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Blast Resistant Fenestration Design & Testing

INTRODUCTION

Blast resistance remains a top priority for high-risk government, defense, and financial buildings. Windows, doors, and skylights are, in most instances, the points of vulnerability when considering a structure's ability to withstand explosive forces and protect its occupants. It is critical that these components be designed to the appropriate standard and thoroughly tested to validate their in-field performance. In fact, many government agencies, private building owners, consultants, and engineering firms mandate that their building components be tested and subsequently rated based upon their ability to mitigate the effects of blast events as well as threats from ballistic and forced entry attack. This article summarizes the characteristics and effects of blast waves, and discusses the hardware, software, and methodology that allows their simulation within a test environment.

BACKGROUND

During any blast-type event, building occupants can be injured or killed by: direct exposure to blast loadings (pressure or shock waves), the impact of fragments and debris, impact with surroundings when either a structural element or the person is impelled by the blast wave, or structural collapse.

Of these, limiting the impact of debris is particularly important in the case of fenestration (windows, doors, and skylights). Statistics show that approximately 80 percent of the injuries resulting from blast events are caused by airborne shards of glass from broken windows. These glass shards can fly inward at speeds greater than 200 feet per second (136 mph).

Blast Characteristics

When an explosion occurs, there is a near instantaneous heating and subsequent expansion of the surrounding air, which results in the formation of a shock wave. The shock wave travels away from the source in a radial fashion at supersonic speeds, while also decreasing rapidly in magnitude. This decrease in magnitude is modeled using the inverse cube of the distance from the explosion site.

The archetypal blast waveform features a positive phase that is characterized by a virtually instantaneous rise to the peak overpressure and rapid exponential decay until it reaches a value of zero. At this point, air backfills the vacuum that is created as the blast wave passes. This is termed the negative pressure phase.

The peak pressure of the blast, which is dependent on the charge weight, and the time over which the initial pressure wave decays to zero together define the impulse energy delivered. While peak pressure is applied instantaneously, the delivered energy or impulse is cumulative.

For most architectural design purposes, the blast impulse or blast loading waveform may be simplified and assumed to be of a triangular shape with the peak overpressure decaying linearly to ambient pressure in a time known as the positive phase duration. In this case, the impulse is simply the area of a triangle as shown in Figure 1. The impulse is calculated using Equation 1, where I is the impulse in (psi-ms), P is the peak pressure (psi), and t_d is the duration time in (ms).

$$I = (½)\ t_d \bullet P \qquad \textit{Equation 1}$$

A more precise characterization may be obtained using a software package that implements the standard Kingery-Bulmash air blast equations used in most Department of Defense (DoD) technical manuals. Alternatively, tables of pre-determined shock parameters may be used to estimate blast pressure and impulse.

When a shock wave encounters a structure, it may be reflected. The reflection causes a pressure load on the structure that also has a peak pressure and impulse. In general, the reflection is a function of the angle of incidence. For the portions of the structure that are perpendicular to the shock wave propagation (zero angle of incidence), the reflected pressure is maximum and greater than that of the original shock wave. For portions of the structure that are parallel to the shock wave propagation (90° angle of incidence), the reflected pressure is approximately equal to the free field pressure of the explosion. As the shock wave traverses, highly damped pressure oscillations occur as the pressure returns to its ambient value. This results in a negative phase pressure in both the free field and reflected pressures. It is the reflected pressure and impulse that the designer must consider when evaluating a structure or its fenestration. Figure 2 illustrates the interaction between a shock wave and a building.

Since a shock wave is characterized by both magnitude and time, it is a dynamic load. Accordingly, the fenestration element will have a dynamic response which is dependent on both the strength and stiffness of the product. Common fenestration materials have different physical and mechanical properties; thus, their dynamic response can be substantially different between two shock waves of identical peak

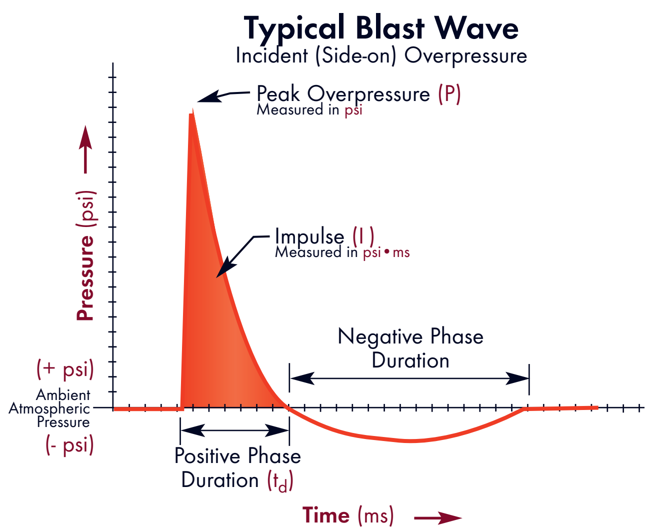

Figure 1. Blast wave diagram (courtesy of American Architectural Manufacturers Association (AAMA))

