Attachment of Window Glass Construction to Framing

For blast resistant glazing, the designer should avoid “dry glazing,” in which gaskets alone hold the blast resistant glazing in its frame. Standard glazing bites with gaskets will not restrain fractured laminated glass under air blast pressure loading and the entire lite could fly from the frame. The use of very deep bites with gaskets might restrain the blast resistant glazing but could lead to other problems such as thermal breakage in annealed laminated glass.

Blast resistant glazing should attach to the frame using either structural silicone sealant or adhesive glazing tape. The bite depth should not exceed standard depths any more than necessary to facilitate the width of the structural silicone bead or the glazing tape. When using structural silicone sealant, the width of the bead forming the structural connection should equal the nominal thickness of the blast resistant glazing material with which it is in contact. This thickness will usually be less than the thickness of the entire blast resistant glazing construction. For example, if the blast resistant glazing construction consists of an insulating glass unit with two nominal 6 mm (1/4 in.) lites and a 12 mm (1/2 in.) air space, the authors recommend a 6 mm (1/4 in.) structural silicone bead. In the event of an explosion, this width should result in tearing of the silicone bead before the PVB interlayer tears. This mode of failure will tend to eliminate flying and falling glass shards while maintaining the blast resistant glazing in its frame, especially insulating glass units. Glazing tape has more flexibility than structural silicone and the designer should use a width of glazing tape 2 to 3 times the thickness of the blast resistant glazing material with which it is in contact. Glass-clad polycarbonate requires extraordinary measures to maintain its frame attachment.

Conclusions

In this paper, the authors describe various glazing types and assess their suitability for use in blast resistant glazing designs. More importantly, the authors present a design chart that relates an explosion, described in terms of its TNT equivalent weight and standoff distance from a building to an equivalent 60-second duration static design load. The designer can use the 60-second duration static design load in conjunction with traditional window glass design procedures in ASTM Standard E1300 [9] to design blast resistant constructions fabricated with laminated glass. The authors considered peak reflected air blast pressure, reflected positive phase impulse, and results of numerous blast tests in constructing the glass chart. Blast resistant glazing designs accomplished using this chart and other recommendations in this paper minimize, if not eliminate, the need for blast testing, significantly reduce or eliminate hazards posed by flying and falling window glass shards in explosions, and reduce damage to building interiors should explosions occur.

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