Use of Probabilistic Methods in Evaluating Blast Performance of Structures

By
Andrew Nicholas Gillis

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Signature of Author: ______________________________
Andrew Nicholas Gillis
Department of Civil and Environmental Engineering
May 11, 2011

Certified by: ______________________________
Jerome J. Connor
Professor of Civil and Environmental Engineering
Thesis Supervisor

Accepted by: ______________________________
Heidi M. Nepf
Chair, Departmental Committee for Graduate Students

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ABSTRACT

The social and political climate of the modern world has lead to increased concern over the ability of engineered structures to resist blast events which may be incurred during terrorist attacks. While blast resistance design has been prominent for years in the industrial and military setting, it is starting to gain importance for structures which have been traditionally designed for aesthetics and which have high occupancy density. In these situations it is important that not only materials but the geometry of the building be optimized to reduce the effects of such an attack. However, designing a structure only for prescribed code requirements does not necessarily give a prediction of the post-blast behavior of the structure. Similar to the use of performance-based engineering for seismic events, the effects on a structure designed for blast loading should not be speculative but rather should exhibit expected behavior which is appropriate for the parameters of the given blast. Accounting for uncertainty of a potential blast event by assessing the structure in a probabilistic approach may lead to a more prudent and predictable assessment of damage and loss for the owner. The work herein attempts to provide an overview of the precedent of use of probabilistic methods in structural engineering, the current state of practice in blast engineering and set forth a framework and example by which probabilistic methods may be extended to blast considerations.

Thesis Supervisor: Jerome J. Connor
Title: Professor of Civil and Environmental Engineering

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1 Introduction

1.1 Problem Statement

The need to design civil structures which may resist the loads created by blast events is not a new concept in the field of structural engineering. However, the nature of blast threats has changed in recent decades and concerns have spread to broader building occupancies. Blast design has traditionally been a concern in military, secure government, and industrial facilities. However, attacks on the World Trade Center in 1993 (see Figure 1.1) and the Murrah Building in 1995 (see Figure 1.2) are largely credited with bringing to light the security risks of office buildings which may have an inherent social or political significance (Whittaker et al., 55). As methods in the structural engineering field advance, it is necessary that appropriate action and diligence be taken to extend the evolving methods of recognizing and designing to reduce risk in this newly recognized field of necessity. The need to evaluate the risk of structures to explosive attacks, as well as the systems susceptibility to failure within a range of possible plausible attacks, is one that has not yet been fully recognized. With the inherent uncertainty of any form of extreme loading, especially one so dependent on building occupancy, human perception, and security effectiveness, the task of fully understanding a structure's risk to blast events is a complicated one. The issue may therefore benefit from the use probabilistic methods, which have become prevalent in other areas of structural engineering. It is proposed that such a probabilistic approach, if organized and approached properly, may provide greater insight into the analysis of both existing and proposed structures. The following herein will attempt to provide an overview of the current state of practice in blast engineering, address the major pitfalls of current deterministic design methods, establish a framework of establishing risk, performance criteria and analysis parameters, and use such parameters to perform a simulation on a theoretical facility to illustrate the possible methods and results from such an analysis.

Figure 1.1 View of damage from 1993 World Trade Center bombing (Source: geopolicraticus.wordpress.com)

Figure 1.2 Aerial view of post-collapse Murrah Building (Source: TruthAlliance.net)

1.2 Current State of Blast Engineering

Currently, blast engineering is typically dictated by code provisions and recommendations by governing bodies in the engineering field. The American Society of Civil Engineers (ASCE) Structural Engineering Institute has a Committee on Blast, Shock, and Impact in which there is an active subcommittee titled the Sub-Committee on "Standards for Blast Design" and which also previously had a Sub-Committee on "Design for Physical Security." Standards have been established in which methods of identifying risk, as well as design recommendations and loading characteristics are established. Moreover, the General Services Administration (GSA) has established strict code requirements for government buildings which include requiring facades to be resistant to a minimum prescribed pressure as well as including redundancy to avoid progressive collapse. Such requirements include the structural stability of a building with the loss of a major load-bearing wall or column in the first two levels (GSA Security Criteria, 5-10). Other design institutes, including the American Concrete Institute (ACI) and the American Institute for Steel Construction (AISC) have also released publications and design recommendations which may aid designers in creating more blast resistant structures.

While there has obviously been a large range of research and publication of design code and recommendations which address blast design, it should be noted that the standard practice of blast engineering is indeed deterministic. These prescriptive design requirements, such as those rigidly established by the GSA, do account for the stochastic nature of explosions in part through the establishment of loads in a similar manner to the Load and Resistance Factor Design method. However, such methods do not allow for the determination of characteristic behavior of a structure in which such prescriptive loads may be exceeded or additional load bearing members be damaged. Additionally, these design methods do not necessarily provide insight into the probabilistic risk of damage other than any inferences which may be drawn during the procedure of designing to mitigate progressive collapse.

1.3 Probabilistic Methods in Structural Engineering

The need to better understand structural response to earthquakes beyond the use of prescriptive design spectra has lead to the development of performance-based methods in the last two decades. Coming from a desire to ensure and understand the damage states which may be expected for certain intensity earthquakes, probabilistic methods attempt to consider earthquakes with distinct probabilities of occurrence. While this provides no guarantee of the load events which will actually be seen in a structure's life, it does establish an expected performance associated with prescribed intensities.

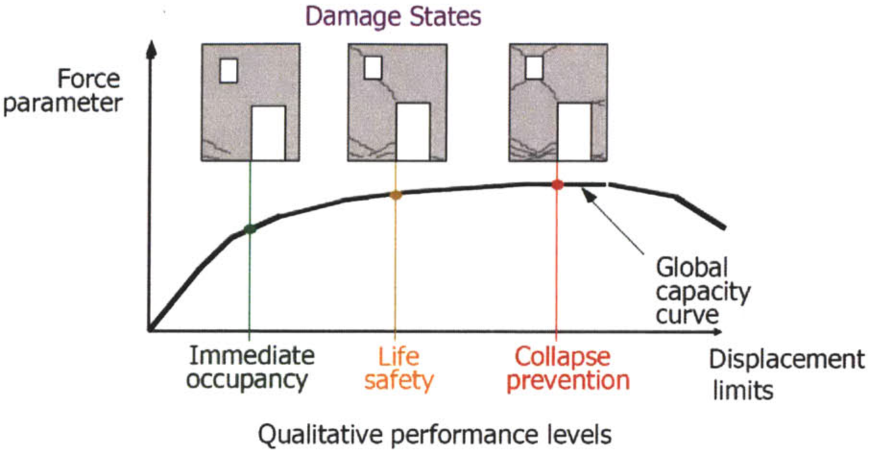


Figure 1.3 Qualitative Performance Levels per FEMA 273/274/356 (Source Whittaker et al., 58)

The principles behind the use of probabilistic methods are the establishment of well defined performance criteria consisting of damage states and loss and the use of a reasonable range of loading patterns applied to a structure which are desired to produce such performance. Typical performance criteria relate to the safety and damage of a structure following the loading event of concern. In the field of earthquake engineering three basic performance criteria levels have been established including: immediate occupancy, life safety and collapse prevention. As defined by the Federal Emergency Management Agency (FEMA), these three primary performance levels are shown qualitatively in Figure 1.3 and described in greater detail in Table 1.1. The damage states are associated with deformation of the structure with non-structural damage resulting from excessive deformation which may be elastic and structural damage resulting from inelastic, permanent, deformation of the structure.

Performance level	*Damage description*	*Downtime*
Immediate occupancy	Negligible structural damage; essential systems operational; minor overall damage	24 hours
Life safety	Probable structural damage; no collapse; minimal falling hazards; adequate emergency egress	Possible total loss
Collapse prevention	Severe structural damage; incipient collapse; probable falling hazards; possible restricted access	Probable total loss

Table 1.1 Building Performance Levels per FEMA 273/274/356 (Source: Whittaker et al., 58)

2 Assessing Threat and Risk

2.1 Stakeholders

Since the threat of a blast event in a structure depends largely on human and process influence on the building, it is necessary that in order for a facility to be appropriately analyzed for risk that the people who will have the most information on the operation of the facility be able to provide insight. Since damage incurred on certain equipment may in itself cause additional hazard, such possible cascade effects must be taken into account in order to provide a true representation of blast threat. Additionally, since a large goal of performance-based engineering seeks not only to avoid loss of life but minimize financial loss, it is necessary that any technical specialists, building occupants, the building owner, security representatives, mechanical and plumbing sub consultants and architects provide information which may help to establish possible points of interest in a building and help to quantify monetary damages from loss of certain assets (Conrath et al., 1-2). It is therefore suggested that prior to an analysis which may seek to establish the performance of any facility that all appropriate stake-holders be consulted and play a role. This is essential for the determination of the possible threat to all or parts of that facility and the safety and financial risks associated with loss of any portions of the building.

2.2 Quantifying Assets

As referred to above in Section 2.1, when attempting to establish a framework which quantifies loss due to both structural and asset damage, a thorough analysis of the interdependence of all facility systems must be analyzed. In the framework being established herein, assets are to be viewed as targets and therefore can be broken down into two different subcategories: primary assets and secondary assets. A primary asset is one which may be viewed as a likely target of aggression while a secondary asset is a component which is interdependently related with a primary asset that would allow the function of the secondary asset to affect the function of the primary (Conrath et al., 1-3).

It should be stated that the asset to be protected first and foremost is human life; per Canon 1 of the ASCE Code of Ethics an engineer "shall hold paramount the safety health and welfare of the public (ASCE)." Human welfare should always be prescribed as the most important of primary assets. However, immediate occupant safety is not the only concern for which this primary asset must be protected. Indeed, certain facilities may have an equally large need to protect secondary assets, such as industrial facilities which may contain hazardous materials or nuclear power facilities in which the effects on immediate building occupancy may be far less influential to human life and public welfare than the potential widespread damage which may be caused by the failure of any operational subsystems. While these examples are unique to certain facilities, more common examples of relationships between primary and secondary assets include a system deemed as a primary asset and its power supply which serves as a secondary asset or a security system which serves to prevent access to the primary asset (Conrath et al., 1-2). Another key aspect in quantifying assets is the replaceability of the asset; often the true price of loss of an asset exceeds the difference between its salvage value and its purchase cost. There are many instances, especially in the case of large and long-term equipment, in which installation considerations are major undertakings.

For the purposes of establishing performance states in a blast analysis, the structure itself must also be considered an asset with certain primary and secondary elements. The risk of total loss or progressive collapse of a structure is one which must be mitigated, for both safety and financial reasons, with high certainty to the highest degree of likely probable threat. However, even if a structure does not experience collapse following a blast event, any inelastic structural response must be repaired. Additionally, as addressed previously, another key aspect in quantifying a structural member's asset value is the cost of installation. For example, the replacement of a major load bearing column is a more costly undertaking then the repair of a section of floor slab or an infill beam.

2.3 Evaluating Threat

Once the major assets, dependence of assets, and values of assets have been defined, it is necessary to determine what the threat of an attack on any given asset might be. There are several aspects which may contribute to the threat on an asset, detailed further within this section, which account for the significance of an asset, the attainability of certain explosive devices and the opportunities which may allow such devices to be used.

2.3.1 Target Attractiveness

One of the first and most easily understood aspects in evaluating the threat on an asset is the significance of that asset and how this significance might make it attractive for a group or individual to eliminate or damage it. Some obvious examples of asset target attractiveness are buildings with historic or political significance. Such sites must be strongly considered as targets for terrorist attacks. Since buildings of this sort may be sought out solely for the significance of what broader ideals they may represent, often the global structure itself may be viewed as the primary asset most targeted as the destruction of the structure may achieve an ideological statement. This method of target selection is very evident in the bombing of the Murrah Building, both the 1993 and 2001 attack on the World Trade Center and the 2001 attack on the Pentagon. While these attacks also have motives relating to operational disruption, they serve to show that a symbol of significance potentially makes a structure an asset at risk.

The other major aspect in evaluating an asset's risk of attack is its criticality to other functions. For example, a power plant's ability to provide power to a large area of customers would make it a critical asset for the region and therefore subject to a high level of risk. Similarly, any structures or facilities which may themselves provide a necessary function of safety, such as levees or dams and their regulating facilities, should be considered to have a high level of risk compared to standard use facilities.

2.3.2 Accessibility

Since the delivery of an explosive device to the site at which it is intended to explode is necessary for an attack to be carried out, when evaluating a threat to an asset it is necessary to examine the proximity to the asset which may be achieved by an attacker. While accessibility is some obviously limited by the physical characteristics of a facility and the surrounding site, in many cases the accessibility is determined by the defined operation procedures of the facility and therefore relies on technological and human input. Therefore, when establishing a model which may determine the possible locations of an explosive device at detonation, physical limitations of accessibility may be viewed as deterministic and may be modeled as null regions for possible blast load origins. However, such zones which may be limited by operational procedures must be considered to have a certain probability of entrance and delivery of an explosive device. This must be evaluated through a thorough examination of security procedures and any inherent weaknesses.

2.4 Limitations of Deterministic Design

In evaluating the risk of a structure and facility assets within, it becomes apparent that the definition of risk and parameters are complex and difficult to encompass through deterministic and prescriptive design guidelines. Rather, it is unrealistic to attempt to predict the potential stand-off distance of a blast from structural elements and facility assets. While deterministic design is valuable in instances of increasing the robustness of a structure and its ability to withstand blast loading it provides no indication of likely damage states under certain blast events and is therefore analogous to the state of seismic engineering prior to the advent of performance-based earthquake engineering. That is, following a blast event, there is likely to be a response which may not have been predicted and a disconnect between the structural engineer and the owner of a facility as to how the building has performed (Whittaker et al., 63). It becomes clear upon examination that the use of deterministic design recommendations and code regulations, set forth by such organizations as ASCE and GSA, may be used in conjunction with probabilistic methods. In this way, the minimum performance of components may still be preserved. However, information collected from a probabilistic assessment of blast performance may be used to supplement such guidelines. This may indeed lead to an increase in safety as well as better mitigate financial loss through the formulation of a more robust design method than deterministic design on its own.