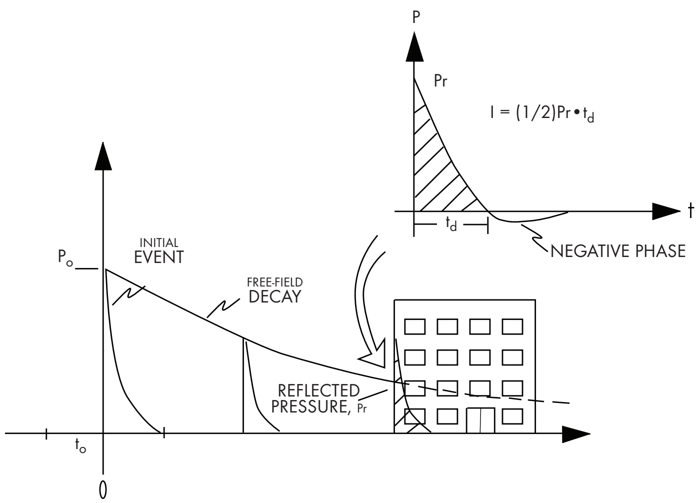

Figure 2. Shock wave interaction with a building.

pressure, but different impulses. If the period of the shock wave is closely matched to the natural period of the component, there may be an amplification of the component response analogous to resonance. Therefore, it is important to evaluate the product at precisely the specified shock wave conditions and for the exact construction intended for the project.

DESIGNING BLAST RESISTANT FENESTRATION

To mitigate the hazards posed by flying glass fragments, window system designs should be balanced, meaning that the glazing*, frames, and anchorage are able to survive a blast loading. In general, if one part of the system fails, the entire system will fail. Similarly, if the system has a higher capacity than the supporting wall, when the wall fails the entire window system may be blown into the facility.

The basic criteria for the design of blast-resistant or blast mitigating fenestration systems are that the glass should remain intact and in the frame, broken but not blown out; the frame must stay attached to the wall; and the wall must remain intact to hold the frame. Protective glazing measures would also be appropriate for buildings that are located near high risk targets, even though the buildings themselves are not considered a target.

To predict the behavior of glass under a blast load damage models should be developed for windows, and the glazing hazard levels determined. These models can be used to predict the outcome of various blast loads. Engineers prepare these models using software such as WinGard†, Winlac‡, and HazL§, developed by US Government agencies. The developed damage models are in the form of resistance-deflection functions, describing how glass deflects and breaks under pressure and how the glass shards are projected once released from the windows. Pressure-impulse (P-I) diagrams, derived from the resistance-deflection functions, help to rapidly analyze windows under a range of loads.

Once the damage functions are set, the applied blast load for each window is plotted on the P-I diagram and the resulting damage level is recorded. A graphic of the damage levels for existing windows helps to visualize the high hazard areas, and the potential for personnel injury. Such analyses, however, are typically done on a component basis only and to different design methodologies. That is, the glazing is analyzed for fragmentation potential with simplified theoretical boundary conditions; frame members are analyzed for deflection and stress without considering the structural integrity of the glazing; and connections and anchors are analyzed for ultimate strength. Estimating a total system response by aggregating these individual analyses often results in a very conservative design. Physical testing of the complete assembly to the actual design loads provides a more realistic validation of the assembly.

Performance Standards

To ensure that components are manufactured and buildings are designed to meet the challenges of blast resistance, standards have been developed. The two most widely used glazing performance standards and hazard-classification schemes are published by the General Services Administration (GSA) and the DoD.

General Services Administration

The GSA first published its *Security Criteria*, which includes criteria for mitigating risk from window glass fragments, in 1997. The Interagency Security Committee (ISC) later adapted these criteria for at-risk facilities of all federal agencies, except those under DoD jurisdiction. The GSA also developed GSA-TS01-2003, *Standard Test Method for Glazing and Glazing Systems Subject to Dynamic Overpressure Loadings* to provide guidelines for testing using actual explosive charges or simulated blasts.

The GSA documents define five performance conditions that indicate whether and how far glass shards penetrate into a room when the window and wall segment are subjected to a blast of specified peak pressure and impulse. The performance conditions are numerically defined on a scale from 1 ("safe" – the glass does not break and there is no visible damage to the glazing or frame) through 5 ("low" – the glass fails catastrophically, projecting fragments more than 10 feet from the window to impact a vertical surface [wall or test "witness panel"] more than two feet above the floor).

