PRINCIPLES OF DESIGN FOR RISK REDUCTION RELATED TO BLASTS

3

Most commercial buildings in the United States have not been designed and constructed to resist blasts. Therefore, the results of a FEMA 452 risk assessment may yield many high-risk scores to explosive blasts. New technologies and mitigation options are available to incrementally reduce the consequences of explosive blasts.[1]

FEMA 452, *Risk Assessment: A How-To Guide to Mitigate Potential Terrorist Attacks Against Buildings,* January 2005, outlines methods for identifying the critical assets and functions within buildings, determining the threats to those assets, and assessing the vulnerabilities associated with those threats. The Guide provides a means to assess the risk and make risk-informed decisions to reduce vulnerability. The Guide also discusses methods to reduce physical damage to structural and non-structural components of buildings and related infrastructure and reducing resultant casualties that may occur during an explosive or CBR attack. Finally, the Guide leads the reader through a process for conducting a risk assessment and selecting mitigation options.

Some existing buildings may require retrofits for explosive threats if changes in purpose, occupancy, or world events make them more likely to be targets of a terrorist attack. Similarly, prudent facility managers should also consider whether nearby buildings are likely targets for terrorist attack. Conducting a risk assessment is the first step in determining the need to upgrade a conventionally designed building to protect its occupants and assets. The risk assessment identifies the maximum credible threats and the associated hazards based on the site conditions, neighboring properties, building layout, access control, structural framing, and facade components.

The effectiveness of the upgrades depends to a great extent on the structural details of the building and the acceptability of the aesthetic and functional impacts. For example, historic preservation requirements may limit secure design alternatives that would otherwise be considered appropriate. The cost of protective design and the impact of this protection on the property may be minimized using advanced analytical methods. These methods, developed over years of explosive testing and numerical simulation, enable the design team to focus resources on portions of the structure that are most likely to sustain damage and minimize materials required to mitigate these hazards. The protective measures that may offer the most benefits from these methods include

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[1] Much of the content for this chapter has been drawn from the articles "Designing to Resist Explosive Threats" and "Retrofits to Resist Explosive Threats" by Robert Smilowitz. These documents were originally prepared for the National Institute of Building Sciences in 2005 and later published on their Web-based portal, Whole Building Design Guide (www.wbdg.org), as a resource for building professionals.

the design of defensible perimeters, the design of protective facade systems, the hardening of structures to resist the effects of progressive collapse, the retrofit of existing structures, and the protection of non-structural components. The following sections describe retrofit upgrades that may be used to either reduce the hazard of debris impact or increase the load resistance of the structure.

This chapter identifies the protective measures that may be applied to the building perimeter, structure, and envelope, and non-structural systems within the incremental framework. Starting from the exterior of the building and working inward, these distinct protective upgrade projects may be combined with building maintenance and capital improvement projects. For buildings perceived as vulnerable to attack by virtue of their iconic nature or controversial occupancy, perimeter protection projects or column hardening may be beneficial. For other buildings, which may be in the vicinity of a likely target, perimeter protection and structural hardening will not reduce the risk of collateral damage. A protective facade upgrade makes more sense for these buildings. The incremental approach allows building owners to identify the best use of limited resources and combine these protective measures with other modernization projects that may increase the value of their property. Following a brief description of significant terrorist attacks against commercial properties, this chapter explores protective measures for:

- Building perimeters
- Building structures
- Building envelopes
- Non-structural systems

3.1 SELECTED EXAMPLES OF TERRORIST ATTACKS ON BUILDINGS

The following sections describe past terrorist attacks on buildings and the extent of collateral damage to neighboring structures.[2] The approximate dollar values for damages correspond to the time of the incident. These descriptions of blast damage inform the methods of assessing building vulnerabilities described in FEMA 452 and the physical and operational enhancements to address vulnerabilities to explosive blasts described in this document.

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[2] These descriptions were first published in 2007 as part of FEMA 430, *Site and Urban Design for Security*.

3.1.1 BALTIC EXCHANGE,[3] CITY OF LONDON, APRIL 1992

Founded in the mid-eighteenth century, the Baltic Exchange is a United Kingdom company that operates the premier global marketplace for shipbrokers, ship owners, and charterers. It occupied a historic London building built in 1903.

In April 1992, at 9:20 p.m., the offices of the Baltic Exchange at 30 St. Mary Axe, London were virtually destroyed in an Irish Republican Army (IRA) bomb attack. A small truck carrying the explosives pulled up to the building on St. Mary Axe, a narrow street in the heart of London's financial district. The attack represents the first use of a large fertilizer-based homemade explosive device: the bomb's power was enhanced by a Semtex-based detonating cord wrapped around the explosives. Although most of the office workers had gone home, the bomb killed three people, all by flying glass, and injured 91. The damage was estimated at about $1.2 billion.

3.1.2 WORLD TRADE CENTER,[4] NEW YORK CITY, FEBRUARY 1993

On Friday, February 26, 1993, at 12:18 p.m. a large explosion ripped through the public parking garage of the World Trade Center. The explosion caused six deaths, more than 1,000 injuries, and $300 million in property damage.

The explosive device, a 1,500-pound urea-nitrate bomb (equivalent to about 900 pounds of trinitrotoluene [TNT]), was detonated in a rented Ford van parked in the basement parking garage using a timer. The explosion created a 200-foot by 100-foot crater several stories deep (Figure 3-1). The power and emergency systems of the World Trade Center were destroyed. Most of the injuries were due to smoke inhalation.

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[3] SOURCES: Jonathan Bell, "The Morning News: Letters from London: Raising the Game"; Peter Dorsman, "Peak Talk, The Baltic Exchange Bomb," from www.peaktalk.com/archives/000143.php; "London Destruction: Baltic Exchange," from http://us.geocities.com/londondestruction/baltic.html; Leslie Hutchings, "Discussion Forum," from www.sapling.info/discussionforum/postings/1104.shtml.

[4] SOURCES: ADL Law Enforcement Agency Resource Network; CNN, "WTC's owners found negligent in 1993 bombing"; "The 1993 Bombing: the First Attack on the World Trade Center," from http://911research.wtc7.net; John V. Parachini, "February 1993 Bombing of the World Trade Center in New York City," CNS Center for Nonproliferation Studies, from http://cns.miis.edu/pubs/reports/wtc93.htm; J. Dwyer et al., *Two Seconds Under the World: Terror Comes to America—The Conspiracy Behind the World Trade Center Bombing,* Crown Publishers, New York, 1994.

Figure 3-1: Damage in WTC garage caused by the 1993 bomb attack.

SOURCE: CORBIS

3.1.3 BISHOPSGATE,[5] CITY OF LONDON, APRIL 1993

A bomb hidden in the back of a large truck exploded in a narrow street, killing one person and injuring more than 40. The explosive was a homemade device using about 1 ton of fertilizer and was similar to the bomb that devastated the nearby Baltic Exchange (Section 3.1.1). The explosion shook buildings and shattered hundreds of windows, sending glass showering down into the streets below. A medieval church, St. Ethelburga's, collapsed. Another church and the Liverpool Street underground station were also destroyed.

The damage was estimated at more than $1.5 billion. The Baltic Exchange, just having reopened following the completion of repairs from the 1992 bombing, was again damaged. Huge insurance payouts contributed to a crisis in the insurance industry, including the near financial collapse of the world's leading insurance market, Lloyds of London.

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[5] SOURCES: BBC On This Day, 1993, "IRA bomb devastates City of London"; Jonathan Liebenau, London School of Economics, "Information and Communications Disaster Recovery."

3.1.4 TOWN CENTER, MANCHESTER,[6] ENGLAND, JUNE 1996

On June 15, 1996, at a peak shopping time on Father's Day, a 3,000-pound IRA bomb (equivalent to about 1,800 pounds of TNT) exploded in Manchester, the second largest city in the United Kingdom. The explosion injured more than 200 people and ripped into the fabric of the city's main shopping center (Figure 3-2).

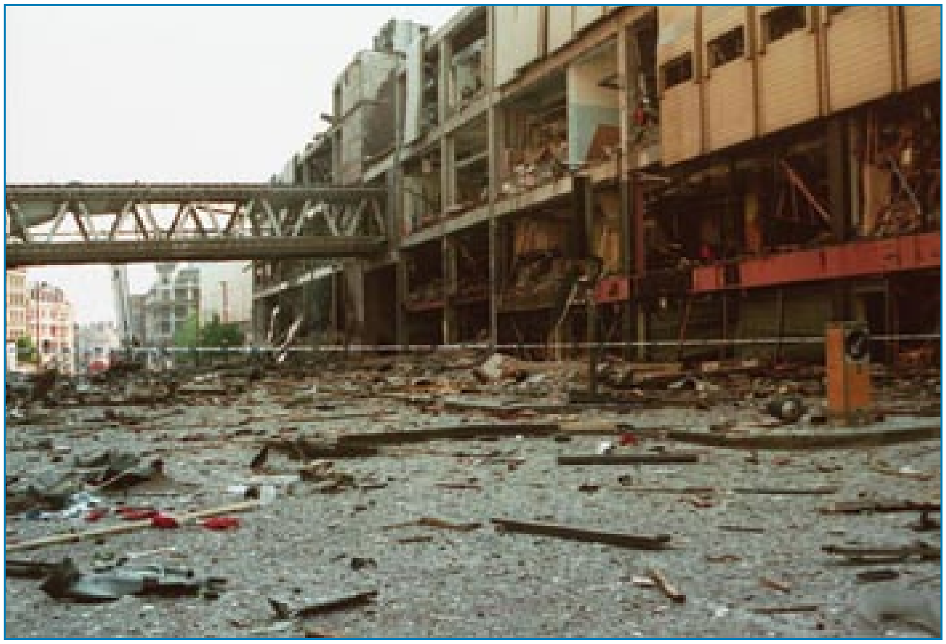

Figure 3-2: Manchester shopping center damage.

