I Design Considerations
1 General Considerations for Blast-Resistant Design

Donald O. Dusenberry

1.1 INTRODUCTION

Until recently, relatively few engineers and architects have had to design structures and their systems to resist the effects of explosions. Military engineering personnel, consultants to the federal government, and consultants to industries that use explosive or volatile materials constituted the primary population of designers routinely analyzing blast effects.

Following the explosion that demolished the Alfred P. Murrah Federal Building in Oklahoma City in 1995, members of the structural design and construction industries have been increasingly quizzed by owners about blast-related hazards, risks, and methods of protection. The types and numbers of clients seeking blast resistance in their structures have expanded.

The terrorist events of the recent past and the fear that others may occur in the future have led many businesses, particularly those with an international presence, to consider their vulnerability. And, of course, as their neighbors work to enhance the performance of their buildings, owners and tenants who do not envision themselves as targets of malevolent acts nevertheless begin to wonder if their structures might be damaged as a consequence of their proximity to targets. Some have argued that adding blast resistance and enforcing standoff for one building on a block unfortunately increases the threat for others, because it encourages aggressors to attempt to assemble bigger bombs and detonate them closer to the target’s neighbors.

There seems to be a sense of anxiety about the vulnerability of our buildings, bridges, tunnels, and utilities in the midst of numerous recognized international social and political instabilities, and given the potential for domestic groups and individuals to seek influence and create disruption by resorting to violent means. As a result, consultants designing rather pedestrian buildings now are expected to provide advice and sometimes specific enhancements in response to quantifiable threats, as well as perceived vulnerabilities.

In this environment, engineers need training and information so that they can provide designs that effectively enhance a building’s response to explosions.
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1.2  DESIGN APPROACHES

Most engineers and architects serving clients with growing interest in blast resistance are uninitiated in the relevant design practice. Blast loading is very different from loadings commonly analyzed by structural engineers. Peak pressures are orders of magnitude higher than those associated with environmental loads, but their durations generally are extremely short compared to natural periods of structures and structural components. In addition, given that the risk of an explosion at any one facility normally is very low and the costs to achieve elastic response often are prohibitive, designs usually engage the energy-dissipating capability of structural and enclosure elements as they are deformed far into their inelastic ranges. This forces engineers to account for geometric and material nonlinearities.

At first, designing for blast resistance might sound similar to designing for seismic resistance because neither is static and both rely on post-yield response. But even those similarities are limited. The dominant frequencies of seismic excitations are on the order of the lowest natural frequencies of building response, not much faster, as is generally the case for blast loadings. Blast loading usually is impulsive, not simply dynamic.

While we tolerate some damage in earthquakes, to dissipate energy, we usually allow more damage for blast events. We expect facades to sustain severe damage. In fact, blast-resistant design often tolerates breaching of the building enclosure (with attendant risk of fatalities) and even sometimes partial collapse of buildings.

Many blast-resistant designs require very sophisticated approaches for the analysis of building response to explosions (National Research Council 1995). There are techniques for accurate assessment of blast pressures and impulses in complicated environments, modeling the influence of those blast loadings on surfaces, and structural response to those loads. There are critical facilities and blast conditions that warrant the use of these techniques. However, much blast-resistant design is performed following simplified procedures (U.S. Department of Defense 2008) that approximate actual conditions, and therefore lack high fidelity. This often is appropriate because of, and at least in part follows from, inevitable uncertainties that mask the phenomenon and the structure’s response. In addition, there are practical matters of prudence, economics, and risk acceptance that drive analyses of blast response.

Risk analyses are important components of the design for blast resistance (Federal Emergency Management Agency 2003). Among the products of such analyses are estimates of the threat for which a structure should be designed. The magnitude of intentional, nonmalevolent explosions and industrial explosions sometimes can be estimated with precision commensurate with that of other common loadings (Center for Chemical Process Safety 1996). The quantity of explosive materials can be estimated, the potential locations of the design-base explosion can be isolated, and often there are relatively few nearby objects that significantly affect the shock front advance.
THE BLAST ENVIRONMENT

This is not the case for many accidental explosions and most malevolent explosions. The assessment of the threat in these instances often does not have a probabilistic base. When sufficient data do not exist, consultants are forced to use judgment rather than hard science to establish the threat.