Department of Defense

In parallel with the GSA/ISC efforts, the DoD has developed standards of its own known as Unified Facilities Criteria (UFC). The most applicable is UFC 4-010-01, entitled *Minimum Antiterrorism Standards for Buildings*. More stringent than those required by the GSA/ISC Security Criteria, this criteria defines its own levels of protection or hazard ratings and, in the architectural category, includes minimum requirements for windows, skylights, and doors in new and retrofitted buildings.

UFC 4-010-01 defines five Levels of Protection based on likelihood and degree of building collapse and personnel injury due to flying glass fragments. These levels of protection are established once the standoff distance is determined and are similar to, but described differently from the performance conditions and protection levels cited in the GSA standard. The levels of protection are summarized in Table 2.1, page 2-7 of UFC 4-010-01.

To minimize the hazards caused by flying glass fragments, UFC 4-010-01 prescribes specific provisions for new and replacement glazing and window frames, noting that "window and door designs must treat glazing, frames, connections, and the structural components to which they are attached as an integrated system."

PERFORMANCE CERTIFICATION AND TESTING

UFC 4-010-01 states that it is acceptable to dynamically test window and skylight systems to determine their performance as equivalent to or better than their applicable hazard rating. This may be done as an alternative to the prescriptive provisions of the standard. Such testing includes the entire window or skylight system and connections, and is conducted in accordance with ASTM F 1642 -04, *Standard Test*

Table 1. Arena test advantages and disadvantages.

Advantages	Disadvantages
• Most accurately reproduces the blast waveform • Several products can be tested simultaneously • Few specimen size limitations	• High cost • Area required must be quite large with long standoff distances, and be isolated from the public • Requires multiple test chambers (witness rooms) and instrumentation if multiple tests are conducted with one blast • Long set-up time for initial and repeat test runs • Subject to weather variations

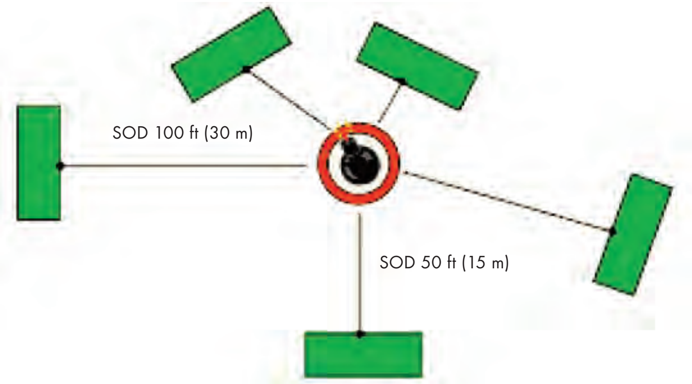

Figure 3. Arena test set-up. Diagram courtesy of American Architectural Manufacturers Association.

Method for Glazing and Window Systems Subject to Airblast Loadings.

Testing reveals problems such as inadequate fasteners, excessive frame deflection, or brittle failure. Testing and the subsequent analysis is a useful tool for designers, architects, consultants, and manufacturers since it aids in the development of improved products that better mitigate the glass fragmentation hazards.

To conduct the tests necessary to qualify a fenestration system, a fully glazed and assembled mock-up must be prepared using approved shop drawings. Since the method of installation for a blast mitigating product is as important as the product itself, it must also be evaluated during the testing. Therefore, the mock-up must accurately represent the project in every detail, including glazing, hardware, operation, installation and the type, number, arrangement, and orientation of the anchoring fasteners. Tests may be conducted in an open air arena with live explosives or using a shock tube.

Arena Test

The arena test is an open-air test in which a test subject is installed in a support structure and exposed to an actual explosion. For arena tests, the characteristics of the blast wave (peak pressure and impulse) are determined from handbooks or with computer software. These characteristics are then used to select an appropriate explosive weight based upon the available standoff distance (SOD) at the arena test facility. Figure 3 shows an example test set-up. The advantages and disadvantages of the arena test are summarized in Table 1.

Shock Tube Test

The shock tube test uses a pressure vessel charged by air or nitrogen to test a sample. The key components are illustrated in Figure 4.

The driver is a pressure vessel with an adjustable volume that is closed by membranes in the initiator flange. When the membranes burst, the rapid release of pressure creates a shock wave that is tuned by the expansion duct, cone, and shells to replicate the reflected pressure profile generated by the specimen.

For a particular charge weight and standoff, the characteristics of the blast wave (peak pressure and impulse) are determined from the same handbooks or computer software used in arena testing. The test engineer uses the parameters to set the shock tube driver volume, driver pressure, and shell configurations such that they replicate the blast wave. Shock tube configurations for various peak pressures and impulses are established by developing performance curves when the shock tube is commissioned. The advantages and disadvantages of the shock tube test are presented in Table 2.

