STATE OF THE ART
OF
BLAST RESISTANT WINDOWS
IN 1996

by

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INTRODUCTION

This paper is written to serve two purposes. The first is to provide a balanced overview on the many glazing materials available for blast resistant windows. As this particular field, unlike steel or concrete design, has many commercial interests actively involved in the marketplace and proposing design procedures, it can be difficult for the user and designer to gain a clear perspective. The second purpose of this paper is to add to the open engineering literature four blast tests performed on polycarbonate during the fall of 1994.

DESIGN APPROACHES

Many solutions exist for designing and fabricating glazing to resist the effects of explosions. Two major design approaches are currently used to choose blast-protective glazing. As the consequences of the choice are severe, it is imperative for the responsible architect or engineer to understand thoroughly the choice and its serious implications for life safety. In the first approach, the glazing can be designed to resist, by conventional strength methods, the overpressure fully and even remain in place to resist further attacks and weather, as well as permitting continued functioning of the building. Design charts, computer programs, and full-scale validating blast tests by this author have shown that tempered glass, laminated tempered glass, and polycarbonate can ably resist a realistic range of blast design loads. An extensive summary of the design predictions compared to actual test results have been published by this author in a paper given at the 26th Department of Defense Explosive Safety Board Seminar in 1994 (Reference 1). In all cases, the established design aids and methods proved to be conservative. Furthermore, practical frame designs have been developed, designed, tested, and deployed to carry the load successfully into the structure.

A second design approach assumes allowing the glass to fail in a mode that provides increased safety through its post-failure behavior. The assumption is that the broken glazing will remain basically intact in the frame and not be propelled into the room. Many of the window films and some design philosophies and procedures marketed for laminated glass use this approach. Some serious shortcomings plague this approach and in general it will only offer limited protection. While anecdotal evidence shows that both filmed and laminated glass provide some additional protection in an explosion, no fundamental engineering theory has been published and accepted to explain how the failed glazing material will provide a quantifiable level of blast protection. It is also unknown how much additional overpressure is required to propel the entire glazing into interior and inhabited spaces at high enough speed to cause serious injury. Most likely, a little higher or longer-lasting overpressure from an explosive blast will be enough to cause catastrophic failure.

Some extend this theory of post-failure behavior design to assume that the negative pressure pulse that in ideal blast conditions will follow the positive pressure pulse will slow down, brake, and retard the

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motion of a failed pane held by either the film or lamination material in place or cause it to fail harmlessly in an outward direction from the interior of the building. While it is true that some tests and even analysis of the post-blast scene will show both filmed and laminated glazing failing outwardly, this may well be due to the fact that most standard window frames are weaker in holding glazing in that direction, such that failure occurred during normal rebound. No known blast tests have been performed with moderate or long positive durations to validate this theory. However, more important from a engineering safety point of view is the fact that the negative pressure may not be applied reliably with the magnitude or duration assumed in many real world blast loading situations. For instance, the explosive source may be less than ideal in that it has a longer burn time. Ammonia-nitrate and fuel oil (ANFO) explosives, some military style explosives with admixtures, and other home-made explosives likely to be used by terrorist groups are well known to behave in this manner. Vapor and dust cloud explosions also exhibit this long lasting positive pressure duration. Furthermore, the blast will be reflected off surrounding surfaces with significant pressure applying a second push to the glazing. As the negative pressure is generally only a fraction of the peak positive pressure, it may be overshadowed by the pressure reflected back from surrounding structures. It is important to note as well that the current ASTM Test Standard on Blast Resistant Glazing may be unconservative for testing post-failure behavior design theory. Both test site safety and the need for reproducibility of the blast wave will tend to dictate a usage of a military explosive such as C-4 or TNT which tend to produce an ideal pressure-time history. Additionally, this test method does not account for reflected shockwaves from blast reflected off surrounding structures, thick vegetation, or hillsides.

However, within these limitations, both film and laminated glass have an important niche in providing an increase in protection as long as its limited protective value is well understood by all including the designer, landlord, and inhabitants who assume the building is designed for protection from blast. If the blast threat is not well defined, these materials will increase the level of protection above that of conventional glazing.

