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Impacts and Analysis for Buildings under Terrorist Attacks

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Literature Survey Report

Impacts and Analysis for Buildings under Terrorist Attacks

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1. Introduction

Buildings are critical to society due to their importance as centers of government, business, education and residence. Some buildings are important to society as a whole due to the type and importance of the work done in them, and the symbolic nature of the structures, for example U.S. Embassies and the Pentagon. Events which can damage these structures, such as earthquakes, extreme winds, blasts, can result in downtime for the buildings operations which, due to their importance, would create a negative impact on society.

There is a rising threat in the world, due to an increase in global terrorism. This creates an increased danger to critical infrastructure. For example, over 150 attacks on US embassies have been reported since 1998 (Lefter 2010). The attack on the World Trade Centers on 9/11/01, where the force of the planes and the fires from the jet fuel caused the twin towers to collapse causing damage to numerous surrounding buildings. The attack on the Murrah Building in Oklahoma City in 1995, where a car bomb destroyed a supporting column, resulted in the building's progressive collapse (Corley 2004). These terrorist attacks, and others like them, can cause significant economic and societal impact to America.

To minimize the potential impact of these terrorist attacks, a systematic approach to assess the causes and outcomes of those events is required. The protection of structures from a terrorist attack can be briefly categorized into three methods: prevention planning, increasing structural resiliency, and accurate post-event analysis. Civil Engineers usually deal with resiliency via structural design and post-event analysis by determining the building damage and assisting in planning future use of the structure post-attack. Two broad approaches to buildings' resiliency to a blast include designing buildings to better resist an explosions blast loads by strengthening critical components using rigid design, or disperse its energy using ductile design. Post-event planning involves analyzing the damage caused by the attack, and determining future action including demolition, repair, and/or a resumption of normal operations. To perform these tasks, one first has to understand the principles behind a terrorist attack. These include understanding explosions, and post-event analysis methodology and feasibility.

The goal of the literature survey in this report is to provide a systematic framework to investigate terrorist attacks and their impacts on building structures. First, common damage types from explosions to general civil structures are provided including the World Trade Center attack on 9/11/01 and the Murrah Building bombing. These examples will provide perspectives on what can occur in a terrorist attack. Then the basic principles of an explosion will be explored, which will be a foundation to design analytical and experimental studies. After that, the impact of an explosion on a structure and how that is determined will be discussed. Analysis techniques for a damaged structure will be explored in depth, as well as experimental methods used to validate and prove those techniques.

2. Common Damage Types from Explosions to Structures

A terrorist attack on a building will frequently involve an explosion which causes damage to the structure. When a bomb detonates in/near/on a building, various forms of damage can be expected including windows breaking, connections failing, cladding failure, damage to the internal non-structural aspects and furniture of the building, major structural failure, and even progressive building collapse. These explosions can be dangerous to people in the vicinity from the pressure and heat of the explosion itself, falling debris, and/or the potential collapse of the building. In this section, we will see many of these affects in two important examples of terrorist attacks in the U.S., with the World Trade Center attack on 9/11/01 and the Murrah Building bombing.

2.1. Murrah Building in Oklahoma City: Major Building Failure

On April 19, 1995, a car bomb set off by Timothy McVeigh detonated outside the Murrah Building in Oklahoma City, OK. This bomb caused the progressive collapse of the building. The building had a 3rd story transfer girder on the northern exterior face of the building for aesthetic appeal, with four columns supporting it. The car bomb set of a blast with a TNT equivalency of 4000 lbs, shattering one of the columns, and causing shear failure in two others. With the damage caused, the transfer girder was no longer able to support the weight of the building, and a progressive collapse of the structure ensued.

The Murrah Building was designed as an ordinary reinforced-concrete-frame structure. At the time of the Murrah Buildings construction, earthquake, blast, or other extreme load cases were not required to be considered in its design. Had the building been designed to today’s building codes, “the north face would have had substantially more inherent resistance to progressive collapse" (Corley 2004). The Murrah Buildings is an example of the destructive impact an explosion can have on a structure.

2.2. World Trade Center 9/11/01

On September 11th 2001, in the biggest terrorist attack in U.S. history, two hijacked airplanes struck the World Trade Center (WTC) towers in NYC. Due to these attacks, the two towers suffered progressive collapse, and several nearby buildings were also severely damaged. This section will summarize the structural damage which lead to the collapse of the WTC towers, as well as the damage caused to some of the nearby buildings. Figure 1 has a map of the buildings as well as their number designations, which will be used in this paper.

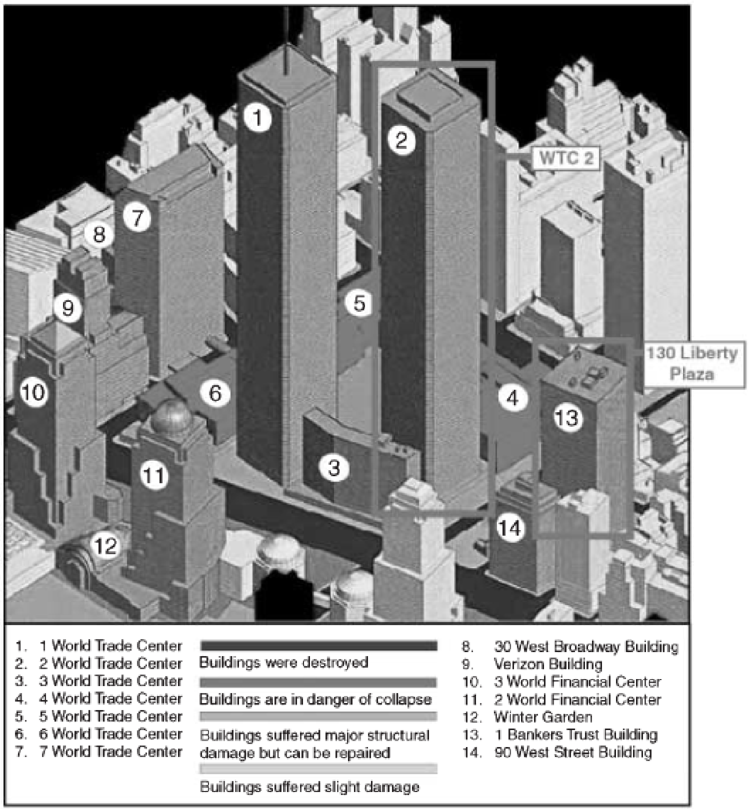

Figure 1 WTC Complex Building designations (Warn et al. 2003)

