Blast Events

Building Design for Extreme Events

By J. David Hadden, Matthew A. Johann, and Brian J. Meacham

Figure 1: Blast-resistant Windows in the Scottish Parliament Building. ©Arup

The events of September 11, 2001, made it clear that terrorism can strike anyone, anywhere. Thousands of unsuspecting individuals were killed or injured inside buildings that most of those people likely thought were impenetrable and safe, and considered their homes-away-from-home. As the stark memory of those events begins to slowly fade, building occupants increasingly expect and demand that the buildings in which they live their daily lives be able to protect them from possible future attacks. Despite the horrific outcome of September 11, the World Trade Center towers and the Pentagon actually performed extremely well under circumstances far more severe than anything anticipated during their design; this demonstrates that buildings can play a vital role in protecting their occupants. Owners and designers have a responsibility to design and construct buildings that will do the best possible job of protecting the people that live and work inside of them.

The June 2006 issue of Structure presented an introduction to building design for extreme events, and the November 2006 issue detailed issues and mitigation approaches related to extreme fire events. The focus of this article is bomb blast mitigation. For more details on designing for bomb blast events, see Chapter 5 of the book *Extreme Event Mitigation in Buildings—Analysis and Design* [*Meacham and Johann 2006*], from which this article is derived.

Response of Buildings to Blast

When considering blast protection measures as part of a building's design, it is important to consider how blast loads may affect the building. Because blast loads are generally intense and transient, as opposed to gravity loads which are sustained, a building will react differently to blast loads than to the sustained loads that are traditionally used to guide structural design.

Traditional structural design must consider loads due to gravity, wind, and, (sometimes) soil pressure. Wind-induced dynamic effects may be important for tall, slender structures, but are frequently neglected for more average structures. For conventional buildings, gravity and wind can usually be treated as static, or sustained, forces that cause deformation of the structure proportional to their magnitude. The amount a structure deforms in relation to these forces depends on the stiffness of the building elements.

Summary of Significant Bomb Blast Attacks

Attacks against buildings have generally increased worldwide since September 11, 2001. However, bombing attacks against buildings and public spaces have long been a weapon of choice used by many terrorist organizations. The table below summarizes significant vehicle bomb attacks between 1946 and 2003.

Location	Year	Size of Bomb (kg TNT Equivalent)[1]	Number of People Killed[1]
St. David Hotel, Jerusalem	1946	350	91
U.S. Marine Barracks, Beirut	1982	5,550	242
U.S. Embassy, Beirut	1983	1,000	63
St. Mary Axe, London	1992	350	0[2]
World Trade Center, New York	1993	900	8[3]
Jewish Community Center, Buenos Aires	1994	275	26
Alfred P. Murrah Federal Building, Oklahoma City	1995	1,800	169
Khobar Towers, Dharan, Saudi Arabia	1996	2,300	20
U.S. Embassy, Nairobi	1998	275	213
Sari Club, Bali	2002	~750 - 1,000	202
Marriott Hotel, Jakarta	2003	220	12
Military Hospital, Mozdok, Chechnya	2003	1,000	50
HSBC Bank, Istanbul	2003	200	15

[1] Information on bomb sizes and the number of casualties was developed from a variety of published sources and may not agree in all cases with "official" figures.

[2] The bomb was detonated near midnight when few people were in the vicinity.

[3] The bomb was detonated in the parking garage in an attempt to collapse the building. Those killed were in the immediate vicinity of the blast.

Figure 2: Blast Damage to the Chamber of Shipping Building in St. Mary Axe, London, 1992. ©Arup

Unlike gravity and wind loads, a blast produces a dynamic load that induces motion into the structure. Inertia may contribute significantly to the building's total resistance to the blast load, to the extent that the stiffness of the structure does not play as important of a role as it does for static loads. The message to draw from this is that the response of a structure or building element to a dynamic load is fundamentally different from the way it responds to a static load.

An explosion can be defined as "a chemical reaction or change of state effected in an exceedingly short period of time with the generation of a high temperature and generally a large quantity of gas. An explosion produces a shockwave in the surrounding medium" [*Meyer et al 1987*]. In this context, a shockwave is "… an intense compression wave produced by the detonation of an explosive" [*Meyer et al 1987*].

The effect of an explosion is a rapid increase in air pressure in the immediate vicinity of the event, accompanied by a release of heat and light. This pressure increase causes a wave of highly compressed air to expand outward from the seat of the explosion. In general, structures experience blast events in the form of pressures applied to their external surfaces as the shockwave propagates past them. This shockwave is analogous to the outward propagation of the leading ripple on the surface of a pool of water into which a stone has been dropped.

