Designer's
NOTEBOOK
BLAST CONSIDERATIONS

## Design Considerations for Blast Resistance of Architectural Precast Concrete Façades

PCI's Architectural Precast Concrete Services Committee discusses items to consider in designing for blast resistance.

Glazing

The façade is comprised of the transparent glazing and opaque exterior wall elements. The glazing, a blast sensitive element, is the first building component likely to fail in response to the initial blast pressure that engulfs the building. Although the opaque wall elements may be designed to resist the loading, the options available for the glass are much more limited. These options include selecting an appropriate type of glass, applying security window (fragment retention) film, installing blast curtains/shields, and / or using laminated glass. Due to the extreme intensity of the blast pressures, all glazing on the blast side of the target structure will fail for most car bomb threats. There is a direct correlation between the degree of fenestration and the amount of debris that enters the occupied space. Historically, failed window glazing due to the direct pressures produced by an explosion has resulted in a considerable proportion of injuries, casualties and loss of use of the facility.

The two keys to protecting the workspace are attempting to prevent the windows from failing and then ensuring that the windows fail properly if overloaded. While a great number of injuries are related to flying glass shards, it is not the only significant source of injury though usually a more visible one. The other visible cause of injury is falling debris. One of the less visible causes of injuries is blast pressure, which can rupture the ear drum, collapse the lung, or even crush the skull. These injuries, which begin at pressures near 15 pounds per square inch (psi), can be reduced if the level of blast pressures entering the space is curtailed. The amount of blast pressure that enters the space is directly proportional to the amount of openings on the façade of a structure. Also, smaller windows will generally break at higher pressures than larger windows, making them less prone to breakage. Consideration should be given to designing narrow recessed windows with sloped sills because they are less vulnerable to blast (see Fig. 13) .To the extent that nonfrangible glass isolates a building's interior from blast shock waves, it can also reduce damage to interior framing elements (e.g., supported floor slabs could be made to be less likely to fail due to uplift forces) for exterior blasts.
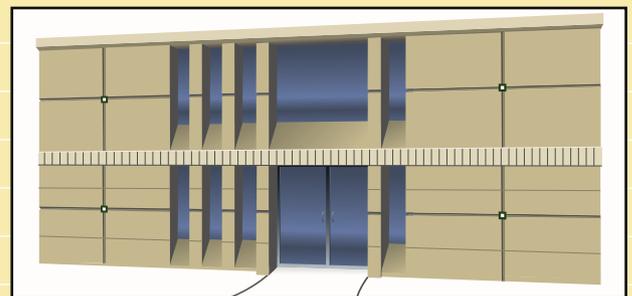
Fig. 13 – Narrow and recessed windows with sloped sills. Source: U.S. Air Force, Installation Force Protection Guide

In embassies, the earliest type of civilian building designed to resist blast events, fenestration is limited to 15 percent of the effective wall area (calculated using the floor-to-floor height and width of a single bay). While this helps in the protective design, it does not provide the proper lighting or open feeling that is desired in modern office buildings; therefore, the fenestration limitations may be increased to 40 percent for commercial buildings.

The second design aspect for windows is to ensure that they fail properly if overloaded. Special blast resistant windows can be designed not to fail for the small to mid-sized opening described above, provided that the loading is limited. Annealed plate glass, the most common form of architectural glass, behaves poorly when loaded dynamically.

While typical annealed plate glass is only capable of resisting, at most, 2 psi (14 kPa) of blast pressure, there exist several other types of glazing that can resist moderately larger blast pressures. Thermally Tempered Glass (TTG) (ANSI Z97.1 or ASTM C1048) and Polycarbonate glazing, also known as bullet-resistant glass, can be made in sheets up to about 1-in. thick and can resist pressures up to about 30 to 40 psi (200 to 275 kPa). Laminated (60 mil interlayer thickness) annealed glass with a 1/4-in (6mm) bead of structural sealant around the inside perimeter exhibits the best post-damage behavior and provides the highest degree of safety to occupants. The lamination holds the shards of glass together in explosive events, reducing its potential to cause laceration injuries. The structural sealant helps to hold the pane in the frame for higher loads. For insulated units, only the inner pane needs to be laminated. Associated with each of these upgrades is a considerable increase in cost for the glazing material. Also, the window bite (i.e., the depth of window captured by the frame) needs to be at least 1/2-in.