2.2.1. Progressive building collapse: WTC Towers 1 and 2

When the airplanes hit the two WTC towers, the result was massive structural damage to the buildings. The planes damaged the structural columns, destroyed wall sections, and destroyed the stairways. The towers also suffered from fire damage caused by the fuel from the airplanes creating a fireball. While the fireballs shockwave didn't damage the structural components of the building, the impact from the airplanes and the shock wave from the fireball, knocked off the fire coating on the structural components. The extreme heat from the fire weakened the steel columns, lowering "the columns' yield strength, modulus of elasticity, and critical buckling strength" (Corley 2004). The high temperature also could have caused the horizontal support elements and floor slabs to lose rigidity, causing end connections to fail and floors to collapse. The fire and impact damage caused the towers to suffer progressive collapses.

2.2.2. Damage to Nearby Buildings: WTC towers

Damage from the airplanes striking the WTC towers was not limited to the towers themselves, but also affected many of the nearby buildings. The damage was mainly caused by the impact from falling debris and fires started by burning debris. Two of the impacted buildings were WTC 5 and WTC 13 (130 Liberty Plaza). These structures suffered localized collapses from fires weakening structural components, structural damage caused by falling debris, as well as non-structural damage such as broken windows and a loss of building cladding.

3. Theoretical Background on Explosions

Designing against, and planning for after a terrorist attack requires knowing about what type of damage will be caused. Bombs and the explosions they create are a common tool used by terrorists. This section will give an introduction into explosions and the theoretical background for the analysis of their impacts.

3.1. Definitions

An explosion is a rapid release of a very large amount of energy, causing a large increase in temperature and pressure, creating hot compressed gases which can expand in a shock wave (Pape et al. 2010a). A shock wave is a short duration pressure wave which moves through the medium of air (blast wave), water, or earth, bringing a sharp increase in pressure at the front of the wave, and a gradual decreasing of pressure as the wave passes, as shown in the example pressure profile in Figure 2. As can be seen, there is a sharp increase to the peak pressure as the blast wave reaches the target point, followed by a gradual decrease, leading to the negative phase, with the pressure eventually returning to ambient. The blast wave is characterized by its peak pressure, the duration of the positive phase, maximum negative pressure, and the duration of the negative phase.

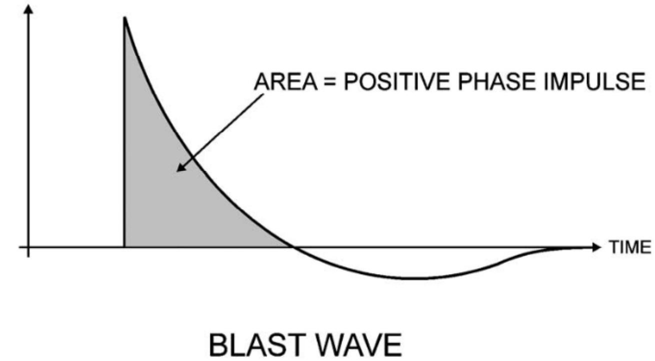

Figure 2 Overpressure Graph for a Blast Wave (Pape et al. 2010a)

The confinement of a blast wave can impact the wave pressure. Incident pressure is the pressure from a shock wave which has yet to interact and be modified by any structures, such as impacting a building. Reflected pressure is seen in a shock wave when it hits a large solid object and bounces back at a higher pressure, usually occurring with strong walls or the ground. If a wave hits a surface at an angle, it will reflect off at a reflection angle as shown in Figure 3. In this figure, R is the reflected wave, I is the incidence wave, C is the point of the shock wave origination, S is the surface of reflection on the ground for a reflected wave, in the air for a Mach wave, α_I is the incidence angle, which is the angle between the incidence wave and the reflective surface, T is the triple point between the Incidence, Reflected and Mach Wave, ρ is the path from the reflective surface and the Mach reflective surface (S), and M is the Mach wave. The Mach wave is a third wave which can form if incidence angle is above a critical value.

