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COST-EFFECTIVE DECISION MAKING FOR BLAST MITIGATION

Molly Princehorn¹ and Debra Laefer², M. ASCE

¹Harris and Sloan Consulting Group, Inc., 213 E Street, Suite B, Davis CA 95616; PH (530) 753-5300; FAX (530) 753 5380; email: mprincehorn@hscgi.com

²Department of Civil Engineering, University College Dublin, Earlsfort Terrace, Room 115, Dublin 2, Ireland; PH (353) 1-716-7276; FAX (353) 1-716-7399; email: debra.laefer@ucd.ie

ABSTRACT

Since the September 11, 2001 terrorist attacks in the United States (U.S.), there has been a marked increase in both public and private sector demand for increased blast-mitigation for existing buildings. To adequately address these new performance requirements, a rational and cost-oriented policy is needed to help building managers and owners make fiscally intelligent decisions regarding the retrofitting of existing structures. This paper presents a cost-rationalized approach to blast-mitigation retrofitting decision making, with respect to a building's criticality to the surrounding community. The proposed method addresses current approaches to blast assessment, typical blast-related vulnerabilities (structural and non-structural), and possible solutions for vulnerability mitigation. Special emphasis is given to non-gravity based loadings, post-incident functionality requirements, and transient versus permanent/semi-permanent loading.

KEYWORDS: Blast Mitigation, Explosives, Structural Retrofitting, Terrorism, Cost Analysis

INTRODUCTION

Although terrorism has an increasingly wide range of manifestations, high explosives' bombings remain the most accessible and widespread. Attacks on the World Trade Center, the Murrah Building in Oklahoma City, and American embassies, as well as numerous smaller, less publicized bombings have unveiled the vulnerability of many governmental and commercial buildings. Mitigating the effects of a potential act of terrorism requires the application of intervention strategies for at-risk buildings in a rational and cost-effective manner. While structural hardening techniques are numerous and can be incorporated relatively easily and economically into the design of a new building, retrofitting an existing building to improve blast resistance poses technical and fiscal challenges. Increasingly, tenants and building owners are demanding "blast-proofing" of their buildings. Yet, to date, non-military engineers have lacked access to a straight-forward mechanism for decision making related to the blast-mitigation of existing structures. This lack of an evaluation system is compounded by an absence of a prioritization scheme for selecting structures to receive intervention measures.

The retrofitting of all potentially vulnerable, public occupancy buildings in the U.S. is an impossible immediate goal, but the situation can be compared to the 1990 American Disabilities Act (ADA) that required every commercial building (both public and private sector) to be accessible to the disabled within a reasonable amount of time based on renovation and modification plans (U.S. 1990). Almost fifteen years later, over 85% of all new and existing commercial buildings are now wheelchair accessible (Hudgins 2004). Given finite resources and a plethora of targets, not only must a prioritization of structures occur, but a hierarchy of interventions must be understood. This paper presents a cost-rationalized course of action for building managers, owners, and designers for the application of blast-mitigation to existing structures.

BACKGROUND

Traditionally, detailed blast analyses are conducted on a building-by building basis and are highly dependent upon a risk assessment, which relies upon selecting a series of threat levels consisting of various amounts of explosives set at various detonation locations (Mays and Smith 1995). For most owners and communities such an approach is simply prohibitive both from a cost perspective and given the limited number of American engineers with extensive training in this area. Alternatively, what is proposed here is a series of intervention levels that can be progressively implemented to improve performance levels based on a general understanding of the loadings a building may experience, when subjected to blasting.

BLAST ASSESSMENT

Typically, buildings are designed to withstand downward “gravity-based” loadings, which are not representative of the lateral and uplift pressures that occur, when a building is subjected to blast loading. Instead of the dead, live, and wind loads, key parameters associated with idealized blast waves are peak positive overpressure, peak negative under pressure, dynamic pressure, positive and negative phase durations, and positive and negative phase impulses (Smith and Rose 2002), as illustrated in Figure 1. During an explosion, blast waves encase and eventually enter the building, and pressures reflect and refract between the walls, ceilings, and floors creating complicated and continuously changing load patterns. Such seemingly random load applications are outside of typical structural analysis and design.

