2014

Blast Resistant Building Design: Building Behavior and Key Elements

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BLAST RESISTANT BUILDING DESIGN

BUILDING BEHAVIOR AND KEY ELEMENTS

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This paper is a technical research paper on blast resistant building designs. Due to the abundance of information and research in this field, our primary focus was on building behavior and the key elements that contribute to the design. Blast resistant building design is the enhancement of building security against the effects of explosives in both architectural and structural design process and design techniques. As seen in the paper, there is much research to be done on this subject in the future.

ABSTRACT

Terrorist attacks and accidental explosions produce extreme and unique loading on structures and can cause widespread damage to the building, its occupants and bystanders. Blast resistant building design provides structural integrity and acceptable levels of safety for buildings. The behavior of the building during a blast event is dictated by the magnitude and location of the blast, as well as the structural properties of the building. Non-structural elements such as standoff distances, safety glass, and accessible building exits are also essential to create a level of safety. Blast resistant building design creates additional levels of safety and redundancy that protect the well-being of the occupant as well as the structural integrity of the building.

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LIST OF TERMS

BRBD – Blast resistant building design
Tb – Time duration of blast
Tn – Natural period of structure
HVM – Hostile vehicle mitigation
VSB – Vehicle safety barrier
IED – Improvised explosive device

1. INTRODUCTION

Blast resistant building design (BRBD) has been a growing concern for researchers and building owners in the United States. Government and military structures, often the target of wartime and terrorist attacks, are required to design for blast loading. In the aftermath of September 11th, and with terrorist attacks worldwide, the United States people have made structural safety a priority. When a blast event occurs, the demands placed on the structure are typically beyond the design capacity for lateral loading. Buildings that are subjected to loads beyond their capacity will fall due to structure failure and create hazards for occupants. For this reason it is typically costly for buildings to be designed to encounter large explosions in close proximity. The goals of blast resistant building design are to provide acceptable safety to the occupant while keeping the overall cost of the structure within reason; however, this paper will not cover the cost-benefit ratio of blast design.

Blast load design can account for accidental explosions, such as those in chemical manufacturing plant, and also preemptive explosions such as car bombs and other explosive detonations. The Department of Defense (DoD), along with other government agencies, has been researching improved structural responses during extreme loads. The location and magnitude of extreme blast loads are difficult to make precautions for and predict. The design process must involve architects and blast consultants as well as the structural engineers. To deal with the growing demand for blast resistant structures, the designers and building owners look into nonstructural aspects of blast mitigation. This includes creating defensive standoff distances, requiring bag and personal screenings and installing safety glass to prevent casualties.

While these nonstructural design components may conflict with the aesthetic goals of building owners and architects, this construction must coexist in order to mitigate potential threat and reduce the danger to more elegant-looking, light and graceful buildings. Many injuries sustained by occupants occur due to flying debris such as glass and building fragments.[1] The flying debris can cause more damage to occupants than the actual explosion in many cases.

While all of these design aspects increase the safety and usability of structures during an explosion, the cost benefit of design must be taken into account with the risk and probability of the blast occurring. Adding protection can save lives, but in the end, the building owner must have justifiable reasons for spending the additional money.

2. BUILDING RESPONSE TO BLAST

Blast events bring about two concerns in building behavior. The first concern is the initial blast. At the time the blast occurs, the loading of the blast and the pressure waves created can cause extreme situations that were not considered in the design. The second concern is the building behavior once the blast impulse subsides. After the initial impulse has passed, the dynamic behavior of the building can also cause high levels of stress and strain as the building continues to shake back and forth.

In determining how to create blast resistant structures, the building behavior during a blast must be taken into account. Duration of an explosion is typically between 0.1-0.001 seconds. This short amount of time is often much less than the natural period of the building. As shown in Figure 1, during an explosion the blast wave initially creates an area of high pressure, followed by a vacuum wave of negative pressure. However, the negative pressure can be ignored when analyzing the blast effect as it has little effect on the maximum response of the structure.