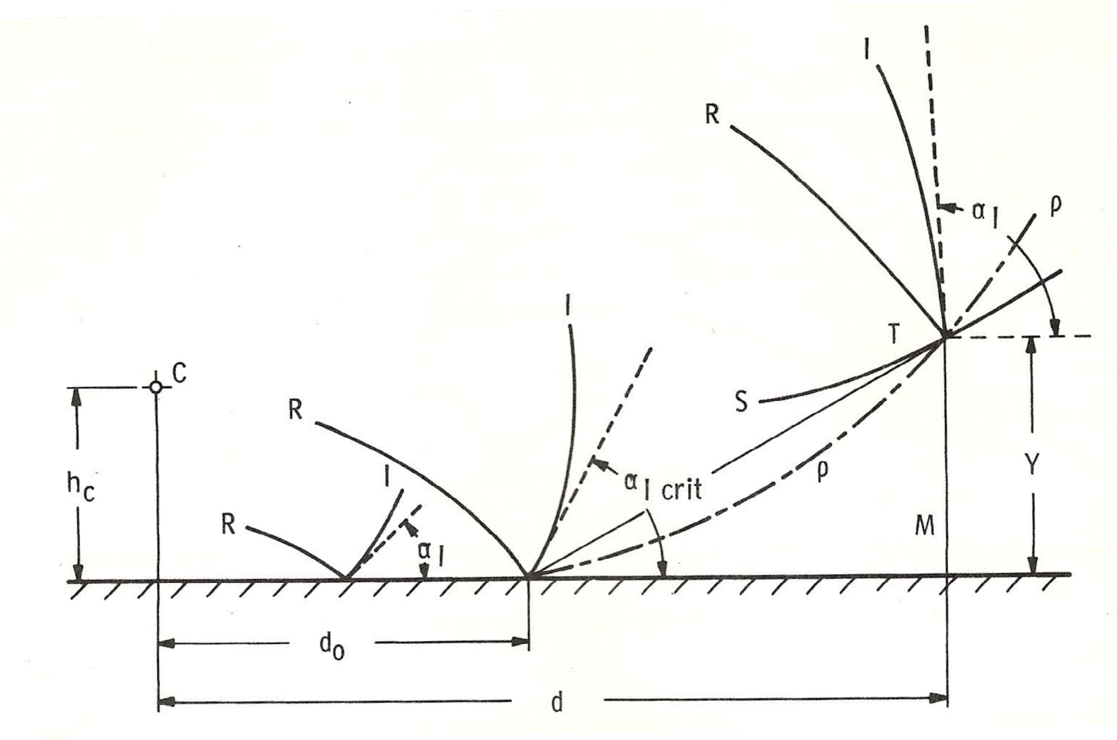

Figure 3 Angled Reflected Waves and Mach Wave (Baker 1973)

3.2. Conditions creating Explosions

Explosions are generalized into four categories on the circumstances that bring about their existence: physical, chemical, electrical, and nuclear depending. In this paper, nuclear and electrical explosions will be only generally defined, due to their limited use in terrorist attacks. Currently, terrorist's do not have, or have not used nuclear weapons, and electrical explosions are highly impracticable for a terrorist attack. On the other hand, the condensed nature of some chemical explosives makes them widely used by terrorists, and terrorists could rig pressurized/high temperature systems already in a facility to detonate in a physical explosion.

3.2.1. Chemical Explosions

Chemical explosions require the presence of fuel for energy, confinement to buildup pressure, proper dispersion into an oxidizer to mix in, and an ignition source. Chemical explosions can be categorized into two types, rapid combustion reactions and condensed material explosion. Rapid combustion reactions involve a vapor, dust, or mist fuel which is dispersed in the air and ignited, and is called rapid combustion reactions. A vapor cloud explosion is analyzed by first performing a dispersion analysis, comparing it to confining objects in the area. Then, either the multi-energy method, where the category of the explosion is determined by an expert and compared to pressure-impulse curves, or the BST method, where the mach number of the flame is determined the appropriate pressure versus impulse curves are selected for that value (Pape et al. 2010b). The other type is a condensed material explosion. These are condensed liquid or solid with a high amount of energy per unit area, which can be induced to explode. This type includes High Energy (HE) explosives, which are frequently used by terrorists, as well as other types such as TNT.

Chemical explosions are either a detonation or a deflagration. “A deflagration is an exothermic chemical reaction which results in a subsonic propagation of a flame front, where the flame speed is less than the speed of sound in the medium. A detonation on the other hand is a supersonic propagation, where the flame speed is greater than the speed of sound in the medium” (Pape et al. 2010a). The strength of the explosion depends on the fuel reactivity, environmental conditions, the configuration and geometry of the area the explosion is occurring in, and the strength of the ignition source.

3.2.2. Physical Explosions

Pape *et al.* (2010a) defined physical explosions as a “physical gas dynamic and thermodynamic effects such as the bursting of a pressure vessel and/or a rapid phase transition.” This means that a physical explosion is the result of the breach of a high pressure container, and/or the result of a pressure wave caused by a rapid change in temperature. Some common examples of physical explosions are a pressurized cylinder rupture, certain types of boiler explosions, and boiling liquid expanding vapor explosions (BLEVEs) (Pape et al. 2010a).

In a pressurized vessel rupture, the blast wave is characterized by the energy output from the vessel. The energy can be used to predict the blast wave using TNT equivalency by dividing the energy obtained from the pressure vessel rupture by the energy of TNT (1,120 cal/g), and finding the blast parameters of that equivalent TNT blast. The energy required to pressurize the container can be calculated such that (Pape et al. 2010b),

$$E_{Brode} = \frac{(p_1 - p_0)V_1}{(\gamma - 1)} \tag{1}$$

where, p is for pressure, V is for volume, γ is for the ratio of specific heats, and the subscript 1 is for the initial condition in the container, and the subscript 0 is for the ambient condition. The work done by the expansion of the gas in the container after it has been released can be calculated such that,

$$E_{work} = \frac{p_1 V_1}{(\gamma - 1)} \left[1 - \left(\frac{p_0}{p_1}\right)^{(\gamma-1)/\gamma} \right] \tag{2}$$

Both methods give you the energy output by the explosion.

In addition, BLEVE explosions involve superheated liquids in a contained vessel, which losses containment, causing the heated, pressurized liquid to explode. The energy in a BLEVE blast comes from the expansion of energy in the vessel before rupture, the flash vaporization of the liquid before rupture suddenly being exposed to ambient conditions, and the potential combustion of flammable vapors.

3.2.3. Electrical Explosions

“Electrical explosions are those resulting from an instantaneous release of electrical energy, e.g., an arc event or other electrical failures (faults)” (Pape et al. 2010a). They occur when the electrical arc fast heats oil or air, causing the medium to expand, and this expansion creates a pressure wave. An example of an electrical blast would be a transformer exploding. These types of explosions are irrelevant for terrorist analysis.