The response of a structure to a blast loading will be both dynamic and nonlinear. The actual response will vary somewhat depending on the type of structural material used. Steel includes a significant amount of ductility, but at the same time is very stiff and strong. The combination of these properties results in a material that has a high degree of blast resistance. However, steel can still be vulnerable to damage by blast loads because steel shapes and connections are generally optimized to support the governing design loads as efficiently as possible. Because a blast loading may differ from the other design loads in magnitude, direction, and location of application, typical steel construction can be vulnerable to explosive attack. Failure often includes member buckling or connection failure. Even if these local failure mechanisms are resisted, large displacements may still lead to global failure.

Concrete has favorable characteristics for blast resistance, primarily because it is used in volume in typical construction. The primary vulnerabilities of reinforced concrete columns, beams, and slabs relate to the fragility of the material. Concrete offers minimal tensile strength in the absence of reinforcing steel and crushes when loaded beyond its capacity in compression. These vulnerabilities can be reduced by providing sufficient reinforcement or by jacketing the section to confine the concrete and minimize spalling effects. However, a lack of robustness can lead to results like those seen when the Chamber of Shipping building in London was bombed in 1992 (*Figure 2*).

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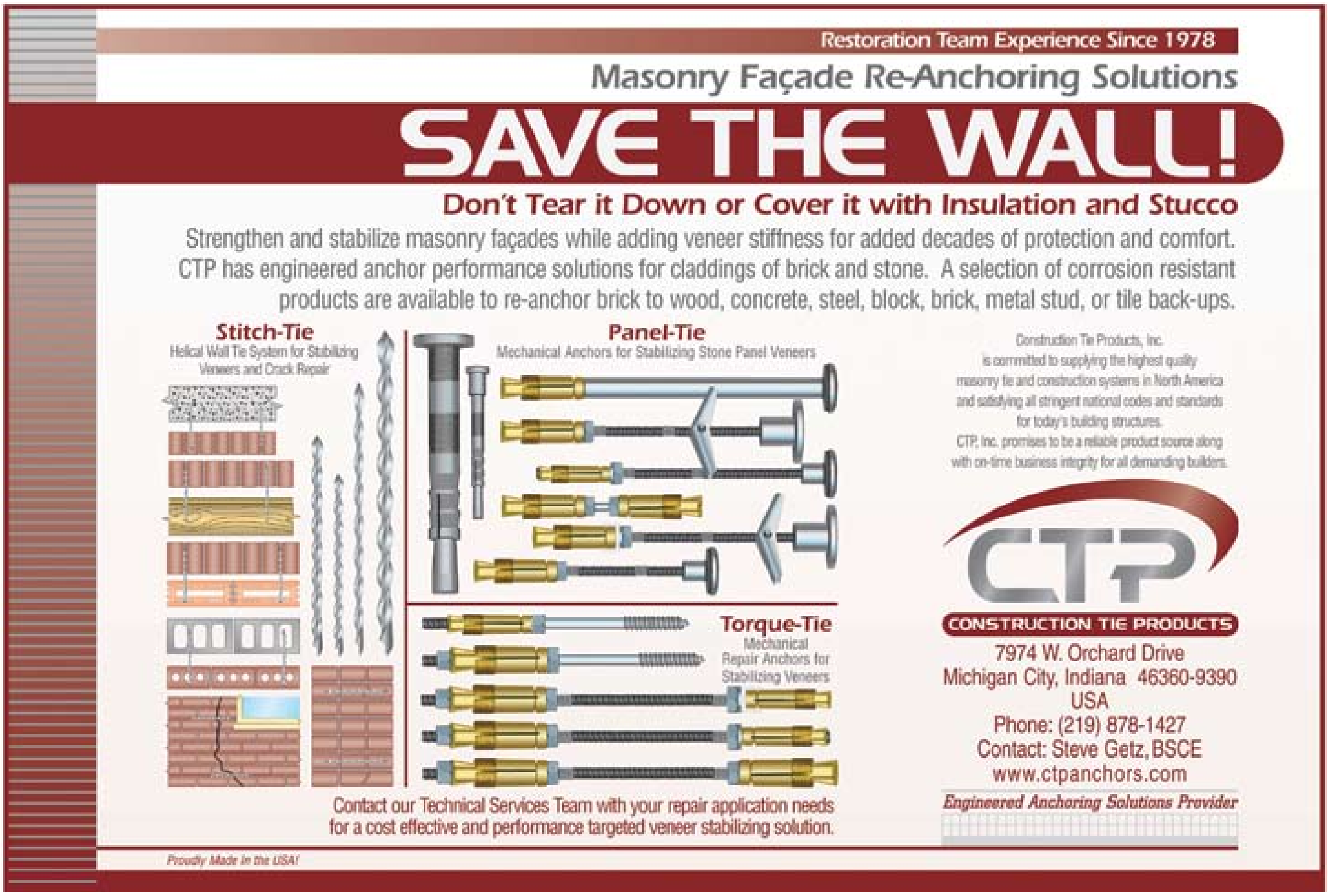