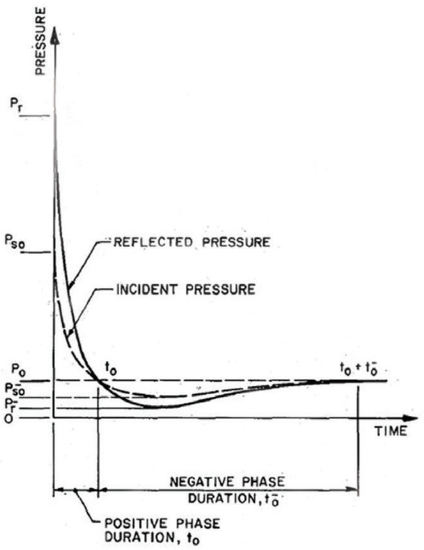

Figure 1. *Qualitative pressure-time history* [2]

When analyzing the response of the structure, it is crucial to know the properties of the building and the predicted blast duration. The phase duration of the blast will be known as T_b and the natural period of the building as T_n. If T_b is much longer than T_n , the building will produce a mostly static response to the blast loading. In a static response, there is a force, a reaction and a deformation. The blast essentially acts like a force that is slowly (with respect to the structure's natural vibration) applied along the structure. This means that the maximum building displacement will have occurred before the blast phase is over. When this is the case, the response of the building is dictated by the stiffness, elastic modulus and magnitude of the extreme load. A building that has been designed with a large value of stiffness will experience less static deformation. When T_b happens to be much shorter than T_n the loading is treated as an impulse load. This causes the maximum displacement to occur after the blast has subsided and the deformation will be determined through dynamic response calculation. If T_b happens to be almost identical to T_n, large deformations, similar to those caused from earthquake loading, must be taken into consideration. By analyzing these maximum dynamic responses, buildings can be designed to sustain the maximum strains that result.[3]

During the blast the nonstructural elements are also subjected to damage. As the initial pressure wave makes contact with the building facade, windows usually shatter and the building's walls and columns deflect under the immediate pressure. When the blast intensity is too great, the walls and facade may suffer permanent displacements as the strain causes plastic deformation, or even structural collapse. If the facade does not remain intact during the blast, the pressure waves may cause upwards and downwards pressure on the floor slabs and columns. These pressures may produce loading reversals that the slabs and columns have not been designed for. Figure 2 shows

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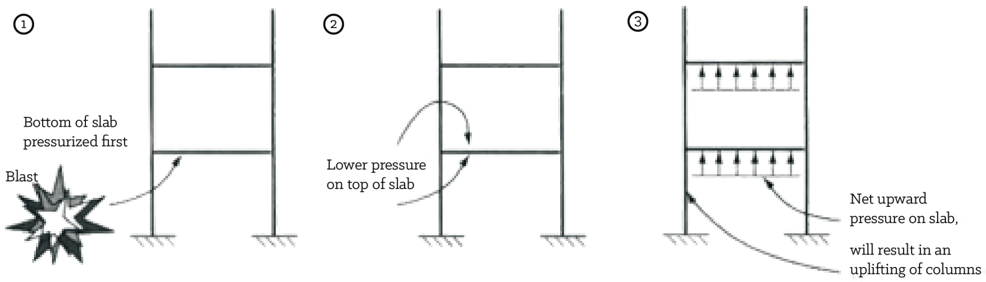

Figure 2. *Uplift pressure during a blast.* [4]

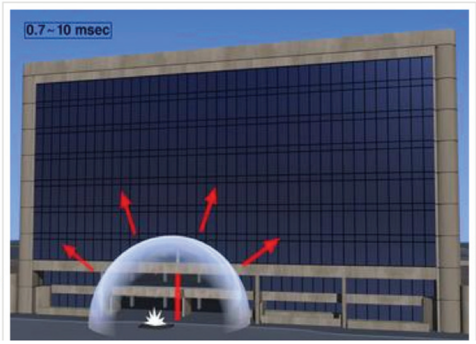

Figure 3. *Blast Expansion* [7]

a visual representation of the uplift pressure and reverse loading.