SOURCE: CORBIS

Several telephone warnings about an hour before the blast and the subsequent police evacuations averted major casualties. Shoppers were evacuated from the Marks and Spencer Department Store at the center of the site, outside which the truck bomb was parked. An army bomb squad employing a robotic anti-bomb device was checking an illegally parked van, which had been recorded by several closed-circuit security cameras in the city, when the bomb exploded.

Most injuries were sustained from falling glass and building debris. The main railroad stations were closed for several hours, and the city center was sealed off.

An estimated 450,000 square feet of retail space and about 200,000 square feet of office space required reconstruction. A master plan for redevelopment of the city center was quickly developed. An international

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[6] SOURCES: John Moss, "Manchester 2004, The Manchester Bombing, June 1996," from www.manchester2002-uk.com/buildings/bombing.html; BBC On This Day, 1996, "Huge explosion rocks central Manchester."

urban design competition launched one month after the bombing provided a cohesive plan for rebuilding. After 4 years, the devastated zone was completely restored. Marks and Spencer rebuilt on its original site, with its largest store in the world (Figure 3-3).

Figure 3-3: New Marks and Spencer store, Manchester.

SOURCE: CHRIS ARNOLD

3.2 PERFORMANCE STANDARDS

Based on such recent experience of terrorism blast damage in commercial buildings, methods of analysis and design have been developed to reduce damage in existing buildings. These methods are discussed below.

A building's performance in response to blast loadings must be evaluated whether it is a likely target or close enough to a likely target to suffer collateral damage. The effects of a near contact detonation, such as a satchel threat placed in contact with a column or a vehicle-transported explosive near the structure, are significantly different from the effects of a distant detonation. Different analytical methods are required to evaluate the likely performance of building systems in response to varied intensities of blast loading.

Appropriate analytical methods are needed to demonstrate compliance with blast criteria or performance specifications established by agencies, such as the General Services Administration, the U.S. Department of

State, and others. Risk-based performance criteria must be established for each building in order to define the protective objectives. Continuity of services objectives require performance criteria that are significantly more severe than those for a life safety objective. Consequently, establishing the design objectives at the onset is important.

Furthermore, many of these performance criteria require that the building system be a balanced design. The objectives of balanced design are to fully utilize the load capacity of all the materials, maximize the potential energy dissipated due to deformation, and manage the failure mechanisms. These objectives can be accomplished by ensuring a controlled sequence of failure. The expected performance of the building systems in response to either a targeted attack or collateral damage will determine the level of protection required, the sizing of the structural and nonstructural members, and the design of the connections between the different building components.

DYNAMIC ANALYSIS OF BUILDINGS

The performance of building systems and components in response to blast loading may be evaluated numerically using the principals of Structural Dynamics. These methods represent the inertia, the stiffness, and the strength of the dynamic system using a combination of nonlinear springs and masses. Simple Single Degree of Freedom (SDOF) models are appropriate for components on which the loading is uniform and the response is well characterized by the nonlinear spring. More complex material behavior, dynamic loading effects, and geometric nonlinearities require more complex Multi-Degree of Freedom (MDOF) models. The most complex structural systems must be analyzed using Finite Element Methods (FEM), which determines the nonlinear dynamic response using an explicit formulation of the equations of motion. Each level of analytical complexity requires successively more experience and expertise on the part of the blast response analyst.

The behavior of structural materials, such as steel and aluminum, in response to explosive loading has been the subject of intensive investigation by the governments of the United Kingdom, Israel, and the United States of America. Some structural materials behave very differently when subjected to high strain rate loading than they do under static conditions. Furthermore, the inelastic deformation of structural members depends on their section properties, shape functions, and extent of deformation. For compound sections composed of different pieces and materials, transformed section properties may be used to characterize an equivalent material and a combined or composite section property may be used to represent its structural resistance. Care must be taken to calculate composite section properties when strain compatibility between components can be justified and combined section properties when deformation compatibility between components is achieved.

The performance of building systems in response to explosive loading is highly dynamic, highly inelastic, and highly interactive. By controlling the flexibility and resulting deformations, the structural or facade component may be designed to dissipate considerable amounts of blast energy. The phasing of the different component responses and the energy that is dissipated through inelastic deformation must be carefully represented in order to accurately determine the behavior of the components. The 'SDOF model' approach commonly used to analyze individual components is likely to produce conservative designs. An accurate representation of the structural system requires a complex MDOF model. These MDOF models may be developed using appropriate inelastic Finite Element software in which an explicit formulation of the equations of motion is solved.

- Advanced analytical methods provide the most authentic representation of the system's ability to resist the dynamic blast loading and will produce the most cost-effective retrofits wherever the strength of the system is being evaluated.
- Simplified analytical methods and empirical relations are sufficient for debris mitigating upgrades, such as a daylight application of fragment retention film or blast resistant glazing fabricated with laminated glass.
- Approximate methods, such as the ASTM F 2248-03, *Standard Practice for Specifying an Equivalent 3-Second Duration Design Loading for Blast Resistant Glazing Fabricated with Laminated Glass,* do not require advanced analytical methods. Although this approximate approach does not quantify the improved behavior of glass in response to blast loading it "provides a design load suitable for sizing blast resistant glazing comprised of laminated glass or insulating glass fabricated with laminated glass" (ASTM, 2003).

3.3 SITE INCREMENTAL UPGRADES: PERIMETER PROTECTION

The risk analysis will help facility owners determine whether their building is a likely target or close enough to a likely target to suffer collateral damage. Perimeter protection only improves the performance of buildings that are targets of explosive attacks and provides no reduction in hazard if the building is vulnerable to collateral damage. However, characteristics of explosives, such as the charge weight, the efficiency of the chemical reaction, and the source location, that would likely be used in such attacks cannot be reliably predicted. Given these uncertainties, the most effective means of protecting a structure is to keep the bomb as far away from the building as possible by maximizing the standoff distance. Facility managers often respond to world events by constructing a perimeter around their building even before they evaluate the risk to their building. This approach presumes the facility will be the target of a terrorist attack and is intended to either discourage the attacking vehicle or to prevent it from driving up against the structure. Although a temporary incremental rehabilitation measure may be an appropriate strategy until a risk assessment can be performed, a permanent perimeter protection installation requires an intensive study of traffic patterns and subgrade conditions.

To guarantee the maximum standoff distance between unscreened vehicles and the structure and to resist a moving vehicle attack, anti-ram barriers must be placed around the entire perimeter of the building. For urban buildings, the defensible perimeter is most effectively located as close to the curb as possible in order to maximize the available standoff distances. More standoff distance is typically available at suburban and rural sites and there may be more options for locating the defensible perimeter without diminishing effectiveness. The site conditions determine the maximum vehicle speeds attainable, and thus the kinetic energy that must be resisted. Both the impact-protective device (bollard or barrier) and its foundation must be designed to resist the maximum load (see Figure 3-4). Permanent barriers, especially ones rated for high impact levels, generally have very large, deep foundations. Placement of these foundations is difficult in urban areas because underground

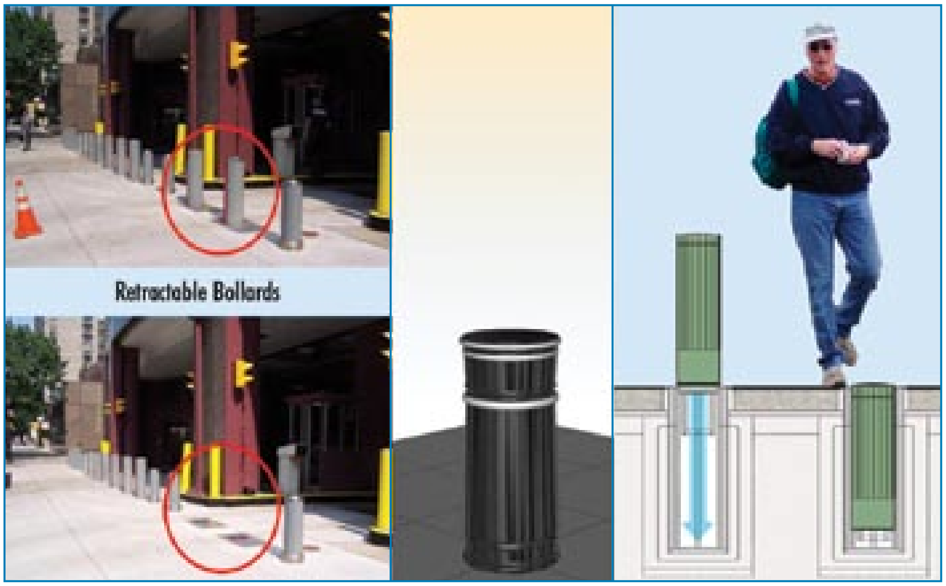


Figure 3-4: Barriers and bollards.

transportation facilities, building vaults, and utilities are often densely packed, and their locations may not be documented correctly or at all. Surveys and testing must be performed before construction begins to fully understand the feasibility and extent of these complications and to develop an appropriate design.