Primary Objectives

Unlike military buildings that require at least partial, post-blast functionality, the operational requirements for civilian structures tend to focus primarily on life-safety concerns. Applying military standards of full post-blast operability to all civilian structures would be both unrealistic and uneconomical. A more reasonable course of action would be to design civilian buildings with the expectation that in the event of an explosion, large-scale damage in close proximity to the blast origin would be unavoidable, but that the building should be protected against progressive collapse similar to the design philosophy of section 1626 of the California Building Code (CBC) regarding post-earthquake performance, “The purpose of the earthquake provision herein is primarily to safeguard against major structural failures and loss of life, not to limit damage or maintain function” (CBC 2002).

Progressive collapse is a primary concern in blast mitigation, in that its deterrence facilitates rescue and recovery and saves lives. Progressive collapse occurs when a building’s load bearing members are structurally reliant upon each other, as was the case of the Ronan Point collapse, where a gas explosion caused a localized failure that then resulted in a chain reaction that imperiled an entire building (Hall et al. 2002). This collapse generated a change in Great

Figure 1. Ideal free-air blast wave

Britain's building code to require a building to withstand the loss of 10-20% (depending on building function) of its structural system without progressive collapse (Baird and Williamson 1997). A progressive collapse analysis involves performing multiple iterations, where selective elements are temporarily incapacitated to ensure that building loads will be effectively redistributed across the remaining structural members.

Loading

In order to structurally retrofit a building to withstand blast loads, the designer must first approximate the quantity of the expected bomb. This is not simple in that the resulting loads are not included in building code design procedures, and determining the quantity, duration, and distribution of the load is left to the discretion of the designer.

Load Selection

Controlling factors in quantifying blast loads tend to be the charge quantity, building façade dimensions, stand-off distance between the explosive and the building, and whether the bomb is detonated within the building or outside. Stand-off distance is the distance an explosive is detonated from the structure in question. In a free-field environment, the blast energy decays according to cube root scaling of the distance from the explosion (Longinow 1996). Based on past acts, vehicle bombs are the favored method of attack as they are able to conceal sufficient explosives to threaten an entire building. Therefore, preventing vehicles from obtaining sufficiently close proximity to the building in question plays a key role in blast-mitigation. Additionally, to date, most blast-loading models are based on a solitary building, oriented in the direction of the blast, and loaded by an idealized blast wave (Smith and Rose 2002). Thus, they fail to incorporate secondary reflective and refractive energy.

When a blast is detonated inside a building, hot gas is released, and the number of blast wave/structure interactions increases. This gas creates a quasi-static, pressure that acts in conjunction with the other blast loads. While all loads from the blast dissipate, the gas pressure decays at approximately half the of the individual shock reflections from the blast. Consequently, the overall duration of the gas pressure loads is typically longer than the structural response time of the elements loading in the building – hence the name quasi-static gas pressure (Smith and Rose 2002). This loading difference must be addressed in the analysis.

Fortunately, without extraordinary measures, hiding a sufficient quantity of explosives without detection is relatively difficult outside of a vehicle. Consequently, it is recommended that the probable design blast load be based on either a car or truck bomb parked at the nearest point of vehicle access depending upon the building's parking and loading policies, which may result in a slightly under conservative analysis but is in compliance with standard blast models (Table 1).

Table 1. Stand-off distances to produce internal flying glass (Mays and Smith 1995).

Device	Stand-off (in m) to shatter 4mm annealed glass
Small package	10
Small briefcase	14
Large briefcase	20
Suitcase	26
Car	60
Small van	120
Large van	140
Small truck	160
Large truck	200

Design Requirements

All building loads can be classified as permanent (e.g. dead loads), semi-permanent (e.g. live,

snow and wind loads) or transient (e.g. seismic and blast loads). Standard, code-based design procedures involve choosing reasonable, factored-load concentrations based upon geographic and usage requirements and, then, checking the capacity of the proposed members. The transient blast loads, however, differ substantially from typical building code-based loads. In standard design procedures, some factor of the expected pressure is imposed on each structural member, and the member is designed to withstand that force. Thus, the short duration of the blast load and the ductile capacity of the structural members are unfairly neglected. Consequently, blast loads modeled as sustained wind loads result in overly conservative designs.

Analysis Methods

Based on the differences between blast loading and conventional building loads, a more specific analysis must be used to effectively model blast loads to avoid an overly conservative design. Ductile analysis and, to a lesser degree, seismic analysis methods are two alternatives.