Floor slabs are typically designed with a downward gravity loading in mind. This design approach calls for placing rebar to resist flexural bending. When the moments change direction, the flexural reinforcement is no longer resisting the bending. This reverse loading may cause shear cracking in the slabs. Perez reported that this case of reverse loading was the cause for the structural collapse of the Alfred P. Murrah Federal Building in Oklahoma City.[5]

Figure 3 shows a computer simulated image of the Oklahoma City explosion. As the pressure wave extends outwards, the glass windows become deadly as the fragmented shards are projected both inwards and outwards. While the building may not collapse, a high number of casualties may still result from nonstructural elements. Approximately two thirds of non-fatal casualties in the Oklahoma City bombing were due to glass shards.[6]

Once the duration of the pressure wave has passed, the building is still in danger of further damage. The blast impulse has transferred its momentum to the building. The building responds by vibrating back and forth freely, or oscillating, at its natural frequency. The building's natural frequency, or the time required to complete one oscillation, is a structural property that depends on the mass and stiffness of a structure. Knowing the structural properties is essential in the calculation of response. These dynamic or movement calculations can be complicated and are usually left to the aid of finite element software. To model this behavior, engineers approximate the building by assuming it behaves as a single degree of freedom mass-spring structure. Designing for dynamic response makes blast response similar to earthquake design loads. A structure is typically designed to resist lateral wind loads. Wind loads may be designed for 200 lb/ft^2 but the pressure wave of a blast event can produce loading of 7000 lb/ft^2, a magnitude 35 times greater. Some engineers may think that the blast load is a static force load that is applied to the building wall. This incorrect assumption ignores the dynamic response of the building and may lead to an over-designed lateral bracing system.[8] Designing for blasts is thus often left to engineering firms that specialize in these extreme loads.

Progressive collapse, or the failure of one member, leads to the progressive failure of subsequent members, and is a common failure mechanism for buildings subjected to blasts. To prevent progressive collapse of the structure, a static design approach may be used to provide additional integrity. One method involves additional reinforcement in the flooring and roofs to allow those elements to span over lost structural elements and encounter reverse loading.[9] Another method determines the capacity of the structure when selected elements are assumed to have failed during the blast. This method determines whether or not the remaining structure has the strength to withstand the new loads and the new loading path. Building codes such as those found in *ASCE (American Society of Civil Engineers) 7 Minimum Design Loads for Buildings and Other Structures and ACI 318 (American Concrete Institute)* have addressed design requirements for structural integrity.

3. BLAST RESISTANT BUILDING COMPONENTS

To analyze blast resistant building design, it is essential to examine key physical elements within structures, the building materials and how the occupants of the structure interact with the building. Before divulging into the aforementioned topics, it should be noted that all blasts discussed in this section will relate to blast attacks coming from outside of a structure, generally from a hostile threat, such as terrorism. Within this generic category of blast attacks, events can be categorized as either standoff explosions or contact detonations. Standoff explosions are detonated at a distance away from the specific target building while contact detonations are in contact with the target structure.[10] The improvised

Figure 4. *IED Baghdad* [11]

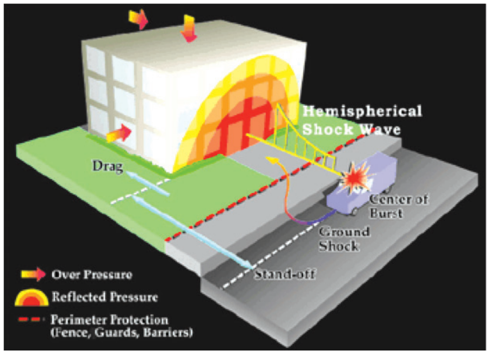

Figure 5. *Vehicle Standoff Explosion* [12]

explosive devices in Figure 4 are examples of a potential contact detonation as they are lying against the wall of a structure in Baghdad, Iraq, and Figure 5 shows a van-delivered standoff explosion.

Both styles of blast produce a powerful wave of positive pressure projected outward from the explosion. Once detonated, the pressure wave produced can travel outward at over 700 mph. Although the initial shock wave caused by both blasts are the same, the actual blast load felt by the structure is inversely related to the distance between the building and the blast. The blast load is reduced by a cubic factor as the blasts location moves away from the building.[13] The simplest way to negate the differences in these two blast attacks is to have every potential contact detonation turned into a standoff explosion, thus lessening the shock wave. Steven H. Miller said that, "for this reason, the first principle of blast resistance is to limit access to the target."[14]

Similarly, Miller went on to state the first priority of limiting access to a structure should be that of limiting access by large and convenient platforms of explosive arrival, such as cars, trucks or vans. These techniques, when utilized to remove the threat of vehicles, have come to be known in the blast resistant building design community as hostile vehicle mitigation (HVM).