Equally important to the design of the glass is the design of the glazing system and the framing to which the glazing is attached. Glazing, frames, and attachments must be treated as an integrated system and be capable of resisting blast pressures and transferring the loads to the cladding to which the frame is attached. To fail as predicted, a window must be held in place long enough to develop the proper stresses that cause failure. Otherwise, the window may disengage from its frame intact and pose a post-event threat or cause serious damage or injury. Therefore, the frame and anchorage should be designed to develop the full loading anticipated for the chosen glazing type. Depending on the façade, the cladding panels to which the windows are attached must be able to support the reaction forces of a window loaded to failure.

Window frames and mullions of steel, steel reinforced aluminum, and heavy walled aluminum are common for blast resistant framing components. Frames, mullions, and window hardware should be designed to resist a minimum static load of 1 psi (7 kPa) applied to the surface of the glazing or a dynamic load may be applied using the peak pressure and impulse values. However, designing for 1 psi static loading will not necessarily ensure that the window frames, mullions and anchorages are capable of developing the full strength of the laminate interlayer. The equivalent static value is dependent on the type of glass, thickness of glass, size of window unit, and thickness of laminate interlayer utilized. Also, a static approach may lead to a design that is not practical, as the mullion can become very deep and heavy, driving up the weight and cost of the window system.

The loading of the frame will depend on the design blast pressure and the size of the window. As a minimum, frame connections to surrounding walls should be designed to resist a combined ultimate loading consisting of a tension force of 200 lbs/in (35 kN/m) and a shear force of 75 lbs/in (13 kN/m). Typically, this requires a plate with anchors rather than a simple bolted connection. Frame supporting elements and their connections should be designed based on their ultimate capacities. In addition, because the resulting dynamic loads are likely to be dissipated through multiple mechanisms, it is not necessary to account for reactions from the supporting elements in the design of the remainder of the structure. Additional reinforcement should be provided at window openings. Vertical and horizontal reinforcement that would have occupied the opening width should be evenly distributed on each side. Also, shear reinforcement should be provided as required around the opening.
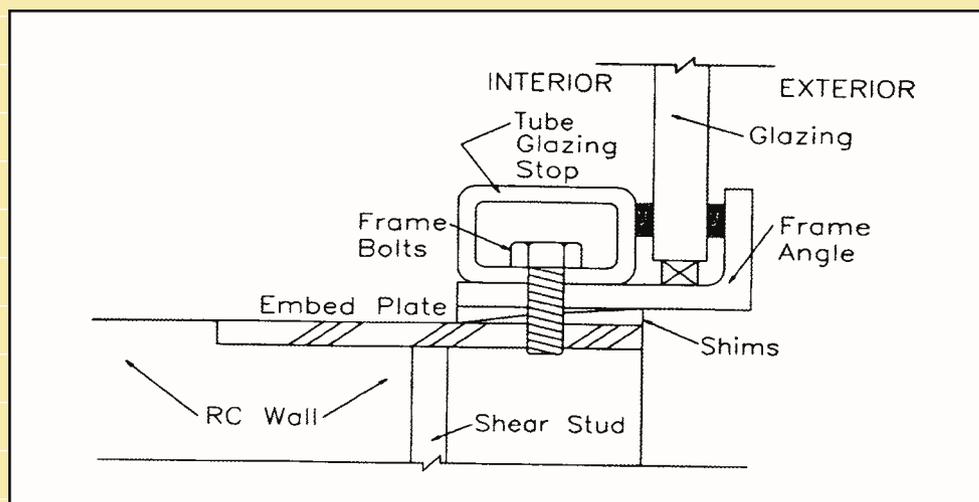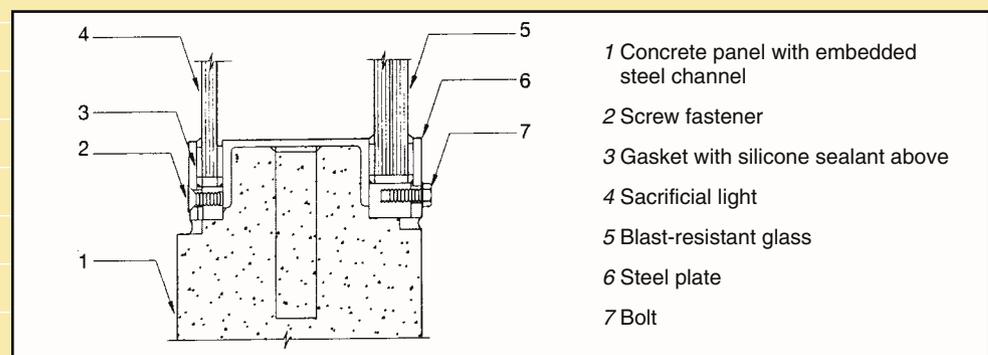

Fig. 14 – Generic blast window glazing and frame detail.
Source: Structural Design for Physical Security: State of the Practice, Structural Engineering Institute of American Society of Civil Engineers, Reston, VA, 1999.