Ductile Analysis

To properly model these complicated load patterns, a non-linear dynamic analysis is needed (Hinman and Hammond 1997). Non-linear dynamic analysis can be performed using multi-degree-of-freedom or finite element methods, but the most common and easily achieved method is use of a single-degree-of-freedom approach, where each member can be modeled as a lumped mass and nonlinear spring (Figure 2). The spring will typically have the properties of an elastic-perfectly-plastic material, with the stiffness and ultimate capacity defined by the end conditions of the system. Equivalency factors for the mass, spring, and load are determined, giving the same displacement of the actual system (Hinman and Hammond 1997). This method is only appropriate for members that respond flexurally to explosive effects. Members located less than 30 meters from an explosion are more likely to fail in either shear or shattering (Corley 1999). Load-bearing masonry and other highly brittle material may require other considerations, such as the need to reduce material disintegration and fragmentation, while increasing load capacity. Ultimately, the inherent load capacity of the building must be approximated, and the effectiveness of various anti-blast solutions must be evaluated at both global and local levels.

Seismic Analysis

A more well-established, transient load design approach exists in the seismic community, which focuses on selective building elements for structural hardening (e.g. moment transfer from beams to columns). Earthquake designs, however, typically focus on the performance of upper levels of buildings (where larger inertia forces are generated), whereas blast-resistant designs should focus

Figure 2. Dynamic analysis of structural components (adapted from Hinman and Hammond 1997)

on the lower stories, which are subjected to higher force levels. Yet some seismic structural retrofit solutions are cross-applicable. Loading mechanisms, however, must be well understood to evaluate such cross-applicability (Table 2).

Table 2. Comparison of Blast and Earthquake Effects on Reinforced Concrete or Steel Structures

Blast	Earthquake	Implications
Adjacent structures are susceptible. Floor slabs and beams most vulnerable to upward pressure and may shatter. Weaker columns may be destroyed, but larger, heavily loaded columns are often not initially shattered.	Damage to brittle vertical supporting elements, while floor slabs and beams usually have minimal initial damage.	Seismic column designs may be applied to blast designs, but seismic beam and floor slab design would be inappropriate.
Pressures radiate from point of detonation and decay rapidly with distance and time. As shock wave passes over building, pressure direction may change.	Affects entire structure and damage occurs because of mismatches in the strength/stiffness ratio of structural members. Irregularities focus the damage on more vulnerable areas (softer and higher stories, and longer columns). Shaking matches earthquake duration; may exceed 60 sec.	Blast resistance should focus on lower and exterior portions of the building, whereas seismic intervention is focused on upper levels and is more uniform in impacting all structural components.
Shattered floors reduce lateral support that can lead to adjacent columns buckling and then the collapse of bays in the structure. If columns are shattered, floor collapse is inevitable.	High lateral loads can compromise or damage vertical supports. Without enough vertical support, relatively undamaged floors will fall onto one another, causing a pancake type collapse.	Hardening lateral elements are higher priority in blast design. Seismic design requires lateral loads to be transferred/absorbed without significantly mitigating vertical structural components.
Secondary collapse is possible, especially if rescue operations require removal of collapsed slab structures that have become the temporary lateral bracing to the remaining, free standing columns.	Aftershocks will cause additional lateral loading, which may readjust load paths, causing a secondary collapse.	Progressive collapse analysis is typically preformed for seismic designs and can, therefore, be applied to blast designs.

RECOMMENDATIONS

Mays and Smith (1995) propose that the design professional's job is to present the client with clear options concerning the level of protection, with regard to potential blast loadings from various standoff distances, and it is the client's responsibility to decide upon the extent of hardening. Unfortunately, without an appreciation for a building's current state of vulnerability, this goal is difficult to achieve. To address this problem, a risk classification system could be proposed similar to that employed in the seismic community (CBC 2002). Consistent, unbiased classification, of structures would assist communities and building owners/managers in applying limited resources to an otherwise limitless vulnerability. This classification would include structural and material issues, usage patterns, average building occupancy, and post-incident operability requirements. Other factors that are more difficult to quantify, such as the criticality

of the building's function and profile, or likelihood as a terrorist target, would also factor into the classification process.