As shown in Figure 6, the top left illustration shows no HVM techniques, while the other three use speed lessening, vehicle indirection or total removal of access to the building by approaching vehicles. Once vehicles have gotten within an attackable distance of a building target, it is necessary to employ vehicle security barriers (VSB). VSBs can be either passive or active in the way they mitigate blast damage. Passive barriers do not move and can include berms, water, fences or bollards among others. Active barriers include operable gates, blockers or retractable bollards. Figure 7 shows examples of VSBs used in blast design.

To measure the effectiveness of VSBs a rating system was developed and is shown in Table 1. This rating system is based on barriers ability to stop a 15,000lb truck traveling at a constant speed. For example, the barrier rated at K8 is able to stop the 15,000lb truck at a speed of 40 mph. At impact, the cargo bed of the truck must not penetrate more than one meter beyond the inside edge of the barrier.

Now that blast attack styles, hostile vehicle mitigation techniques, and vehicle security barriers have been discussed, the integrated physical security system of a blast resistant building can be addressed. As stated before, the first priority in improving a buildings blast resistance is the ability to limit the overall access to the target. This is achieved first by utilizing vehicle mitigation techniques to limit not only the ability of

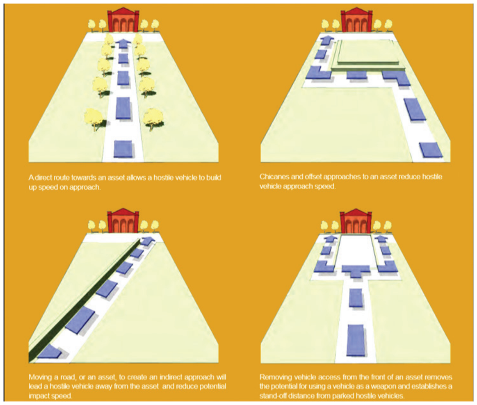

Figure 6. *Hostile Vehicle Mitigation* [15]

Figure 7: Vehicle Security Barriers[16]

Speed at Impact	*Barrier Rating*
30 mph	K4
40 mph	K8
50 mph	K12

Table 1. *U.S. Department of State 2003 Certification Standards*[17]

TO ANALYZE BLAST RESISTANT BUILDING DESIGN, IT IS ESSENTIAL TO EXAMINE KEY PHYSICAL ELEMENTS WITHIN STRUCTURES, THE BUILDING MATERIALS AND HOW THE OCCUPANTS OF THE STRUCTURE INTERACT WITH THE BUILDING.

cars and trucks to get near a structure, but also with which the speed they can. As the threat vehicle approaches, at a reduced speed, it is met with both passive and active VSBs. Security personnel operate the active VSBs. Their job is to examine the approaching vehicle and inspect the car or truck, its occupants, and their credentials before allowing them to proceed into the structure.

The integrated physical security system can be seen in Figure 8, which shows the techniques used to increase blast resistance at a high-value government facility. Here, HVM offset techniques at A reduce speed and increase distance from structure. Once the vehicle is closer, active VSBs are utilized at B, preventing immediate entrance into the space. Throughout the figure, passive VSBs can be seen at C, D and E. Overall, these combined systems form a site that is increasingly resistant to blast attacks, regardless of the construction of the critical facility at its center due in