Fig. 14 shows a typical section through a frame containing a blast window. The primary elements include an inner frame holding the glazing and an outer frame anchored to the structure. The inner frame consists of a frame angle and glazing stop. The frame angle is typically an A36 angle cut to the desired dimensions. The glazing stop is fabricated from a structural angle, a structural tube (as shown), or an A36 bar with countersunk holes. The entire inner frame is designed to allow replacement of the glazing. Windows are typically factory-glazed and mounted in the window openings as a complete unit.

The window is held and supported by continuous gaskets on the inside and outside faces of the glazing. Neoprene gaskets are used for glass and santoprene is used for polycarbonate/glass lay-ups. Setting blocks provide a cushion for the glazing and clearance for thermal expansion and rotation of the glazing during blast loading.

The outer frame, referred to as an embed, is fabricated from A36 plate, channel, or angle depending upon the particular geometry of the concrete wall and architectural treatment. The embed shown in Fig. 14 consists of a 1/2 in. x by 6 in. (1 cm x 15 cm) steel plate. The inner frame is connected to the embed using high-strength bolts in drilled and tapped holes in the embed plate. Shim space should not be greater than 1/4 in. to minimize the length of the frame bolts. Corrosion resistant, usually stainless, shims are placed at each bolt when required. The frames may be cantilevered out from the edge of the wall to reduce the recessed distance when a thick architectural façade is used. This cantilevered distance is usually not greater than 1.5 in. (4 cm).

The blast-resistant glazing for the Lloyd D. George Federal Building and United States Courthouse, Las Vegas is a 1 inch (24 mm) thick insulating unit composed of an annealed exterior light, a 1/2 inch (12 mm) air space, and a laminated interior lite held in place by an aluminum frame, Fig. 15. The inboard lite is composed of a polyvinyl-butral layer between two sheets of 1/8 inch (3 mm) thick annealed glass. This design uses annealed glass in lieu of the stronger tempered glass because it has more flexible properties, which absorb the impact of the explosion.

1 Concrete panel with embedded steel channel
2 Screw fastener
3 Gasket with silicone sealant above
4 Sacrificial light
5 Blast-resistant glass
6 Steel plate
7 Bolt

Fig. 15 – Blast-resistant glazing detail.

Window glazing assessments and designs for blast response may be performed using one of the government produced and sponsored computer programs such as WINGARD (WINdow Glazing Analysis Response & Design). This computer program was developed by the US General Services Administration and is available to Government Agencies and their contractors. WINGARD may be downloaded from the GSA's Office of the Chief Architect web site (www.oca.gsa.gov) or obtained from the developer (Applied Research Associates, 119 Monument Place, Vicksburg, MS 39180). The engineer should define the structural design criteria and coordinate with the building's architect to assure the window manufacturer's correct interpretation.

Drawbacks of high-performance glazing systems include cost and high maintenance. When the cost for installing blast-resistant windows is significant relative to the total cost of the

building, resources allocated to protective design may be better applied toward upgrading the structural frame to be blast resistant. This is because the blast pressures from a close in car or truck bomb can far exceed the allowable pressures any window system can resist. As a point of reference, façade blast pressures in the Oklahoma City bombing were on the order of 4,000 psi - 100 times higher than the design pressures described above.

Atriums incorporating large vertical glazed openings on the building façade, common in prestigious office buildings, cannot be designed to withstand blast pressures from a close-in explosion. It is not reasonable to harden the exterior walls of the structure and leave an atrium's exterior wall of this type as an inviting target. Atrium balcony parapets, spandrel beams, and exposed slabs must be strengthened to withstand loads that are transmitted through exterior glass or framing. Another approach is to use an internal atrium with no outward facing windows or an atrium with clerestory windows that are close to the ceiling and angling the windows away from the curb to reduce the pressure levels.

Initial Costs

The initial construction cost of protection has two components; fixed and variable. Fixed costs include such items as security hardware and space requirements. These costs do not depend on the level of an attack; that is, it costs the same to keep a truck away from a building whether the truck contains 500 or 5000 lbs. of TNT. Blast protection, on the other hand, is a variable cost. It depends on the threat level, which is a function of the explosive charge weight and the stand-off distance.

The optimal stand-off distance is determined by defining the total cost of protection as the sum of the cost of protection (construction cost) and the cost of stand-off (land cost). These two costs are considered as a function of the stand-off for a given explosive charge weight. The cost of protection is assumed to be proportional to the peak pressure at the building envelope, and the cost of land is a function of the square of the stand-off distance. The optimal stand-off is the one that minimizes the sum of these costs.

