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Blast Vulnerability Assessment: Challenges and Myths

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Blast Vulnerability Assessment: Challenges and Myths

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Abstract

The terrorist attacks of September 11, 2001 in the United States and the foiled terrorist action in Canada in 2006 have drastically increased the awareness of terrorists attack in Canada. Now more than ever, federal government departments and owners of "iconic" structures are seeking to understand the vulnerabilities of their structures to blast load and what can be done to increase the survivability of the structures and their occupants. The greatest problem hindering the engineering community is an understanding of the threat (explosive quantity to design against) and incorporating existing physical security measures into a comprehensive mitigation design.

In Canada, there is a lack of standardized threat (credible explosive quantity) that can be used in design or assessment of vulnerability of existing infrastructure. Every institution uses an arbitrary amount of explosive in vulnerability assessment without adequate attention to the capability of the adversary. There is an urgent need for a multi-disciplinary group of experts with expertise and information of terrorist activities in the country to estimate current and forecast future terrorist capability and credible amount of explosive to use in assessments.

The use of pressure-impulse (P-I) diagrams for the assessment of component response to blast load is now prevalent in the engineering community because of the ease of use and availability of automated tools for this task. The P-I diagrams are, however, based on single modes of failure and could fail to capture more critical failure modes than the flexural failure mode on which most diagrams are based. The engineering and research community need to develop P-I envelopes that capture all the failure modes of building components to ensure that the vulnerability assessments do not erroneously overestimate the blast load resistance of infrastructure.

Keywords: Blast, explosives, vulnerability assessment, blast loading, terrorists, P-I diagrams

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1.0 Introduction

The terrorist attacks of September 11, 2001 in the United States and the foiled terrorist action in Canada in June 2006 have drastically changed the way both the government and private sectors do business. These and other incidents have increased awareness and the possibility of terrorist attacks in Canada. The myth in many circles that a terrorist action in Canada is unlikely was forever dispelled when 17 plotters were arrested in Toronto. Now more than ever, government departments and owners of "iconic" structures are seeking to understand the vulnerabilities of their structures to blast load and what can be done to increase the survivability of the structures and their occupants in the event of a terrorist attack. The biggest problems hindering the blast engineering community to offer a comprehensive response, however, is an understanding of the threat (explosive quantity) to design against and incorporating existing physical security measures into a comprehensive blast protective design for the long-term.

A blast vulnerability assessment, as compared to an all-hazards vulnerability assessment, is simplified in that the threats and assets are partly defined and established. The threat is known to be an explosive device, with its attendant destructive attributes, high blast pressures and potential to generate fragments, ground motion, and cratering. The target, most often a structure, is typically identified, but its criticalities, contents, processes or people within are not fully identified or rated in importance. In many cases threat risk assessments are not been performed prior to the blast vulnerability assessment. Thus explosive charge mass determination, deployment locations, asset identification and their criticality, and blast mitigation methodologies form the core of the blast vulnerability assessment.

In Canada, there is a lack of a standardized credible explosive quantity that is accepted for use as a minimum requirement in vulnerability assessments of existing infrastructure or for design of new infrastructure, nor is there a minimum construction standard for buildings deemed to be terrorist targets. When performing blast vulnerability assessments, most institutions begin with a seemingly arbitrary explosive quantity without considering who the adversary may be or what his/her capabilities are. In fact, in many cases the institution seeking to understand the vulnerability of their structures to blast loading has no idea who the potential adversary is.

Blast vulnerability assessment must be based on a defined threat; an explosive quantity and a charge location relative to the target/asset. The explosive quantity and standoff distance of the charge from the target must be chosen with the current security situation and the future terrorism trends in mind. Today's estimated threat must remain valid tomorrow otherwise the vulnerability assessment and resultant mitigation design cannot provide the desired level of protection to the structure and occupants. In general, the principle of layers of defence, in the form of the 4-D's, Deter, Detect, Deny, Devalue, is used as a guide.

In the field of blast design and mitigation, the risk of attack or damage to the structure can never be eliminated. Thus blast vulnerability assessment and risk analysis is a science of balancing the retrofit options (capital investment) and the probability of an adversary attack. In most cases a level of threat is assumed based on asset criticality and used for the development of blast mitigation strategies and effective physical security measures to ensure desired levels of protection. Future increases to the threat can be addressed with deployment of mobile physical security measures, such increase of guarded zones with barriers or posting of security details on the perimeter of the facility.

