Title: **Protective Design: Saving Lives Through Structural Engineering**

Authors: Robert Smilowitz, Principal, Weidlinger Associates
Tod Rittenhouse, Principal, Weidlinger Associates

Subject: Structural Engineering

Keywords: Façade
Life Safety
Structure

Publication Date: 2003

Original Publication: CTBUH Journal, Spring 2003

Paper Type:
1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

Protective Design: Saving Lives Through Structural Engineering

Tod Rittenhouse and Robert Smilowitz

In recent years the engineering community has had to consider new design criteria, the terrorist explosive threat. Whether developing new or renovation projects, protective design and dynamic analysis has become part of the structural engineering service. The difficult task faced by design teams is to create facilities that are desirable workspaces while at the same time provide protection from terrorist explosive threats. Typically situated on urban sites, these structures are limited in the ability to restrict terrorist access to effective keepout distances and architectural design criteria often violates the blast-mitigating objectives. Given these conditions, along with the limited resources dedicated to physical protection, the design objectives are to protect life safety for the occupants. However, physical security alone does not assure a safe structure. A comprehensive security plan requires a balance between operational, technical and physical security measures. When site conditions do not provide adequate keep-out distance, or technical security

The difficult task faced by design teams is to create facilities that are desirable workspaces, while at the same time providing protection from terrorist explosive threats.

does not identify an explosive device, or lapses in operational security permit threats to approach the structure, then physical security is required to provide the last line of defense.

The four basic features of physical protection for buildings involve the establishment of a secure perimeter, the prevention of progressive collapse, the isolation of internal threats from occupied spaces and the mitigation of debris resulting from the damaged façade. Other considerations, such as the tethering of non-structural components and the protection of emergency services, are also key design objectives that require special attention. The size of the explosive threat will determine the effectiveness of each of these protective features and the extent of resources needed to protect the occupants. The selection of the appropriate threat is fundamental to the design process and therefore requires careful consideration.

Defined Threat and Standoff Distance

The definition of the design threat is based on history and expectation; however, it is limited in size by the means of delivery. Conventional explosives weigh approximately 100 pounds per cubic foot. Therefore, a small hand-carried device could easily be concealed in a large brief case or small luggage. The hand carried satchel threat, though limited in size may be introduced deep into the structure where it can do considerable damage. As a result, screening stations at the entrances, mailrooms and loading docks provide the best means of preventing these threats from entering the occupied spaces. A vehicle can carry significantly larger explosive charge weights. As a result, perimeters must be secured and the presence of underground parking or loading docks require comprehensive screening procedures. Physical protection recognizes the limitations of screening procedures and the potential for threats to bypass their scrutiny. Therefore, the selection of the design level explosive threat depends on the features of the building, the site conditions and the level of risk the client is prepared to accept.

The intensity of the blast is a function of the charge weight and the standoff distance to the protected space. Charges situated extremely close to a target structure impose a load over a localized region of the structure. At greater distances, the intensity of the peak pressure is significantly reduced, however, the surface area over which it acts is much greater. As a result, the hazard potential in increased over a larger portion of the structure.

The intensity of the blast is a function of the charge weight and the standoff distance to the protected space. Charges situated extremely close to a target structure impose a load over a localized region of the structure.

While it may be possible to predict effects of a given charge weight at a specified standoff distance, the actual charge weight of explosive used by the terrorist, the efficiency of the chemical reaction and the source location are not reliably predictable. One approach, adopted by regulatory agencies is the use of predefined levels of protection. These levels are associated with a perceived risk to the facility and are based on relative costs to mitigate the hazards. The perception of risk considers factors such as symbolic importance, criticality and consequence of loss. Although this approach provides a framework for performing a risk analysis, once the perception of risk is acknowledged, the most rational assumption regarding the charge weight of the terrorist threat, is to determine the capacity of the delivery vehicle. Given the uncertainties, the most significant observation which one draws from blast pressure phenomenology is that the most effective means of protecting a structure is to keep the bomb as far away as possible, by maximizing the keep-out distance.

To guarantee the maximum keep-out distance, sufficiently sized anti-ram bollards or large planters must be placed at the curb around the perimeter of the building. Furthermore, public parking abutting the building must be secured or eliminated, and street parking should not be permitted adjacent to the building.

Façade and Glazing

The building's exterior is its first real defense against the effects of a bomb. The key to protective glazing is preventing blast waves and broken glass shards from entering the building. Therefore the design philosophy might best be served by concentrating on the improvement of the post-damaged behavior of the façade. For new construction, this may correspond to the specification of laminated glass. For existing glazing, this may correspond to the application of an anti-shatter film. While these features will do little to improve the strength of the glass, they attempt to hold the shards of glass together and better protect the occupants from hazardous debris. The effectiveness of Mylar films depends on the method of application and the thickness of the film. The common film systems range from a simple edge-to-edge (daylight) application to a wet glazed adhesion and finally a mechanical attachment to the existing window frame. The mechanical attachments are most effective when they are anchored to the underlying structure. Regardless of the method, there are architectural issues and life cycle costs associated with the use of anti-shatter films. Laminated glass possesses the best post-damage behavior, may be used with a wide variety of glazing materials and thickness, and provides the highest degree of safety to occupants.

> The key to protective glazing is preventing blast waves and broken glass shards from entering the building.