Conversely, if design restrictions limit the capacity of the impact-protective device or its foundation, then site restrictions will be required to limit the maximum speeds attainable. Speed calming devices may be installed to control the speed of oncoming vehicles. Furthermore, public parking abutting the building must be secured or eliminated, and street parking should not be permitted adjacent to the building. Removing one lane of traffic and turning it into an extended sidewalk or plaza can add additional standoff distance. However, the practical benefit of increasing the standoff depends on the charge weight. If the charge weight is small, this measure will significantly reduce the forces to a more manageable level. If the threat is a large charge weight, the blast forces may overwhelm the structure despite the addition of several feet to the standoff distance, and the measure may not significantly improve survivability of the occupants or the structure.

Entrances to parking garages and loading docks require operable barriers so that security personnel have the means to deny access to unauthorized vehicles following an inspection of their credentials or the contents of their cargo space. These operable barriers must be located to provide security personnel an effective means to inspect vehicles while minimizing the impact of queues on surrounding traffic patterns. Furthermore, the surrounding structure must be designed to accept the large dynamic forces that may be transferred upon impact.

3.4 INCREMENTAL BUILDING REHABILITATION MEASURES

3.4.1 BUILDING ENVELOPE

One of the most formidable tasks facing property owners is the upgrade of an existing facade to resist blasts. Blast pressures engulf a structure, and glass damage can occur as far as a mile from a sizable vehicle detonation. Glass damage from the terrorist bombing in Oklahoma City was reported up to 4,000 feet away from the Murrah Building (see Figure 3-5). Because the intensity of blast loads vary as a function of height and exposure relative to the point of detonation, facility managers may be able to prioritize upgrades to take advantage of site-specific features. This is particularly true if another nearby building is

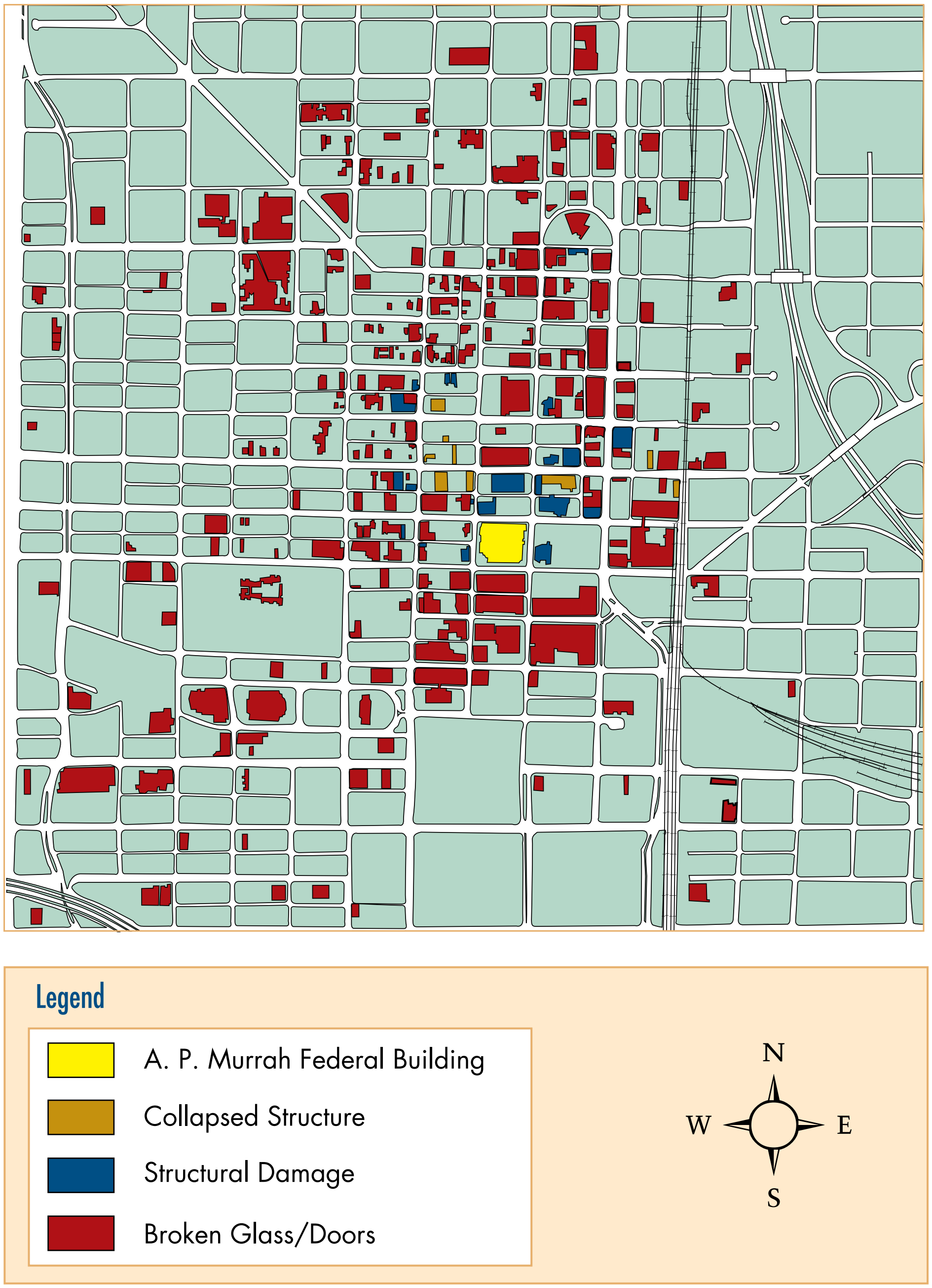


Figure 3-5: Locations of Murrah Building and other damaged structures.

identified to be the likely target of the attack and the directionality of the blast waves produce reflected pressures on some surfaces and not others. Similarly, results of a blast analysis may permit upper floors to be treated differently from lower floors.

Contractors rarely have access to the entire facade from within the building unless the building is undergoing a major modernization. But when these opportunities do arise, a significant level of protection can be introduced into the existing structure. This is particularly true when the design team uses state-of-the-art technologies. With conventional approaches, all glazing is treated as if it were supported in rigid openings; however, the actual performance of flexible facade systems in response to blast loading may be far more forgiving. An accurate representation of the glazing response to blast loading requires proper understanding of the facade's flexibility. The full load-bearing capacity of all the components may then be realized through the appropriate detailing of the mullions, connections, and anchorages. Over-design of glass and its support structure can lead to wasted money and in some cases premature failure.

Since the retrofit of existing structures is often hampered by insufficient information about the structure and the presence of brittle materials, innovative energy-absorbing retrofit systems may provide the best protection for these aging structures. Although difficult to quantify by simplified analytical approaches, these energy absorbing systems have been demonstrated to transfer reduced forces to the surrounding structure. Once the decision to upgrade a facade is made, advanced analytical methods can be used to enhance blast resistance at a minimum cost.

The increased mass of precast panels and masonry walls make them more vulnerable to greater intensity blast pressures than glazed facades. The strength of unreinforced masonry (URM) or lightly reinforced precast panels may be increased with the adhesion of fiber reinforcement to the inner surface, and debris may be restrained with the application of an elastopolymer; however, the connection details typically present the greatest difficulty for new construction and for incremental rehabilitation measures. The anchorages of precast concrete panels must develop the panels' ultimate capacity, in response to direct loading and rebound, in order to develop the full blast resistance of the material. Similarly, the anchorage of grouted and reinforced masonry walls must be designed to take full advantage of the materials' strength. Debris catch systems, such as geotextile fabrics and steel stud walls, may be installed interior to the precast panels and masonry walls if the reinforcement is insufficient and the anchorages are inaccessible.

3.4.2 FRAGMENT RETENTION FILM

Fragment retention film, also commonly known as "shatter-resistant window film" or "security film," is a laminate used to improve post-failure performance of existing windows. Applied to the interior face of glass, fragment retention film holds the fragments of broken glass together in one sheet, thus reducing the projectile hazard of flying glass fragments. A more appropriate name for fragment retention film would be "fragment reduction" film, since the methodology behind this hazard mitigation technique focuses on retaining glass fragments resulting from blast overpressures.

