Expanding Bomb Blast Performance of Architectural Glass

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Abstract

In this contribution we explore the use of laminated glass as a method of providing blast mitigation for a transparent façade. While much progress has been made over the years with PVB-based laminates, the ultimate blast capacity is limited by the interlayer tear energy. We discuss the use of a new ionoplast interlayer for bomb blast applications and demonstrate significant improved blast mitigation capacity over PVB laminates. This improved performance is afforded by the greater tear energy of ionoplast polymers and an associated opportunity for new attachment and framing designs. The full potential of an ionoplast laminate may be realized by optimizing the supporting framing and glazing attachment systems. Examples of increased blast performance that are up to four times the US GSA level D specification are presented. Ionoplast laminates provide enabling technology for extending pressure-impulse loading capacity and for extending glazing design to large vision areas.

Introduction

Recent acts of terror, in the form of bomb attacks on buildings, have led to renewed effort in the design of transparent facades that mitigate injuries and structural damage from blast loading [1,2]. The most commonly used performance specifications for bomb blast in the USA are the GSA (Government Services Administration) levels C and D. These two levels are defined in terms of 1) an overpressure, and 2) an impulse (integrated pressure-duration product). Level C specifies a 4 psi (27.6 kPa) 28 psi.ms (193 kPa.ms) loading and Level D specifies a 10 psi (69.0 kPa) 89 psi.ms (614 kPa.ms) loading. The behavior of glazing under the given pressure impulse conditions is then classified in terms of the breakage mode, from category 1 (no break) to category 5 (high hazard). We have seen significant growth in requests for designs that call for higher pressure-impulse combinations than the GSA specifications, particularly if the building is considered to be a primary target. Even for buildings that are considered to be under threat by virtue of their proximity to a perceived primary target, we see a desire to provide transparent facades with large vision areas that would be severely challenged to meet either of the existing GSA criteria.

Laminated glass made with a PVB interlayer has become the glazing of choice for blast mitigation. PVB laminates and framing systems can be designed to meet either of the GSA levels, providing the vision area is not too large, for a reasonable price [3]. However, for performance above the GSA levels PVB laminates become increasingly challenged and often require the use of multiple interlayers and glass plies coupled with restrictions on glazing vision area. Increased performance has usually required the use of glass-clad polycarbonate glazing with significant cost increase and limitations around energy management and the manufacture of insulated units. There is a clear industry need to provide affordable glazing technology that significantly expands the blast capacity of transparent facades.

Factors Influencing Laminate Blast Performance

The performance of a laminate during blast loading is determined by many factors. From a materials perspective the following are key: 1) laminate mass (thickness); 2) post-glass breakage laminate stiffness; 3) interlayer-glass adhesion, and 4) interlayer tear energy. Typical strain rates of the laminate can approach 1,000 /second during blast loading so the materials properties over a wide range of deformation rates are needed to understand fully laminate behavior. Of course, other design issues such as framing system details are important. Edge capture and structural adhesives need to be considered carefully to prevent disengagement of the laminate during loading. Also, frame dynamics are important in determining overall glazing performance.

PVB laminates are usually designed to just tear during dynamic loading and are restrained accordingly, with deep edge bites and structural silicone adhesives. This mode of tear failure is considered preferable over disengagement of the laminate [3]. However, the capacity to minimize infill pressure of the structure is limited by tearing performance.

When looking for opportunities to modify materials properties for extended blast performance the main property that emerges is the interlayer tear energy. Thus increasing the tear energy, or toughness, of the interlayer will result in greater blast capacity and permit the use of high glass-polymer adhesion states to minimize spall. To take advantage of enhanced tear energy it is also necessary to restrain the laminate in the frame to realize maximum performance.

Ionoplast Interlayer Properties

Here we review the essential mechanical properties of an ionoplast interlayer (DuPont SentryGlas® Plus). Figure 1 plots the stress-strain behavior of the ionoplast and compares it to a PVB (DuPont Butacite®) interlayer. Note that the tensile behavior was obtained for deformation rates ~ 1,000 /second, by either direct high-speed tensile testing or by cooling the polymer and using time-temperature superposition [4].

Several features may be noted from these data. First regarding PVB, at these high rates the polymer behaves in an elasto-plastic manner with a well-defined yield stress followed by strain softening, and then hardening to ultimate failure. This behavior is in sharp contrast to the behavior of an elastomeric polymer that is common to most user experience. This experience is usually gained by handling PVB at room temperature, i.e. around its glass transition temperature, at quasi-static rates. Under these conditions

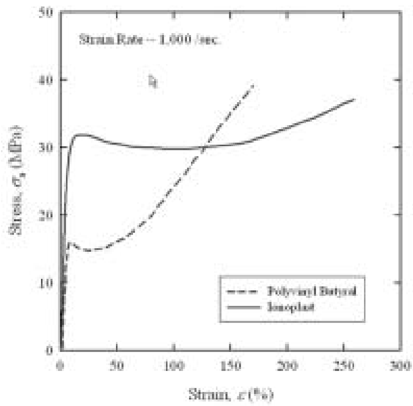

Fig 1

Tensile stress-strain curves for ionoplast and PVB interlayers.