If additional land is not available to move the secured perimeter farther from the building, the required floor area of the building can be distributed among additional floors. As the number of floors is increased, the footprint decreases, providing an increased stand-off distance. Balancing the increasing cost of the structure (due to the added floors) and the corresponding decrease in protection cost (due to added stand-off), it is possible to find the optimal number of floors to minimize the cost of protection.

Though it is difficult to assign costs to various upgrade measures because they vary based on the site specific design, some generalizations can be made (see Fig. 16). In some cases, the owner may decide to prioritize enhancements, based on their effectiveness in saving lives and reducing injuries. For instance, measures against progressive collapse are perhaps the most effective actions that can be implemented to save lives and should be
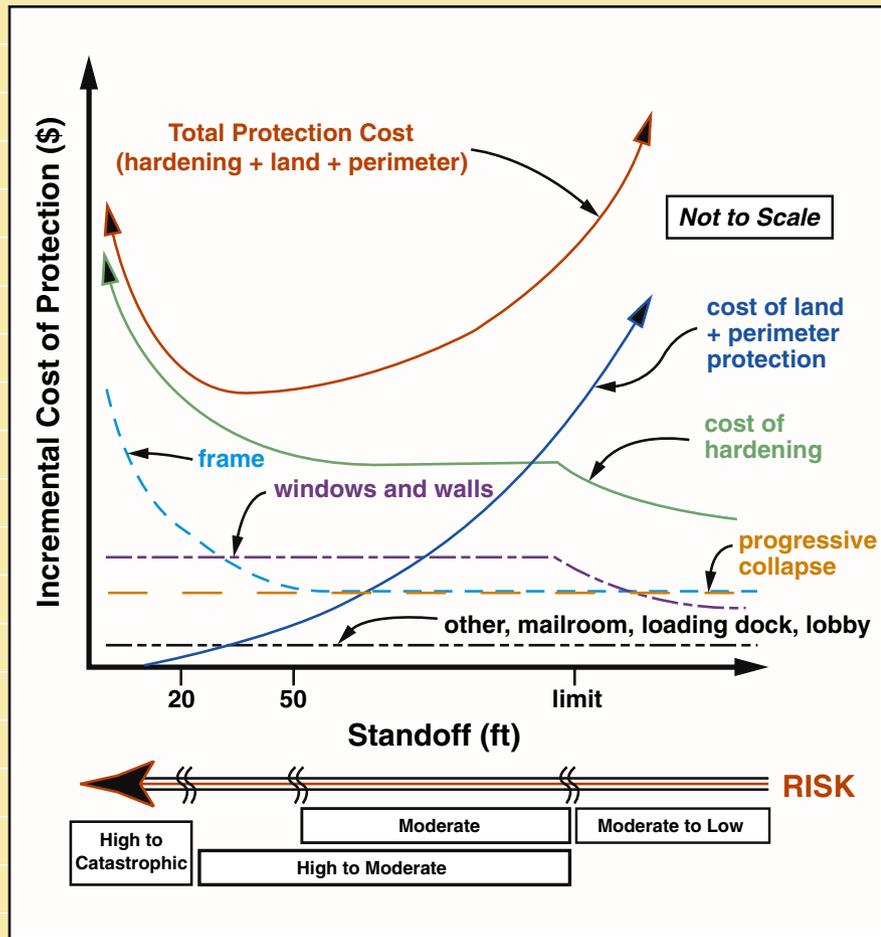
Fig. 16 – Plots showing relationship between cost of upgrading various building components, standoff distance, and risk.
Source: Federal Emergency Management Agency. Primer for Design of Commercial Buildings to Mitigate Terrorist Attacks. FEMA 427 (Washington, DC: Federal Emergency Management Agency, December 2003).

considered above any other upgrades. Laminated glass is perhaps the single most effective measure to reduce extensive non-fatal injuries.

An awareness of a blast threat from the beginning of a project helps to decide early what the priorities are for the facility. Including protective measures as part of the discussion regarding trade-offs early in the design process often helps to clarify the issues. Ultimately the willingness to pay the additional cost for protection against blast hazards is a function of the "probability of regrets" in the event a sizable incident occurs. In some situations, the small probability of an incident may not be compelling enough to institute the design enhancements. Using this type of logic, it is likely to lead to a selection process in which buildings stratify into two groups: those that incorporate no measures at all or only the most minimal provisions and those that incorporate high levels of protection. It also leads to the conclusion that it may not be appropriate to consider any but the most minimal measures for most buildings.