AVAILABLE GLAZING MATERIALS

Many glazing materials offer an improvement over the grave danger posed by standard annealed, plate, or float glass commonly used in windows. Fragment retention film is probably the most used and possibly the most misunderstood. Considerable anecdotal evidence by bomb investigators attests that it generally restricts fragments and may add a slight increase in strength due to its membrane behavior. However, its protective value lies in attempting to provide protection through its post-failure behavior. While generally the film has been 4 mils or 0.004 inch thick, lately much thicker versions with innovative frame engagement are appearing on the marketplace. Logic indicates that this will improve performance. To assess the benefits of new films properly and correctly, a test program needs to be conducted. The tests should be designed with positive pressures that are moderate to long . To generalize the results, a design theory needs to be developed by the industry. A general consensus exists that if this is the only available protection, it is a worthwhile improvement. In no way is it a panacea or a complete solution for successful blast design.

Tempered glass has been proven in blast tests to possess a good blast resistance for a practical range of threats to general buildings. A design theory with charts and software has been developed by this author and has been adopted by many agencies in the Federal government. Actual blast test validation of 35 tests has been conducted on these curves and it is generally believed that a conservative design has been validated. Blast pressures up to 15 psi on practical window sizes and thicknesses have been resisted by off-the-shelf tempered glass.

Laminated glass is really a type of fabrication of layered glass. Generally, it refers to laminated annealed glass. Its addition to strength design lies not in its stronger glass, but in its greater thickness. The material has proven to be long-lived and provides good fragment resistance. However, resistance to fragmentation does not translate physically into resistance against instantaneous applied uniform pressure from an explosion. If the glazing is fabricated from annealed panes, its strength is limited by the inherent weakness of annealed glazing and as a rough rule of thumb will be three times weaker than an equivalent thickness of tempered glass. While the product is lately marketed as providing post-failure protection, it is uncertain that it truly does provide such protection under the full range of blast conditions.

Spall or high speed ejection of glass fragments from the back side of a laminated annealed glazing that has survived in a post-failure mode is a very often observed occurrence. While these fragments may not be as life threatening as blasted-in glass, they can be a threat to vision and have the possibly of causing injury. Either a spall shield such as a film will need to be employed on the inner side of the glass or prudence may limit its use to less populated areas.

Laminated glass can also be fabricated from either heat-treated or tempered glass. Although the laminate may loose some strength at extreme high and low temperatures, good and reasonable levels of blast resistance can be achieved by these materials. Computer codes such as SAFEVUE, BLASTOP, and GLASTOP easily predict blast protection levels for these materials. Eight validating blast tests have been successfully conducted on laminated tempered glass. It is recommended that if laminated glass be used for blast resistance, it should be either heat treated or tempered glass designed by a reasonable and generally accepted design theory and placed into frames that can carry the blast load.

Polycarbonate offers another possibility for blast-resistant glazing based upon the principle of structural strength. It is available off-the-shelf in thicknesses from 1/8 up to 1-1/4 inches thick. It can also be cut in the field for rapid installation. Computer programs such as GLASTOP, BLASTOP, and SAFEVUE permit fast and conservative design selections. Design curves are also published in the open and peer reviewed engineering literature by this author. Twenty blast validation tests have been conducted in a variety of venues and blast protection capacities at least five times higher than other materials have been achieved. Fifteen of these tests are summarized in a paper by this author at the 26th DDESB Seminar (Reference 1). Four new data points are added in this paper .

Blast pressures of 50 psi with moderate positive durations have been resisted with off-the-shelf polycarbonate. The material offers superior fragment resistance. Testing has indicated that a considerable reserve safety factor is inherent in the strength of polycarbonate against blast. Recent also tests have indicated that by developing its ability to behave inelastically, it can survive at blast loads considerably above its design load. Also, being flexible, polycarbonate reacts with poor coupling to bomb blasts with short pressure durations. This means that for the threat of close-in bombs, the polycarbonate's very low dynamic amplification factor means an extra strength bonus of up to 200% and the transfer of less structural load into the building.

Polycarbonate is available in both monolithic and laminated configurations. Laminated polycarbonate offers several advantages. First, as polycarbonate is opaque to ultra-violet radiation, the outer layer protects inner layers from degradation. Second, polycarbonate laminated from thinner sections has proven to be very resistant against cracking caused by concentrated energetic assaults such as impact, ballistics, or fragments.