3.2.4. Nuclear Explosions

Nuclear explosions are the result of nuclear weapons using fission or fusion technology. The fission or fusion releases a large amount of energy and radiation. Nuclear weapons can cause immense damage to a structure; however, studying nuclear blasts for post-event analysis is a moot point. The blast would either destroy the structure, or the radiation would be too high to make building re-occupation possible, rendering post-explosion analysis irrelevant. Therefore, nuclear weapons analysis with respect to terrorism shall be ignored in this paper. There is also the possibility of an accidental nuclear explosion from a nuclear reactor, however to this date no nuclear explosion has occurred because of a nuclear reactor.

3.3. Major Effects of an Explosion

When an explosion occurs, there are different types of effects that can occur and cause damage to nearby structures. Some major causes of damage are overpressure, thermal affects, energized projectiles, cratering and ground shock. These will each be discussed in the following section.

3.3.1. Overpressure

Overpressure is the pressure difference between the explosion pressure and the ambient pressure, which was shown in Figure 2. The strength of the overpressure blast wave is directly related to the distance the receiving object is from the center of the explosion, with the overpressure decreasing with increased distance. Damage to structures, people, and other objects can be caused by both the positive and negative overpressure from the blast. The damage from a blast wave is related to the magnitude of the peak overpressure, rise time, duration, and impulse (Pape et al. 2010a). Impulse, I, the pressure from the wave over the positive phase of the blast wave is calculated by,

$$I = \int_{t_1}^{t_2} p dt \tag{3}$$

where, t_1 is the arrival of the pressure wave at the structure, t_2 is when the blast pressure is back to ambient, and p is the pressure from the blast wave.

3.3.2. Thermal Effects

Another major effect of an explosion is the thermal impact, which mainly occurs when a fireball, or a volume of hot gases, is generated. When a structure is engulfed by a fireball, because the building is usually near the center of the explosion, the thermal effects are generally not as important as those from overpressure and fragment or debris. However, if the fireball impact and overpressure impact damage a structures fire-resisting system (i.e. knocking off columns fire coating), intense heat from the explosion can weaken structural members, which can assist in the failure of those members, leading to potential localized or progressive collapse. An example of an instance of this was in the World Trade Center attack on 9/11/01. Thermal energy can also injure people, and ignite various objects in a structure such as furniture.

When a fireball is created from an explosion, it can cause significant damage. The strength of the fireball (radiant output) is determined by the fuel mass, fireball diameter, duration of the fireball, and the thermal emissive power (Pape et al. 2010b). The diameter of a fireball (D_c) and its duration (t_c) can be estimated,

$$D_c(m) = 5.8{m_f}^{1/3} \tag{5}$$

$$t_c(s) = 0.45{m_f}^{1/3} \ when\, m_f < 30{,}000\ kg \tag{6}$$

$$t_c(s) = 2.6{m_f}^{1/6} \ when\, m_f > 30{,}000\ kg \tag{7}$$

where D_c is the fireball diameter, t_c is the fireball duration, and m_f is the fuel mass of the fireball.

The impact from a fireball can also be estimated by analyzing its radiant flux (q_{12}) is,

$$q_{12} = F_{12} * E_1 * A_1 \tag{8}$$

where F_{12} is a configuration factor taking into account the fireball geometry and distance to the target, E_1 is effective surface emissive power of the fireball, and A_1 is effective area of the fireball. The radiant flux can then be compared to previously determined damage caused by that flux level. An example of the radiant heat flux versus the thermal energy is shown in Figure 4.

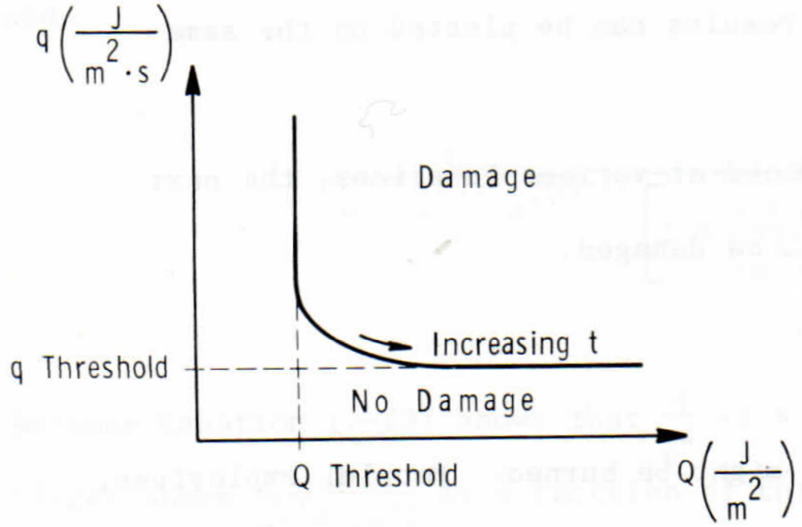

Figure 4 Heat Flux (q) vs Thermal Energy (Q) Damage Plot Example (Baker et al. 1983)

The y-axis is the radiant flux (q) and the x-axis is the thermal energy (Q). If the value from a fireball falls below the threshold line, then the damage is not likely to have occurred, and if they fall above the line, then the damage likely occurred.

3.3.3. Debris Damage

Debris and fragments thrown through the air by an explosion can be the cause of significant damage when an explosion occurs. Fragments are either primary, or secondary. Primary fragments, are generally chunky objects with a mass of around a gram which were originally part of the explosive container which are thrown at high speeds when the explosion occurs. Secondary fragments are either constrained or unconstrained objects which are near the explosion, which are flung by the explosion based on their size, shape and level of constraint.