the polymer relaxes on a time scale of seconds. At the high rates used in this test, the interlayer behaves closer to a glassy polymer and is well below its effective glass transition temperature for the rate specified. During the time scale of a blast test the PVB will react initially as a glassy polymer and relax to an elastomer as time progresses

Regarding the ionoplast, it too behaves in an elasto-plastic manner. Here the ionoplast glass transition temperature is around 55 C and this elasto-plastic behavior persists throughout the time scale of blast loading. The main feature to note is that the ionoplast requires significantly greater energy to rupture the polymer, i.e. area under the stress-strain curve is greater for the ionoplast versus PVB.

Case Study in the Use of Ionoplast Laminates

We now present results of shock-tube blast testing of a series of ionoplast laminates. The laminates tested comprised of two plies of 3 mm annealed glass with a 1.56 mm ionoplast (DuPont SentryGlas® Plus) interlayer. The laminates were prepared by standard laminating procedures and attached to the reaction structure of the shock tube by a dry-glazing fix only. A range of effective edge capture of 30 – 80 mm was used. Laminates were tested over a range of pressure and impulse conditions and spall performance was monitored through high-speed video and a witness panel.

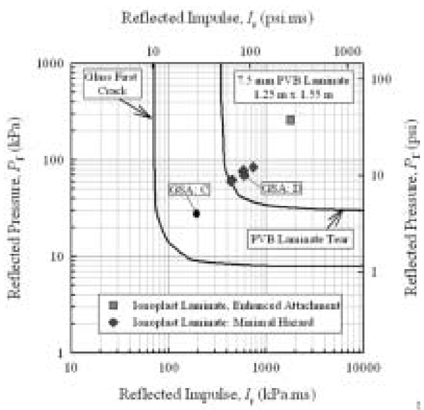

Fig 2

Pressure-impulse performance map for laminated glass.

Figure 2 is a pressure impulse (P-I) diagram re-drawn from reference 3 and shows the accepted performance for a 7.5 mm PVB laminate (3 mm glass / 1.52 mm PVB / 3 mm glass, panel 1.25 m x 1.55 m). The two solid curves on the figure show the predicted glass first break condition and the laminate tear condition, assuming a robust laminate fix. This is usually assumed to be a 30 mm edge bite with structural silicon adhesive. Also plotted on Figure 2 are the US GSA levels C and D.

Results of our ionoplast laminate tests are show on the P-I diagram in Figure 2. At blast levels, comparable to and greater than level D, it can be seen that the laminates made with ionoplast interlayers capably extends the performance past that expected for PVB. These laminates showed glass breakage but with some spall and generally a category 3-4, low hazard performance, Figure 3. Increasing pressure-impulse combinations resulted in the fragmented laminate starting to pullout along one long edge with an associated increase in spall. The system specified showed an acceptable performance level of 12.2 psi (84 kPa)-108 psi.ms (745 kPa.ms). Interestingly this system did not reach the laminate tear point and pullout became the design issue to resolve. Use of structural silicone would certainly aid performance of these ionoplast laminates.

Enhanced Edge-Fix System Design

A significant feature of ionoplast interlayers is that they can be molecularly engineered to adhere well to various metals as well as glass. This allows integration of metal components in the laminate either during autoclaving or in post-autoclaving attachment process. Our results presented in the previous section showed that we did not attain the tear resistance of the laminate but ultimate performance was limited by laminate pullout. The final test result plotted on Figure 2 (upper right-hand corner) is that of a laminate with an enhanced fixing method. The glazing was tested in an arena blast test in collaboration with the US Department of State. During laminate manufacture a channel section of aluminum was attached to the laminate. This was done in such a way as to assure contact between interlayer and metal and allow a strong adhesive bond to develop. The laminate tested consisted of a significantly increased interlayer thickness: 5 mm glass / 6.4 mm interlayer / 5 mm glass. The panel size was 1.83 m x 1.22 m, significantly larger than the panel size specified in Figure 2.

Fig 3

Post test photograph of ionoplast laminate.

The integrated channel then connected to the window frame with a metal stop system. Such a system allows very high pressure-impulse to be mitigated in large window panels. The system described showed a capacity of 37.8 psi (261 kPa) - 258 psi.ms (1,779 kPa.ms) with little infill pressure and minimal spall. Such systems are being considered for embassy structures and other facilities considered at risk from significant bomb threats.

Conclusions

Ionoplast interlayers have the potential to increase the blast mitigation capacity of laminated glass facades. This increased capacity comes through increased polymer tear energy versus traditional PVB interlayers. Performance of ionoplast laminates is generally determined by pullout and full potential maybe realized through modified fixing details. One important feature of an ionoplast is the capability to integrate metal attachments during or after laminating. Such attachments adhere well to the interlayer and allow secure attachment to frame and enable full blast mitigation performance.

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