Concrete masonry unit (CMU) walls have received significant attention from the blast engineering community because they are a common form of construction. CMU walls can fail in a fragmentary fashion as a result of flexure of the wall; this may pose a significant hazard to building occupants. This is particularly true for non-load-bearing walls that may be only lightly reinforced and therefore may have minimal resistance to blast forces.

All of the above materials have a certain degree of inherent blast resistance. Blast loads will often find the weak point in building, and if the primary structure of the building is well designed and robustly detailed, it is likely that the glazing will pose the most significant hazard to occupants.

Blast Mitigation and Protection Measures for Buildings

When a threat and risk assessment, or some other methodology or discussion, has indicated that a blast threat needs to be considered for a given building, what can a designer do to reduce the risk to those in and around the building? Short of constructing buildings as foreboding bunkers, the designer must find a reasonable balance between blast protection and all of the other criteria necessary for a successful building.

The starting point for choosing blast mitigation features is for the designer and client (the developer, owner, or tenant) to agree on the levels and types of threats to be considered and the objectives of the blast-protection measures. This should be done as part of a threat and risk assessment. Conducting threat assessments and defining blast-protection objectives are parts of a process of selecting a range of possible events that must be protected against. Because the actual range of blast events possible for a given building is so large, solutions based on certain design parameters need to be capable of responding well to other scenarios as well.

The following methodologies can be used to provide blast mitigation.

- **Building Design and Layout.** At an early stage, a threat and risk assessment can be carried out to guide the layout and design of a building such that elements are included to help limit blast effects due to confinement and reflection of the blast wave. For instance, increasing standoff distance through site lay out can greatly reduce potential exterior blast threats.
- **Opening Protection.** As discussed previously, glazing and openings are often the most vulnerable elements of a building. The most widespread cause of injuries and internal disruption from an external bomb blast is the fragmentation and inward projection of window glass. Laminated glass, and to lesser degrees tempered glass and glass fitted with anti-shatter films, can, when installed in suitably designed frames, provide increased resilience to blasts [*Smith and Hadden 2004*].
- **Cladding Design.** By designing cladding to span vertically between floors rather than fixing it to structural columns, blast forces imposed on the facade will be distributed throughout the structure by the floor slabs, which act as diaphragms with high in-plane strength and stiffness.
- **Structural Resilience.** Even with the benefit of a protective facade, a building's structure can still be damaged by a bomb blast when extensive collapse does occur, it is usually because of damage to one or more elements that are critical to resisting gravity loads. The structural designer's objective is to ensure that damage is limited in its extent and that any collapse is not disproportionate to its cause. This can be accomplished by employing analysis techniques such as those discussed earlier in this article. For example, structural designers may need to closely consider beam-to-column connections, as these can be critical for blast resistance. The ability of floor slabs to resist upward loads from a blast may also need to be reviewed. Similarly, when using precast concrete elements, it is critical that these elements be well tied to other robust structural elements.
- **Vehicle and Curbside Barriers.** For a building with limited or no set back from the side walk, the use of curbside barriers may reduce vulnerability to severe structural dam age. However, due to the interplay of slope distance and the angle of incidence of the blast wave, the standoff that would bring about the most extensive facade damage may be a significant distance from the face of a building, in which case curbside barriers would do little to reduce the hazard.

Figure 3: Full-scale Test of Vehicle Barrier System. ©Arup/David Hadden

Structural Analysis for Blast Effects

At an early stage in the design of a building, the best possible blast protective systems should be identified by prioritizing security-related countermeasures and then comparing the cost and performance of different mitigation options. Because the modern threat environment includes a wide range of potential scenarios, these prioritizations should ideally be part of an overall threat and risk assessment (TARA) begun in advance of the actual design.

During the design of a building, quantitative analysis is required to provide a reasonable level of confidence that the details of the design will offer the necessary level of performance under a given design threat. Because code-based guidance is not typically available for blast-resistant design, performance-based methodologies are required. Appropriate design threats and desired performance criteria need to be agreed upon with the client in the early stages of the design process.