When data are not available, consultants often establish the magnitude of the threat of a malevolent explosion by assessing the probable size of the container (e.g., letter, satchel, package) in which a bomb is likely to be delivered (U.S. Department of Defense 2002a), and then selecting a design-base explosive mass based on a fairly arbitrary assignment of the quantity of explosive that could reasonably be accommodated in that container. In these cases, there is relatively high uncertainty about the intensity of the explosion that might actually occur. Obviously under these circumstances, there is a commensurate level of uncertainty about the outcome.

1.3 THE BLAST ENVIRONMENT

Engineers skilled in the design of buildings for occupancy-related and environmental loads (e.g., dead, live, wind, snow, and seismic loads), but faced with a new challenge to design for blast loads, often find themselves ill-equipped for the challenge. Designers are used to treating all other common loadings as either static or quasi-static, because the rise time and duration for the equivalent load are on the order of, or longer than, the longest natural periods of the structure. Designing for blast loading generally cannot follow this approach.

Conventional design for common time-varying loads, including wind and seismic, includes techniques that allow conversion of these dynamic phenomena into quasi-static events that recognize and simplify the dynamics. Wind loads defined in one of the most common references (American Society of Civil Engineers 2005) are based on an acknowledgment of the range of natural frequencies of common structural frames, and are calibrated to those values. When the frequency of a subject building falls outside of that default range, common design approaches provide for specified adjustments to the quasi-static design loads to account for dynamic response.

Common seismic design (American Society of Civil Engineers 2005) involves a very elaborate conversion of the dynamic loading environment into a quasi-static analysis problem. Building systems are characterized for stiffness and ductility, and site conditions are evaluated for seismic exposures and characteristics of shaking. On the basis of extensive research into building performance and a fair amount of cumulative experience evaluating the actual earthquake response of designed structures, the complicated loadings—which are as much a function of the building design as they are of the environment in which structures are built—are idealized as a series of externally applied loads that are thought to mimic the loading effects of an earthquake. Complicated though the approach is, many buildings can be designed for earthquakes by engineers with little familiarity with dynamic behavior.
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Our conventional approach to blast design is similar to that for seismic design, in two important ways: (1) both loadings clearly are dynamic and, hence, solutions are energy-based, and (2) the way we detail structural elements determines the effective loads for which structures must be designed (meaning, we limit the strength we need to supply by allowing post-elastic behavior to dissipate energy). However, blast loading, with its extremely fast rise time and usually short duration, is either dynamic or impulsive, depending on the nature of the explosive, its distance from the subject structure, and the level of confinement that the structure creates for the expanding hot gases (Mays and Smith 1995).

The impulsive form of the very fast load rise time and very short load duration normally associated with blast loading requires analytical approaches that generally demand direct solution of energy balance equations (U.S. Department of Defense 2008; Mays and Smith 1995).

1.4 STRUCTURE AS AN INFLUENCE ON BLAST LOADS

The pressure and duration of the impulse associated with a blast are influenced by reflections of the shock front (U.S. Department of Defense 2008). Reflection sources include the ground below the detonation point and building surfaces that have sufficient mass or ductility to remain largely in place for the duration of the impulse. When shock fronts are reflected, their pressures are magnified as a function of the proximity, robustness, and material characteristics of the impacted object (Bangash 1993). The more robust that object, the greater the reflected energy because less energy is dissipated by the response (such as ground cratering) of the surface. These variations often are neglected in conventional design.