What is here proposed are levels A through F, with A being the least critical and F the most. Low profile public buildings (e.g. small restaurants and boutiques) would be in class A; small libraries and office buildings, class B; large office buildings and schools, class C; high profile arenas and civic centers, class D, federal buildings and essential public facilities, such as police stations and hospitals, class E, and high profile buildings, class F. Blast resistant design of military structures is in a class by itself, in that they must remain fully operational during and after an attack. For the purposes of this proposed system, therefore, only civilian buildings are considered. A general consensus is still needed as to reasonable post-blast functionality levels. Intervention prioritization can then occur. The specifics of this prioritization list can then be formulated and a course of action evaluated. Once a categorization is determined and economic resources are assessed, the level of intervention can be selected.

POSSIBLE SOLUTIONS

Figure 3 provides a flow chart of a progressive series of intervention steps for the blast-proofing of existing structures. The hierarchy is based upon the level of protection afforded versus the cost/difficulty of the intervention. The system begins with the architectural and moves towards various elements of the structural system.

Common Architectural Weaknesses

The majority of injuries that occur during a blast are due to non-structural elements: glass and other flying debris. In contrast to hardening of structural elements, architectural weaknesses can be assessed and altered more simply and cost-effectively. These weaknesses include increasing the minimum stand-off distance; altering the position, function and orientation of the atrium with respect to the rest of the building; and minimizing the amount of high vulnerability, exterior glazing.

Evaluate Site Layout to Improve Stand-off Distance

Widening perimeter sidewalks, removing traffic lanes, and disallowing on-street parking increase minimum stand-off distance, and large bollards or planters around the building perimeter further improves security by preventing vehicles from mounting the sidewalk. Unfortunately, most traffic based solutions involve public policy, which requires governmental cooperation, which may be viable for public buildings but difficult to achieve for private owners. When options are limited, removing garbage cans and relocating postal boxes can help deter potential terrorists from concealing smaller bombs in close proximity to the building. Even if the perimeter line is out of the owner's control, the vulnerable regions of the building within close-range of the perimeter line are under the owner's domain. Specifically, critical facilities (e.g. computer resources) can be further isolated within the core of the building and encased by a series of heavily reinforced walls, thereby affording additional redundancy for critical building elements.

Retrofit Windows and Frames

Glazing has been attributed to 90% of all blast related injuries (Mays and Smith 1995) and, thus, is a critical component in blast mitigation. Typically, annealed plate glass breaks at only 14 kilopascals compared to the 2,100 kilopascals expected in a typical blast (Mays and Smith 1995). Annealed plate glass also behaves poorly when loaded dynamically, creating large, sharp-edged

Figure 3. Flow Chart

shards. Fewer and/or smaller windows generate less airborne debris and limit the amount of air pressure entering the facility, thus also reducing interior damage. Assuming a bomb is detonated at ground level, efforts to remove or resize windows should be concentrated on the lower floor, where the pressures will be highest. Since the blast intensity decreases exponentially in both horizontal and vertical distances, the use of clerestory windows, located close to the ceiling, above the heads of the occupants is a compensatory solution (Hinman and Hammond, 1997).

Thermally tempered glass or polycarbonate security glazings are common options for window replacements (Table 3). The breaking pressures of these two types of glass range from 200 to 310 kilopascals. More importantly, thermally tempered glass breaks into small cube-shaped pieces, and polycarbonate remains together in one big piece, both minimizing the shrapnel effect of standard window glass. When comparing breaking pressure, breaking fashion and cost, thermally tempered glass is preferred.

Table 3. Thermally Tempered Glass vs. Polycarbonate

	Thermally Tempered Glass (TTG)	Polycarbonate
Breaking Pressure	200 kPa-280 kPa	280 kPa-310 kPa
Breaking Fashion	Cube-shaped rock/salt sized pieces	Remains in one big piece
Relative Cost	~\$500 per m ²	~\$1000 per m ²

The structural designs of the mullions, frames, and the supporting walls must also be capable of holding the window in place during an explosion. Blast-resistant glass is of little use, if the glass is blown out of the surrounding casing or the frame detaches from the wall. Similarly, window retrofitting is dependent upon the structural integrity of the wall in which the window is located and the manner in which the window is installed,. An alternate approach is to use an internal atrium design (or redesign) for the first two or three floors, with glazed areas only facing interior spaces instead of the street.

Evaluate Atrium

Any ground floor atrium in close range to the perimeter line is usually the least securable and most highly populated section of a public building, making it one of the most vulnerable and popular targets for attack. If a bomb is detonated in front of the building, the blast pressures will most likely enter the building via the atrium, exposing it to the highest loads. Unfortunately, the atrium with its large open areas typically lacks the structural redundancy often present in other portions of the building.