Most fragment retention films are made from polyester-based materials and coated with adhesives. Clear and tinted fragment retention films are available. Clear film has minimal effects on the optical characteristics of the glass; tinted film can increase the effectiveness of existing heating/ cooling systems, while also providing a variety of aesthetic and optical enhancements. Most films are designed with solar inhibitors to screen out ultraviolet (UV) rays, though over time the UV absorption damages the film's adhesive and degrades its effectiveness.

Film is packaged on rolls in widths as small as 24 inches and as large as 72 inches, depending on the manufacturer. Some manufacturers laminate multiple layers of film together to enhance performance. Whether one-ply or multi-ply, the overall film thickness can range from 2 to 15 mils. According to some government criteria (and verified by published test results), a 7-mil thick fragment retention security film, or specially manufactured 4-mil thick film, is considered to be the minimum thickness required to provide effective response to blast loads.

There are three types of fragment retention film installation methods. Each of the methods is capable of resisting different intensities of blast pressure, with the daylighting installation providing the lowest level of protection and the mechanically anchored installation providing the highest level of protection. Therefore, the selected installation method for incremental rehabilitation should be based on the required level of protection. For example, the reduction of fragment hazard in response to collateral damage may permit the use of the least invasive installations. The different installation methods are:

- Dry-Glazed Installation
- Wet-Glazed Installation
- Mechanically Anchored Installation

Dry-Glazed Installation. The application of security film must, at a minimum, cover the clear area of the window (i.e., the portion of the glass unobstructed by the frame). This minimum application to the exposed glass without any means of attachment or capture within the frame, termed "daylighting installation," is commonly used for retrofitting windows. Application of the film to the edge of the glass panel where it would cover the glass within the bite is called an edge-to-edge installation. Other methods of application may improve film performance and further reduce hazards but are typically more expensive to install, especially in retrofits.

Energy absorbing catch systems, used in conjunction with a daylight application of fragment retention film, is another mechanism for retaining and reducing debris hazards. Cables spanning the window will impede the flight of filmed glass and absorb a considerable amount of energy upon impact. These cable catch systems are demonstrated, through explosive testing, to be more efficient and effective than the more rigid catch bar systems described below.

Wet-Glazed Installation. The wet-glazed installation is a method in which the film is positively attached to the frame using a high-strength, liquid sealant, such as silicone. Frequently used for field retrofits, the method allows the flexible frame to deform slightly, reducing glass fragments entering the building and offering more protection than the dry-glazed installation. The wet-glazed installation system is more costly than the dry-glazed installation method, but is less expensive than the mechanically anchored/attached installation method described below.

Mechanically Anchored/Attached Installation. Fragment retention film is most effective when it is used in conjunction with a blast-tested anchorage system. While a film may be effective in keeping glass fragments together, it may not be particularly effective in retaining the glass in the frame. Securing the film to the frame with a mechanically connected anchorage system further reduces the likelihood of the glazing system exiting the frame. Mechanical anchorage systems employ screws and/or batten strips to attach the film to the frame along 2 or 4 sides. Because additional framework is necessary, the mechanical attachment method can be less aesthetically pleasing than the wet-glazed installation system.

All application and attachment methods can be installed on site in either steel or aluminum frames. While some mechanically attached systems may be used for a wide variety of windows, others are designed for a particular type of window frame. Certain types of window frames may require a custom-fabricated anchorage system.

In addition to considering the various methods of installation, the designer must consider the thickness of the film and the task of positioning the film on the glass. A lighter weight or thinner film eases installation. Water used to aid in positioning the film during application must be thoroughly extruded, as the film is not very permeable and moisture that does not dry will prevent the development of the full adhesive bond strength. Fragment retention film should be carefully selected for its physical, optical, and thermal characteristics, with special consideration given to the adhesive used, the window thickness, and the window area. Window frame systems must also be capable of transferring the load collected by the glazing system. Corner-welded frames are preferred over frames constructed of individual components. A schematic of this mitigation measure is shown in Figure 3-6.

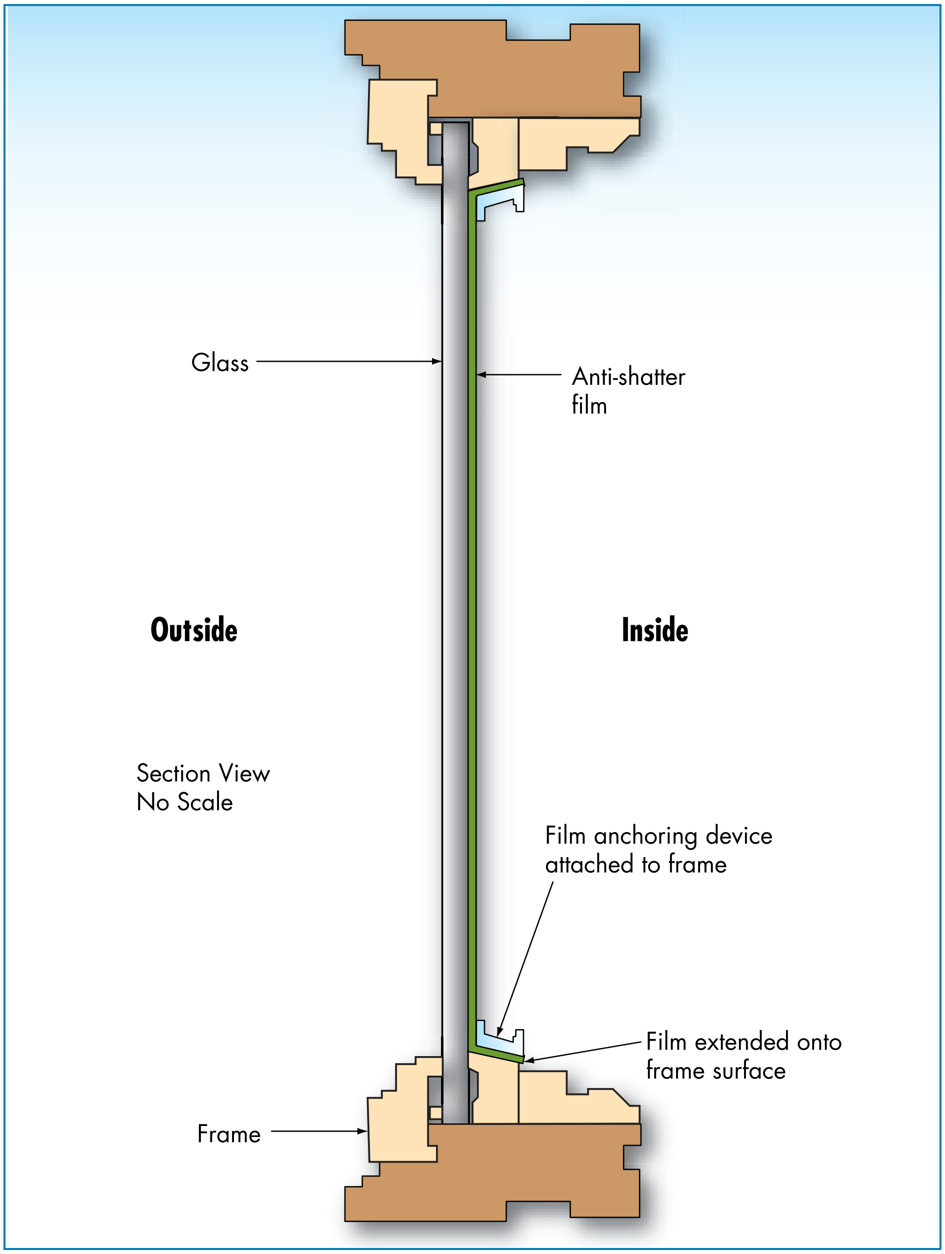


Figure 3-6: Mechanically attached fragment retention film.

3.4.3 LAMINATED GLASS

Laminated glass consists of two or more pieces of glass permanently bonded together by a tough plastic interlayer made of polyvinyl butyral (PVB) resin. Once sealed together, the glass "sandwich" behaves as a single unit. Annealed, heat strengthened, tempered glass or polycarbonate glazing can be mixed and matched between layers of laminated glass in order to design the most effective lite for a given application. When fractured, fragments of laminated glass tend to adhere to the PVB interlayer instead of falling freely and potentially causing injury.

Laminated glass usually lasts as long as ordinary glass if it is not broken or damaged. The correct installation of laminated glass is very important to ensure long life. Manufacturers typically recommend installation of laminated glass on setting blocks that are at least 6 inches long and placed at the quarter points of the pane. Architectural details should incorporate a weep system for exterior glazing systems. Regardless of the degree of protection required, laminated glass needs to be installed with a proper sealant to ensure that no water comes in contact with the edges of the glass. The sealant supplier should verify that the sealant and PVB interlayer are compatible. Generic sealants shown to be compatible with PVB are the polysulfides, silicones, butyl or polybutene tapes, and polyurethanes. Minimum face and edge clearance should be provided as required by the manufacturer. Field cutting should be minimized in butt glazing installations to minimize edge defects. Glazing guidelines, such as those presented in the Glass Association of North America (formerly Flat Glass Marketing Association) Glazing Manual should be followed to avoid installation problems. Typical allowances for glass, metal, and erection tolerance, expansion, and contraction should be made.