Polycarbonate can also be combined with glass to fabricate a tough glass-polycarbonate composition. The polycarbonate may be directly laminated or mounted behind laminated glass with an air-gap in a manner similar to insulated glass. Typically, these compositions are often employed to provide bullet and physical assault resistance. Blast tests have proven that these configurations can resist high blast loads. However, the air-gap offers some advantages. Testing has shown the same thickness of polycarbonate will deflect less under blast than the same laminated cross-section. This means that the maximum stress will be reduced in the polycarbonate and also that less bite or frame rebate is required. Less load is transferred to the polycarbonate because the glass up front takes a finite time to respond to the instantly applied blast load. The polycarbonate, in back, feels the blast load, transferred across the air-gap, as a more gradually applied load with a less severe structural response. In the event that the outer glass fails, the polycarbonate has always shown itself in actual blast tests capable of resisting the glass impact and more importantly resisting continued blast, ballistic, and forced entry threats. As the air-gap precludes the need to directly laminate glass to polycarbonate, temperature variations will not induce a delamination problem. Also, as each component can be replaced individually without the need for custom laminating, repair can often be done quickly and locally.

FRAMES

All protective glazing systems require that engineering consideration be given to frames. Protective glazing schemes that concentrate only on glazing and not the frames should be considered suspect as many standard window frames will not hold the glazing in place under blast pressure attack. Design methods have been published in Army TM5-1300 (Reference 2) for framing and many glazings have been built to these specifications. Other structural engineers have used similar structural engineering approaches for successful frame design.

The path to blast protection is not an easy one, but with the skill of rational engineering design, a solution commensurate with the risks and available resources is possible.

POLYCARBONATE BLAST TESTS

Full-scale blast tests were performed on four polycarbonate-based glazings by the government of the United Kingdom in Scotland during October, 1994. The samples were provided by Insulguard Corporation. The purpose of the testing was to proof-test air-gapped glass-polycarbonate physical security glazing and also to probe the ability of polycarbonate to withstand a blast load well above its elastic design limit by taking advantage of its ductile capability. This not only gives polycarbonate a considerable safety factor against blast loading, but also can serve as a basis of design for a post-yield design procedure.

This blast test series represents a realistic test of how the polycarbonate-based glazing behaves. As the opportunity to test and even the test dates themselves became known only weeks before the test, this test series was not intended to be a fully comprehensive test series. However, the testing increases the set of scientific blast testing of polycarbonate by four. Its results provide strong additional support for the validation of the elastic design theory.

All glazing samples were secured by frames which were designed by fundamental engineering principles to transmit the blast load into the test structure. This stands in notable contrast to many of the competing glazing products that claim to be blast resistant. The Insulgard glazing and the MP1000 Lexan 1-inch (25.4 mm.) thick sheet were held in SWB-15 security frames standardly produced for Insulgard. All testing was done in fully enclosed cubicles. This prevented the problem of wrap-around pressures leaking around the back of free-standing test rigs which may actually reduce the net blast loading to 30% of the actual. Clearing time calculations also were performed to assure that overpressure leaking off the front face did not reduce the blast impulse. Testing also was conducted at sea-level so that the full blast load from the test explosive charge was transmitted to the glazing.

An Insulgard 534 security window consisting of 3/4-inch (19 mm.) laminated annealed glass on the blast side, a 1/2-inch (14.7 mm.) air gap, and a 1-inch sheet of Lexan polycarbonate MP1000 sheet) was tested 15 meters (49.2 feet) from a 150 pound (68 kg.) charge of TNT equivalent plastic explosive. Side by side a 1-inch (25.4 mm.) thick sheet of Lexan MP1000 also was tested. Both windows were 49.6 by 37.4 inches (1.26 x 0.95 meters) as measured from centerline of gasket to centerline of gasket. Both windows, which were mounted in the test cubicle, had two-inch (50.8 mm.) frame bites or rebates in Insulgard-designed frames. The explosive was hemispherical and was set approximately 1 meter above the ground to simulate a car bomb. Blast overpressure was expected to be 28.5 psi (196 kPA) with an effective positive duration of 7.4 milliseconds (msec).