When the atrium is the height of two or more stories, a soft story condition may exist (Ettouney et al. 1996). In this case, the columns around the perimeter of the atrium are not supported in all directions and are, therefore, more susceptible to buckling. Due to its vulnerability, structurally retrofitting the atrium with may play a major role in preventing a substantial building collapse and decreasing the likelihood of death and injury.

Assess Transfer Girders

Transfer girders (most commonly used over atriums or lobbies) concentrate the load-bearing system into a smaller number of structural elements, which allows for the wide spacing of columns to create vast, unimpeded lobby areas. Unfortunately, the incorporation of transfer girders limits the redundancy provided by the structural system. If however, these girders are able to behave as cantilever beams, progressive collapse resulting from a blast can be delayed or

possibly avoided. Designing the girder to act as a cantilever beam would require either end of the girder to support the majority of the loads, thereby preventing further collapse.

Identify and Harden Specific Other Structural Components

While glass causes nine out of ten bomb-related injuries, the vast majority of the deaths are due to falling debris or crushing during structural collapse (Corley 2004). Consequently, hardening the structural framework is one of the most effective (although difficult and expensive) ways to save lives. Since beam behavior is dependent on column behavior, which is dependent floor slab behavior, these components must be analyzed first individually and then collectively.

Determine Column Risk

Typical building columns are designed to resist gravity loads without regard for lateral ductility. Ettouney (1996) proposed that for the purpose of column design/hardening to consider only two blast scenarios: standoff distances less than 30m and those over 30m. At less than 30m, the hardening of beams and floor slabs is of equal or greater importance to column hardening. Beyond 30m, the column absorbs the majority of the blast load and thus, column hardening should take precedence over that of beams and floor slabs. The direct pressure on the column results in severe bending, and in order for the column to sustain the effects of both the axial load and the lateral displacement, the column requires sufficient ductility (Figure 4).

Figure 4. Direct Column Loading
(adapted from Ettouney et al. 1996)

Independent of stand-off distance, most blast pressures enter the building at the lower floors and load the underside of the floor slabs above, not only imposing an upward load/uplift on the slabs but also creating a brief tensile force in the columns (Figure 5). Since columns are not typically designed to withstand tensile forces or severe lateral pressure loads, column retrofitting should address these loading models, again placing emphasis on the strength and ductility of the lower columns.

The columns should be evaluated for ductile capacity and then for their ability to withstand brief tensile loading. The ductile capacity of columns is more vital to preventing collapse than tensile strength. This is due to the fact that lateral, exterior loads will most likely exceed internal blast pressures, and steel, as the primary material or as the reinforcing element, can withstand the tensile loads.

Hardening existing columns is best achieved through column jacketing by encasing in steel, concrete

Figure 5. Uplifting of Columns
(adapted from Ettouney et al. 1996)

or fiberglass. While jacketing is most often used to seismically upgrade buildings, this technique is also effective in toughening columns against blast loads by improving ductility and tensile capacity. Tests by Glover (1998) performed on columns similar to those in the Murrah Building but encased in fiberglass reinforced polymers (FRP) withstood a 900 kilogram TNT equivalent explosion at 4.5 meters (about half the size of the Murrah Building bomb at the same standoff distance) and remained serviceable. Exterior columns should be given priority to interior ones.

Retrofit Floor Slabs

Many of the major components that failed in the Murrah Building were the floor slabs (Hinman and Hammond, 1997). Typically, the blast loads cause the floor slabs to crack or rip into pieces, severely weakening their connection to the surrounding columns. Once the moment-resisting capacity of the slabs at the columns is lost, the slab loses its ability to transfer forces to the load bearing walls, severely weakening the overall structure (Figure 6).

Figure 6. Loss of Lateral Column Support
(adapted from Ettouney et al. 1996)

The installation of spandrel beams around the perimeter of the building helps tie the structure together and enhances the performance of the slab edge. Another option is to install drop panels and column capitols on exterior bays of the lower floor — the most vulnerable areas of the building (Figure 7). The drop panels shorten the effective slab length, while the column capitols improve the punching shear resistance. Additional shear reinforcement along the entire length of the support beams improves slab performance under blast loading by providing confinement and promoting a ductile response. Additional reinforcement may require attaching or encasing steel members to the slabs, which is not a common American practice but has been done in the United Kingdom and Northern Ireland (Ettouney et al. 1996).