Equally important to the design of the glass is the design of the window frames. For the window to properly fail, the glass must be held in place long enough to develop the proper stresses that cause failure. Short of that, the glazing will dislodge from the housing intact and cause serious damage or injury. Therefore, the frame system should be designed to develop the full capacity of the chosen glazing type. The bite, including the possible use of structural silicone sealant, must be adequate to assure the failed glass is retained within the frame. The mullions in turn must be capable of withstanding the reactions of a window loaded to failure. Finally, the walls to which these windows are attached, must be able to accept the reaction forces.

Beyond the simple punched window or ribbon window system is the curtain wall systems which can also be designed to withstand the effects of explosive loading. The effectiveness of this system is more dependent on the performance of the various elements that comprise the curtain wall system. While the glazing may be the most brittle component, the performance of the system and the reduction of hazard to the occupants depend on the interaction between the capacities of the various elements. In addition to hardening the individual members that comprise the curtain wall system, the attachments to the floor slabs or spandrel beams require special attention. These connections must be adjustable to compensate for the fabrication tolerances, accommodate the differential inter-story drifts and thermal deformations, and yet be designed to transfer gravity loads, wind loads and blast loads.

An alternative approach is to allow the window systems to absorb a considerable amount of the blast energy through deformation while preventing debris from entering the occupied space. Curtain wall systems, which are considerably more flexible than the conventional hardened windows, have been subjected to explosive tests and the flexibility of their response allowed the glazing to survive greater blast environments than rigidly supported counterparts.

Structural Response and Progressive Collapse

In addition to the hazard of impact by façade debris propelled into the building, the occupants may also be vulnerable to much heavier debris resulting from structural damage. Progressive collapse occurs when an initial localized failure causes adjoining members to be overloaded and fail, resulting in an extent of damage that is disproportionate to the originating region of localized failure. A protective design may avoid structural systems that either facilitate or are vulnerable to a progression of collapse resulting from the loss of a primary vertical load-bearing member. In particular, new facilities may be designed to accept the loss of an exterior column for one or possibly two floors above grade without precipitating collapse to an extent disproportionate to the original cause of the damage. These design requirements are intended to be threat independent, resulting in adequate redundant load paths in the structure should damage occur due to an unspecified abnormal loading. This threat independent requirement is intended to protect against an explosion of indeterminate size that might damage a single column. The upgrade of existing structures to prevent localized damage from developing into a progressive collapse may not be easily accomplished through the alternate path method. The loss of support at a column line would increase the spans of all beams directly above the zone of damage and require different patterns of reinforcement and different types of connection details than those typically detailed for conventional structural design.

Progressive collapse occurs when an initial localized failure causes adjoining members to be overloaded and fail, resulting in an extent of damage that is disproportionate to the originating region of localized failure.

Alternatively, columns may be sized, reinforced or protected to prevent critical damage resulting from the explosion of the design threat charge weight placed in close proximity to the column. The vulnerable concrete columns may be jacketed with steel plate or wrapped with composite materials, and the vulnerable steel columns may be encased in concrete to protect the cross sections and add mass. For the upgrade of existing structures, the strengthening approach offers a better opportunity to prevent a progressive collapse than attempting to supplement the capacity of the connecting beams and girders. However, the effectiveness of these approaches is predicated on the operational and technical security procedures that will limit the magnitude of the explosive threat. This includes the establishment of effective perimeter protection, adequate screening of vehicles entering an underground parking facility or loading dock, and inspection of parcels that may be hand carried into the building.

Transfer girders and the columns supporting transfer girders are particularly vulnerable to blast loading. Transfer girders typically reduce the load bearing system into a fewer number of structural elements which runs contrary to the concept of redundancy desired in a blast environment. Typically, the transfer girder spans a large opening, such as a loading dock, or provides the means to shift the location of column lines at a particular floor. Damage to the transfer girder may leave one or more columns, which terminate at the girder from above, totally unsupported. Similarly, the loss of a support column from below, will create a much larger span carrying critical load-bearing structure. Transfer girders are therefore critical structural elements whose loss may result in a progressive collapse. If a transfer girder is required and is vulnerable to an explosive loading, it is desirable that the girder be continuous over several supports and have substantial structure framing into it to create a two-way redundancy and thereby an alternate load path in the event of a failure.

Non-Structural Considerations

The walls surrounding the loading docks, mailrooms and lobbies, into which explosive threats may be introduced prior to inspection and screening, must be hardened to protect building occupants in adjacent spaces. Non-structural building components, such as piping, ducts, lighting units and conduits, must be sufficiently tied back to competent structure to prevent failure of the services and the hazard of falling debris. To mitigate this hazard, these non-structural systems should be located below the raised floors or tied to the ceiling slabs with Seismic Zone IV restraints.

The improved performance of a building in response to an explosive threat requires the services of a trained professional engineer, experienced in both the conventional and the protective design of structures. The design professional will be able to perform a blast Threat Assessment and Risk Analysis (TARA) to identify the vulnerabilities and hazards associated with a given facility. Working with the owner and the security staff, the protective design consultant will help balance the three disciplines of security services, operational, technical and physical that will combine to provide the desired level of protection within the available design budget.

About the Authors

Tod Rittenhouse, PE and Robert Smilowitz, PE are Principals of Weidlinger Associates Consulting Engineers. They both participated in the development of the US Department of State's Embassy Anti-Terrorist Design Guidelines and collaborated on the GSA/ISC Security Criteria. Together they have completed over 150 Embassy and GSA building evaluations, designs, and upgrades. Since September 11th 2001, they have provided similar services for the commercial non-government building community, who are now addressing the concern for building safety related to terrorist events. Mr. Rittenhouse is a member of the Council on Tall Buildings and Urban Habitat Task Force on Building Protection. Dr. Smilowitz was a member the World Trade Center Building Performance Assessment Team.