One serious form of secondary fragments is shards from windows, which can cause major injury to individuals impacted by the shards. The damage caused by these fragments is determined by their initial velocity, the distance from the explosion to the object hit by the fragment (target), the angle the fragment strikes the target, and the physical properties of the fragment and the target.

3.3.4. Energized Projectiles

Energized projectiles consist of fragments, debris, and missiles, which can strike structures and people, causing significant impact damage. These objects are thrown by the explosion with varying levels of force depending on the object, the objects proximity to the explosion, and the explosions strength. When impacting a structure, fragments can cause significant harm and damage to the walls, structural components, equipment, and people which they strike.

3.3.5. Cratering and Ground Shock

When an explosion occurs there can also be cratering and ground shock damage depending on the location of the blast. If on or close to the ground, a tremor is transmitted over a distance by the ground; which is excavated locally (Medard 1989). The strength of the cratering is related to the soil type and blast location. The tremor can cause damage to a structures foundation, and the cratering can shoot out debris which can damage a structure and injure bystanders.

3.4. Analysis Considerations of an Explosion

3.4.1. TNT Equivalency

The simplest method to evaluate an explosion when one does not have the time or resources to perform experimental analysis on an explosive is to use TNT equivalency. TNT equivalency is based on a series of tests performed by the department of defense, where they tested the pressures from various explosives at various distances, and compared it to the air blast that would be produced by detonation of a TNT explosive placed on a rigid ground surface (Pape et al.2010b). The results were then scaled, to show the equivalent weight of TNT required to produce the same blast at a given distance. An example of TNT equivalency when applied to scaled distance (d_r) is shown,

$$d_r = \frac{d}{\sqrt[3]{W_{TNT}}} \tag{4}$$

where W_{TNT} is the equivalent TNT weight, and d is the distance from the explosion.

However, there are some potential issues with using TNT equivalency for analysis. According to Medard (1989), the use of unit charges in explosion analysis is complicated by secondary reactions which can impact the peak pressures and impulses in chemically different atmospheres (ex: oxygen-rich vs. oxygen deficient) unless taken into account. If the atmospheric impacts are taken into account by modifying the equivalent TNT weight, or they aren't significantly large, then they shouldn't be a major concern.

It should also be noted that while TNT equivalency is used in the United States, there are other standard units for explosions. For example, in France and other European nations, they use a picric acid standard. TNT is about 0.94 times the power of picric acid.

3.4.2. Enclosed Combustion Explosion

Explosions inside of structures vary from those in open areas. One important determining factor of an enclosed explosion is the presence of a vent. In an unvented enclosure, the pressure of a deflagration will rise at an increasing rate, as shown in curve A of Figure 5. However, if a vent is open, a window fails, or a similar occurrence which creates a path for the pressure to vent out, the pressure will decrease as shown in curve B, unless an increase in turbulence from the venting enhances the explosion as in curve C.

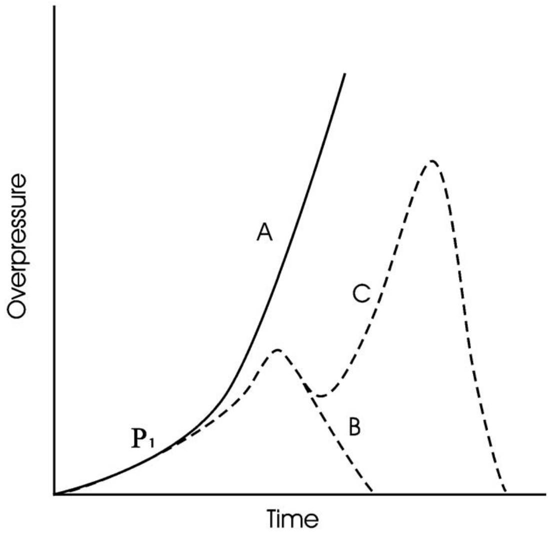

Figure 5 Sample Overpressure Curve inside an Enclosure (Pape et al.2010a)

In an internal blast, the reflected pressure waves can be simplified into three blasts, with each reflection decreasing in peak pressure and impulse as the reflections die out. Any reflections past three are assumed to be negligible for simple analysis. This simplified determination of an internal blast pressure is shown in Figure 6.

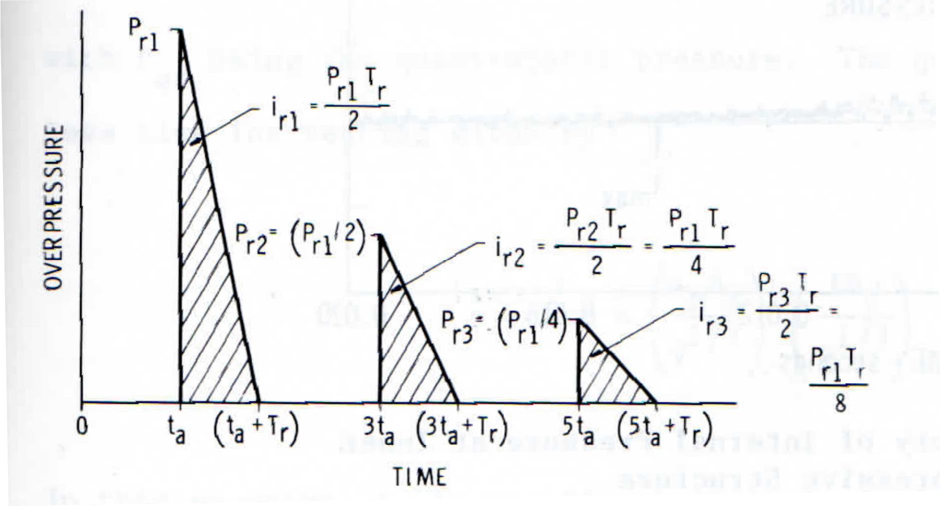

Figure 6 Triple Reflection of an internal blast (Baker et al. 1983)

The three relevant reflections are shown, with the peak overpressure of each consecutive wave decreasing as time passes.