3 Typical Design Recommendations

In designing a structure to resist blast loads there are two basic categories which envelope the measures which may be taken to mitigate the success of an attack to damage the structure. The physical security of a structure refers specifically to the structure, architectural aspects, and surrounding site which may be designed in a way to either deter or limit the ability to attack or to withstand the loads produced if there is an attack. Since such physical features exist at the site and do not require continuing operation they are also often referred to as passive security. Additionally, a facility with security which continuously provides additional security systems which do not exist without ongoing maintenance and operation may be said to implement operational, or active, security. Such systems are subject to human and technological limitations which must be considered without optimism.

3.1 Physical (Passive) Security

Physical security may be provided by several design considerations. A major consideration in increasing a structures resistance to blast loading is increasing its strength and ductility. However, other less obvious design strategies may be used to reduce damage due to a blast by ensuring symmetrical lateral load resisting systems and by limiting accessibility.

3.1.1 Hardened Exteriors

A way to mitigate the effects of a blast event on a structure is simply to harden its exterior and allow blast pressures to be taken by the building without significant failure. It is necessary that a hardened exterior reduce the transmittal of forces to the interior components of the structure designed for standard serviceability considerations. This is often accomplished through two primary designs; a thick, well reinforced concrete exterior or a strengthened steel curtain wall. While the obvious solution to potential external blast attacks is to provide a strong concrete exterior, recent advances in materials and glazings have allowed architectural concerns to gain more influence in the blast design field. Thus, more innovative and aesthetically pleasing solutions have begun to gain prominence in typical buildings designed for blast concerns.

Concrete is a naturally effective material for shielding against blast pressures. It has a high mass, surface resistance to penetration and fragmentation, and when reinforced with steel, may dissipate energy efficiently through crack formation. Additionally, it is relatively economically efficient to create a large surface barrier using concrete due to its low unit price and wide use in the construction field. However, beyond external blast walls, concrete can be a difficult material to use effectively for a structural system as it is a brittle material and therefore poses a challenge when attempting to design a globally ductile structural system. While progress has been made recently to increase the ductility of concrete beam-column joints due to seismic concern, there is a lack of construction experience in many areas of low to moderate seismic concern and therefore detailing more ductile connections in such construction markets would prove to be difficult. Additionally, concrete's poor tensile strength does not allow flexural members to remain stable under large deflections due to catenary action. While this does not discount concrete as a primary structural material for a building being designed for blast loading, strong considerations must be taken to ensure that there is not an onset of progressive collapse due to a lack of ductility (Punch, 132).

Concrete has become a material of choice for use with other materials to form blast-resistant composite walls. Figure 3.1 shows a cross-section of such a product (produced by Aigis) which utilizes several materials including a hardened surface designed to fracture without producing large and dangerous projectiles, a flexible energy-absorbing layer and a final layer of concrete to provide overall strength against blast pressures. Such a system may be used both in interior and exterior walls and provides an example of a concrete blast wall which is not only intended for use with concrete construction, make it versatile for use in different projects (Aigis).

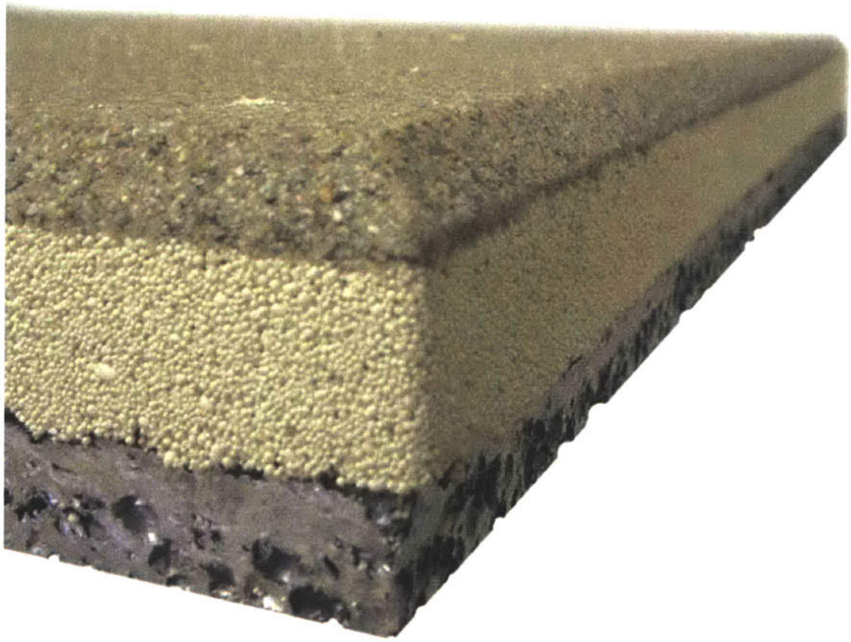


Figure 3.1 Cross-section of Aigis blast resistant wall product (Source: Aigis Blast Protection)

In comparison with concrete, steel is a much more ductile material and therefore is desirous for use in structures which may see extreme dynamic loads. When coupled with steels ability to form catenary action, these characteristics allow the preservation of stability under very large deflections. It is therefore desired in many cases that the primary structural system for a structure in which blast, or earthquakes for that matter, be steel frame (Punch, 132). However, it is impractical that for a typical building steel be used as a total barrier against severe blast pressures. Also, plate steel is susceptible to penetration from blast fragments and projectiles (Bulson). Therefore, while steel itself is not a suitable material for enveloping a building, recent advances in glazings and blast resistant glasses has allowed the use of steel to create blast resistant curtain walls. In this way, a continuous barrier may be formed by such glasses and carry loads to a steel frame capable of absorbing the blast impulse; Figure 3.2 shows such a curtain wall under construction. Such construction provides much more flexibility and is especially appealing to architects. For these reasons, blast resistant steel frame curtain walls are becoming fairly normal in the blast design field (Punch, 133).

Figure 3.2 Blast curtain wall under construction (Source: Hardened Structures)

3.1.2 Strengthened Connections

Structural systems subjected to any form of high intensity impact or dynamic loading require additional considerations to allow the system to deflect and dissipate energy without experiencing inelastic deformation under immediate occupancy performance states and without experiencing catastrophic failure under life safety and collapse prevention performance states. In order to achieve such ductility, it is necessary that the connections between individual structural members be not only stronger than the yielding limits of the elements it joins but ductile enough to maintain a connection through its own inelastic deformation. Such connections may be more reliably achieved in steel frame and precast concrete buildings than in monolithic, cast in place concrete frames.

Steel frame connections for dynamic loading fall generally into two different categories: brace and moment connections. Most work in detailing such brace connections has focused on detailing adequate gusset plates. Gusset plates allow the connection to maintain strength with greater deflections due to the two-dimensional nature of plates which allows tension-field action to maintain strength in the plate after buckling occurs. The use of gusset plates is very desirable, therefore, compared with standard weld or bolted end plate connections, allowing for out-of-plane deformation and the formation of plastic hinges (Lundeen, 25-2). Such gusset connections are displayed in Figure 3.3 and Figure 3.4 with Figure 3.3 showing the use of the brace connection with a standard shear connection between the beam and column of the frame.

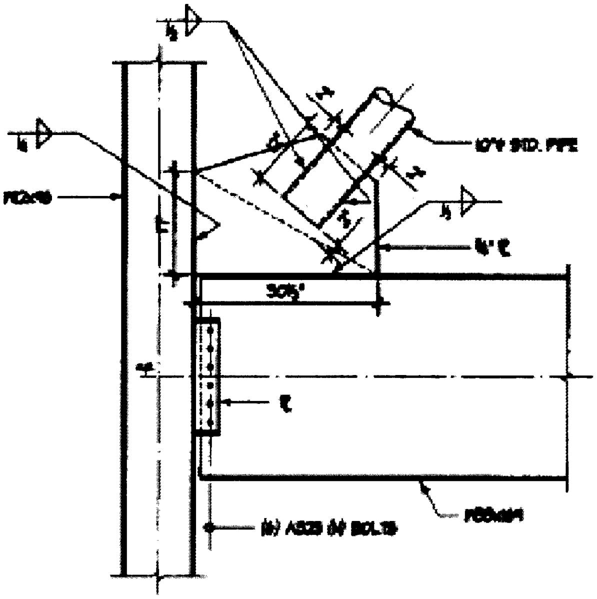


Figure 3.3 Seismic beam-column-brace welded gusset connection (Source: Lundeen, 25-5)

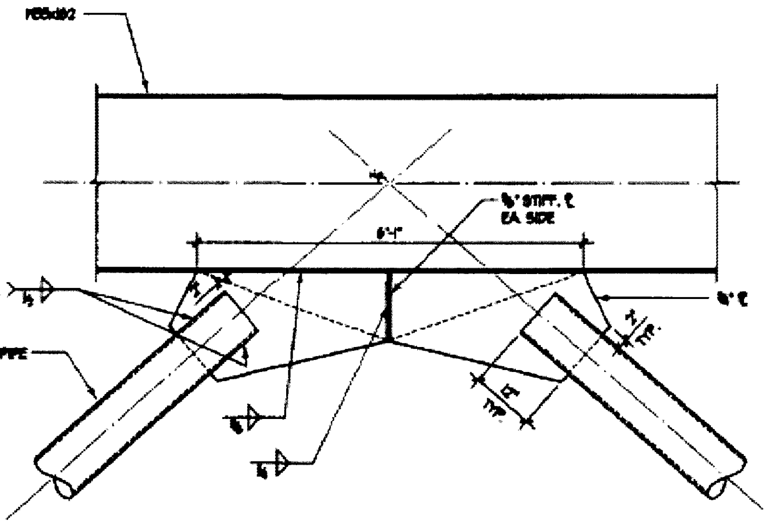


Figure 3.4 Seismic brace-beam welded chevron gusset connection (Source: Lundeen, 25-7)

Similar considerations are taken with moment frame connections and one specific detail, patented by *Side Plate*, is gaining popularity in use. The schematic of such a moment connection is shown in Figure 3.5; it can be seen that the moment connection is established through the attachment of the "cover plates" which allow transmission of loads in the flanges to the column in the same fashion as a typical flange-plated fixed moment connection. The connection is then strengthened against shear and torsion by the vertical shear plates. Similar to the use of gusset plates, the side plates on the connection are what truly give it additional ductility; again, by loading a plate multi-directionally it is possible to experience large rotational deformations in the column while still maintain capacity to keep the join intact. With regards to Section 3.1.1, Figure 3.6 shows the use of such a connection in the construction of a blast resistant steel curtain wall (Punch, 134).

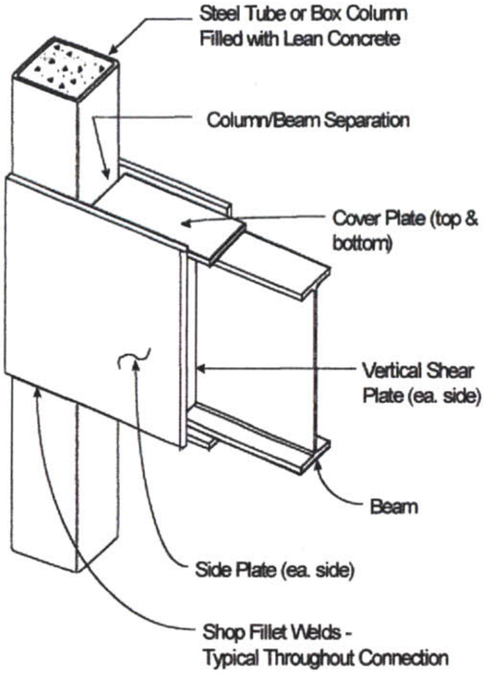


Figure 3.5 ***Side Plate*** **moment connection (Source: Punch, 138)**

Figure 3.6 Strengthened blast connection (Source: Hardened Structures)

While steps have been made to ensure greater ductility in cast-in-place beam-column joints the vast majority of advances in increasing ductility have come in precast concrete joints. Figure 3.7 shows a patented ductile precast connection in which the stiffness of the joint is governed by ductile embedded rods which are well confined by the column in which they are anchored. This ensures that the shear and moment transfer into the beam will not exceed certain values prescribed by the designer and ensures that the concrete beam itself will stay intact (Englekirik, 217-219).