For instance, facades normally are designed on the assumption that they are perfect reflectors of the shock front. Designers following common procedures are assuming that the facade components remain stationary for the duration of the impinging shock front, causing peak pressures and impulses sufficient to reverse the direction of the shock front. In practice, there can be some displacement of the facade during the loading cycle. This displacement reduces the effectiveness of the reflector, and correspondingly the impulse.

Analyses for interior explosions have additional complications, as designers attempt to deal with the multiple reflections of the shock front within the structure, and pressures that develop from containment of expanding hot gases (Mays and Smith 1995)—a phenomenon normally neglected for external explosions. Further, the geometry of the confining volume and the location of the explosion within the volume can substantially affect the pressures on surfaces (U.S. Department of Defense 2008). The science that describes the pressure history on interior surfaces is complex, and not generally considered rigorously in common blast-resistant design processes.

Providing blast venting through frangible components to mitigate the effects of interior explosions is even more complex, since the release time for the venting component is a key, but difficult to assess, factor in the determination of the
magnitude of the pressure buildup. Approximations usually govern the analyses (U.S. Department of Defense 2008).

Clearly, there is interplay between the performances of building facades and frames. While in most cases the primary reason we enhance the performance of a facade is to protect occupants, we gain protection for the structure as well. Blast shock fronts that are not repelled by the facade will advance into a building, inducing pressures on interior surfaces of the structure and threatening interior columns, walls, and floor systems. Blast-related upward impulses on floor slabs can reverse force distributions in these structural elements. In systems that are not strong and ductile enough for these reversed forces, blast-induced deflections can fracture structural elements that are required to resist gravity loads. Hence, floor systems can fail after the direct effects of the blast pass and the slab falls back downward under the influence of gravity.

Of course, by designing the facade to resist the effects of an explosion, the designer is forcing the structure to become a support for the blast loads. Depending on the performance criteria, designers need to demonstrate that the framing system can support the applied loads, and that the structure as a whole will remain standing with an acceptable level of damage.

Building enclosures normally are designed to resist blast effects by inelastic flexural action, but it is possible to design facades to resist blast effects through catenary action as well. In particular, blast retrofits sometimes include new “catch systems” that are intended to reduce intrusion of blast pressures and creation of lethal missiles, by acting as a net inside the original exterior wall system.

In any case, the lateral displacement of the system often is large enough to open gaps between wall panels or between panels and floor slabs. When this happens, there is potential for leakage pressures to enter the building (U.S. Department of Defense 2002b), even when windows stay in place. This is particularly true in response to large, relatively distant explosions that have relatively long-duration impulses.

Pressure fronts that leak past facades that are damaged but remain in place normally are assumed to have insufficient energy to induce significant damage to interior structural components. However, these leakage pressures can cause personal injuries and damage to architectural and mechanical systems if they are not designed for resistance.

Add to the effects of leakage pressures the possibility that structural and architectural features on the inward-facing surfaces of facade components can become missiles when the facade sustains damage as it deforms, and there remains substantial risk to occupants inside blast-resistant buildings even with well-developed designs.

It is well established that breached fenestration leads to lethal missiles and internal pressurization (American Society of Civil Engineers 1999). Common design for blast resistance for malevolent attacks often is based on the premise that a significant fraction of the fenestration in a building will fail (General Services Administration 2003). This is due in part to the variability of the properties of glass, but also results from risk acceptance that employs the philosophy that
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an explosion is unlikely and that full, “guaranteed” protection is prohibitively difficult or expensive.

Hence, the effects of leakage pressures and missiles that are the product of building materials fracturing in response to a blast often can be destructive to the interiors of buildings, even when the facades of those buildings are designed to resist the effects of an explosion. Except when the most restrictive approaches to blast-resistant design are employed (e.g., with elastic response, so a building can remain functional), parties with standing in the design process need to understand that substantial interior damage and occupant injuries are possible should the design-base explosion occur.