3.4.3. Damping

When modeling a dynamic system, the damping affect reduces the impact of a vibration. However, when dealing with buildings (or similarly large structures), the internal damping of the structure is generally neglected. This is because the damping is generally small and hard to compute, and the load is applied too fast for it to make a significant impact. This assumption is accepted in analysis due to the fact that neglecting damping only leads to more conservative estimates of structural damage.

4. Explosion's Impact on a Structure

When explosions occur near structures, it is important to be able to assess the damage that is caused by the blast. This damage is impacted by many different factors, from the characteristics of the explosion, such as the peak pressure and impulse from the blast wave on the structure, to the nature of the building, such as the strength, ductility, lateral load resistance, and inertia. It is extremely important to be able to determine the impact of a blast on a structure. This section will cover approximate analysis, more detailed analysis methods, and some important analysis principles.

4.1. Approximate Analysis

Detailed and complex explosion analysis on a structure is technically difficult, economically costly, and comes with a degree of uncertainty due to varying loading conditions, which can make complex analysis methods unpractical. To this end, an approximate method of analysis can be used to determine the impact of an explosion on a structure. Approximate analysis can use peak pressure, or P-I diagrams. The peak pressure method involves finding the peak pressure of an explosion, and comparing it to experimental data from similar explosions on similar buildings. The logic chart for this methodology is shown in Figure 7. This method is useful for preliminary design and design of non-elastic materials like windows. However, since it does not take into account the duration impact of an explosion, it is limited in use.

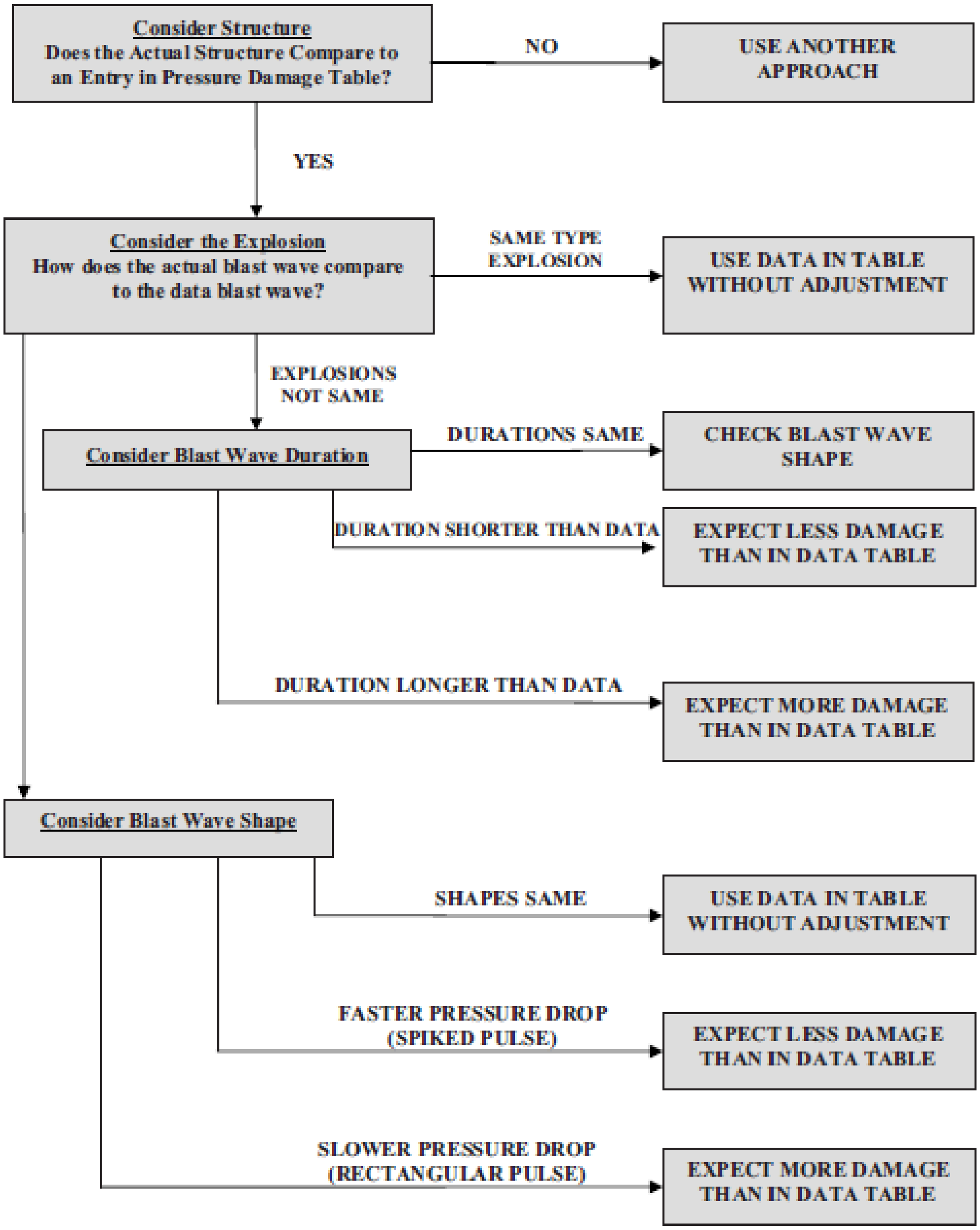

Figure 7 Approximate Explosion Analysis Methodology Logic Chart (Pape et al. 2010)

To get a more accurate result, a P-I can be used. A P-I diagram, shows pressure versus impulse, and presents experimental data on when certain failure events will occur. The failure thresholds are developed using experimental data. If the pressure and impulse of an explosion are under the P-I diagram threshold, then the structure will not endure the failing condition, if they are above the threshold it will. An example is shown in Figure 8 with two damage thresholds, a and b, and Pressure (P) as the y-axis and Impulse (I) as the x-axis.