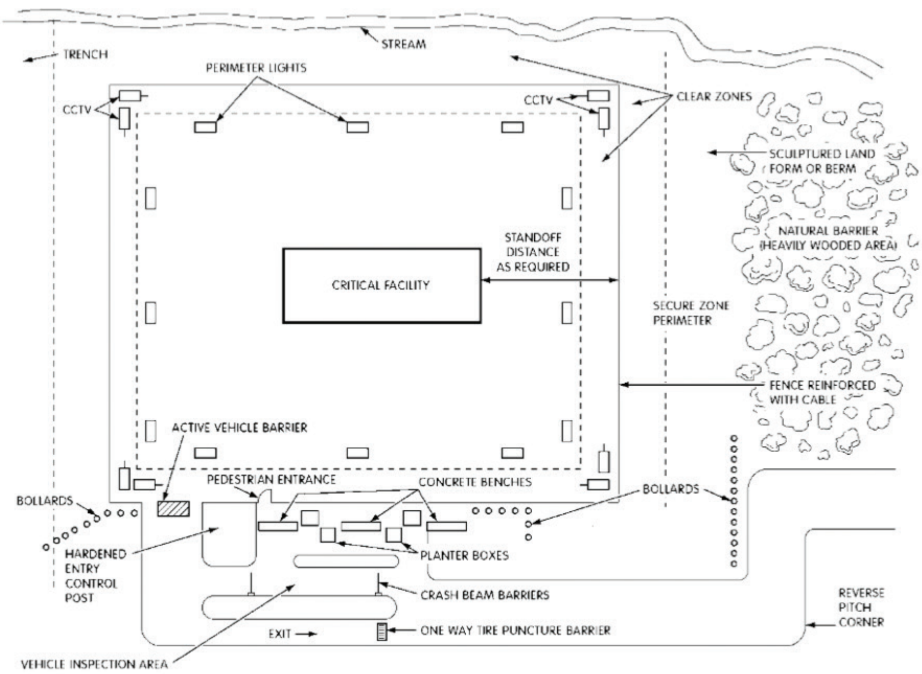

Figure 8. *Integrated Physical Security System*[18]

large part to the large standoff zone, which will negate contact detonations from large delivery devices and lessen any standoff explosions that may occur.

Most techniques covered so far have been in relation to large delivery devices such as cars or trucks; many can be modified to, or already are useful in deterring smaller delivery techniques such as improvised explosive devices (IEDs) or suicide bombing styles. Water bodies, fences, lighting, and increased surveillance techniques are also practical approaches in deterring human delivered blast attacks.

While increased standoff distance and large delivery prevention are crucial in increasing building blast resistance, it is sometimes inevitable that a blast attack will occur. This is when the construction of the target building and the materials chosen will be put to the test. When a blast attack occurs outside of a target building, generally the walls of the structure are the first of its components to be affected by the pressure waves generated. Exterior walls must be designed to fail in a ductile manner rather than in a brittle manner. Because of this, the preferred material for exterior wall construction is poured-in-place reinforced concrete. In fact, “virtually all new U.S. embassies are constructed using this material.”[19] This material is preferred because it has significant mass, unparalleled continuity between members, and extensive research and performance testing by the military as it is readily used for defensive bunkers. It is essential that the concrete be designed in a ductile manner. Ductile design allows for significant deflections of structural members before failure. These significant deflections warn building occupants of the impeding failure, allowing time for evacuation. Ductile failures also produce less shrapnel, which can reduce the injuries caused. Buildings built with a non-ductile concrete design can have catastrophic consequences when subjected to a blast attack.[20] As seen in Figure 9, the Alfred P. Murrah Building in Oklahoma City was constructed using non-ductile concrete design and its design proved to be catastrophic.

Figure 9. *Oklahoma City Bombing*[21]

While not as popular as cast-in-place reinforced concrete, pre-cast concrete panels are another viable option for constructing a blast resistant structure. These pre-cast panels should be at least 5 inches thick and have two-way steel reinforcement bars to increase ductility, which is still one the most necessary properties, which is similar to cast-in-place. Two-way reinforcement will aid in the prevention flying concrete debris.[22] Embedding wire mesh within the pre-cast slabs can also reduce flying concrete debris. Recently, the blast resistant building community has been addressing concrete reinforcement in nonconventional ways such as the use of embedded fiber reinforcement or textile. Lafarge, the building materials company, has produced a concrete mixture reinforced with needle-size steel fibers throughout. This new style of concrete can increase tensile strength by up to ten times by providing a better bond than conventional steel rebar.[23] The steel fiber reinforced concrete from Lafarge was subjected to blast tests at RAF Spadeadam in Cumbria resulting in cracking but no shrapnel production.

Improving concrete mixtures and reinforcement is not the only way blast resistant builders are combatting fragmentation of the target structure. Surprisingly enough, pickup truck spray on bed liners have become a mainstay in fragmentation prevention. Liner treated rooms survived a 200 pound TNT explosion at 30 feet which destroyed the same room that was left untreated.[24] The truck bed liners

DESIGNING FOR BLAST LOADS HAS SEEN AN INCREASE OVER THE LAST DECADE DUE IN LARGE PART TO THE EVENTS OF SEPTEMBER 11TH, 2001, THE PREVALENCE OF TERRORISTIC THREATS AROUND THE GLOBE AND THE UNITED STATES’ AND UNITED NATIONS’ INVOLVEMENT IN MULTIPLE WAR ZONES.