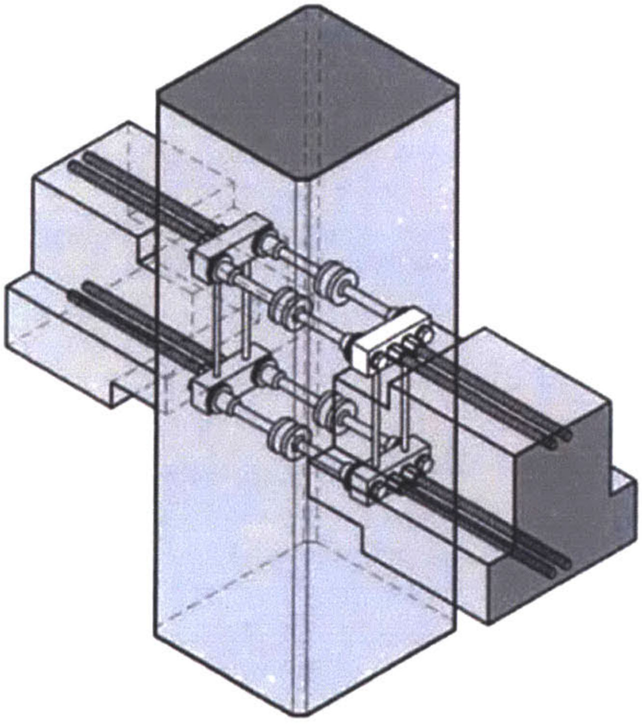


Figure 3.7 View of *Dywidag Ductile Connector (DDC)* System (Source: Englekirk, 217)

For the modeling a building frame subjected to blast loading, the type of connections used is an important consideration when determining the precision of model needed in order to accurately represent structural behavior. Any analysis which uses frame elements without modeling connections themselves may lose reliability if the connections are under-designed for dynamic loading. That is, for example, the reliability of an analysis of a moment frame under severe loading and deformations may be unexceptably low if the moment connections represented in the model to not allow substantial plastic deformation. If connections were to fracture, the assumption of energy dissipation through rotation of plastic hinges is null.

3.1.3 Building Geometry

Two major aspects of building geometry may contribute to the amplification of blast effects. Different envelope shapes may intensify the blast loading experienced by the building itself while the placement of lateral load resisting systems (LLRS) may very well dictate the post-blast structural behavior. Such concerns often have architectural implications and therefore it is necessary that a structural engineer adequately address such issues for a building being designed in order to understand the hazards which may result from such geometry choices. When designing a building which may be subjected to blast pressures, any vertices forming L or U-shapes in a building's façade will serve to amplify loads. It is therefore advised that any reentrant corners be avoided when possible (Conrath et al., 3-10). Additionally, if any such geometry is used, a detailed study should be carried out before running an analysis to determine what the amplification of pressures will be and these amplifications should be applied appropriately to ensure the adequacy of a façade and its structural system.

The use of symmetrical LLRS placements is strongly advised in order to decrease the probability of progressive collapse in a building. Studies of the collapse of the Murrah Building in 1995 show that the vast portion of the building which collapse was due in part to a lack of lateral load resistance at the front of the building (Nair, 3). Since the loss of structural members tends near a blast origination point tends to create forces towards this point due to inward local collapses, a lack of bracing or shear walls in the region allows the local collapses to spread until the members at the edge of previous collapse are in close enough proximity to members which may adequately resist these lateral loads. While not a large concern in moment frames, for any steel braced frames it is necessary to symmetrically locate LLRS appropriately also to help avoid any torsional effects on the structre which may result in a structural framing discontinuity near the blast origin point.

3.1.4 Load Reversal and Redundancy Considerations

The major causes of major structural failure and collapse in a building subjected to blast loading is not only excessive pressures but the application of loads in an opposite direction of design loading and the lack of stability provided by a damaged structural system. Especially in the case of internal explosions, structural members such as beams and slabs, which are designed only for gravity loads, may experience a strong and complete reversal of forces. For this reason, it is necessary that such load reversals be accounted for. This may be done by keeping continuous reinforcement in concrete members as well as ensuring that a reasonable pressure be considered for any steel beams which may have a lower moment capacity due to a decrease in compression flange restraint. However, it is infeasible to prevent the loss of any members under some blast loading conditions. In this case, it is necessary that redundancy be built into the structural system to ensure that a new, stable load path may be established. Redundancy considerations should allow for the loss of major structural members at the bottom two levels of a building. Two-way slabs are also recommended in order to ensure more flexibility in load redistribution (Perez).

3.1.5 Site Design

As discussed previously in Section 2.3.2 accessibility plays a large role in the threat of a building to a blast attack. When considering any bomb delivered by a vehicle accessibility may be viewed as a concern of the combination of both physical and operational security. For the purpose of this section the effects of physical design to accessibility will be considered. Site design may be used to form either a perimeter around a facility so that vehicles, or in more severe cases people, may not ever come within a certain prescribed proximity of the facility; typical bollard and physical obstacle implementation can be seen in Figure 3.8. This ensures with fairly reasonable certainty that the maximum considered explosive device may not reach a standoff distance to produce damage exceeding the desired performance level and may rightfully justify the use of deterministic design. However, site design to limit accessibility may also be used in a way which may limit certain areas deemed most critical, such as points of high human traffic or concentration of windows. In many instances a facility may not practically ensure such a physical barrier around a building for several reasons: facilities may require entrance of vehicles for deliveries or may require close proximity parking due to limited site space. In such cases it is necessary to evaluate what portions of exterior have had access reliably restricted and, for the purpose of the probabilistic methods presented herein, what the relative probabilities of access to certain portions of the exterior are.

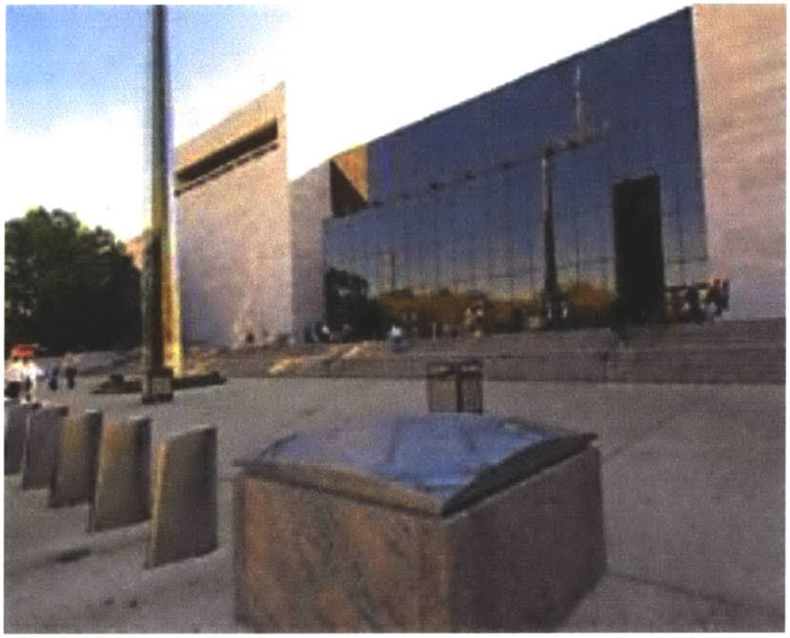


Figure 3.8 Use of physical barriers to limit access (Source: Whole Building Design Guide)

3.2 Operational (Active) Security

Since operational security relies on the proper functioning and implementation of either technological or human systems it is more susceptible to variable performance. For this reason, regions of a facility and its site which are controlled using operational methods may be better understood and designed with the use of probabilistic methods to aid in understanding areas of vulnerability and risk. Whether for use in the design of a facility or for analysis, it is necessary that an accurate and realistic estimation for the effectiveness of any system be taken into account as probabilities associated with the success of a security system is conditional with the probability of reaching certain performance states in the case of an explosive attack.

Operational security should consist of two general tasks: risk identification and threat mitigation. Risk identification should typically be aligned with the conclusions drawn during the quantification of assets and evaluation of threats detailed in Chapter 2. Operational security systems should give strong preference to the surveillance of regions of close proximity to major assets. Threat mitigation can be achieved in several basic methods ranging from looking for suspicious behavior to completely limiting access to a region besides authorized personnel. Also, screening and searches, such as the use of metal detectors, may be used as a security measure which does not limit access but help to ensure that no explosive devices may enter certain regions.

4 Blast Load Characteristics

4.1 Basics of Explosions

An explosion, contrary to deflagration, refers to a chemical reaction by which pressures within a mass of explosive propagates through the material away from a point of initiation. Unlike deflagration (the method of combustion of gunpowder), in which the material maintains a uniform internal pressure equal to the surrounding pressure while producing gasses, a high-explosive generates an outward wave velocity as it combusts. The primary necessity for a material to be considered an explosive is the materials ability to supply energy through chemical reaction which allows the further propagation of the shock wave. The rapid expansion of the gasses outward from the explosive casing focus into a high density wave known as the shock front or blast wave. The blast wave travels through air and acts essentially as a near-instantaneous spike in pressure, the magnitude of which is referred to as peak overpressure which dissipates with time as shown in Figure 4.1. Figure 4.1 also shows the typical blast wave characteristic of both a positive and negative phase; suction occurs in a blast zone after the major blast wave impact. The exact dissipation characteristics vary greatly depending on the environment in which the blast occurs. Much work, theoretical and experimental, has been done to understand the exact nature of blast waves, mostly during and immediately following World War II.

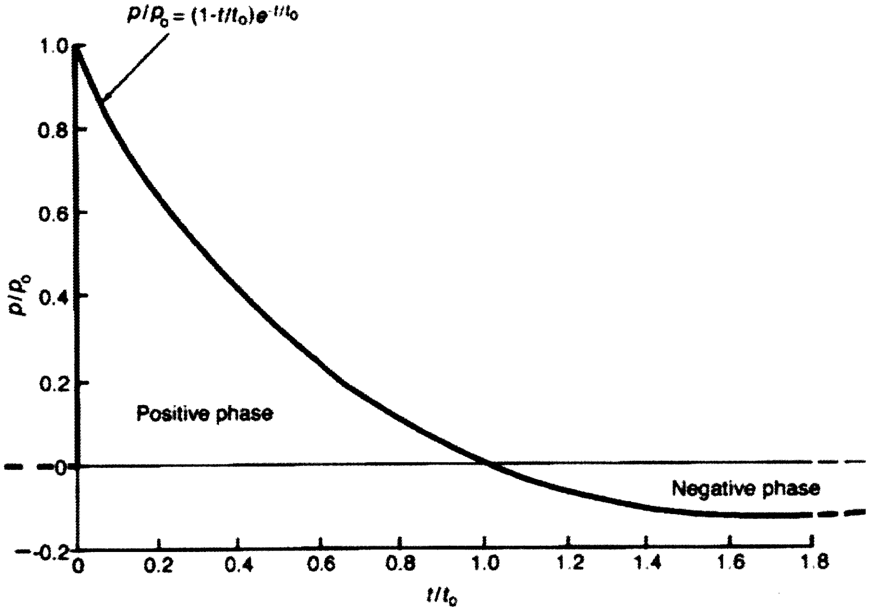


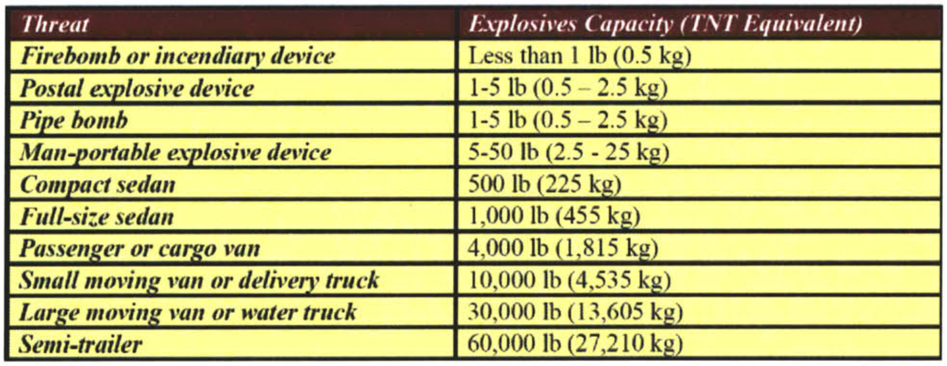
Figure 4.1 Simplified and normalized plot of blast pressure vs. time (Source: Bulson)

At a generalized level, the effects of explosions on civil structures may be viewed as being less critical for external blast events and more critical for internal explosions. As will be discussed in greater detail herein, external explosions, while potentially much larger for terrorist threats, typically result in fairly uniform pressures which often act in the same direction as primary loads on the building and therefore are more readily resisted. However, the potential for opposite direction of loading on elements due to internal explosions often results in greater damage due to internal explosions. Especially when considering concrete frames and composite steel beam/floor slab construction this load reversal may result in underconservative design of elements or lack of stability. Well designed frame buildings are inherently resistant to blast effects, especially external (Bulson). This is due, in part, to the decentralization of the LLRS compared to braced or shear wall reinforced structures.

4.2 Types of Explosive Devices

While there have been many different high explosives developed, they are typically scaled to a standard of trinitrotoluene (TNT). TNT was one of the first safe and reliable explosives and gained broad military and civil use and therefore has been used as a comparison point for all other explosive impulses, shock wave velocities and overpressures. For probabilistic purposes, it is necessary to consider the ranges of pressure loadings which are associated with the use of different explosive materials. The scaling of blast load characteristics of different materials is addressed further in Section 4.3.

While it is important to understand the differences between explosive devices, a more important consideration when considering probabilistic loading due to blast events is the amount of explosive which may be successfully delivered and its method as this dictates the reasonably considered load magnitudes as well as the blast load origin. Table 4.1 details several of the bomb delivery methods and the approximate reasonably considered weights of explosive.