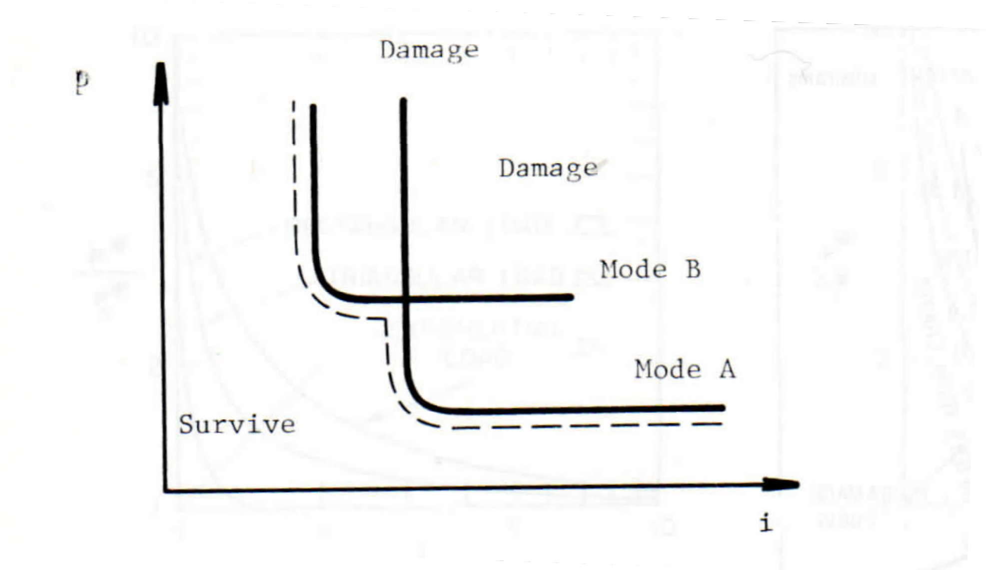

Figure 8 Sample P-I Diagram with two Damage Cases (Baker et al. 1983)

If the explosions pressure and impulse are below damage mode A threshold then no damage would occur, and if they are above it then damage happens. The same applies to damage mode B.

4.2. Numerical Analysis

When approximate analysis is not adequate to determine the damage on a structure, more complex analysis methods can be used. Some basic simplified computational analysis can be performed if your structure can be modeled as a one or two degree-of-freedom equivalent systems. However, for complex structures or multi-degree-of-freedom systems, the mathematics quickly becomes too complex to reasonably perform by hand. To compute these problems, Finite Element (FE) software is used to solve the complex scenarios. Many different computer programs exist, which have different benefits and drawbacks, and the decision on which to use depends on the analyst and the project to be analyzed. A more detailed discussion on numerical methods is given in section 5.

4.3. Experimental Analysis of an Explosion

4.3.1. Lead Block Test

One type of experimental explosion analysis is the lead block test. In this test, an explosive substance is detonated at the bottom of a standardized hole in a lead block. The change in volume of the block from pre-detonation to post-detonation is then measured, and the expansion in the block's holes volume is used to determine the relative power of the explosive. A diagram showing a sample lead block test is shown in Figure 9.

Figure 9 Lead Block Test (Medard 1989)

4.3.2. Experimental Scaling

When doing experimental studies on explosions, a common requirement is to scale down the experiments. Large scale testing is not only expensive, but also difficult due to the increased security and safety requirements. To this end, three very important factors in explosion experiments are the Scaled Distance, Scaled Duration and Scaled Impulse. "If the scale distance is the same between two different events, the blast effects will be the same regardless of explosive weight and distance from the source" (Son et al. 2011). The same goes for scaled duration and scaled impulse. The principles behind this are shown in Figure 10. This allows us to use small-scale testing to model the pressures, impulses and phase durations of large problems.

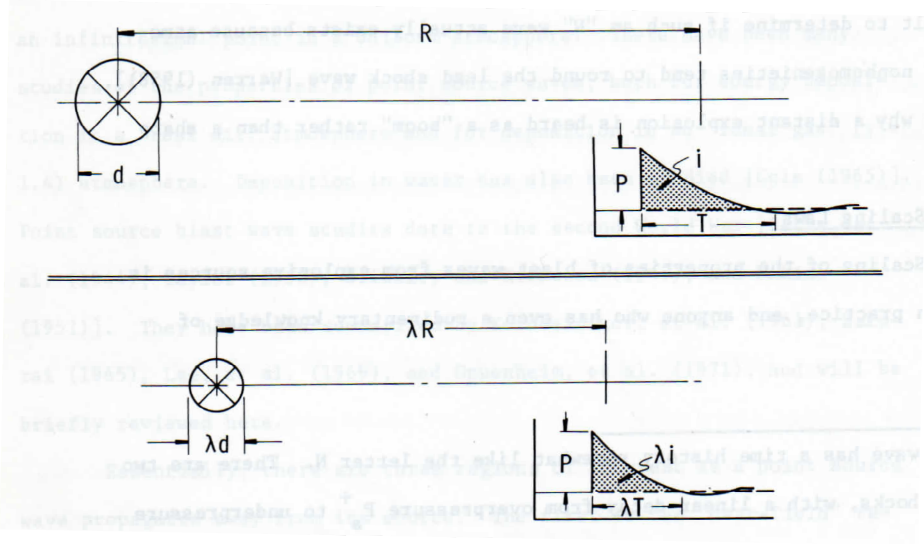

Figure 10 Scaled Distance Principles (Baker et al. 1983)

The formulas for Hopkinson-Cranz cube-root scaled distance, duration and impulse are given,

$$d_r = \frac{d}{\sqrt[3]{m}} \tag{9}$$

$$t_r = \frac{t}{\sqrt[3]{m}} \tag{10}$$

$$I_r = \frac{I}{\sqrt[3]{m}} \tag{11}$$

where d is the distance from the center of the explosion, t is the duration of the explosion, I is the impulse of the explosion, M is the mass of the explosion, d_r is the scaled distance, t_r is the scaled duration, and I_r is the scaled impulse. Another common form of scaling is Sach’s scaling, which takes into account the effects of altitude and other ambient conditions on a blast.