3.4.4 BLAST CURTAINS

Blast curtains (see Figure 3-7) are attached to the interior frame of a window opening and essentially catch the glass fragments produced by a blast wave. The debris is then deposited on the floor at the base of the window. The use of these curtains does not eliminate the possibility of glass fragments penetrating the interior of the occupied space, but instead limits the travel distance of the airborne debris. Overall, the hazard level to occupants is significantly reduced by the installation of blast curtains. However, a person sitting directly adjacent to a window outfitted with a blast curtain may still be injured by shards of glass in the event of an explosion.

Figure 3-7: Blast curtains.

Blast curtains are made from a variety of materials, including a warp knit fabric or a polyethylene fiber. The fiber can be woven into a panel as thin as 0.029 inch that weighs less than 1.5 ounces per square foot. This fact dispels the myth that blast curtains are heavy sheets of lead that completely obstruct a window opening and eliminate all natural light from the interior of a protected building.

The main components of any blast curtain system are the curtains themselves, the mechanism by which the curtain is attached to the window frame, and either a trough or another retaining mechanism at the base of the window to hold the excess curtain material. Blast curtains, with curtain rod attachment and sill trough, differ largely from one manufacturer to the next. The curtain fabric, material properties, method of attachment, and manner in which they operate also vary, providing many options within the overall classification of blast curtains, which makes blast curtains applicable in many situations.

As shown in Figure 3-8, blast curtains differ from standard curtains in that they do not open and close in the typical manner. Blast curtains are designed to remain in a closed position at all times. The curtain may be pulled away from the window to allow for cleaning, blind or shade operation, or occupant egress in the case of fire. However, the curtains can be rendered ineffective if the building occupants do not use them

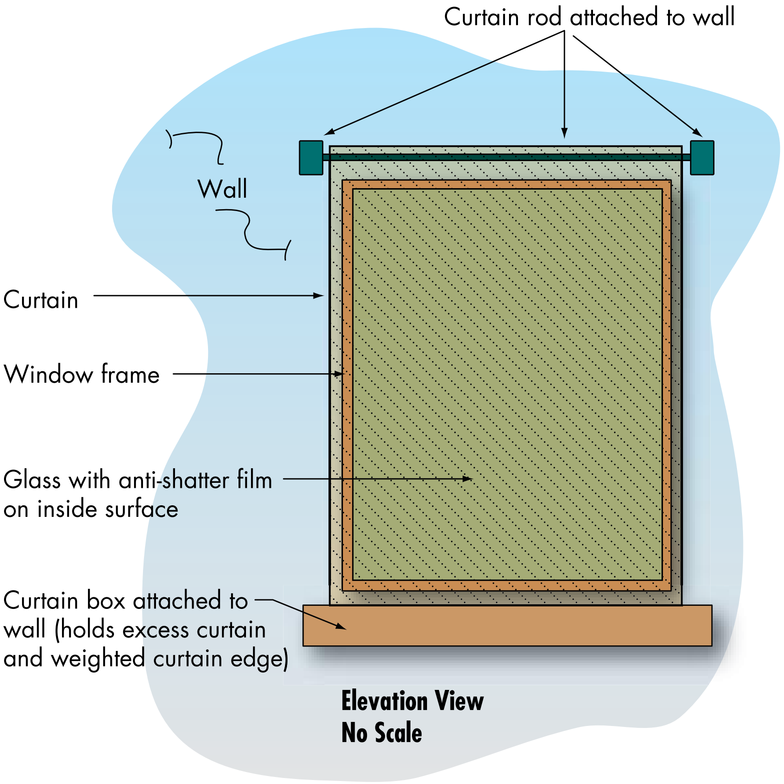


Figure 3-8: Blast curtain system.

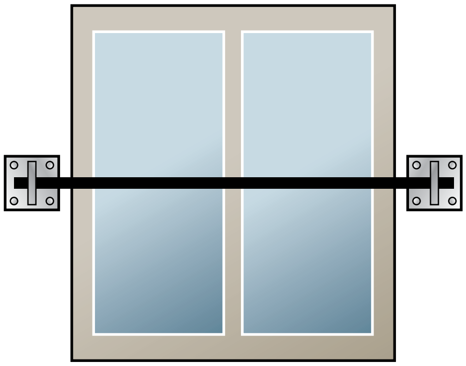
correctly by pulling them away from the glazing. The color and openness factor of the fabric contributes to the amount of light that is transmitted through the curtains and their transparency. While the color and weave of these curtains may be varied to suit the aesthetics of the interior décor, the appearance of the windows is altered by the presence of the curtains.

The curtains may either be anchored at the top and bottom of the window frame or anchored at the top only and outfitted with a weighted hem. The curtain needs to be extra long relative to the window with the surplus either wound around a dynamic tension retainer or stored in a reservoir housing. When an explosion occurs, the curtain feeds out of the receptacle to absorb the force of the flying glass fragments.

3.4.5 GLAZING CATCH CABLE/BAR RETROFIT

As explained earlier, laminated and filmed glazing is designed to hold the glass shards together if the window is damaged. Unless the window frames and attachments are upgraded to withstand the capacity of the laminated glass, there is a high possibility that entire sheets of glass would fly free of the window frames in a blast environment. Rigid catch bar systems have been designed and tested as a means of increasing the effectiveness of laminated window upgrades. The rigid catch bars intercept the laminated glass and disrupt their flight (see Figure 3-9).

Figure 3-9: Glazing catch bar.



Rigid catch systems collect huge forces upon impact and require substantial anchorage into a very substantial structure to prevent failure. If either the attachments or the supporting structure are incapable of restraining the forces, the catch system will be dislodged and become part of the debris. Alternatively, the debris may be sliced by the rigid impact, severely limiting the effectiveness of the catch bars.

Flexible catch bars can be designed to absorb a significant amount of the energy upon impact, thereby keeping the debris intact and impeding their flight into occupied spaces. They also may be designed to repel the debris from the failed glazing, as well as the walls in which the windows are mounted. The debris restraint system must be strong enough to withstand the momentum transferred upon impact, and the connections must be capable of transferring the forces to the supporting slabs and spandrel beams. Under no circumstances should the design of the restraint system add significant amounts of mass to the structure because it could be dislodged and present an even greater risk to the occupants of the building.

3.4.6 ENERGY-ABSORBING CATCH CABLE SYSTEMS

The use of cable systems has long been recognized as an effective means of stopping massive objects moving at high velocity. Cables are extensively used to absorb significant amounts of energy upon impact, and their flexibility makes them easily adaptable to many situations. The diameter of the cable, the spacing of the strands, and the means of attachment are all critical in designing an effective catch system. These catch cable concepts have been used by protective design window manufacturers as restraints for laminated lites. An analytical simulation or a physical test is required to confirm the adequacy of the cable catch system to restrain the debris resulting from an explosive event.

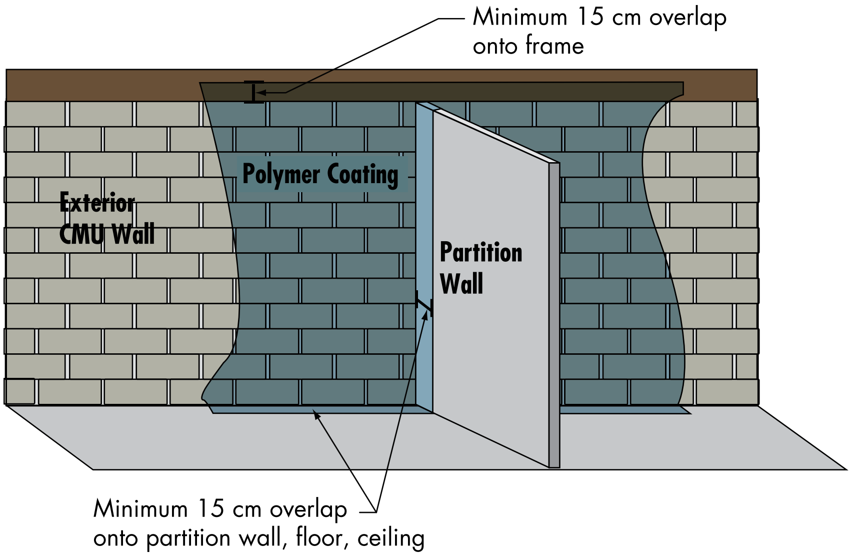
High-performance energy-absorbing cable catcher systems retain glass and frame fragments and limit the force transmitted to the supporting structure. These commercially available retrofit products consist of a series of ¼-inch diameter stainless steel cables connected with a shock-absorbing device to an aluminum box section, which is attached to the jambs, the underside of the header, and topside of the sill. The energy-absorbing characteristics allow the catch systems to be attached to relatively weakly constructed walls without the need for additional costly structural reinforcement. To reduce the possibility of slicing the laminated glass, the cable may either be sheathed in a tube or an aluminum strip may be affixed to the glass directly behind the cable.