The definition of the design basis threat (DBT) is also a concept that must be developed early in the blast assessment exercise in concert with a number of other disciplines since, most often, the engineer lacks the training and/or expertise to establish credible explosive threats (mass and point of deployment) to use in the blast vulnerability assessments.

2.0 Current State of Blast Vulnerability Assessment in Canada

Currently in Canada, some property owners and government departments and agencies understand the importance of ensuring the survivability of their structures and personnel, and have taken proactive measures to understand the vulnerabilities of their facilities to blast loads from terrorist attacks. However, lacking information such as the identity and capabilities of the aggressor makes it almost impossible to establish the aggressors' preferred mode of attack, their capability of carrying out an attack using explosives and the potential magnitude of such an attack. The intelligence/law enforcement agencies most often have some information about which terrorist groups or violent protesters are active within a given locale, but it is not easy to acquire enough information about their capability and likelihood of an attack establish a credible charge mass. The challenge facing the blast engineering community is determining the credible explosive charge mass to use in blast vulnerability assessments. A credible explosive quantity that will address the current security situation and future terrorism trends is fundamental to determining blast loads on critical building components and predicting their survivability from a terrorist attack.

The establishment of DBT consisting of a credible explosive mass and standoff distance for the blast vulnerability assessment should be a multi-disciplinary effort involving intelligence/law enforcement agencies, physical security engineers, landscape architects (planners) and design engineers. The intelligence/law enforcement agencies are most suited to provide advice on active terrorist groups and violent protesters, their capabilities, and their region of activity. They are also most suited to advice on what quantity of explosive or explosive-making ingredients can be surreptitiously accumulated by an adversary without detection. The physical security engineers and landscape architects (planners) on the other hand can use the principles of Deter, Detect, Deny, Devalue to achieve security targets. For example, they can establish layers of secure perimeters using natural terrain features or landscape architectural features to maximize, standoff to the structure. The design of and provision of suitable barriers and vehicle inspection posts on access routes can also assist in guaranteeing design basis standoff distances.

Currently, the lack of standardized DBT for blast vulnerability assessments has led to the common practice of selecting a delivery vehicle and estimating the probable payload based on published values such as Table 1 [1]. Usually a car or delivery truck bomb is chosen depending on the perceived importance of the facility or accessibility of the site to different vehicle types. The choice of car or delivery truck bomb does not, however, preclude an attack with a vehicle with a larger payload. In fact there are bulk explosive trucks plying the highways with up to 20,000 kg of explosive that could be commandeered by an aggressor and used for a terrorist attack. The choice of attack vehicle is most often limited to a delivery truck bomb because larger explosive masses, at typical standoff distances, will cause wide-scale damage that is very difficult to mitigate, especially in a downtown scenario where standoff distances are very limited. Also, the probability of a successful attack with such a charge mass is extremely low considering past records of terrorist action in North America.

Table 1: Typical bomb delivery mechanism and explosive capacity [1]

Delivery mechanism	Explosive charge mass capacity [kg]
Pipe Bomb /Mail Bomb	2.3
Suitcase/Backpack Bomb	23
Car Bomb – compact sedan	227
Car Bomb - Sedan	454
Passenger/Cargo Van Bomb	1814
Small Van/Delivery Truck Bomb	4536
Moving Van/Water Truck Bomb	13608
Semi-trailer bomb	27216

A typical vulnerability assessment begins with a site survey consisting of a walk around the exterior and through the interior of the facility. The exterior inspection is important to ascertain approach routes to the exterior of the façade, neighbouring buildings and their use and occupancy, and physical security features that can limit vehicular access. The interior inspection, on the other hand, typically establishes critical assets and critical structural elements and their location relative to the explosive charge. These inspections are followed by a thorough review of the building drawings with an objective to understanding the structural framing, façade composition, and blast resistance of these elements.