1.5 STRUCTURAL RESPONSE

The shock front radiating from a detonation strikes a building component, it is instantaneously reflected. This impact with a structure imparts momentum to exterior components of the building. The associated kinetic energy of the moving components must be absorbed or dissipated in order for them to survive. Generally, this is achieved by converting the kinetic energy of the moving facade component to strain energy in resisting elements. Following the philosophy that blast events are unusual loading cases that can be allowed to impart potentially unreparable damage to structures, efficiency in design is achieved through post-yield deformation of the resisting components, during which energy can be dissipated through inelastic strain.

Of course, this means that the components that need evaluation often are deformed far beyond limits normally established for other loading types, and many of the assumptions that form the basis for conventional design approaches might not be valid. For instance, recognition of the extreme damage state normally associated with dissipation of blast energy has led to debate about appropriate values of the strength reduction factors (Φ factors) to be used for design.

In conventional design (American Concrete Institute 2005; American Institute of Steel Construction 2005), the nominal strengths of structural elements are reduced by Φ factors to account for uncertainty in the actual strength of the elements, and for the consequences of failure. Their magnitudes for conventional design have been developed based on studies of structural responses that are commensurate with service performance of buildings and, for seismic design, responses that are anticipated to be sufficiently limited and ductile to allow elements to retain most of their original load-carrying capacity. Blast resistance, on the other hand, often takes structural elements far into the inelastic range, to where residual strengths might be reduced from their peaks, and alternative load-carrying mechanisms (e.g., catenary action) are engaged. Sometimes, designers anticipate complete failure of certain elements if they are subjected to the design-base event. In this environment, it is not at all clear that Φ factors developed for conventional, nonblast design are relevant.
NONSTRUCTURAL ELEMENTS

Common blast-resistant design often takes the values of the $\Phi$ factors to be 1.0 (U.S. Department of Defense 2008). The bases for this approach range from the uncertainty about what the actual values ought to be to the observation that loads we assume for blast-resistant design are sufficiently uncertain that precision in the values for $\Phi$ is unjustified. It is further prudent to assume $\Phi = 1.0$ when performing “balanced design,” in which each structural element in a load path is designed to resist the reactions associated with the preceding element loaded to its full strength. Using $\Phi = 1.0$ for determination of the full strength of the elements in the load path tends to add conservatism to the loads required for the design of the subsequent elements.

On the other side of the equation, designers often apply load factors equal to 1.0 to the blast effects (U.S. Department of Defense 2008). This follows from the lack of a probabilistic base from which to determine the design threat, and the rationale that conservatism can be achieved by directly increasing the design threat. In any event, the absence of complete agreement on how to address strength reduction factors, and the valid observation that blast threats—particularly for malevolent explosions—generally are difficult to quantify, reduce our confidence in our ability to predict structural response with precision.

It is common in blast-resistant design to treat individual elements as single-degree-of-freedom nonlinear systems (U.S. Department of Defense 2008). Performance is judged by comparison of response to limiting ductility factors (i.e., the ratio of peak displacement to displacement at yield) or support rotations, with the response calculated as though the structural element were subjected to a pressure function while isolated from other structural influences. Of course, much more sophisticated approaches are pursued for critical structures and complicated structural systems. However, research on structural response for very high strain rates and very large deformations is limited, and results often are not widely disseminated. In many respects, the sophisticated software now available makes it possible to analyze with precision that exceeds our understanding of structural response.

Hence, the simplified, single-degree-of-freedom approach forms the basis for many designs. This approach usually is consistent with the precision with which we model the blast environment and our knowledge of element behavior, but it generally identifies the true level of damage only approximately. When considering elements as components of structural systems under the influence of blast, the response of the individual elements can differ significantly from that determined by analyses in isolation.

1.6 NONSTRUCTURAL ELEMENTS

Designers usually assume that the blast resistance of a structure is derived from the elements that they design for this purpose. While this clearly is true in large measure, in actual explosions, nonstructural elements—components disregarded in blast design—can act to reduce damage in a structure. It usually is
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conservative, and therefore prudent, to ignore these components because the designer cannot be certain about the reliability, or even the long-term existence, of building components that are not part of the structural design.