3.4.7 UNREINFORCED MASONRY WALL DEBRIS CONTROL

URM facade provides limited protection against air blast due to explosions. When subjected to overload from air blast, brittle unreinforced concrete masonry unit (CMU) walls will fail and the debris will be propelled into the interior of the structure, possibly causing severe injury or death to the occupants. Masonry debris may result from a

100-pound TNT equivalent detonation within 300 feet or a 1,000-pound explosion within 1,000 feet and buildings may be subject to collateral damage due to an attack against a nearby building. Existing unreinforced CMU walls may be retrofitted with a sprayed-on polyurea coating to improve their air blast resistance. Polyurea materials are widely used as truck-bed liners and roof coatings; however, this innovative incremental rehabilitation technique takes advantage of their toughness and resiliency to effectively deform and dissipate the blast energy while containing the shattered wall fragments (see Figure 3-10). Although the sprayed walls may shatter in a blast event, the polyurea material remains intact and contains the debris.

Figure 3-10: Spray-on polyurea.



The blast mitigation retrofit for unreinforced CMU walls consists of an interior (and an optional exterior) layer of polyurea applied to exterior walls and lapped onto the adjacent floor and ceiling slabs. The polyurea provides a ductile and resilient membrane that catches and retains secondary fragments from the existing concrete block as it breaks apart in response to an air blast wave. The effectiveness of a spray-on polymer coating in controlling debris has been demonstrated through explosive testing at the Air Force Research Laboratory and by extensive numerical simulations. This retrofit is not applicable to load-bearing walls for which the preservation of structural integrity is required.

Instead of the spray-on polyurea, an aramid (geotextile) debris catching system may be attached to the structure by means of plates bolted through the floor and ceiling slabs (see Figure 3-11). Similar to the polyurea retrofit, the aramid layer does not strengthen the wall, but instead restrains the debris from being hurled into the occupied spaces in the case of an explosion.

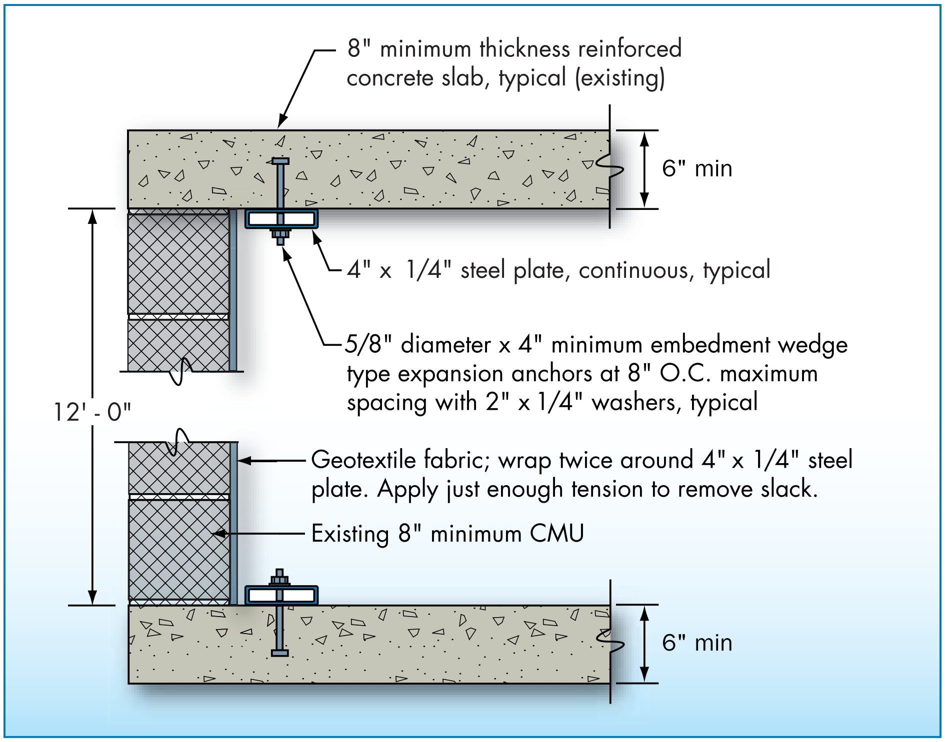


Figure 3-11: Geotextile debris catch system.

A steel stud wall construction may also be used to limit debris associated with masonry wall failure (see Figure 3-12). Commercially available 18 gauge steel studs may be attached web to web (back to back) and 16 gauge sheet metal may be installed outboard of the steel studs behind

Figure 3-12: Metal stud blast wall.

the cladding. While the wall absorbs a considerable amount of the blast energy through deformation, its connection to the surrounding structure must develop large tensile reaction forces. In order to prevent a premature failure, these connections should be able to develop the ultimate capacity of the stud in tension (FEMA, 2006a). The interior face of the stud should be finished with a steel-backed composite gypsum board product.

3.4.8 OTHER FACADE RETROFITS

In addition to upgrading the facade to minimize debris associated with failed glass, other retrofits might include the bracing of parapets, gables, ornamentation, and appendages that might be propelled into occupied space. Although these upgrades are more likely to be associated with increased resistance to seismic motions or hurricane force wind loads, they may also be warranted for buildings exposed to blast loading. Similarly, masonry veneer, steel stud back-up, and the exterior wythe of cavity walls may be upgraded to improve their resistance to extreme loads; however, these upgrades are relatively invasive and are rarely implemented to minimize the debris associated with blast loading. Due to the difficulty of improving the capacity of these building components, debris catch systems are typically installed instead of strengthening the components themselves. Although canopies at building entrances are vulnerable to an exterior explosion, they are outside of the building envelope and are rarely upgraded to improve their resistance to blast loading.

3.5 NONSTRUCTURAL MEMBERS

Because of the likelihood of glass damage and the associated infill pressures, significant damage to nonstructural members in the exterior bays is likely. This damage will produce additional debris that may cause injuries and disrupt emergency mechanical systems, such as sprinkler systems, emergency lighting, and smoke exhaust systems. Consequently, critical nonstructural systems should be protected by means of improved support and lateral bracing. While it may not be feasible to upgrade mechanical systems without conducting a comprehensive interior renovation, there may be an opportunity to perform incremental rehabilitation as systems are renovated. Some nonstructural systems that may be considered for upgrade are:

- Sprinkler piping
- Emergency lighting

- Mechanical and electrical equipment above ceilings
- Masonry walls at interior stairs
- Hazardous materials container
- Transformers
- Emergency generators
- Boilers
- Tanks
- Chillers

3.6 STRUCTURAL RETROFITS

Unlike seismic upgrades of structural systems, which generally address the global lateral load resisting system, upgrade to resist blast loads are more local. Generally, measures that tie the structure together, that increase the redundancy and ductility of individual members and upgrades, and that transfer the lateral loads into the diaphragms improve the structure's ability to resist blast loads. Since the capacity of members may be limited by the strength of the connections, upgrades must be comprehensive if they are to be effective.

The incremental rehabilitation of the structure to accept the threat independent removal of any load-bearing member, as required by the alternate path method, is generally invasive and expensive. This typically requires the development of beam-to-column moment connections for steel frame construction and the installation of tension reinforcement through beam/column connections. Steel frame connections are often difficult to access and connection upgrades may be infeasible unless the structure is fully exposed. Similarly, the inclusion of tension reinforcement through concrete frame connections may be accomplished by grooving the existing concrete and bonding supplemental reinforcement with epoxy or the adhesion of a composite fiber reinforcement to the exterior of the members.

In some cases, it may not be possible to retrofit an existing building to limit the extent of collapse to one floor on either side of a failed column. If the members are retrofitted to act as a catenary—the natural curve created by a flexible cord freely suspended between two fixed points—the adjoining bays must be upgraded to resist the large lateral forces associated with this mode of response. The catenary behavior may be achieved through the application of a glass or carbon fiber material to the top and underside of the spandrel beams and slabs. Alternatively, steel plates may be through-bolted to the spandrel beams in order to develop continuity and axial capacity. However, developing the large lateral forces may require more extensive retrofit than is either feasible or desirable. In such a situation, it may be desirable to isolate the collapsed region rather than risk propagating the collapse to adjoining bays. This approach is best suited for arresting the horizontal progression of collapse in low structures with large floor plates. The creation of structural fuse planes prevents the lateral propagation of collapse. Vertical compartmentalization requires the structure resist the impact of debris from above without pancaking the floors below and this is more difficult to achieve.

The incremental rehabilitation of existing structures to protect against a potential progressive collapse resulting from the detonation of a terrorist explosive may best be achieved through the localized hardening of vulnerable columns. These columns need only be upgraded to a level of resistance that balances the capacities of all adjacent structural elements. At greater blast intensities, the resulting damage would be extensive and termed global collapse rather than progressive collapse.