If the facility is in a fenced-in area and the fencing material is sufficiently robust to defeat ramming by vehicles, then maximum standoff distances can be established at various locations around the perimeter and the associated blast loads calculated for those threat scenarios. Also, vehicular and pedestrian traffic into the facility can be routed through check-points where interior and undercarriage searches of vehicles can be performed. Bollards, natural boulder landscaping, ditches and berms are very effective in limiting vehicular access [2] and should be incorporated into the landscape design, especially if the fencing material is not sufficiently robust to defeat ramming. In the downtown scenario the standoff distance is typically limited to the distance to the roadside curb. If parking can be prohibited and prevented on bounding streets the scenario with a stationary vehicular bomb is precluded but the suicide bomber scenario still remains a viable attack mode.

A vulnerability assessment and accompanying physical security measures can provide the desired protection levels insofar as the physical security measures are active and effective. It is a myth that implementing physical security measures without the necessary checks or surveillances will guarantee the desired protection. If the standoff distance for the DBT is chosen assuming that vehicles allowed into the guarded perimeter will be inspected (interior and undercarriage), then if the inspection is relaxed with time, the designated standoff distance is no longer valid. Thus a mitigation design using the DBT will no longer provide the desired level of protection.

3.0 Blast Load Parameters

Blast load (pressure and impulse) on a structure can be calculated from a known quantity of explosive and standoff distance. There are various methods available to the design engineer for calculating the blast load parameters necessary for structural analysis and retrofit design. These methods vary in their complexity from simple lookup curves (or tables) and empirical methods to high-level computational fluid dynamic (CFD) computer codes. Unlike many structural loads, blast loads calculated from either the simplistic models or CFD computer codes are deterministic, without an accompanying appreciation for the uncertainty of the load.

The blast loads thus calculated are not without variability and error. Blast load determination is highly uncertain and no two computer codes or calculation methodologies will yield the same result. Also, different blast communities prefer different calculation methods that will often lead to discrepancies when such two communities interact or collaborate [3]. So a correct blast load is a myth and highly dependent on the analyst and the blast load determination models used.

In every blast vulnerability assessment, whether triggered by the possibility of a terrorist attack as with civil infrastructure, or accidental explosion as in industrial processing plants involving detonable materials, the quantity of explosive is key to determining the risk of damage to the infrastructure. In industrial processing plants it would be fairly easy to determine the maximum amount of explosive material. Alternatively, the maximum amount can be regulated by operational procedures. In the case of terrorism, however, it is almost impossible to establish an amount that would be valid today and in the future in the face of the changing global dynamics. Thus the first source of variability is the amount of explosive quantity to be used in an analysis and what blast model to employ.

Most engineering professionals base their blast load calculations on the Kingery-Bulmash polynomials [4] instead of on CFD computer codes because of the complexity, computer resource requirements, and highly specialized knowledge required to perform a successful CFD analysis. Even though the Kingery-Bulmash polynomials are curve fits to data taken from four large tests (5 – 500 tons TNT) between 1959 and 1964 [5] they have been incorporated into computer programs such as CONWEP [6] and BLASTX [7] and numerous design manual such as TM5-1300 [8]. With the use of the Kingery-Bulmash polynomials so widespread in engineering practice to determine blast load parameters, it is important to understand the accuracy of the results and uncertainties associated with their use.

Bogosian et al. [3] compared the pressure (reflected and incident) and impulse (reflected and incident) of the positive phase calculated with the Kingery-Bulmash polynomials with test data from several field test programs. The field tests used various explosive types, masses, and shapes and detonated at different heights of bursts. The authors reported that the Kingery-Bulmash polynomials accurately predicted the blast loads (pressure and impulse) with minimal scatter in the data. A statistical analysis of the data, ratio of Kingery-Bulmash to experimental results, indicated mean values ranging from 0.86 to 1.19. The mean value of incident pressure values was 1.19 (standard deviation = 0.24), while for the reflected pressure it was 1.06 (standard deviation = 0.33). The mean value for incident impulse was found to be 0.86 (standard deviation = 0.18). The experimental results for reflected impulse were very much dependent on target size due to the differences in clearing effects for each test.

As with most engineering loads, the blast loads calculated with the Kingery-Bulmash polynomials can be multiplied by a load factor to ensure that the calculated loads are not underestimated. In fact, TM5-1300 [8] recommends the charge mass be multiplied by a factor of 1.20 before the determination of blast load parameters.

TNT equivalency, a conversion methodology used to convert explosive effects of explosives to common bases, also adds to the variability in blast load determination. The TNT equivalency values are often affected by confinement, mass, range etc.; values not normally considered in the computer models.