Threat	*Explosives Capacity (TNT Equivalent)*
Firebomb or incendiary device	Less than 1 lb (0.5 kg)
Postal explosive device	1-5 lb (0.5 – 2.5 kg)
Pipe bomb	1-5 lb (0.5 – 2.5 kg)
Man-portable explosive device	5-50 lb (2.5 - 25 kg)
Compact sedan	500 lb (225 kg)
Full-size sedan	1,000 lb (455 kg)
Passenger or cargo van	4,000 lb (1,815 kg)
Small moving van or delivery truck	10,000 lb (4,535 kg)
Large moving van or water truck	30,000 lb (13,605 kg)
Semi-trailer	60,000 lb (27,210 kg)

Table 4.1 Types of explosive devices/deliveries and relative TNT equivalent weights (Source Sullivan et al., 53)

4.3 Blast Scaling

It is intuitively obvious that the magnitude of pressures observed decrease as the distance from the blast point of origin of the increases. While there are several theories by which scaling is described, the most commonly accepted method of scaling blast loads is Hopkinson-Cranz scaling which relates a scaling factor to the cube root of the energy of the explosive device.

$$Z=\frac{R}{W^{1/3}}$$

Equation 1

Equation 1 shows this form of scaling where *Z* is a scaling coefficient, *R* is the distance from the observation point to the center of the blast origin, and *W* is the TNT-equivalent weight of the explosive. This factor is then used in several variations of empirical formulas which attempt to relate the scaling factor to observed peak overpressures. While there are many formulae which have been proposed, many are specific to charge shapes, explosive type or are valid only for certain explosive sizes.

$$p_0\approx\frac{500}{Z^2}$$

Equation 2

Equation 2, however, presents an approximation for the peak overburden pressure (p_0) which is often used for preliminary design. While more detailed definition of explosive types and sizes could be used to develop an increased reliability in pressures, such a generalized equation suits well a probabilistic analysis as the range of pressures and impulses are more important than the precise representation of one blast event (Bulson).

Since a number of explosive materials may be used, as detailed in Section 4.2, it is also important that the charge weight is appropriately scaled to the standard of TNT. The term *W* Equation 1 refers to equivalent weight and therefore the type of explosive must be considered when scaling the pressures of the blast wave. This is done by comparing the heat of detonation for each explosive as detailed in Equation 3 (Conrath et al., 2-9).

$$W=\left(\frac{\Delta H_{exp}}{\Delta H_{TNT}}\right)W_{exp}$$

Equation 3

where:

W=TNT equivalent charge weight
ΔH_{exp}=heat of detonation of explosive
ΔH_{TNT}=heat of detonation of TNT
W_{exp}=weight of explosive

Additionally, another aspect of blast loading, besides the peak overburden pressure, is its impulse which is described as follows in :

$$I = \int_{0}^{t_d} p(t)dt$$

Equation 4

where:

I=impulse
t_d=duration of the load
$p(t)$=blast pressure time-history function

Common explosives are detailed in Table 4.2 (Conrath et al., 2-11). It can be seen that there are two major factors which may be considered when detailing blast load characteristics on a building; depending on the explosive used there is a variance of 82%-170% the peak overpressure of TNT as referred to previously. However, since the pressure is not directly related to the impulse created by an equivalent weight of explosive it can be shown that the duration of loading must vary in order to preserve equivalence of ratios. This difference in duration must therefore be accounted for in the pressure time-history function, being sure to scale the time scale so that the integral of the pressure loading function is equal to the impulse specified.

Explosive	Equivalent Weight, Pressure (lbm)	Equivalent Weight, Impulse (lbm)	Pressure Range (psi)
ANFO	0.82	--	1-100
Composition A-3	1.09	1.08	5-50
Composition B	1.11 1.20	0.98 1.30	5-50 100-1,000
Composition C-4	1.37	1.19	10-100
Cyclotol (70/30)	1.14	1.09	5-50
HBX-1	1.17	1.16	5-20
HBX-3	1.14	0.97	5-25
H-6	1.38	1.15	5-100
Minol II	1.20	1.11	3-20
Octol (70/30, 75/25)	1.06	--	E
PBX - 9404	1.13 1.70	-- 1.20	5-30 100-1,000
PBX - 9010	1.29	--	5-30
PETN	1.27	--	5-100
Pentolite	1.42 1.38 1.50	1.00 1.14 1.00	5-100 5-600 100-1,000
Picratol	0.90	0.93	--
Tetryl	1.07	--	3-20
Tetrytol (Tetryl/TNT) (75/25, 70/30, 65/35)	1.06	--	E
TNETB	1.36	1.10	5-100
TNT	1.00	1.00	Standard
Tritonal	1.07	0.96	5-100

Table 4.2 Explosive characteristics

One last concern in the application of loads due to a blast event is the time at which the pressure shock front of the blast load first reaches any structural element. Since the initial detonation shock velocity is greater than the speed of sound, the shock wave travels supersonically. Experiments performed by Henrych show that typical values for the shock front velocity (V_s) range from 7,100 m/s (23,300 ft/s) for TNT to 8,450 m/s (27,700 ft/s) (Bulson). The resulting loading on a surface at one instance in time due to a spherical charge is shown in Figure 4.2 and shows that modeling the loading of a blast load on a structural element requires careful attention to scaling the arrival time of a blast load to ensure realistic global time-history impulse characteristics.

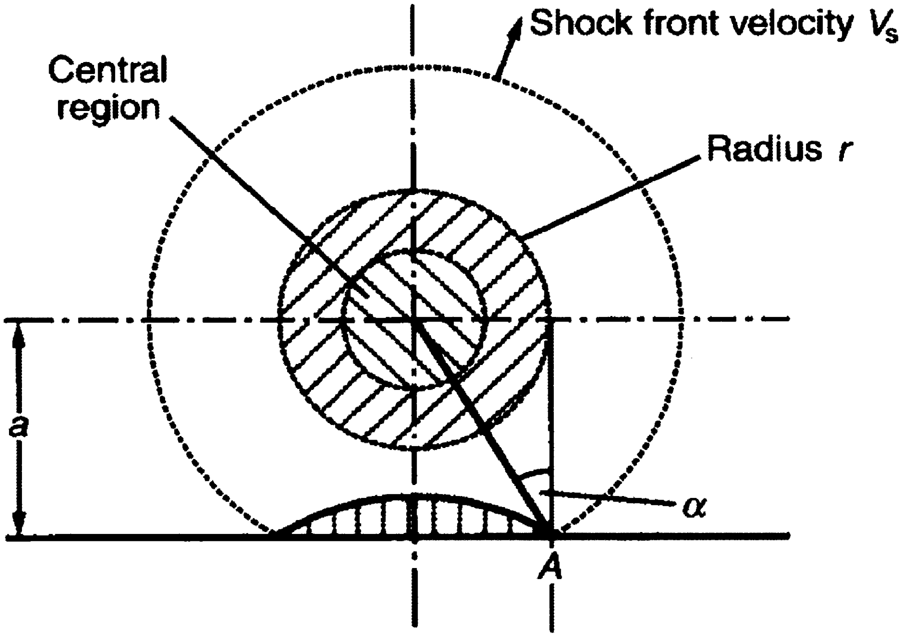


Figure 4.2 Propagation of blast wave from a spherical explosive charge (Source: Bulson)

4.4 Unconfined Behavior

Explosions which occur in free air, that is, the resulting expansion of gasses does not result in an appreciable increase in surrounding pressure. With regard to attacks, unconfined explosions typically result from vehicle bombs which occur outside of a facility and result, as mentioned previously, in relatively uniform loading of the exterior surfaces of a structure. It is therefore necessary to distinguish a blast event which is unconfined from one which is confined in order to develop the appropriate time-history loading which the structure will experience.

4.4.1 Time-History Characteristics

An unconfined explosion has two distinct phases of pressure loading, the positive phase and negative phase, is previously shown in Figure 4.1. This makes the modeling of external blast loading slightly simpler than internal. A complication of modeling the blast load pressure diagram, however, results as the impulse is scaled with distance, therefore causing a change in the positive and negative phase durations with respect to distance from the blast load origin. The value of positive phase arrival and duration are shown scaled according to Hopkinson-Cranz scaling in Figure 4.3 (Conrath et al., 2-13)..

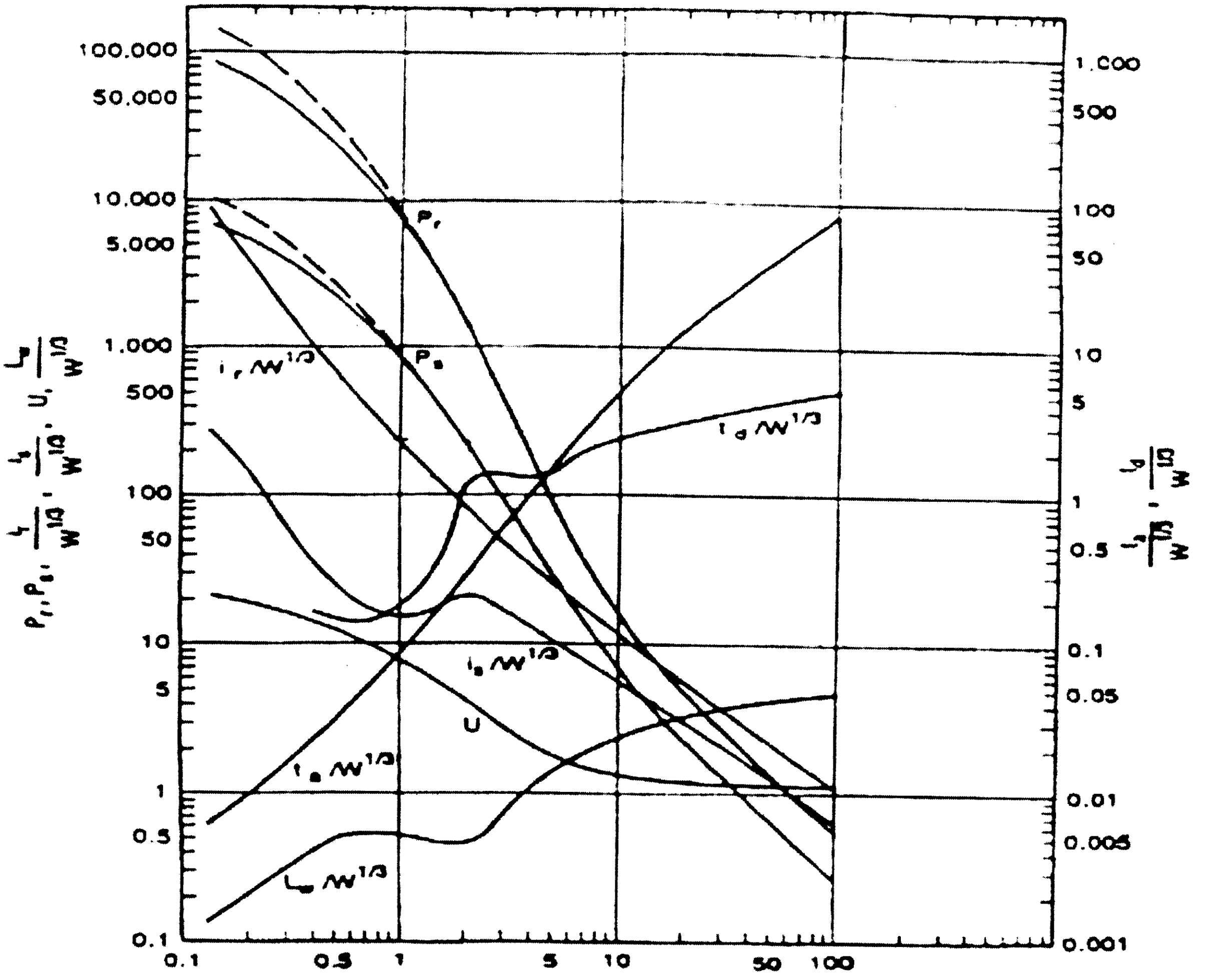


Figure 4.3 Unconfined blast load pressure characteristics (Source: Conrath et al., 2-13)

While there is little data that may be found on the negative phase duration, as it depends greatly on the surrounding environment and restoration to atmospheric pressure, it has been found through the examination of many typical unconfined blast pressure diagrams that the negative phase duration of a blast load is typically on the order of 1-3 times the positive phase duration and the magnitude of pressure on the order of 1/10th the peak overpressure (Krauthammer,73).

4.4.2 Assumptions and Simplifications for Analysis

For computational efficiency, it is common that several assumptions be made to simplify the blast wave characteristics. First, it is common to simplify the pressure diagram as linear with a triangular positive phase having an instantaneous increase from atmospheric to peak overpressure at the arrival time of the blast wave. This peak pressure dissipates until a triangular approximation may be used for representing the negative phase. Also, since the duration periods of each phase are dependent on standoff and explosive, it is necessary to establish a means of determining the duration in a reasonably simplified manner (Punch, 136). Referring to Figure 4.3 and viewing the positive phase duration (t_d, on the right axis) it is possible to view the plot in three distinct regions: a zone of immediate proximity with a scaled distance of 0.5-2 ft where there is a duration on the order of 0.5 ms, a zone of close proximity with a scaled distance of 2-5 ft where the duration is essentially constant at 1.5 ms and region of decreasing proximity with a scaled distance of 5-100 ft. In the region of decreasing proximity, there is fairly uniform logarithmic increase for which an approximate mathematical relationship can be developed.