Lightweight metal deck roof structures, without a concrete fill, are particularly susceptible to direct blast loading and suction associated with diffusion over the edge of the roof. Strengthening these roof systems may require extensive upgrades; however, the connections of the metal deck to the roof framing members and the roof framing members to the columns may also be upgraded to limit the extent of debris. While these systems may sustain significant damage in response to a sizeable vehicle-borne explosive threat, particularly for low buildings, improved connections protect occupants from falling debris hazards. Openings in walls and reentrant corners are not as critical for blasts as they are for multiple cycles of seismic base motions; however, they will create stress concentrations and must be developed with sufficient ductility to accept larger deformations.

3.6.1 COLUMNS

Conventionally designed columns may be vulnerable to the effects of explosives, particularly when placed in contact with their surface. Standoff elements such as partitions and enclosures may be designed to guarantee a minimum standoff distance; however, this alone may not be sufficient. A steel jacket or a carbon fiber wrap may be used to provide additional resistance to reinforced concrete structures (see Figure 3-13). These systems effectively confine the concrete core, increase the confined strength and shear capacity of the column, and hold the rubble together to permit it to continue carrying the axial loads. The capacity of steel flanged

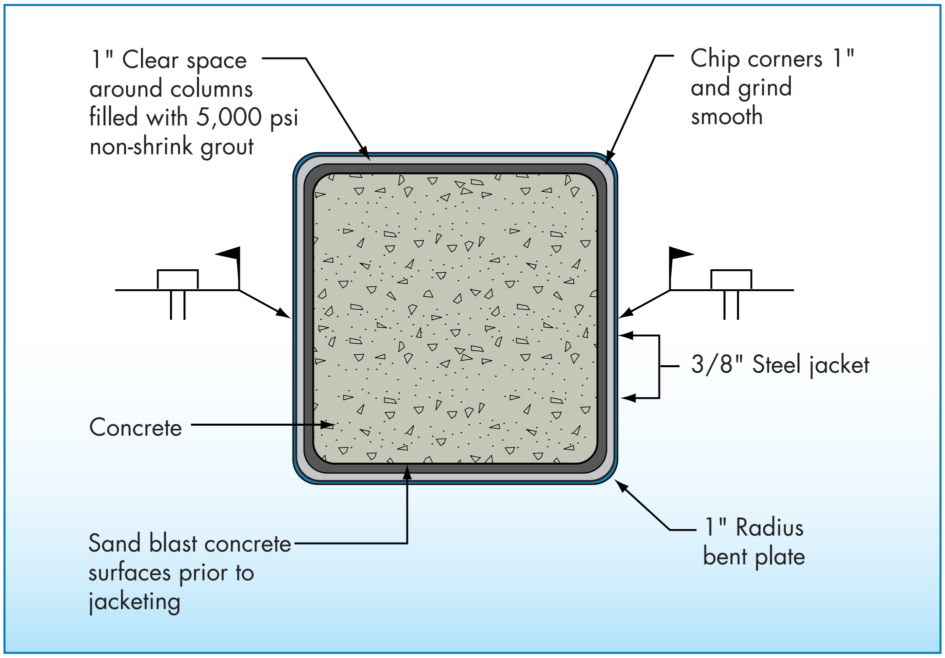


Figure 3-13: Steel jacket retrofit detail.

columns may be increased with a reinforced concrete encasement that adds mass to the steel section and protects the relatively thin flange sections. Alternatively, steel plate may be welded to flanged sections to create a box section that is more resistant to explosion. The details for these retrofits, and the corresponding connection upgrades, must be designed to resist the specific weight of the explosives and the standoff distance.

3.6.2 FLOOR SYSTEMS

Floor systems that span between column lines resist gravity loads and contribute to the lateral resistance of the building, either through frame action or as diaphragms that transfer lateral forces to braced frames or shear walls. Steel construction typically relies on concrete-filled metal decking that spans between closely spaced filler beams, which in turn span girders along the column lines. Steel beams and girders typically possess equal resistance to both upward and downward loading and are capable of developing large inelastic deformations; however, their ability to resist extreme loading is often limited by the capacity of their connections.

There is a greater variety of reinforced concrete floor systems, which may consist of beams and concrete slabs, beams and joists, waffle slabs, and flat slabs. Each of these systems optimizes the placement of reinforcement where they most efficiently resist the design loads; top reinforcement near the supports and bottom reinforcement at mid-span. Although the American Concrete Institute *Building Code Requirements for Structural*

Concrete (ACI, 2005) requires additional continuous reinforcement for enhanced structural integrity, these nominal quantities do not resist the effects of direct blast loading and rebound. Furthermore, the effectiveness of the concrete sections to develop large inelastic deformations is governed by the confinement of the concrete within the steel cages. This confinement enhances both the ductility of the members and the ability to transfer shear forces across the cracked sections. Beam-to-column connections are often congested with vertical column reinforcement and horizontal beam reinforcements and are particularly vulnerable to blast loading. Confinement of the connection details, such as those used in the design of structures to resist seismic loading, is more likely to resist the effects of blast loading than conventional concrete detailing; however, the effectiveness of critical connection details must be confirmed through dynamic analysis.

Flat slab structures do not rely on beams along edges to transfer loads to the columns; instead, they contain patterns of steel reinforcement within column strips and middle strips that develop the positive and negative moments that are imposed by the design loads. Because of the efficient use of materials, flat slab structures lack the redundancy of beam-slab systems and are vulnerable to punching shear failures around the columns (see Figure 3-14).

Floor slabs are typically designed to resist downward gravity loading and have limited capacity to resist uplift pressures or the upward deformations experienced during a load reversal (i.e., blast). Therefore, floor slabs that may be subjected to significant uplift pressures, which may overcome the gravity loads and subject the slabs to reversals in curvature, require tension reinforcement at the top fiber of the mid-span locations and bottom tension reinforcement at the underside near the supports (see Figure 3-15). The failure of floor slabs in response to explosive loading propels debris onto to the slab below and increases the unbraced length of the supporting columns. Both the pancaking of slabs and the destabilization of columns increases the potential for progressive collapse.

The incremental rehabilitation of steel floor systems typically involves the welding of plates at the connections to increase their capacity. Often, the inaccessibility of the connections makes these upgrades difficult to achieve. The incremental rehabilitation of conventional concrete construction in order to increase confinement, improve ductility, and provide for load reversals relies on techniques that were developed for the seismic upgrade of structures. If the slab does not contain this tension reinforcement, it must be supplemented with a lightweight carbon fiber application that may be bonded to the surface at critical locations. Carbon fiber reinforcing mats bonded to the top surface of slabs would strengthen the floors for upward loading and reduce the likelihood of