Blast pressure was measured free field or incident at 13.5 psi. (92.7 kPA). The reflected pressure that the glazing actually experienced with this blast load can be calculated to be at 36.4 psi. (249 kPA). This peak pressure is indicative of a 200 lb. (91 kg.) TNT explosive based upon analysis of the peak pressure and positive durations using the standard blast pressure curves. This blast exceeded the design blast capacity predicted by the BLASTOP computer program for the single sheet of polycarbonate with a low probability of failure within the elastic response range. While there is an overwhelming consensus among engineers of blast resistant structures in support of the view that the air-gapped glazing adds considerable strength, a design theory to quantify this added benefit has yet to be developed.

Both windows survived the blast tests without any spall or disengagement from the frame. This was in marked contrast to some laminated glass samples in the same blast trials where most of the surviving panes exhibited disengagement and spall. The outer pane of the Insulgard 534 window was cracked, but remained fully engaged in the pane. The polycarbonate inner pane was undamaged. The single sheet of Lexan MP1000 was undamaged. The glazing retained considerable residual blast, physical security, and ballistic protection.

For the first time, pressure measurements were made in the interstitial space in the air-gapped glazing. A pressure of 18 psi maximum overpressure was recorded. This indicates that both panes are truly sharing the blast load. It also provides the first preliminary evidence that the back polycarbonate pane is seeing less than the full pressure. If a rise time proves to be discernable in the interstitial pressure, principles of structural dynamics will dictate that the back polycarbonate also will react less fully to the dynamic aspect of the blast load. This is because the pressure rise time is dependent on the finite time required for the structural response of the outer pane.

The second test series tested polycarbonate-based glazing well above the design load. A 59.4 by 47.6 inch (1.51 x 1.21 meters) Insulgard 322 glazing was tested at 68.6 feet (20.9 meters) from a 150-pound (68 kg.) TNT equivalent charge weight of a military explosive. The cross-section of the glazing was 1/2-inch (12.7 mm.) laminated glass on the outboard side facing the explosive, a 1/2-inch air-gap, and a 1/2-inch thick MP500 Lexan polycarbonate. The design blast capacity of this glazing by the elastic strength of the polycarbonate is 6.1 psi with an effective positive duration of 10.6 msec. The actual blast load anticipated was 13.4 psi reflected pressure at this duration. The BLASTOP computer code predicts an 80 to 85% probability of failure based upon this blast overload. The measured blast load was 6.1 psi (41.9 kPA) incident overpressure. This directly correlates to a reflected overpressure of 14.25 psi (98.0 kPA) acting upon the window. These pressures are typical of an ideal TNT explosive of 160 lbs. (72.6 kg.). This glazing survived this load without spall although the outer laminated glass pane was shattered and partially disengaged. The window prevented any blast pressure leakage while also maintaining a weather-proof seal. Additionally, this glazing would also provide considerable physical security post-blast.

A sheet of MP500 1/2-inch (12.7 mm.) Lexan also was tested during this blast at the 15-meter (49.2 feet) distance to probe the ductile capability of polycarbonate. This was the first test in the engineering literature to test the ability of polycarbonate to respond beyond the plastic limit. The pane was mounted in a frame fabricated from standard steel angles which were previously used by another manufacturer during the blast trials. The clear viewing area of this pane was 73.75 by 34.25 inches (1.87 x 0.87 meters) with a 1.675-inch (42.5 mm.) bite or frame rebate. The actual blast load was 35.9 psi reflected pressure with an effective positive pressure duration of 6.4 msec. The measured incident air blast was 13.3 psi (91.6 kPA). Similar to the first test, these peak blast overpressures and durations are typical of a 200 lb. (90.7 kg.) TNT explosive. The elastic design capacity of this pane as calculated by BLASTOP is 9.6 psi at this duration of positive pressure. The research computer program POLYDUCK was written and used to design this glazing with a ductility factor of 1.2. The program predicted that the glazing would survive a 300% blast overload beyond elastic design, but would need a bite of at least 2 inches (50.8 mm.). This indicated that some pull out of the frame might occur.

The glazing survived the test with a large deflection and partial disengagement. The middle of the pane was deflected 9-1/2 inches (241 mm.). It held this deflection until removed from the frame by the pulling power of a fork lift when it returned to its original shape. The polycarbonate did not spall and any blast leakage into the structure was minimal as the leakage orifice was small and no leakage occurred until most of the overpressure had decayed. The test indicated that the POLYDUCK program may be a good predictor of performance.

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