Nevertheless, elements with mass and ductility that stand between an explosion site and a target area can act to dissipate energy as they fail from the effects of the blast. In fact, designers sometimes do rely on specific sacrificial elements to reduce the blast effects on critical structural elements. The bases for this consideration are twofold: (1) through its failure, the sacrificial element dissipates energy that would otherwise be imparted to the structural element, and (2) for the brief time that the sacrificial element stays in place, it acts to reflect the shock front, thereby reducing the impulse felt by the protected structural element. For near-range conditions, when a bomb might otherwise be placed essentially in contact with a key structural element, a sacrificial element such as an architectural column enclosure can enhance survivability simply by inhibiting close placement of the explosive.

Of course, any shielding element that has inadequate strength, ductility, and connection to remain attached to resisting elements is likely to become a missile. Some of the energy these elements absorb is dissipated through strain, but the rest is retained as kinetic energy. The hazards created by these flying elements end only when that kinetic energy is brought to zero. Furthermore, care is needed in the evaluation of the value of shielding elements that are not positioned closely to the structure under consideration, since shock fronts reform beyond such elements, mitigating the protective value of the shield.

1.7 EFFECT OF MASS

The first influence of gravity comes to play when assessing the weights that the designer assumes are present in the structure at the time of an explosion. These weights, which are derived from the structure itself and its contents, act concurrently with the explosion-induced loadings. As a result, they “consume” some of the resisting capacity of the elements that are designed to resist the explosion. In addition, for the most part, they remain on the structure after the explosion and therefore must be supported by the damaged structure. The post-blast distribution of these weights often will be uncertain.

On the beneficial side, mass often augments the blast resistance of structural elements. Blast effects usually are impulsive, meaning that they impart velocity to objects through development of momentum. With momentum being proportional to the product of mass and velocity (Eq. 1-1), and kinetic energy being proportional to the product of mass and velocity squared, the larger the mass, the smaller the velocity and, hence, the smaller the energy that must be dissipated through strain (Eq. 1-2).

\[ I = \int_{u_0}^{u_1} F(t) \, dt = MV \]  

(1.1)
where: \( I = \text{impulse} \)
\[ F(t) = \text{time-varying force} \]
\( t = \text{time} \)
\( M = \text{mass} \)
\( V = \text{velocity} \)

\[ E_k = \frac{1}{2} MV^2 = \frac{1}{2} \frac{I^2}{M} \]  \hspace{1cm} (1.2)

where: \( E_k = \text{kinetic energy} \)

Gravity also must be considered when elements or overall structures deform. Vertical load-carrying elements often are designed to resist simultaneous vertical and lateral loads. Even when columns are not part of a structure’s lateral load resisting system, it is common for them to be designed for an eccentricity of the vertical load to account for inevitable moments that will develop in use. Sometimes the magnitude of the eccentricity causing moment is assumed to be on the order of 3\% to 10\% of the element’s cross section dimension (American Concrete Institute 2005). Response to blast often deforms vertical structural elements far more than limits assumed for conventional design. The designer needs to evaluate the ability to resist the resulting P-\( \Delta \) effects, both for individual elements and for the structure overall.

Structures as a whole generally are not pushed over by a common explosion. The overall mass of a structure usually is large enough to keep the kinetic energy imparted to the structure as a whole small enough that it can be absorbed by the multiple elements that would need to fail before the building topples.

In many explosions that cause extensive destruction, the damage develops in two phases: (1) the energy released by the explosion degrades or destroys important structural elements, and (2) the damaged structure is unable to resist gravity and collapses beyond the area of initial damage. In some of the most devastating explosions, most of the structural damage has been caused by gravity (Federal Emergency Management Agency 1996, Hinman and Hammond 1997).