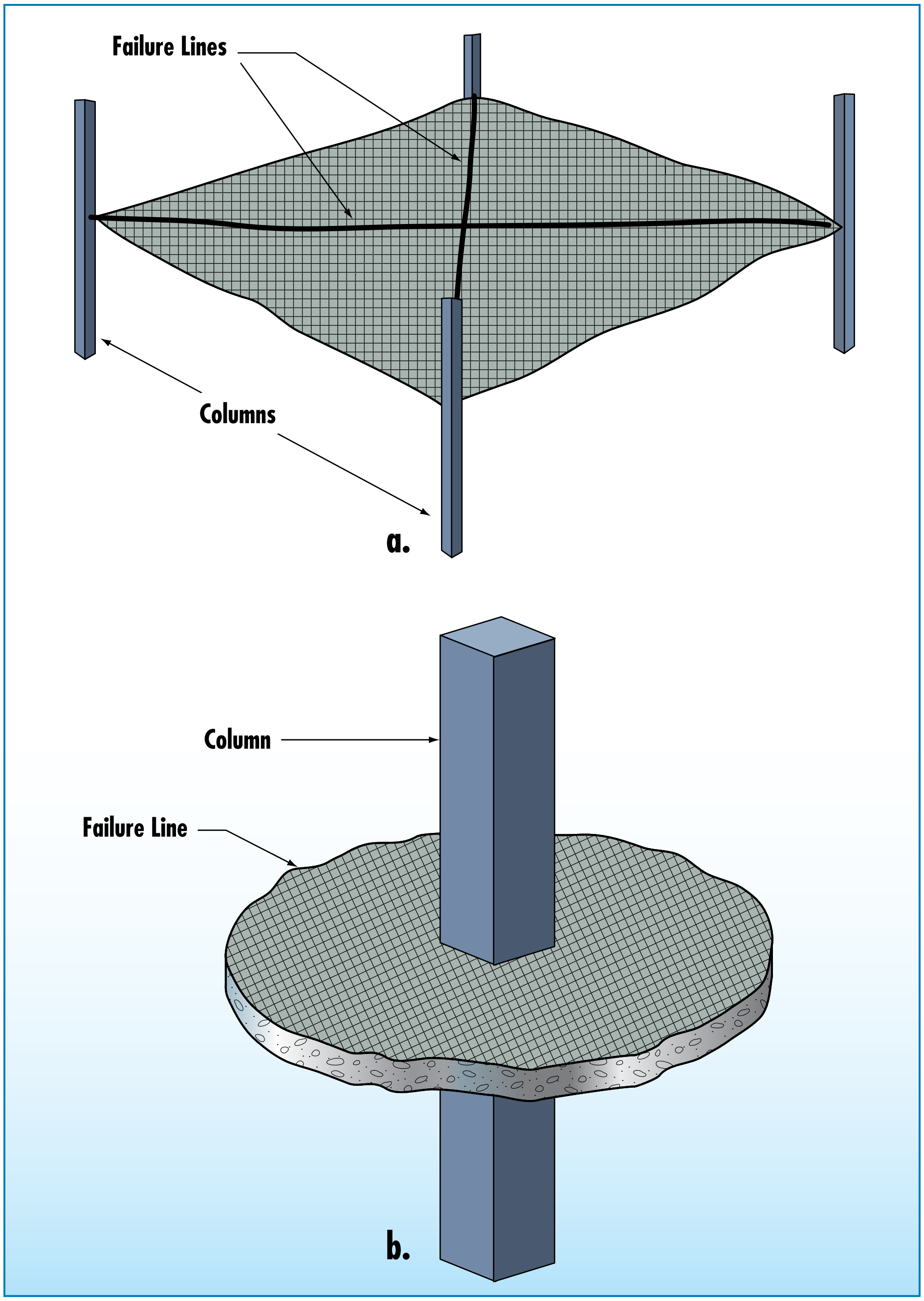
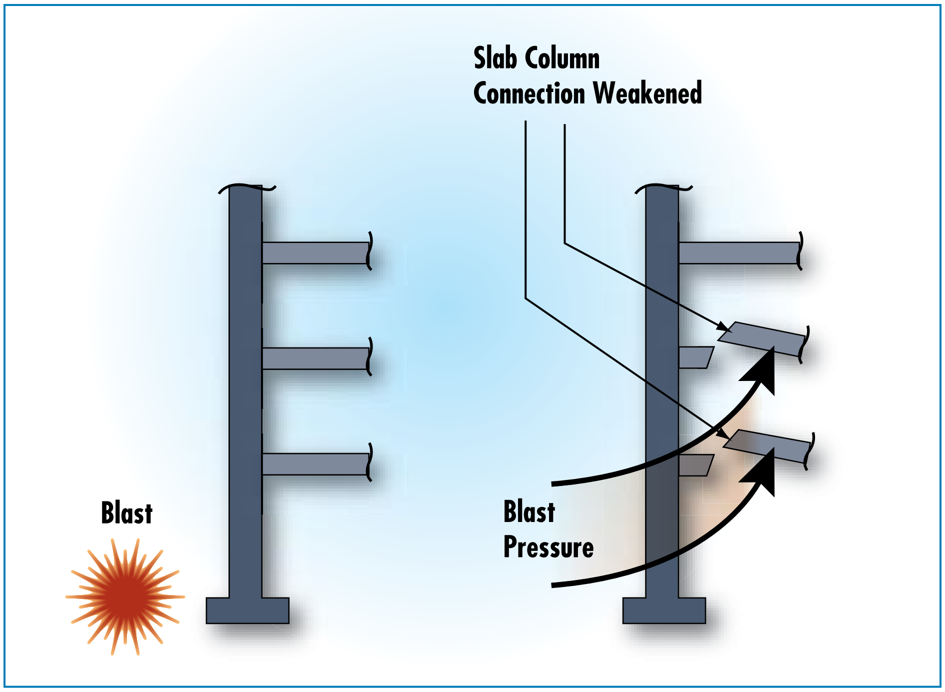


Figure 3-14: Flat slab failure mechanisms.

slab collapse from blast infill uplift pressures, as well as from internal explosions in mailrooms or other susceptible spaces. This lightweight high tensile strength material would supplement the limited capacity of the concrete to resist these unnatural loading conditions. Preliminary experience shows these retrofits to be effective. An alternative approach is to notch grooves into the top of the concrete slabs and then epoxy carbon fiber rods into those grooves. Although this approach may offer greater capacity, it is much more invasive and has not been evaluated with explosive testing.

Figure 3-15: Effects of uplift and load reversal.



3.6.3 LOAD-BEARING UNREINFORCED MASONRY WALLS

URM load-bearing-wall buildings are prohibited by the Department of Defense Unified Facilities Criteria where blast resistance is required. These buildings may sustain severe damage when subjected to 100 pounds of TNT-equivalent explosives at a standoff distance of 30 feet or 1,000 pounds of TNT-equivalent at a standoff distance of 150 feet. This makes the URM, load-bearing-wall buildings vulnerable to damage even when the structure is not the primary target of the attack. For this type of structure, it is not enough to just control the debris resulting from an explosive event; the structural integrity of the walls must be preserved to prevent structural collapse. Strengthening of the walls may be accomplished by means of a shotcrete sprayed onto the wall with a welded wire fabric. This method supplements the tensile capacity of the existing wall and limits the extent of debris that might be propelled into the protected space. Steel sections may also be installed against existing walls to reduce the span and provide an alternate load transfer to the floor diaphragms. Alternatively, stiffened steel-plate wall systems may be designed to withstand the effects of explosive loading by providing both redundancy and fragment protection. These load-bearing-wall retrofits require a more stringent design, capable of resisting lateral loads and the transfer of axial forces. Stiffened wall panels, consisting of a steel plate to catch the debris and welded tube sections spaced approximately 3 feet on center, supplement the gravity load-carrying capacity of the bearing walls and prevent the debris from entering the protected space. Finally, internal strengthening of URM walls may be achieved using a system wherein cables are snaked through holes that are cored through the wall and anchored in place with an injected grout without disturbing the finishes.

3.6.4 TRANSFER GIRDERS

Key elements that may be exposed to the explosive threat, such as transfer girders and mega-columns, warrant the most immediate attention to incremental rehabilitation. The risk assessment will identify the most critical members and the priority for hardening. If structural upgrades such as concrete encasement or steel jacketing are not feasible, then vulnerability of key elements may be reduced by means of architectural enclosures that provide increased standoff distance. Small increases in standoff distance greatly reduce the intensity of the near-contact blast loading and increase the survivability of structural members. If the architecture permits, this approach is both inexpensive and highly effective; however, advanced analysis may be required to demonstrate the performance of the structural members in response to the reduced load intensity. These key components should also be upgraded to increase the resistance of fireproofing in response to blasts to account for a wider range of potential threats and hazards. If the connections of vulnerable steel-braced and moment-frame members are accessible, they may be upgraded to develop the plastic capacity.

3.7 BLAST PROTECTION MEASURES

The preceding discussions of blast threat mitigation measures (Sections 3.3–3.6) can be condensed into the following list. It is presented here as an example of measures that might be generated by the FEMA 452 process and implemented using FEMA 459, as discussed in Chapter 2. These measures are all included in the list that comprises the vertical axes of the matrices in Section 2.3.

Site upgrades

- Increased standoff distance
- Anti-ram barriers
- Speed calming devices
- Operable barriers

Building envelope upgrades

- ○ **Glazing**
  - ○ Fragment retention film
  - ○ Laminated glass
  - ○ Blast curtains
  - ○ Glazing catch cable/bar
  - ○ Energy-absorbing cable systems
- ○ **URM**
  - ○ Sprayed-on polymer
  - ○ Geotextile fabric
  - ○ Steel stud and sheetmetal construction
- ○ **Other building envelope retrofits**
  - ○ Bracing parapets, gables, ornamentation, and appendages
  - ○ Anchoring cladding
  - ○ Anchoring masonry veneer
  - ○ Anchoring steel stud backup
  - ○ Anchoring exterior wythe in cavity walls
  - ○ Installing debris catch systems for facade elements
  - ○ Increasing the roof's resistance to blast
  - ○ Upgrading connections of light metal deck roofs to the structure

Structural upgrades

- ○ Upgrading the structure to make it more ductile
- ○ Upgrading spandrel beams to achieve catenary response
- ○ Upgrading slabs to achieve catenary response
- ○ Increasing standoff distance around vulnerable columns
- ○ Localized hardening of vulnerable columns
- ○ Enhancing floor slab upload resistance
- ○ Installing load-bearing URM retrofits
  - ○ Shotcrete

    - Steel sections
    - Stiffened steel-plate wall system
    - Reinforcing
- Retrofitting transfer girders

Nonstructural upgrades

- Sprinkler piping
- Emergency lighting
- Mechanical and electrical equipment above ceilings
- Masonry walls at interior stairs
- Restraint of hazardous materials containers
- Transformers
- Emergency generators
- Boilers
- Tanks
- Chillers

3.8 BLAST PROTECTION MEASURE COST CONSIDERATIONS

The major costs to consider in protection are those associated with standoff distance and building component costs. Cost reduction achieved by decreasing standoff and perimeter length must be evaluated against the comparative increased cost of other solutions, such as hardening the building, providing more guards, increasing camera surveillance, relocating the facility, or relocating key building occupants to interior locations. These costs must be evaluated with respect to achieving an acceptable level of risk.