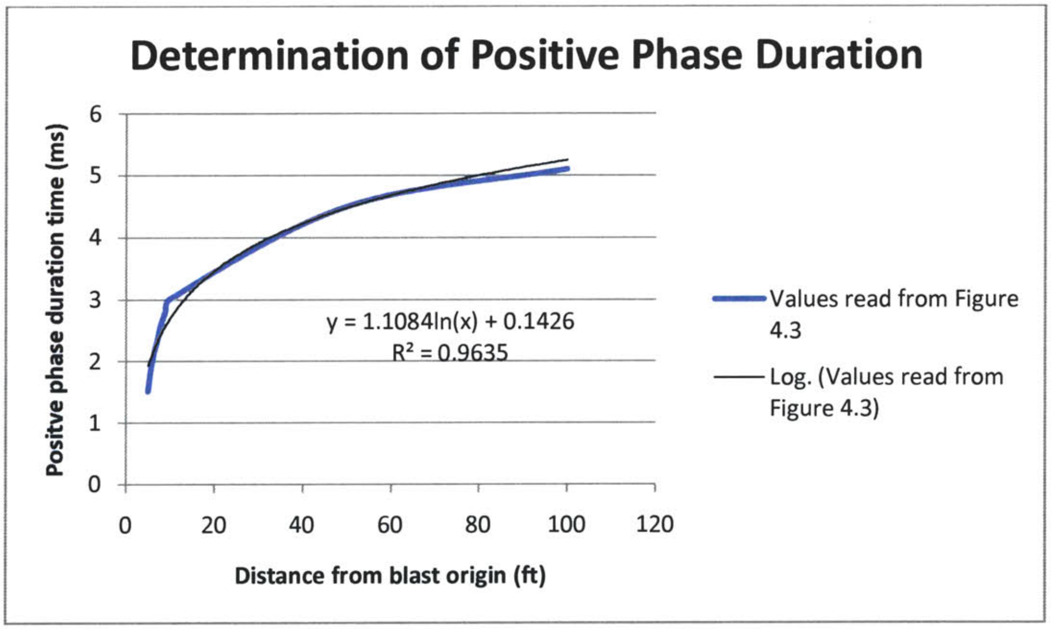


Figure 4.4 Plot used to develop expression for positive phase duration

$$t_d = (1.1084 \times \ln(R) + 0.1426)\text{ms}$$

Equation 5

Figure 4.4 shows the Microsoft Excel plot used to determine the duration phase mathematical relationship (Equation 5). It can be seen that a reasonable amount of confidence may be achieved by fitting a logarithmic trend-line to the data. Additionally, to simplify the determination of the negative phase duration, a multiplier of one, two and three may be used corresponding with the zones of immediate proximity, close proximity, and decreasing proximity respectively, thus well correlating with the typical range of negative phase durations and the increasing duration nature associated with increasing distance from a blast point of origin. Additionally, while not entirely accurate, the assumption of arrival time based off of shock-wave velocity is proposed to simplify the relationship found experimentally. While the arrival time behaves logarithmically rather than linearly, since the major effect of arrival time is the differential loading of different parts of the structure and the plot of arrival time in Figure 4.4 shows slight logarithmic behavior for smaller distances from blast origin this assumption is deemed appropriate.

4.5 Confined Behavior

When an explosion occurs in a region where the escape of gas pressures is not essentially immediate, attention must be paid to the effect on the increase in pressure following the main blast event. While a great deal of the shock wave characteristics remain essentially the same as an unconfined explosion, an internal explosion is also characterized by a gas loading phase associated with the pressure shock following the blast wave impact and a quasi-static loading due to the inability of the pressure to equilibrate with atmospheric pressure.

4.5.1 Time-History Characteristics

Pressure time-histories for confined explosions are largely variable. As shown in Figure 4.5 there are two peaks corresponding with two distinct loading phases: the blast wave loading and the gas pressure loading. Since the pressure loading phase of a confined explosion is governed by the venting of the structure the second peak of the diagram may not be definitively determined without an extensive study of flow of air within the structure. Additionally, the duration of the quasi-static phase of pressure loading is determined by the ability of the structure's envelope to equilibrate with the outside atmosphere. Therefore, while the primary blast wave impact, governed by the peak overpressure and the time duration, is essentially the same as that detailed in Section 4.4.1 the total time-history diagram must account for the pressure in a reasonable fashion.

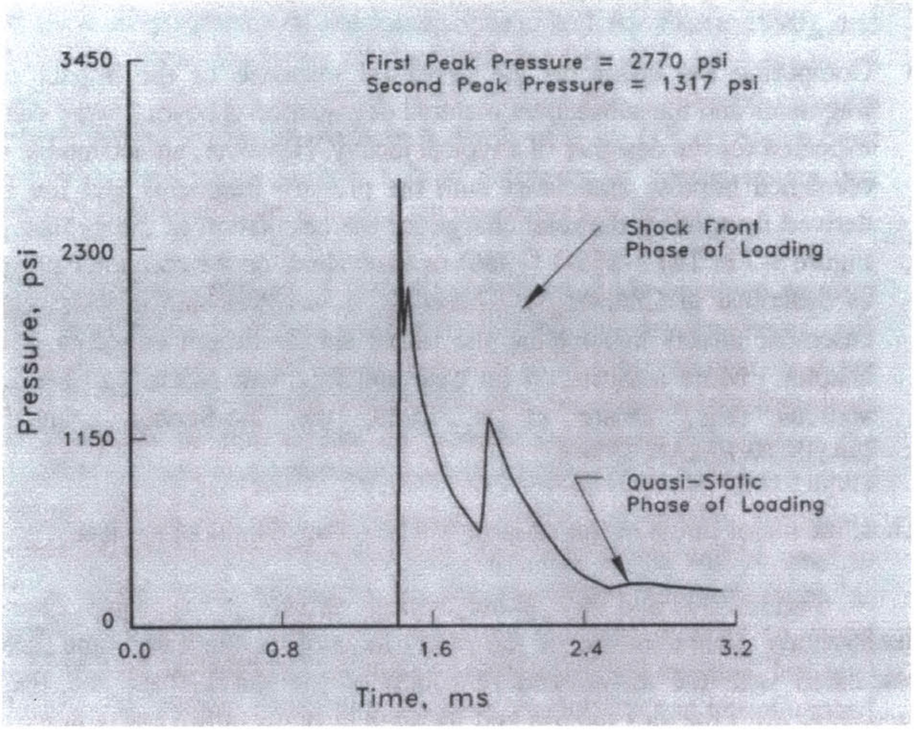


Figure 4.5 Confined explosion pressure time-history plot (Source: Conrath et al. 4-6)

4.5.2 Assumptions and Simplifications for Analysis

While the actual blast pressure time-history contains two distinct peaks, research by the U.S. Army, Navy and Air Force have shown that it is reasonable to consider a bilinear pressure function which essentially combines the effects of the blast wave and the quasi-static pressure loading (See Figure 4.6). While actual pressure loads coincide in time with the blast wave impulse, they are not considered as additive due to the arrival of the blast wave peak before the pressure load. It should also be noted that the negative phase of the blast wave load does exist but is lower in magnitude than the gas pressure loading magnitude (Conrath et al. 2-21). Additionally, the blast wave duration times are essentially the same as for unconfined explosions and Equation 5 may be used in conjunction with Equation 2 to determine the slope of the first portion of the bilinear approximation. Last to determine is the magnitude and duration of the gas loading phase of the bilinear pressure time-history. Since this feature is dependent completely on the venting of the structure, it is necessary that this characteristic be reasonably approximated unless detailed study is possible. Through examination of multiple sources of test data it can be established that the magnitude of the gas loading quasi-static phase is typically between 1/5th and 1/10th of the peak overpressure for typical structures with a duration on the order of 10 times the blast wave loading duration (Krauthammer, 74).

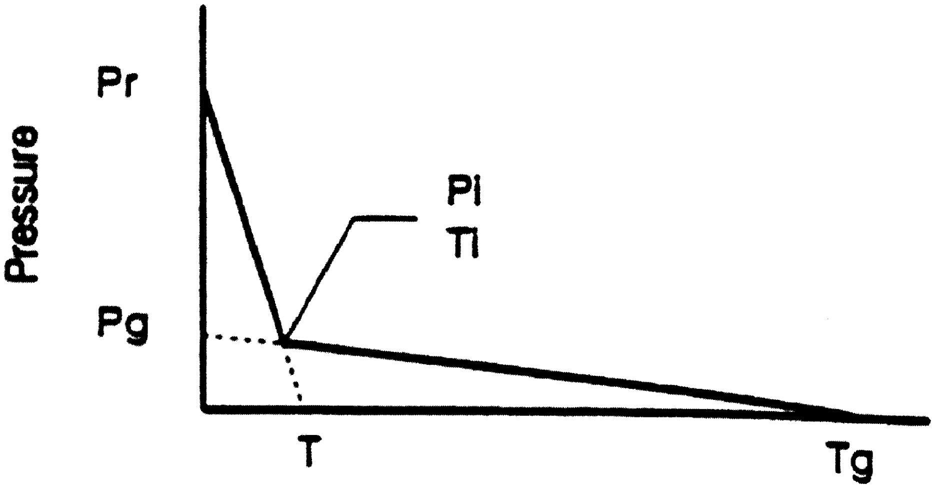


Figure 4.6 Simplified confined explosion pressure time-history plot (Source: *Structures to Resist…*)

5 Simulation

In order to demonstrate the methods by which a probabilistic assessment of a structure's blast performance may be carried out and by which data may be interpreted, the following herein seeks to establish the performance of a hypothetical facility. Through the definition of reasonably considered threats, security systems (both physical and operational) and site geometry, including a reasonably designed structure, it is possible to establish the damage state of the structure under a blast event. With automation the analysis may be repeated many times for a random distribution of blast origin locations, explosive charge size, and likelihood of success in carrying out an attack in a desired region. It should be noted that the probabilistic nature of the analysis ends with blast load determination as the building is analyzed deterministically for practical purposes. The result of such a procedure is a Monte Carlo simulation which allows an engineer to gain insight into the sensitivity of a structure to certain types of threats and what attacks are most critical to prevent. In order to carry out this simulation, the program Minitab was used to develop random data in accordance with desired distributions, the program Matlab was used to develop the pressure time-history loading data for all structural members and the program SAP 2000 v.14 was used to carry out the structural analysis and assess structural damage

5.1 Hypothetical Site

This section describes the facility to be analyzed. While the main goal of this simulation is to establish structural performance, it is necessary, as detailed in Chapter 2, to establish the characteristics of the entire site. The hypothetical site analyzed herein is considered to be a secure two story research facility of importance which must facilitate visitors for operational reasons.

5.1.1 Programming

In order to display a facility which is feasibly demanding of a blast performance assessment, a mixed facility considered to be of significance was established. As shown in Figure 5.1 the ground floor of the facility consists of several different programs including a meeting room, an entrance and check-in space, a laboratory and special equipment space and warehouse and delivery processing space to supplement physical research activities. The upstairs of the structure is considered to be office space and is not considered in the analysis beyond its contribution to service loading.

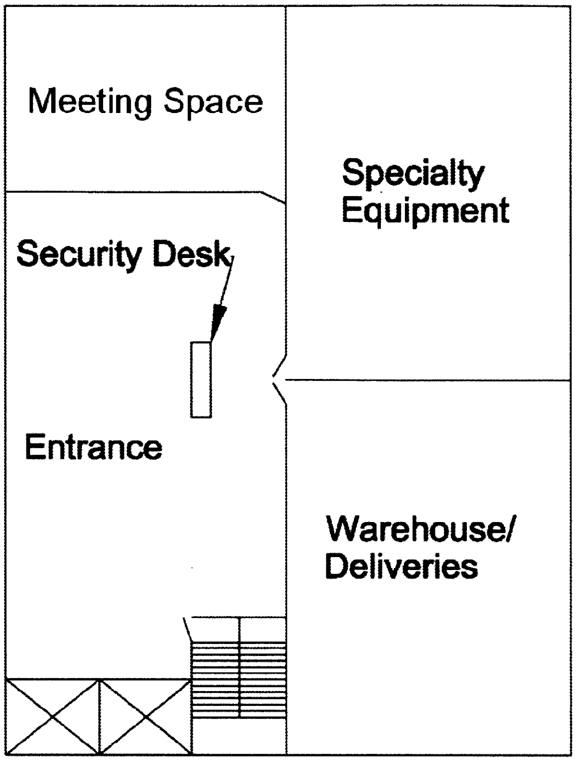


Figure 5.1 Ground-floor floor plan and programming

5.1.2 Site Access

The entire site of the facility, shown in Figure 5.2 shows the layout and special relations between the different site regions and the structure itself. Two major passive security systems are evident in the site layout with the implementation of bollards preventing the access of vehicles beyond a certain perimeter. Additionally, a wall at the rear of the facility prevents the access of any vehicle with access to the loading dock from entering the region of the facility protected by the bollards. For the purpose of this simulation, these systems are completely effective and create a null zone of blast origins around the structure. Additionally site access is considered to be limited with some efficiency by the operational security points, including a security booth at the entrance of the parking lot and a gate limiting access to the loading dock of the structure. Within the structure, certain regions are considered secure and are protected with certain efficiency due to the presence of a security desk. However, as will be discussed further in Section 5.3, regions are still subjected to a prescribed probability of success, allowing one to determine the criticality of security operations for certain regions.