Figure 7. Flat Slab Detailing
(adapted from Hinman and Hammond 1997)

Floor slabs are dependent upon column integrity. The slab's moment resistant capacity, as well as the capacity to transfer moments from the slab to the column, should be checked. Shear resistance of the floor slabs and their ability to withstand a temporary upward load are also important. These two problems can be remedied respectively with column heads or drop panels and mesh mats. The shear resistance is not necessarily more important to the overall building's structural integrity, but retrofitting this aspect is relatively easier and more practical than adding reinforcement to existing slabs.

Shear Walls

Retrofitting or installing shear walls is extensive and expensive. Although quantifying the benefits from a blast resistant retrofit is only general, additional shear walls typically produce a

lower cost/benefit ratio than hardened columns, slabs, beams, and often times, even facades (Baird and Williamson, 1997). Shear walls are traditionally designed to withstand lateral loading from wind or earthquakes. Wind loads are typically applied over an exterior area of the building and seismic loads over the entire foundation. Blast loads, however, will impose a more intense load over a smaller portion of the building (Ettouney et al. 1996). While the load imposed by blast or earthquake may be nominally the same, the lateral resisting behavior of the building is not. For these reasons, examining and hardening a limited number of vulnerable elements is a more realistic and cost-effective approach, when compared to redesigning and installing an entirely new lateral-resisting system.

Shear wall locations should be checked with respect to the potential threat position. For example, if the shear walls are currently located in only limited building areas, a blast could potentially eradicate the entire lateral load resisting system. Alternatively, if the shear walls are dispersed throughout the building, a blast would only damage a portion of the system, and the lateral loads could potentially be redistributed throughout the remaining elements. Additional shear walls could be added to the building in architecturally feasible locations. A second option is the installation of a perimeter moment-resisting frame, which requires strengthening of the spandrel beams and the connections to the exterior columns (Ettouney et al., 1996).

Facades

While they do not generate a major danger when exposed to a blast, building facades do typically experience significant damage. Heavy building facades that are adequately connected to the structural frame are less likely to dislodge, collapse, produce injuries through falling debris, or delay rescuers, when a blast occurs; conversely, lightweight materials, such as fiberglass or thin, lightweight concrete panels, of varying levels of attachment, result in highly vulnerable facades. A hardened wall behind the existing façade can be installed or the entire face replaced but at a relatively high cost. If this option is selected, the new façade design must adequately transmit loads from the exterior walls to the shear and/or load-bearing walls that are designed to absorb the lateral loads.

Historically, pieces of building facade have spalled off, when the blast pressure travels inside the building and creates an internal load on the exterior walls – in effect “popping” pieces from the façade, hence the importance of securely fastening the façade material to the walls and ensuring that loads can be transmitted from the façade to the structural elements and eventually to the shear walls. Steel plates help minimize spalling, when the wall is exposed to exterior blast loads. Several more high-tech blast and energy-absorbing wall systems for façade retrofit are in development. Many of the materials in these systems have been in use on airplane baggage holds for some time, but incorporating them into building designs has only been done minimally in Israel (Glover, 1998). When hardening the facade, attaching interior steel plates to the inside face of reinforced concrete walls is preferable to constructing an entirely new wall, but in many cases (particularly when the wall was not originally composed of reinforced concrete), a full replacement may have to be implemented.

Joints

While the independent structural integrity of the beams and columns is important, their behavior at the connections is vital to the strength of the building as a whole. Joints, and the overall structure, must be capable of resisting stress reversals. A typical column-beam joint is not designed to transfer moments into the column, because the moment at each end of the beam

equalizes. During blast response, a building sways, and the moments are transferred to the columns. The beam may then try to pull out of the column. Properly detailing the design of each column-beam connection could prevent this type of failure.

CONCLUSION

Ease and cost are controlling factors for intervention prioritization for blast-mitigation of existing structures. By applying a rational and hierarchical approach to such interventions, a more effective upgrading can be achieved at a lower cost. This would facilitate a greater number of structures being effectively upgraded against blast loading and upgraded to a sufficient level for their post-blast functionality requirements, which should be founded in a building typology-based system. When combined with a building prioritization and performance evaluation chart, communities and individual can better allocate limited resources amongst a potentially limitless candidate pool of structures to upgrade.

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