Normally, individual elements fail, necessitating the activation of alternative load paths within the structure to carry the gravity loads that remain after the direct effects of the blast pass. Studies that assess these alternate load paths need to consider the dynamic application of the redirected internal forces, as the sudden removal of load-carrying elements implies a change in potential energy, as portions of a structure begin to drop. This change in potential energy necessarily imparts kinetic energy that must be converted to strain energy for the falling mass to be brought to rest.

Hence, the evaluation of the full effect of a blast does not end with calculations of blast damage to individual elements or limited structural systems. Designers need to consider the ongoing effects in the damaged structure, under the influence of gravity.
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1.8 SYSTEMS APPROACH

In our efforts to enhance the blast resistance of a facility, we need to remain cognizant about how our designs affect the performance and viability of the facility for nonblast events. As is always the case, there are competing goals and influences in the design of a facility, and those factors need to be balanced to achieve the most satisfactory end product.

Consider the conflicts between the structural performance preferred for seismic events and that preferred for explosions. One important goal in seismic design is to force failures to occur in beams before columns, so that the load-carrying capacity of columns is preserved even when the earthquake induces damage. This is accomplished by detailing connections between beams and columns so that plastic moments occur in the beams before the columns. This is the “strong column, weak beam” approach.

Consultants designing for blast often provide for the possibility that a column will be severely damaged by an explosion, in spite of our best efforts at prevention. When consultants assume that a column has lost its strength, they must develop alternative load paths to prevent a collapse from progressing from the initially damaged column through the structure. One form of alternative resistance involves making beams strong and ductile enough to span over the area of damage, thereby redistributing the load on the damaged column to adjacent columns. This requires strong beams which, if implemented without consideration of seismic response, can run counter to philosophies for robust seismic resistance.

Designers working to enhance blast resistance must also consider occupant egress and the needs of emergency responders. Blast resistance invariably includes fenestration with blast-resistant glass. By definition, such glass is difficult to break. Firefighters will need to use special tools and engage unusual tactics to fight a fire in a building that is difficult to enter and vent, and that has features that inhibit extraction of trapped occupants. Designers might need to compensate for blast-resistance features or enhance fire resistance.

Distance is the single most important asset to a structural engineer designing for blast resistance. The farther the explosion is from the structure, the lower are the effects that the structure must resist. Further, there often is merit to the construction of blast walls or line-of-sight barriers to add protection to a facility. However, the need to create an impenetrable perimeter, and the temptation to make it one that effectively hides the facility, can detract from the function of the facility.

First, there is the dilemma caused by features that are intended to keep aggressors away from a building, but that also block lines of sight to the building in the process. While such features add security, they also provide opportunities for the aggressors to effectively hide from observers in and around the building. A slowly developing assault may be more difficult to detect if the perimeter cannot be monitored effectively.

Next, there is the potential impact on the quality of life for occupants of buildings that have very robust defenses. Imposing perimeters and minimized fenestration display the robustness and the fortresslike design intent.
this might be perceived as an asset for what it says to the aggressor, it also communicates a sobering message to occupants and welcomed visitors. There has to be a balance between the means to provide the necessary resistance and the architectural and functional goals of the facility. Aesthetics need consideration for most facilities.

Overall security design needs to properly balance the efforts applied to the defense against a variety of threats. It is unsatisfactory to provide a very robust design to resist blast if the real threat to a facility is through the mechanical system. Clients will be unhappy if security protocols address perceived threats (e.g., outside aggressors detonating bombs near a building), but fail to prevent real threats (e.g., disgruntled employees intent on committing sabotage or violence inside the facility). Any overall security evaluation needs to consider all perceived threats and provide guidance that will allow clients to determine where best to apply their efforts to maximize their benefits. In many cases, a robust resistance to an explosion threat will not be the best expenditure of funds.

Given a security design developed for the spectrum of potential threats to a facility, owners sometimes face costs that exceed their means. When this occurs, and for facilities that risk assessments show to be at relatively low risk, owners must make decisions. Sometimes they instruct consultants to design to a particular cost, representing the amount that the owner can commit to the added security to be provided to the facility. In these instances, consultants must identify priorities that address the most likely threats and provide the greatest protection for the limited funds. When this happens, the consultants must explain to the owners the limitations of the options so that the owners can make educated decisions.