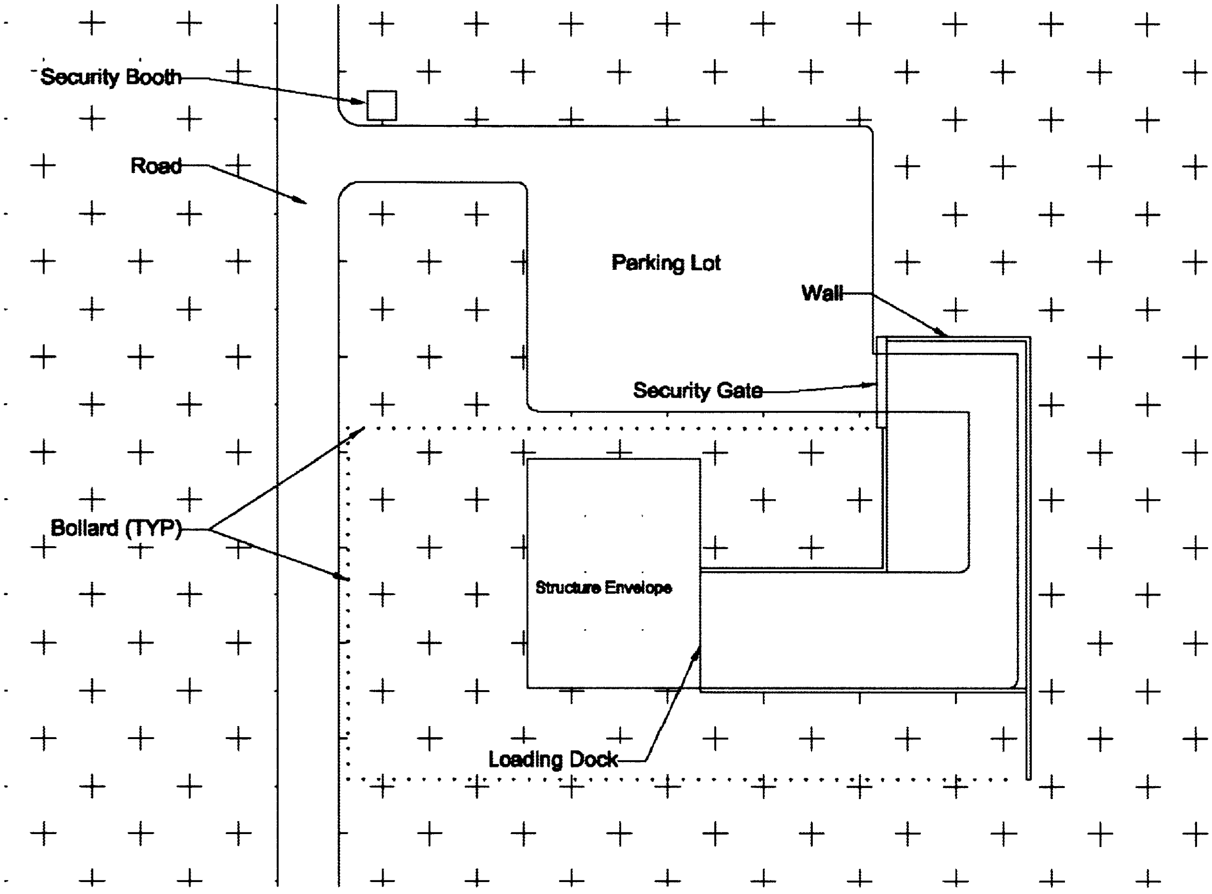


Figure 5.2 Facility site plan

5.1.3 Structural System Detail

The structural system considered is a two story, three-bay by four-bay steel moment frame building with infill beams and one way slabs. It is important to make the distinction at this point that the connections considered for this simulation are designed for blast considerations, similar to the *Side Plate* moment connections discussed in Section 3.1.2. This allows the use of a structural model which considers moment connections and adequately allows both the formation and rotation of plastic hinges at frame member ends. Without such connections, the limitations of connections used must be examined in greater detail.

To ensure the realism of the simulation, the structure was designed for typical loads factored according to LRFD standards. The actual deadweight of the structure was considered along with a 100 psf live load considering office space per ASCE 7-05 and a "simplified procedure" wind load per ASCE 7-02 as generated in SAP 2000 v.14. Ground floor columns were then increased to ensure only local failure under the loss of any ground floor column as is typical for blast design to prevent progressive collapse. Infill beams were modeled as simply supported while all column-to-column beams and girders were modeled with fixed connections. The slabs were modeled as 4" reinforced concrete one-way slabs spanning 6 feet between infill beams. The global finite element model is shown in Figure 5.3. It can be seen that for the sake of examining importance of major structural elements that a transfer girder spanning two bays is located at the front of the building to create a larger open span at the building's entrance.

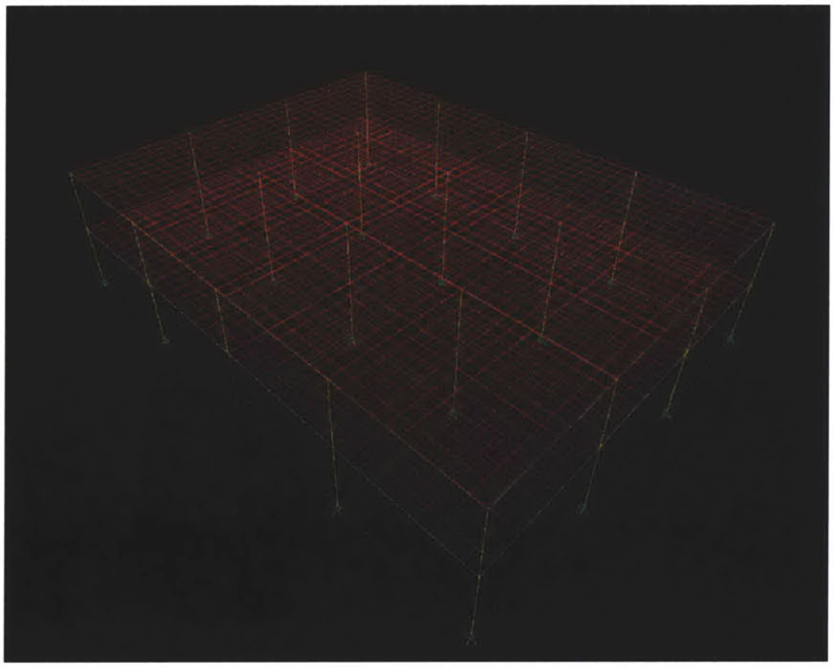


Figure 5.3 SAP 2000 model of structural frame

5.2 Asset Importance Definitions

In order to determine the performance of the structure in this simulation it is necessary that the structures components and elements be analyzed for significance not only in regards to the global behavior of the structure but also with regards to assets in the building. While the primary purpose of this simulation is to determine the structural damage, structural damage may be indicative of asset damage and therefore member significance may be weighted in order that damage to structure in proximity to major assets can be used to determine overall financial damage to the structure. It should be noted that while a significant source of monetary damage due to an explosive attack may come from the destruction of non-structural elements this simulation does not account for such components.

5.2.1 Evaluation of Structural Member Significance

The establishment of structural member significance is a process which requires all primary assets in the facility to be examined and the structural elements which these assets depend on for safety are identified as the secondary assets. For this simulation it was determined that there are three primary assets: life, structure and laboratory equipment. The primary assets of life and structure are inherently strongly similar as the integrity of a structure following a blast event and the absence of progressive collapse is necessary to minimize immediate loss of life and to allow egress from the structure. In this simulation the two assets are distinguished by inhabitant density and path of egress. Therefore, for life safety the "Deliveries/Warehouse" region, shown in Figure 5.1 is considered of less importance due to a low inhabitant density. Additionally, the region in the immediate vicinity of the elevator and stair core are considered to be more important as preservation of this region is necessary for safe an orderly egress. The primary asset of laboratory equipment is characterized as being a high monetary risk assuming that the equipment is costly to replace. Damage done to the immediate vicinity therefore should be weighted in order to provide a better measure of the overall damage and necessary downtime for the facility following a blast event.

5.2.2 Weighting Scheme for Defining Performance

Since not all structural members should be viewed as having the same importance or cost for replacement it is necessary to create a scheme by which damage may be quantified, normalized and used to judge the performance level of the building. To do so, it is necessary that heuristic and engineering judgment be used. While such a weighting scheme could benefit from the input of cost estimator who may have expertise in evaluating the exact cost and ease of repair. However, for this simulation a relatively simple weighting scheme was used as detailed in Table 5.1. However, these values only reflect the primary asset of the structure and are therefore weighted again for proximity to primary assets as discussed in Section 5.2.1. This is done by assigning a multiplier of 1.2 to any elements in immediate proximity to the "Specialty Equipment" room in the facility and a multiplier of 0.8 to any elements in immediate proximity to the "Warehouse/Deliveries" room. Again, it should be reiterated that these multipliers were developed using judgment and for an actual simulation an in-depth analysis should be performed in order to adequately assign any multipliers related to assets. Once these multipliers are applied to the weighting factors assigned for each structural element the final damage factor for each structural element in the model is assigned for the entire simulation. The number of each type of structural element which fail during an iteration are multiplied by this damage factor and the values summed to produce an overall damage index for the iteration.

Structural Element	Weighting Factor
First floor perimeter column	5
First floor interior column	4
Second floor transfer girder	4
Second floor girder	3
Second floor beam/floor slab	2
Second floor perimeter column	3
Second floor interior column	2
Roof girder	2
Roof beam/floor slab	1

Table 5.1 Weighting factors for structural elements

In order to establish performance criteria for the building it is necessary to define thresholds for the three basic performance levels. Again, for this simulation, this was done heuristically and attempts to establish reasonable standards in order to define the performance of the building; for an actual structure the thresholds could benefit from calibration from an experienced professional. The thresholds were defined as presented in Table 5.2.

Performance Level	Damage Index Threshold
Immediate Occupancy	0-15
Life Safety	16-100
Collapse Prevention	>100

Table 5.2 Performance level definition

5.3 Threat Probability Definitions

5.3.1 Vehicle Bombs

Vehicle bombs are largely variable in size as well as likelihood of success in a facility with security systems. For the purpose of this simulation, vehicle bomb weights were chosen in accordance with Table 4.1 with the exception that the maximum credible threat was chosen as "large moving van or water truck." Therefore, the explosive size used in each iteration is a random choice of a 500, 1,000, 4,000, 10,000 or 30,000 lb TNT equivalent bomb as determined from the software MINITAB. After establishing the site layout for the facility, it is then possible to reasonably divide the site into several zones where the likelihood of an attack being successfully carried out is unique to others. This division of zones relies on the location of security features and the probability of occurrence within these zones relies on the effectiveness of the security system in place. Figure 5.4 shows the division of the site into five different probability zones and Table 5.3 shows the associated probability of success of an attack within each zone. It should be noted that the probabilities are normalized to the zone of highest probability as the differential probabilities of success attempt only to reduce the number of trials within the simulation which occur in a zone which is vastly unlikely. This helps to provide a more realistic assessment of the types of threats and attacks which may be encountered in the life of the structure.

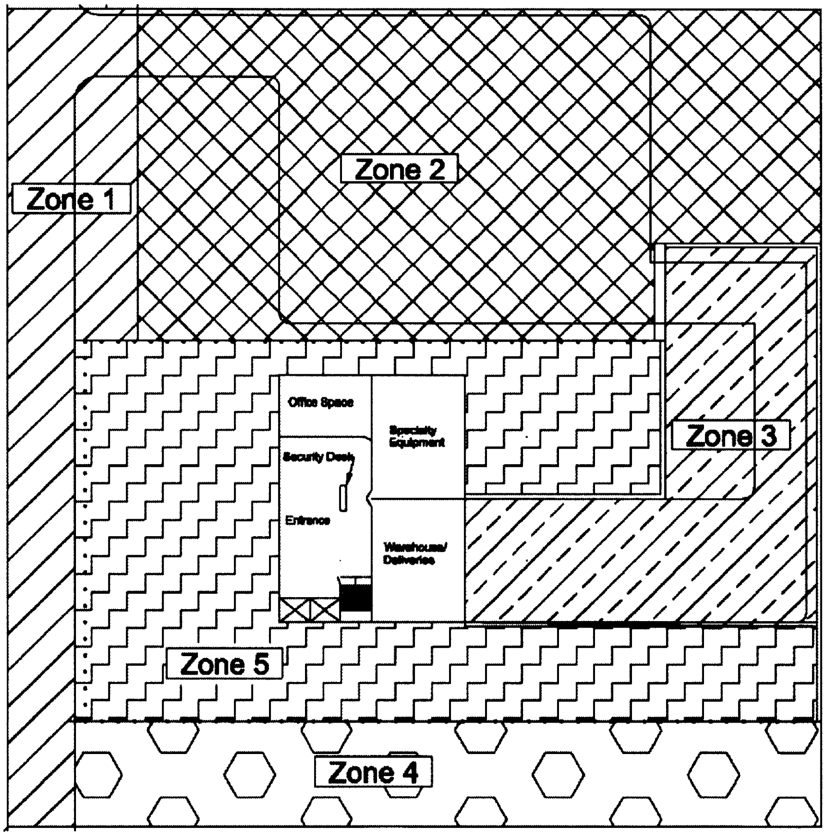


Figure 5.4 Definition of probability zones for vehicle threats

Zone	1	2	3	4	5
Probability of success	1.00	0.50	0.05	0.80	0.00

Table 5.3 Definition of probabilities for vehicle threats

5.3.2 Bombs on Person

To evaluate the effect of bombs on one's person, it was necessary to establish the maximum credible explosive weight for an explosive device which may be reasonably considered for a person to carry into the structure without security intervention. The explosive weights used for the simulation were generated as a uniform distribution between five and fifty pounds per Sullivan et al. The location of the blast origin was determined as a uniform distribution within the confines of the structure and the floor plan was divided into two probability zones as shown below in Figure 5.5 and with the corresponding probabilities of success described in Table 5.4. The lower probability of Zone 2 is due to the consideration of the security desk meant to prevent unauthorized intruders into the "Warehouse/Deliveries" and "Specialty Equipment" rooms of the facility.