4.0 Blast Load Resistance of Elements (Pressure-Impulse Diagrams)

To determine the vulnerability of both structural and non-structural components to blast loads, the components' resistance to high strain rates must be established. All materials possess an apparent higher strength when subjected to fast acting loads such as blast. There is limited comprehensive information about the increased in strength of common construction materials such as concrete, masonry, structural steel, and reinforcing steel, at loading rates that approaches that of blast load.

The increase in material strength in comparison to the static strength is quantified by a dynamic increase factor (DIF); the ratio of dynamic to static strength. A number of researchers have reported that under high strain rates the yield and ultimate strength of reinforcing steel increases by about 60% [9,10] while the DIF of the tensile strength of concrete is reported as high as 7.0 for strains rates of about 100 s^{-1}[11, 12]. The effect of strain rates on the compressive strength of concrete is less significant in comparison to tensile strength. At strain rates of about 100 s^{-1} the DIF of concrete compressive strength is about 1.5 [12].

For a comprehensive blast vulnerability assessment the capacity of structural and non-structural members of a building façade must be evaluated against the blast loads from the DBT. The response of the building members is most often modeled as a single-degree-of-freedom (SDOF) system. Most engineers use automated tools to assess the vulnerability of buildings to the blast loads. The requirement to quickly complete assessments with very limited information has led to the use of pressure-impulse (P-I) diagrams (iso-response curves) for various elements and material types. The P-I diagrams chart the response of components based on a single critical parameter, most often the maximum deflection as with structural elements or the fragment trajectory in a standard test cubicle as with glazing. Figure 1 presents typical P-I diagrams for window glass based on the United States General Services Administration (GSA) Performance Criteria [13].

P-I diagrams are very simple graphical depictions of a component's response to blast loading. The curves represent iso-response behaviours and delineate the "failure-survival" domains of response. The response of a component to a given blast load (pressure and impulse) will signify failure if it is to the right and above the iso-response curve and survival if it is to the left or below the iso-response curve. Thus the vulnerability of the element of a structure becomes as simple as determining the domain the imposed blast load falls in on the P-I curve.

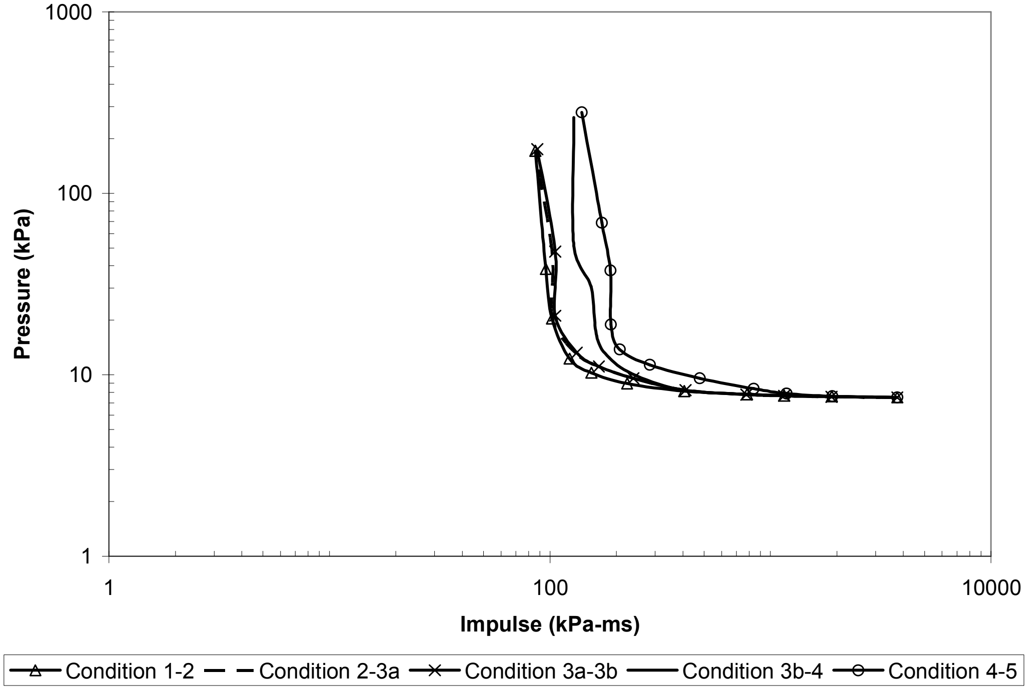

Figure 1. Typical window glass Pressure-Impulse diagram.