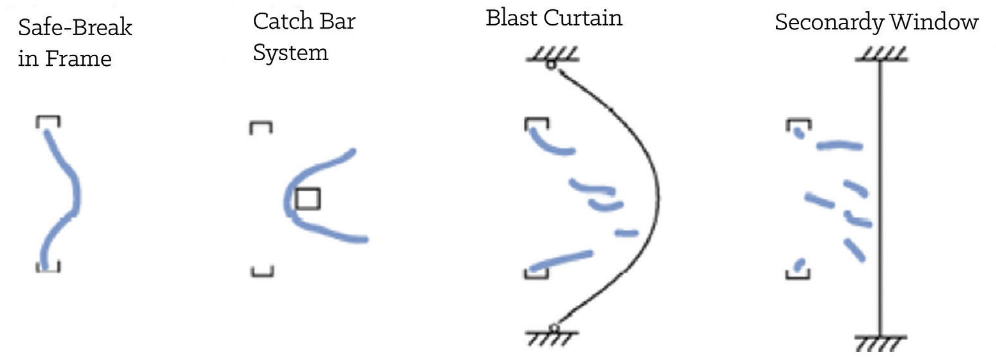

Figure 10. *Shard Reduction in Windows*[27]

are so effective at increasing a buildings blast resistance that the pentagon began a program to coat the entire building after the attacks of September 11th, 2001.[25]

Although it is essential that the outer walls of structures targeted for blast attacks be resistant, they are often limited by their weakest links, namely windows and doors. Windows are incredibly vulnerable during a blast attack and it can be hard to prevent their failure. Because of this, windows are generally designed to fail before their anchoring system, and to fail in a way that prevents excessive shards. It is imperative to prevent widespread glass shards, as this is responsible for a large number of injuries during a blast attack.[26] After decreasing the number of windows in a blast resistant building, the next step is to utilize shard reduction techniques such as those in Figure 10. Here, safety bars, blast curtains or a secondary window are used to catch shards and prevent them from entering an occupied room in a target building. For each design in Figure 11, the blast is occurring to the left and the target room is to the right. To further prevent glass shards, many designers use laminated annealed glass. The lamination holds the glass shards together when broken and the annealed glass is weaker than others preventing it from transferring further load to the structural components of the building.

In blast resistant building design, doors do not receive the attention that windows usually do, as people in target structures are generally not near exterior wall doors for extended periods of time. Exterior blast resistant doors are often double steel with internal cross bracing. They have an increased number of fasteners connecting them to the wall and secured as to not propel inwards upon a blast attack.

SUMMARY

Blast resistant design is an important aspect for high-risk structures, including public, commercial and government buildings. Designing for blast loads has seen an increase over the last decade due in large part to the events of September 11th, 2001, the prevalence of terroristic threats around the globe and the United States' and United Nations' involvement in multiple war zones. To better design structures to negate the effects of a blast attack, it is necessary to examine a structure's specific response to the initial blast pressure wave as well as the secondary building behavior once the blast has subsided. Research must be conducted to determine the buildings' natural properties (mass, stiffness, natural frequency) in order to predict the buildings' responses. Buildings' strength is essential in preventing immediate collapse from the blast magnitude, and to withstand the dynamic response. Building damage through progressive collapse can be prevented with redundancy systems. Furthermore, a building's response is not limited to its structural elements. Designing for extreme loading involves the building owner, structural engineer, architect and blast design experts. It is crucial to mitigate the threat of hostile vehicles as well as design a structure in coordination with the integrated physical security system. Building materials and architectural elements can provide increased levels of safety and performance of structures. The first, and most important step in increasing blast resistance is the need to create a large standoff distance. This is achieved through multiple techniques of hostile vehicle mitigation and vehicle security barriers. Once a blast is detonated outside of the standoff zone, while lessened, the blast will still affect the target building. For this reason, potential target buildings must be built with extreme durable materials such a cast-in-place reinforced concrete or steel-fiber-reinforced pre-cast concrete. Once the exterior of the building is constructed from either of these, windows capable of handling specific blast zthreats must be installed as well as similarly capable doors.

FUTURE WORK

Blast resistant building design research has been growing rapidly. The prediction models are quickly becoming more advanced as technology improves. The high demand for blast resistant buildings is creating opportunities for research and development. Focused efforts will lead to finding better materials and techniques to be used in the building of protective structures. As improved methods are discovered and implemented, people will have to continually look for the most cost effective ways to adequately withstand the blasts to be expected.