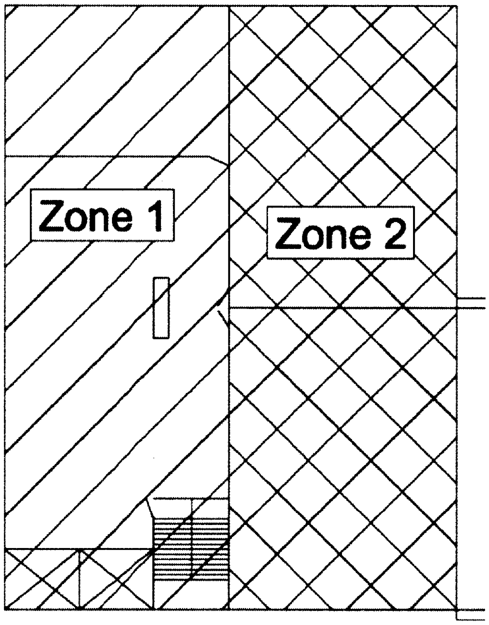


Figure 5.5 Definition of probability zones for person threats

Zone	1	2
Probability of success	1.00	0.20

Table 5.4 Definition of probabilities for bombs on person threats

5.3.3 Mail and Package Bombs

The methodology used to evaluate mail and package bomb threats is very similar to that described for bombs on a person in Section 5.3.2. Per Sullivan et al. the explosive weights were generated as a random uniform distribution between one and five pounds. The random locations of the blast origin for each iteration were determined as a uniform distribution within the confines of the structure and the floor plan was divided into two different probability zones as shown in Figure 5.6 and with the corresponding probabilities of success described in Table 5.5. The lower probability of success in Zone 1 comes from an assumption that the majority of attacks by mail and package would logically occur in the deliveries and storage portion of the facility.

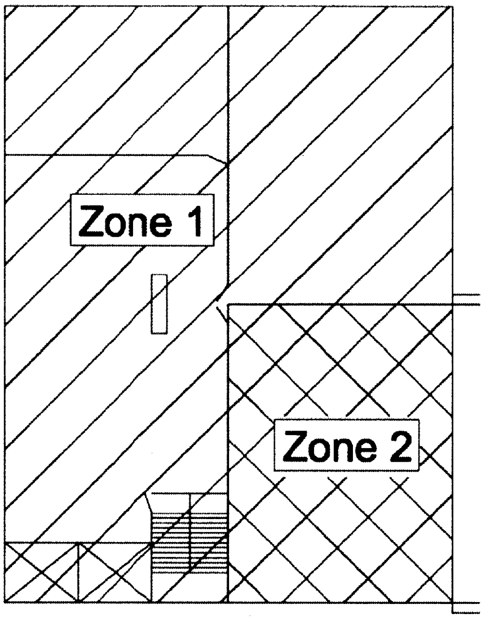


Figure 5.6 Definition of probability zones for mail and package threats

Zone	1	2
Probability of success	0.30	1.00

Table 5.5 Definition of probabilities for mail and package bomb threats

5.4 Blast Force Determination

While the determination of the blast threats was probabilistic for this simulation, the rest of the analysis was calculated deterministically. Given a location and equivalent TNT weight it is possible to determine the structural members which will be subjected to blast loading due to the geometry of the facility. It was then necessary to calculate the charge standoff for all structural members exposed to the blast loading and using Equation 1 and Equation 2 develop the peak overpressure. Using the parameters described in Sections 4.4.2 & 4.5.2 the positive phase duration and either the negative phase (unconfined) or gas loading duration (confined) were calculated for vehicle threats and bombs on person and mail and package threats respectively. Given these characteristics, it was possible to divide the pressure into its three principal coordinates to allow load assignment in the SAP model described in Section 5.1.3.

In order to increase computation speed to a reasonable level to facilitate the running of a large number of iterations necessary for a Monte Carlo simulation, it was deemed necessary and acceptable to simplify the loading of the structure by computing loads for groups of elements rather than each individual element in the SAP 2000 finite element model. In this respect, some accuracy was lost in the blast loading of the structure. The pressure time-histories were developed automatically through the implementation of a Matlab code which wrote unique files for each principal direction component of each loading group every iteration. Typical pressure time-history functions are presented in Figure 5.8 and Figure 5.7 for the vehicle threat and mail and package threat simulations respectively. These two figures display the difference between unconfined and confined pressure tim-histories. It should be noted that the bombs on person threat pressure time-history functions are of the same nature of that shown in Figure 5.7.

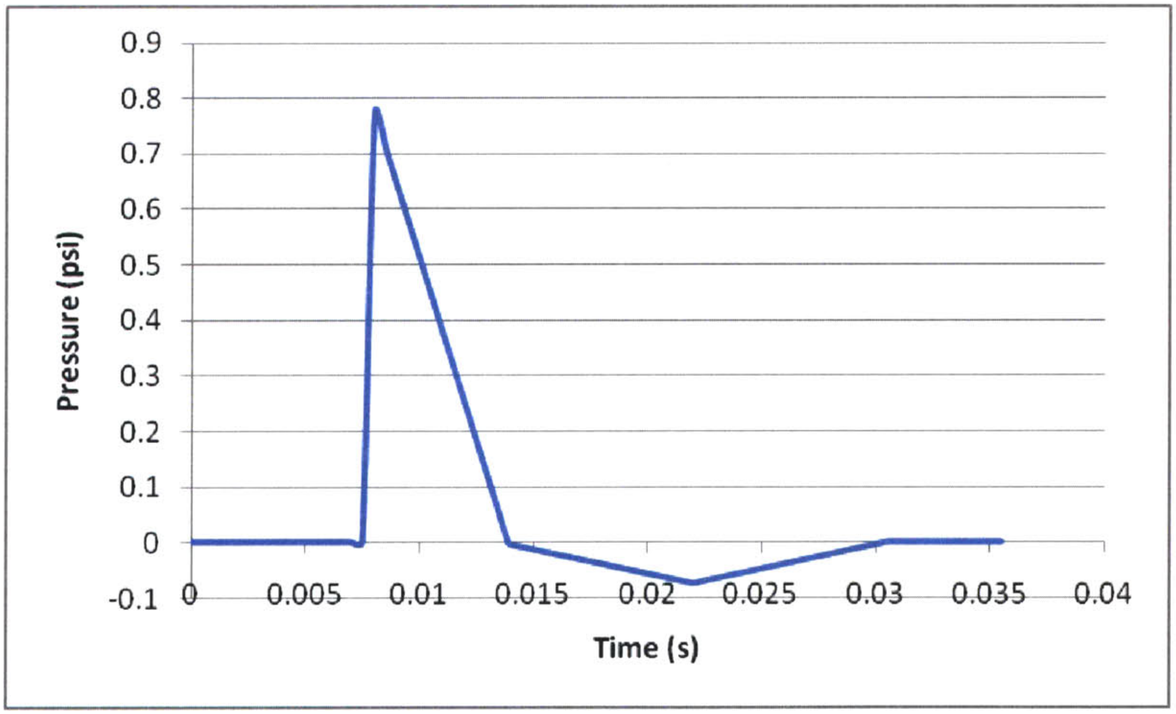


Figure 5.7 Typical pressure time-history function for confined explosion (mail and package threat analysis)

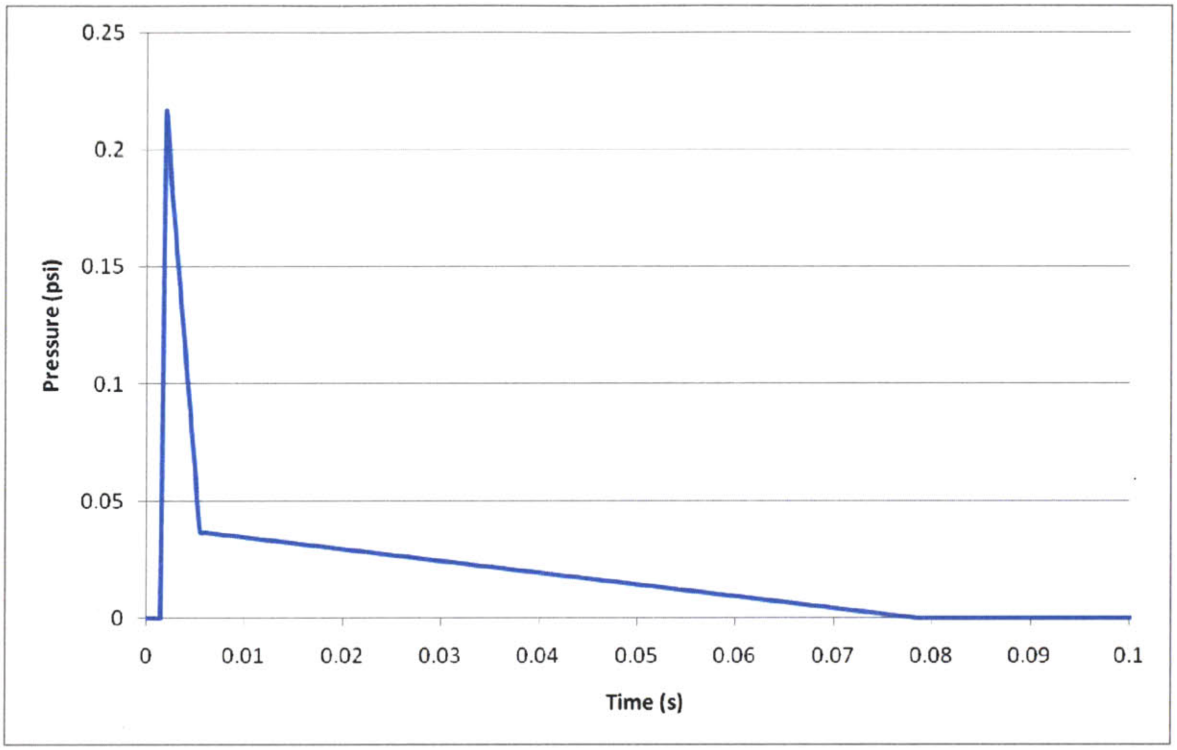


Figure 5.8 Typical pressure time-history function for unconfined explosion (vehicle threat analysis)

Since the data generated by this code was representative only of the pressures which the structural elements would encounter it was necessary that unit loads corresponding to the projected surface area for each principal direction component of each structural member. This unit load was then scaled appropriately by the magnitude of the time-history functions which were applied as unique load cases for all members and directional components.

5.5 Analysis Parameters

Using the finite element analysis program SAP 2000 v.14 it was possible to take all of the loading data generated through the use of MINITAB and a Matlab code and determine the structural response. While an analysis in which damage and large deflections is expected would typically warrant the use of direct integration methods, it was found necessary for computational efficiency and speed to utilize non-linear modal methods. Each iteration was therefore run as a non-linear time-history analysis. Damage was determined by checking for the exceedance of member capacity due to a load combination which included all blast loading cases for the iteration as well as the unfactored dead and live loads. The analysis method used accounts for moment redistribution due to hinge formation as well as P-delta effects on stiffness.

6 Analysis Results

6.1 Evaluation of Damage/Performance

Through the running of multiple iterations it was possible to establish trends of damage caused in the structure and the weighted damage index, allowing inferences to be drawn as to the overall performance of the facility to specific types of attacks. While the factors of both charge weight and standoff affect the structural damage caused by an explosive attack, since there is more control in this simulation of the locations of the blast origins due to probability zone definitions, it becomes of greater interest to establish minimum criteria of charge sizes related to damage states.

6.1.1 Vehicle Bombs

Due to the relatively large number of probability zones as well as large area of consideration for blast origins in the vehicle bomb portion of the simulation, a higher number of simulations (40) were performed than for interior blasts to develop the necessary data to draw conclusions from the simulation. The discrete nature of explosive weights for the vehicle bomb charge weights used in the simulation provides an example in which the effect of standoff and location to assets becomes strongly evident. Figure 6.1 shows clearly that, as would be expected, there is an increase in damage inflicted on the structure as the charge weight of the vehicle bomb is increased. It should be noted that the red line (damage index = 15) denotes the threshold between immediate occupancy and life safety performance while the orange line (damage index = 100) denotes the threshold between life safety and collapse avoidance performance. Additionally, it can be seen that while the potential to inflict damage grows considerably with increasing charge weight, the large variability evident in larger vehicle bombs shows a strong dependence of damage on location and proximity to the structure.

Since the desired result from the simulation is to determine likelihoods of exceedance of defined performance standards based off of two random variables, it was determined that the display of simple percentages of likelihood of occurrence is the most valuable and all encompassing method of presenting the data developed. Table 6.1 shows the likelihood of structural damage as well as performance of the structure for the entire vehicle bomb portion of the simulation. It can be seen that given the parameter definition of the hypothetical site, the likelihood of experiencing any damage at all is 42.5%. Also very notably, it is shown that the likelihood of reaching collapse prevention performance, which is associated with probable total loss, is 7.5%. These percentages are well supplemented by the necessary charge weight apparently necessary to inflict certain levels of damage. It appears necessary that a vehicle bomb of significantly greater weight than 10,000 lbs TNT equivalent, associated with a "small moving van or delivery truck (Sullivan et al.)," is necessary to reach the collapse prevention performance state. Also, it appears that it would be necessary for a vehicle bomb larger than a full-size sedan to be used in order to reach the life-safety performance state.