The magnitude of a blast is dependent on numerous variables:

- The amount of explosive material used (commonly referred to as charge weight)
- The placement of the device (commonly referred to as standoff)
- The type of explosive material used
- The size, shape, and orientation of the surfaces exposed to the blast

Figure 4: Arrangement for Full-scale Testing of the Blast Resistance of Exterior Windows in the Scottish Parliament Building. ©Arup

- The location and orientation of adjacent reflecting surfaces
- The shape of the charge itself

It is not possible to accurately predict many of these parameters, just as the characteristics of natural hazards cannot be definitively predicted. Additionally, the probabilistic methods that are typically employed to characterize natural hazard design loads (i.e., wind and earthquake loads) are not appropriate for man-made hazards such as a terrorist attack. However, the performance-based design approach requires that educated assumptions regarding the nature of these characteristics must be agreed upon with the client. The most significant of these design assumptions is the determination of appropriate threat scenarios for a given facility (e.g., vehicle bomb at curbside, package bomb in lobby), which should be agreed upon with the client as part of a TARA study.

Regardless of the variability of potential blast threats and their associated characteristics, analytical tools are available to help designers estimate design-level blast loads for a given scenario. The methods available for commercial-scale work fall into three categories: empirical, semi-empirical, and first principles. Current research will likely produce more sophisticated methods that will enable coupled detailed fluid and structural models to provide realistic simulations of blast events in which this interactive behavior is important. Although this technology represents the future of blast analysis, it is not yet ready for wide application in the building design environment.

Generally speaking, the evaluation tools available for structural response to blast loading fall into two categories: single degree-of-freedom (SDOF) and multiple degree-of-freedom (MDOF) methods. Here, degree-of-freedom refers the level of structural motion allowed by the analysis. The more degrees of freedom that are included in the analysis, the higher the resolution of the solution and the more computationally intensive the solution.

Although real structures have a theoretically infinite number of modes of deformation, it is sometimes possible to provide a reasonable approximation of structure response based on a single dominant deformation mode (SDOF). This is especially true when considering single elements, such as beams or columns. In these instances, a reasonable estimation of the response of the element can be obtained using hand calculations or simple computer programs. The simplicity of this method enables engineers to evaluate a wide variety of scenarios and elements very quickly, which is valuable at the early stages of a design.

Performing a higher-resolution analysis can alleviate many of the limitations of the SDOF method. The most common analytical approach for conducting an MDOF analysis is the finite element method. It consists of constructing a relatively detailed geometric model of the structure and applying appropriate approximations of the support and loading conditions. The results of such an analysis can be used to compare the expected performance of the structure with the agreed design criteria. The benefits offered by this method of analysis come with a significant penalty: high computational cost. Further, the expertise of the user contributes significantly to the outcome of the analysis. The modeler must have substantial experience with nonlinear dynamic structural behavior and blast load phenomenology, as well as with the computational methodology itself.

Summary

Because clear regulatory guidance is not available for designing blast resistance in buildings, the field of blast design may be described as tumultuous. Numerous guidelines state how blast loading and resultant responses should be determined, but these guidelines frequently offer conflicting or incomplete information. Although the design team generally needs to rely heavily on the experience of the blast consultant to fully develop the most appropriate design solutions for a given project, it is important to keep the following primary objectives in mind:

- Minimize blast-related hazards that contribute to casualty and loss of life.
- Minimize disruption of service associate with a blast event.
- Balance blast-design criteria with the overall design objectives of the project.

Given the high degree of uncertainty associated with blast loading, particularly with regard to determining design threats, the design should be developed using risk-informed techniques to meet the performance criteria agreed by the stakeholders. Additionally, it is important to consider that, since each and every possible threat cannot be considered in the design, the design should be such that failure due to an unforeseen event that overmatches the design occurs in a relatively benign way.▪

Further details and in-depth descriptions of the approaches described here are provided in *Extreme Event Mitigation in Buildings – Analysis and Design [Meacham and Johann 2006].*

The next installment of this series will focus on the impact of extreme natural hazard events on buildings.

J. David Hadden is an Associate Director with Arup in their London office. He leads the blast-engineering team within Arup Security Consulting. David can be reached via email at ***david.hadden@arup.com.***

Matthew A. Johann, MSc, is a fire specialist with Arup in their Westborough, MA office. He is also a Certified Fire and Explosion Investigator. Matt can be reached via email at ***matt.johann@arup.com.***

Brian J. Meacham, PhD, P.E., is a Principal with Arup in their Westborough, MA office. He is the Business Leader of Arup's global Risk Consultancy. Brian can be reached via email at ***brian.meacham@arup.com.***

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