The blast engineering community is currently generating a lot of P-I diagrams for standard building components for use in automated tools for performing blast vulnerability assessments of critical infrastructure [14,15,16]. The most widely used P-I diagrams are those for window glass and retrofit window glass. WINGARD PE© developed for GSA is one tool that generates P-I diagrams for window systems [17].

Window glass, being the weakest of the façade components, causes most of the injuries in a blast event [18, 19, 20]. A number of researchers have studied the response of various types of glass to blast load. The response is most often quantified in terms of blast pressure and blast impulse, and in terms of glass shard flight and impact onto walls of a standard test cubicle (Performance Criteria). These Performance Criteria are then related to the protection levels afforded by the glass and the hazard posed to the occupants of a building [13].

P-I diagrams lend themselves ideally to the response of standardized elements with unique failure modes such as window glass. For structural elements such as concrete, where the size and reinforcement content of components are not standardized, the usefulness of P-I diagrams diminishes. Unless the P-I diagrams capture all failure modes of a structural system, their use in determining vulnerability to blast loads should be limited. It is a myth to think that P-I diagrams generated for unique failure modes are globally applicable to all structural components of similar construction material and type.

Most P-I diagrams are generated based on a SDOF analysis under a triangular blast load pulse. For such a system two asymptotic behaviours can be distinguished; impulsive and quasi-static [21, 22]. The transition between these two asymptotes, the dynamic regime, is difficult to generate and is often neglected. Elements in the dynamic behaviour realm could be erroneously assessed since theoretically generated P-I diagrams do not generally describe the behaviour of elements in the dynamic realm. Also, most P-I diagrams fail to capture other failure modes that could be more critical than the flexural failure mode. Shear failure, diagonal and direct shear, can precede flexural failure modes especially when peripheral columns that are designed for gravity loads only are exposed to blast (lateral) loads. The connections in steel structures also have additional failure modes that are not captured in most P-I diagrams.

The use of P-I diagrams in blast vulnerability assessments has become very popular with design engineers and their ease and quickness to complete assessment support their popularity. However, the P-I diagrams limitations may lead to over simplification and errors. Thus, to use P-I diagrams in blast vulnerability assessments, the analyst should be ensure that the curves adequately represent the element being analyzed (material properties and support conditions), have been verified with testing, and represent an envelope of all possible failure modes of the element.

5.0 Conclusions and Recommendations

Conducting a blast vulnerability assessment to determine the vulnerability and survivability of structures and occupants during a terrorist attack is a prerequisite for blast mitigation design and building upgrades. Even though a blast vulnerability assessment should be preceded by a threat risk assessment to identify the threat, assets, and criticality, the information about the adversary and their most likely mode of attack maybe lacking, as is a design basis credible explosive charge mass. This has led to the practice of choosing a car or delivery truck bomb as the most probable attack mechanism depending on building criticality and accessibility to the delivery vehicle.

The blast vulnerability assessment and the resultant mitigation design provide a level of protection commensurate with the DBT. Thus, it is essential that a credible charge mass be used in the assessment that reflects the current security environment and remains valid for the future. Failure to do so would diminish the level of protection in the face of increased DBT. It is important that the best estimate for the DBT be developed by a multi-disciplinary group of specialist which has the necessary expertise and information to estimate current and future terrorist capability. The alternative of increased physical security by increasing guarded zones with barriers or posting security details in the future presupposes advance knowledge of the attack; which can never be guaranteed.

The use of automated procedures based on P-I diagrams to estimate the vulnerability of structural and non-structural building components and window shard hazard to occupants is prevalent in the engineering community because of its ease of use. However, most P-I diagrams available for structural components are generated for flexural response without due consideration to other failure modes such as shear failure and connection failure. This leaves buildings assessed with the iso-flexural response curves vulnerable to failure by either shear or connection failure under blast loads.

The challenge facing the engineering community, however, is to develop comprehensive P-I diagrams that consist of envelopes that address all failure modes. These P-I diagrams should be validated with testing to determine their suitability and applicability in blast vulnerability assessments.

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