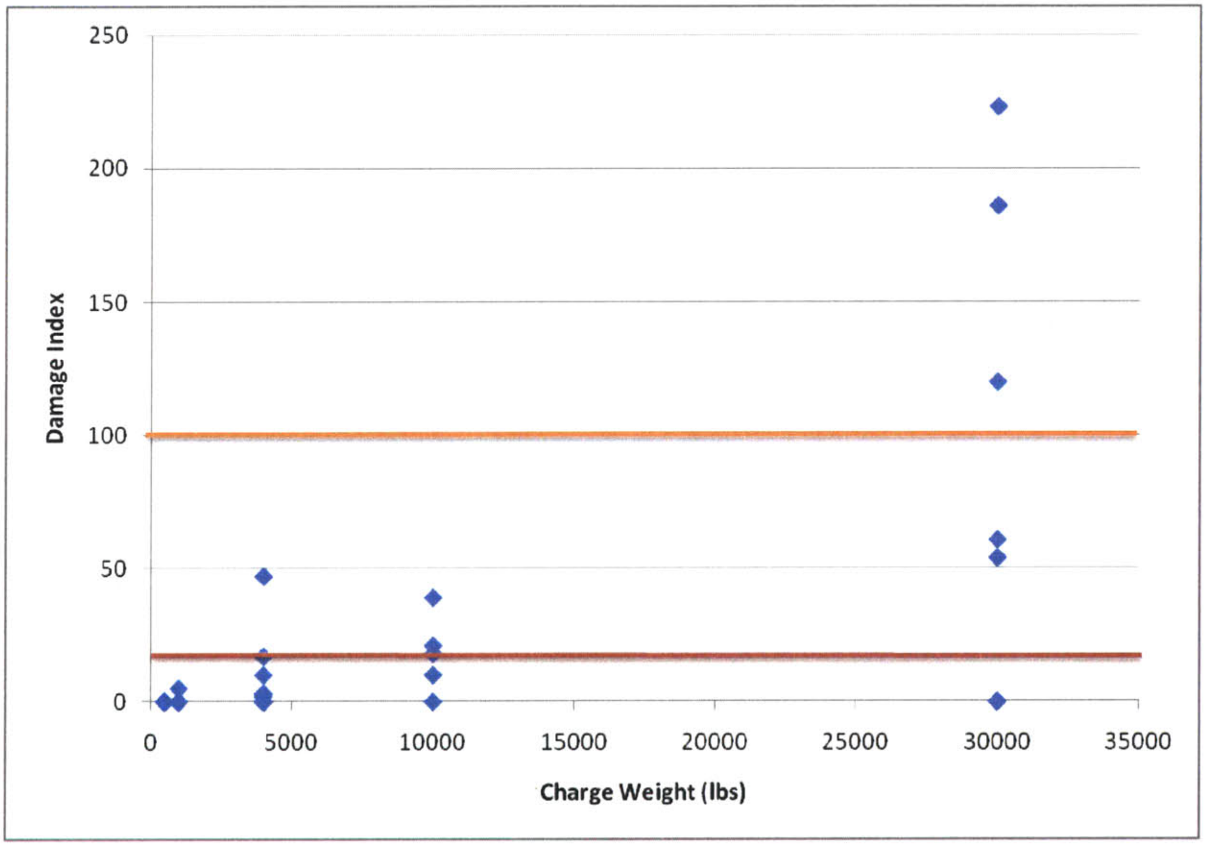


Figure 6.1 Vehicle bomb damage index vs. charge weight

		Likelihood of Occurrence
Total	40	
Iterations w/ Structural Damage	17	42.50%
Iterations with Immediate Occupancy Performance	30	75.00%
Iterations with Life Safety Performance	7	17.50%
Iterations with Collapse Prevention Performance	3	7.50%

Table 6.1 Vehicle bomb simulation building performance

6.1.2 Bombs on Person

Due to the decrease in variability for the parameters of bombs on a person compared to vehicle bombs, it was deemed prudent to decrease the number of iterations to 25 in order to have adequate data from which to draw conclusions. The data again was viewed with respect to charge weight, displayed in Figure

6.2 with the threshold between immediate occupancy and life safety performance (damage index=15) denoted by the orange line. As expected, there is a trend of increasing damage with increasing charge weight corresponding with an increasing likelihood of life safety performance of the building. It is evident that it is unlikely that any structural damage will be caused by explosive charges of less than ten lbs TNT equivalent while it appears that an explosive charge around 30 lbs TNT equivalent is necessary to exceed immediate occupancy criteria on a regular basis.

The likelihood probabilities presented in Table 6.2 show that due to the immediate proximity to structural elements (i.e. all blast origins occurred within the building) leads to a higher likelihood of structural damage compared to the vehicle bomb simulation even though the charge sizes are significantly less. However, it can also be seen that in no instance was the collapse prevention performance state reached.

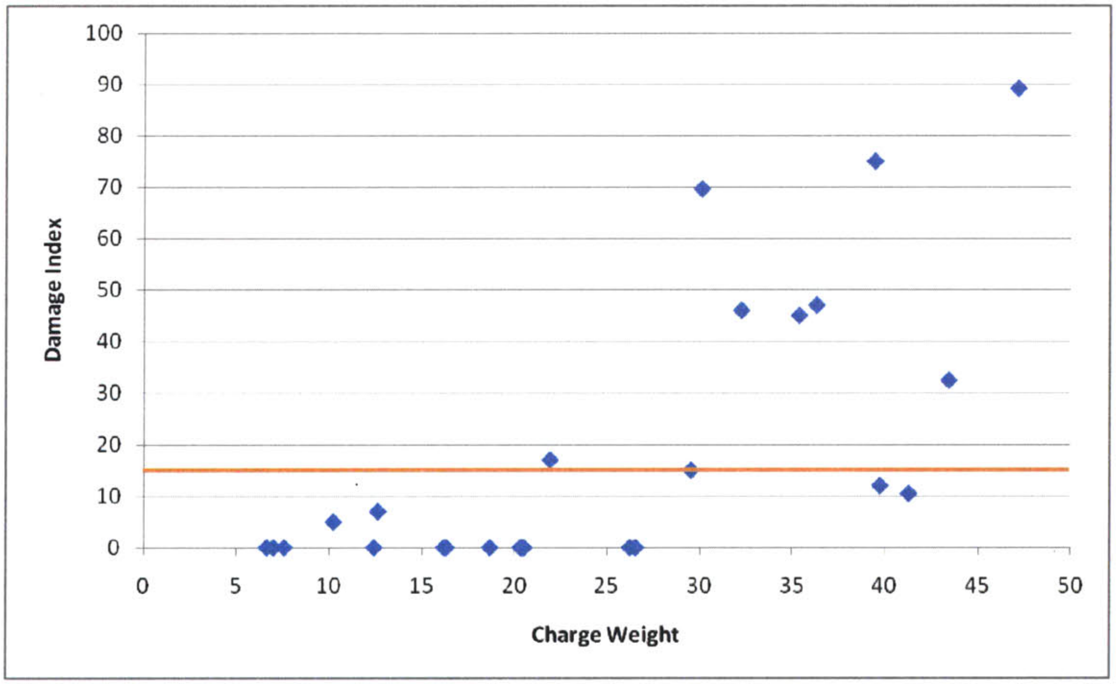


Figure 6.2 Bombs on person damage index vs. charge weight

		Likelihood of Occurrence
Total	25	
Iterations w/ Structural Damage	13	52.00%
Iterations with Immediate Occupancy Performance	16	64.00%
Iterations with Life Safety Performance	9	36.00%
Iterations with Collapse Prevention Performance	0	0.00%

Table 6.2 Bombs on person simulation building performance

6.1.3 Mail and Package Bombs

Through running the simulation with regards to mail and package bombs it was found that such iteration results were trivial. It is apparent that while charge weights between one and five lbs TNT equivalent should not be neglected as a threat, they lack the ability to cause damage to an adequately designed steel moment frame.

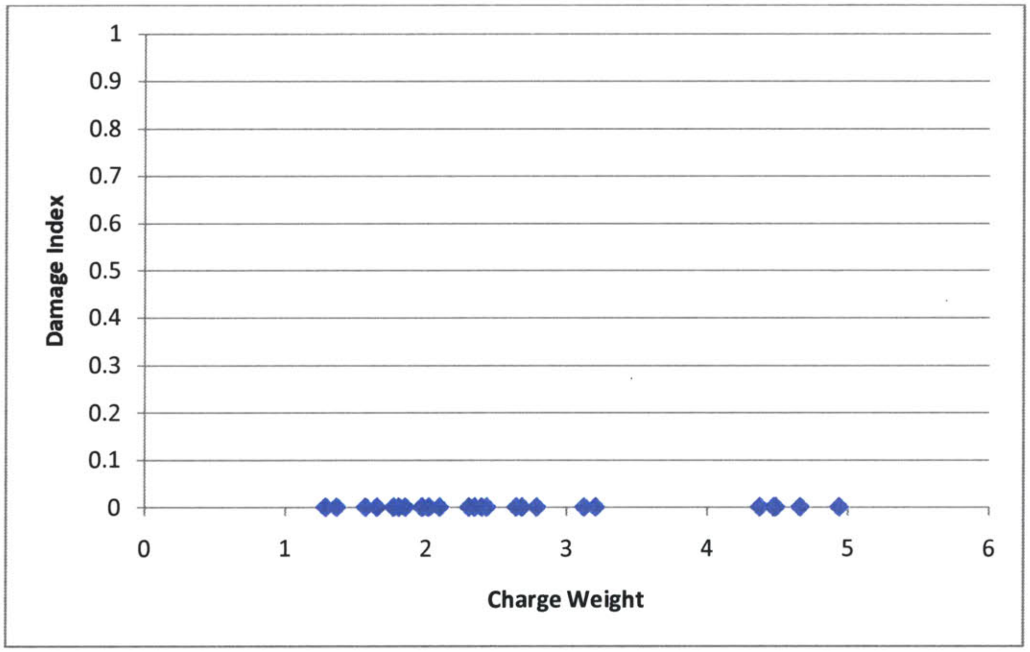


Figure 6.3 Mail and package bombs damage index vs. charge weight

		Likelihood of Occurrence
Total	25	
Iterations w/ Structural Damage	0	0.00%
Iterations with Immediate Occupancy Performance	25	100.00%
Iterations with Life Safety Performance	0	0.00%
Iterations with Collapse Prevention Performance	0	0.00%

Table 6.3 Mail and package bombs simulation building performance

6.1.4 Comparison of Results

The three different threat simulations help to provide not only a holistic view of the performance of the structure but also insight into the strengths and weaknesses of the structure's resistance to threats. It is apparent that, with regards to structural damage, the majority of all major attack types result in little to no structural damage. Additionally, of attacks which may cause significant structural damage, very special conditions are necessary in order to reach collapse prevention performance. By viewing these results it is possible to prioritize which attack threats should receive further attention. Vehicle bombs of 10,000 lbs TNT equivalent and greater and bombs on a person of 30 lbs TNT equivalent pose the largest and most consistent threat. The matter of threat consistency becomes very apparent when comparing the magnitude of range of damage indices associated with vehicle bombs with that of bombs on a person for these consistently damaging charge weights: 223 and 78.7 respectively. This large range for vehicle bombs suggests that location rather than charge weight truly dominates the influence on structural damage and a more pointed analysis with smaller variance in location be attempted in order to better represent a well-planned attack rather than a uniform distribution.

6.2 Recommendations

The focus of this simulation was indeed to establish a method by which a probabilistic analysis may be carried out with the interest of determining structural damage. Given the capabilities of the analysis, it was necessary to weight structural damage in an attempt to understand total damage on the structure. However, for a real world exercise, it is suggested that more exact methods be used in order to quantify and understand non-structural damage. While the finite element program SAP 2000 v.14 was utilized for time-history responses, there have been programs more tailored to blast analysis developed, such as the program BLASTX (Conrath et al., 2-12). Utilizing such a program provides a more accurate analysis for non-structural elements such as unreinforced walls but also, through fluid and particle finite element modeling, accounts for pressure amplification due to geometry as well as the effects of fragmentation and penetration. While a similar probabilistic method could be implemented, the use of more accurate and tailored modeling programs may indeed increase the reliability of probabilistic risk assessment. Also, it is recommended that a larger number of simulations be run in order to increase the reliability of the results and increase the odds of detecting behavior very specific to certain blast characteristics.

It is also recommended that more emphasis in real world simulations be placed on the quantification of assets and the differentiation between damage and loss. Due to the hypothetical nature of the facility and simulation performed there was no true distinction between damage and loss as they, without specific asset quantification, were deemed totally interdependent and therefore reported strictly as a weighted damage index. However, as the trend of performance based engineering moves towards probabilistic confidence in repair costs these two factors must be separated and dealt with in a more targeted nature.

7 Conclusions

As blast engineering becomes more prevalent and standard in the field of structural engineering, it is inevitable that the same approach which has been developed to deal with the stochastic nature of earthquakes will be applied to the field. It can be seen that there has been a large focus on developing building technologies which better enable a structure to withstand prescribed blasts and the future developments of such technologies is crucial. Regardless of the building codes and standards used by design engineers, these developments will prove effective in preserving life and monetary investments. However, the analysis technique and design standards of blast engineering have lagged behind its extreme event partner of earthquake engineering. Given the inherently similar nature of unknown loading, it is necessary that engineers in the field of blast engineering begin to take steps to establish a probability based design method similar to the current performance-based earthquake engineering methods.

It has been shown herein, through a probabilistic simulation of a hypothetical site, that, given an extensive security methods and efficiency analysis, it is possible to attain valuable data from which actionable conclusions may be drawn in a performance-based manner. Having established a procedure and framework by which threats may be defined, likelihoods of success be accounted for and loading be defined, it is possible to quantify damage in a weighted manner which may provide valuable information for the engineer, owner, security representative and indeed all share holders of a facility. This information may be used to not only verify performance expectations but provide insight into the faults of the facility layout and possibly lead to remedies for such faults. It is desired that in future work, methods be refined and implemented in practice side by side with the deterministic standards established by authorities in the field.

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