1.9 INFORMATION SENSITIVITY

When blast-resistant designs are for the security and safety of a facility in response to a threat of a malevolent attack, information about the assumed size and location of an explosion should be kept confidential. This information could be useful to an aggressor because it can reveal a strategy to overwhelm the designed defenses.

The common practice of specifying the design loads on drawings should not include a specific statement about the assumptions for blast loading when facility security is at issue. Potentially public communications among members of the design team and between the design team and the owner should avoid revelations about the design-base explosion.

In most cases, the design assumptions for accidental explosions are not sensitive. Precautions about security-related confidentiality usually do not apply, and customary processes for documenting the design bases may be followed. In addition, there might be legal requirements or other circumstances that dictate the documentation of otherwise sensitive information. As always, designers will need to comply with the law and to work with stakeholders in the design of a facility to contain the unnecessary dissemination of information that could potentially be misused.
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1.10 SUMMARY

As consultants in the building design industry have been drawn into the matter of blast-resistant design, many have been handicapped by lack of familiarity with the blast environment, including not knowing how to determine loads for design, or with proper approaches for structural design. Consultants often anticipate that they will be able to provide effective designs by following approaches common in building design when blast is not an issue. Unfortunately, consultants expecting to apply their familiar approaches usually are proceeding along an improper path.

An explosion is a violent thermochemical event. It involves supersonic detonation of the explosive material, violently expanding hot gases, and radiation of a shock front that has peak pressures that are orders of magnitude higher than those that buildings normally experience under any other loadings. Designers hoping to solve the blast problem by designing for a quasi-static pressure are likely to be very conservative, at best, but more probably will simply be wrong.

Designers need to understand that the magnitudes of the pressures that an explosion imparts to a structure are highly dependent on the nature of the explosive material, the shape and casing of the device, the size and range of the explosion, the angle of incidence between the advancing shock front and the impacted surface, the presence of nearby surfaces that restrict the expansion of hot gases or that reflect pressure fronts, and the robustness of the impacted surface itself. Designers also need to understand that the durations of the pressures induced by an external explosion generally are extremely short compared to the durations of other loads and compared to natural periods of structures. Further, there is interplay between blast pressure magnitudes and durations, which is a function of distance from the detonation point, among other factors.

Designing for the very high peak pressures and short durations of blast loadings requires applications of principles of dynamic response. Accurate prediction of the peak response of a building will require the designer to analyze dynamic properties of the structure, and apply approaches that respect dynamic behavior. Further, most cost-efficient designs rely on deformation far beyond elastic limits to dissipate energy. Hence, many of the assumptions designers normally make when designing for loads other than blast do not apply when designing for blast resistance.

Consultants engaged in the design for blast resistance need to be qualified by education, training, and experience to properly determine the effects of an explosion on a structure. They must have specialized expertise in blast characterization, structural dynamics, nonlinear behavior, and numerical modeling of structures. Blast resistance designers must be licensed design professionals who are knowledgeable in the principles of structural dynamics and experienced with their proper application in predicting the response of elements and systems to the types of loadings that result from an explosion, or they must work under the direct supervision of licensed professionals with appropriate training and experience.
The present practice for blast-resistant design employs many approximations and, in many aspects, relies on incomplete understanding of the blast environment and structural behavior. While available approaches serve the public by increasing the ability of our structures to resist the effects of explosions, these conventional approaches generally are ill suited to provide a clear understanding of the post-blast condition of the structure. Consultants providing blast-resistant design need to understand the limitations of the tools they apply, and provide clients with appropriate explanations of the assumptions, risks, and expectations for the performance of blast-resistant structures. In many cases, those explanations need to make clear that the performance of the structure and the safety of individuals inside the protected spaces are not guaranteed.

REFERENCES


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