Some shock tubes have data capture capabilities that include high-speed, high-resolution color digital video up to 5,000 frames per second and data collection rates up to 10,000,000 samples per channel per second. If equipped with a reusable test frame, fast test set-up and repeat testing are enabled. In addition, tests can be rerun with varied parameters simply “dialed in,” allowing repeated testing of specimens in rapid succession, typically ten tests per day, under a spectrum of conditions. Thus, shock tubes are well suited for balanced design validation by progressively increasing load on one window to establish glass break before frame failure.

Once the tests are completed, post-blast engineering analysis of blast parameters and shatter patterns determines the level of blast protection rating provided by a product.

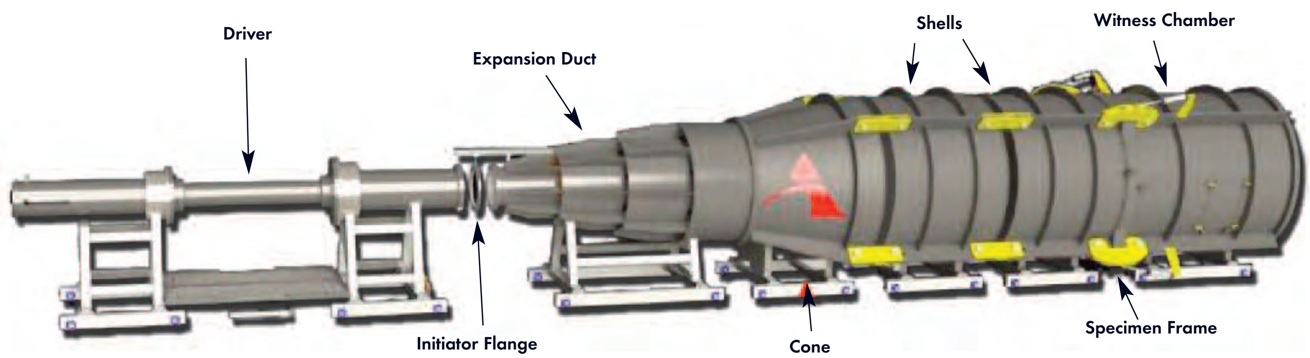

Figure 4. The key elements of a shock tube.

Table 2. **Shock tube test advantages and disadvantages.**

Advantages	Disadvantages
• Lower cost when compared to the arena test • Indoor environment permits control and reproducibility of test conditions • No weather delays • Rapid "test-adjust-retest" capability assists design efforts • Unique test parameters can be easily dialed in	• Limitations on peak pressure • Limitations on specimen size

BLAST CERTIFICATION

Once the test results and analyses are completed, blast-resistant fenestration products may be third-party certified by programs that include laboratory testing, validation of the manufacturer's quality assurance program, and plant inspections.

Certification can take either a "product-specific" path by testing at an ISO 17025-accredited laboratory according to UFC, GSA or other accepted performance standards, or a "project specific" path by testing to confirm compliance with individual project specifications and approved shop drawings. Either path requires continued, demonstrated compliance with ICC-ES AC10 quality control documentation requirements at the manufacturing plant and verification. Each certified product and actual installation must comply with the referenced standards, as confirmed during periodic on-site audits of manufacturing plants and installation sites.

CONCLUSION

While comprehensive protection against the range of possible threats may be cost prohibitive, an appropriate level of protection intended to lessen the risk of mass casualties resulting from blast-type events can be provided for all personnel at a reasonable cost.

Testing and rating of the ability of blast-resistant fenestration products to meet current standards, while not a guarantee of absolute safety, is the best way to maximize protection while optimizing building enclosure design to meet all building and site functional requirements. In general, the lower cost and fast turnaround of shock tube testing is likely to result in more products being tested and verified for blast-resistant performance than if arena testing alone is used.

NOTES

* Window glazing is the glass portion of the window assembly.

† Window Glazing Analysis Response Design. This software was the first available for the prediction of glass hazards and has become a national standard used by many agencies. A state-of-the-art method to analyze and predict the behavior of window glass under blast loads, this program calculates and graphically displays the response of window systems subjected to blast loads. WinGARD is available for download at www.oca.gsa.gov.

‡ Window Lite Analysis Code. Versions 4.0 and later are derivative versions of the WinGARD GSA code adapted to meet the unique requirements of the US Department of State.

§ Window Fragment Hazard Level Analysis. This program calculates the glazing response to a blast loading and provides a debris transport model for predicting fragment trajectory. It allows modeling of monolithic glass or plastic windows, laminated windows, insulated glass units and windows retrofitted with anti-shatter film. HazL is available for download from https://pdc.usace.army.mil/software/hazl/.

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