An example of a small-scale test is presented by Cheval et al (2010). In their paper, Cheval et al describe their design of a small scale testing apparatus for studying the pressures from blast waves. It involves exploding a small charge (of varying weights) on a testing table with gauges at varying distances to measure the overpressure wave of the blast. The same blast apparatus was then used in Cheval et al (2012) to test the impact of reflected blasts.

5. Structural Analysis

When a blast occurs near a structure, it is essential to be able to determine the extent of the damage. The structural damage is a relationship between the strength and location of the explosion, and the resilience of the structure. When dealing with large and complex buildings determining these relationships accurately can be very complicated. Various methodologies have been developed to calculate the damage to the structure. This section will discuss analysis principles, two major analysis techniques [Finite Element Analysis (FEA) and the Applied Element Method (AEM)], and the basics behind simplified methods.

5.1. Analysis Principles

5.1.1. Coupling vs. Decoupling

For complex explosion analysis, an important question is whether or not to couple or decouple the explosion. Coupling is when the explosion itself is used in the analysis calculations, while in decoupling the impact of the explosion is determined (ex: weakened or missing structural components) and put into the model without the explosion. Pape et al (2010) reported that the structural response can be decoupled from the fluid dynamic analysis describing the blast pressure field, in situations where the structure does not deform significantly or moves slowly while the blast loading is present. However, if the structure could deform significantly, that movement could modify the blast and must be accounted for. By decoupling, the analysis can significantly simplified. This can also be referred to as direct (coupled) and indirect (decoupled) analysis.

5.1.2. Computation Time and Expense

When deciding upon an analysis method, it is important to take into account the computation time required for the analysis. There are methods which can determine the damage caused by an explosion with extreme accuracy, and which take into account numerous aspects, such as soil, air, and façade failure. However, the more detailed the analysis, the longer the computer computation time, and the greater the computation cost becomes. Therefore, when deciding upon the type of analysis to use, it is important to incorporate the level of accuracy required for your purposes, versus the computation cost and time required.

5.2. Finite Element Analysis

The Finite Element Method (FEM) involves splitting up the structure into small elements. These elements have nodes (the number of which varies depending upon the level of analysis). The values of stress and deformation are measured at these nodes, and then interpolated across the rest of the element. With these values, it can then be determined if the structural element has failed.

FEA can incorporate varying depths of analysis. For simplicity, one can perform a linear elastic analysis, as done in Warn et al. To make a more accurate analysis, one can use a

Computational Fluid Dynamics (CFD) application. CFD can model the blast loading with greater detail then a normal FEM program, taking into account aspects like reflected blasts, mach waves, a blasts negative phase, and other aspects of a blast in a confined (urban) environment. This loading can then be placed into the FEM model for the structure. Other modeling considerations include soil, air and façade failure. These can be included in the FEM model to varying extents, depending upon the level of accuracy and computation time and cost restrictions.

5.3. Applied Element Method

Another common method for structural analysis of blasts is the AEM. AEM involves breaking the structure into small elements. The elements have six degrees of freedom, and are attached with normal and shear springs, which model the loading through the structure. The accuracy of the analysis depends on the size of the elements, and the number of springs between elements. A commonly used software which uses AEM is ELS (Extreme Loading for Structures).

The AEM has certain benefits over the FEM. FEM follows a structure/structural component up until failure. AEM goes from initial loading, through failure and shows how the building will collapse. This can be important for analysis of post-blast damage. AEM does this while also maintaining reasonable computational times.

5.4. Simplified Methods

When dealing with computational time/cost considerations, there are two ways to limit these factors. One method is to simplify the analysis, by eliminating extraneous considerations which have a nonessential impact on the structural analysis (ex: soil impacts, thermal considerations, impact of building siding, etc.). The other method is to use a simplified analysis method. These usually involve reducing the analysis into a Single Degree of Freedom (SDOF) or a simple Multiple Degree of Freedom (MDOF) system. Simplified SDOF and MDOF techniques can greatly reduce the required computational time, however there is also a loss of analysis accuracy which must be considered. An example of one such technique is shown in Bogosian (1999).

Another simplified analysis method involves simply comparing blast parameters to experimental data. The pressure-impulse (PI) data for an explosion can be compared to thresholds of experimental data of damage to similar structures under with similar explosions. If the PI of the blast is above the damage threshold, there is a likelihood of the damage occurring. While extremely fast, this method is also very unreliable due to variations between scenarios, and should only be used for basic analysis (such as potential cladding failure, window breaking, human injury from blast, extremely simple structures, etc.). The use of PI diagrams was previously discussed in section 4.1 Approximate Analysis.

6. Structural Experimentation

It is important to have experimental results, to validate numerical studies and to provide a better understanding of a blasts impact on a structure. To that end, this section will look into different types of experimental studies. Some controlled experiments will be provided followed by those using terrorist attacks/accidental explosions as experimental data.

6.1. Controlled Experiments

As the name suggests, controlled experiments suggest that they are designed and run to gather results in a controlled environment. These types of experiments are usually performed by researchers to prove a point or validate a numerical model. With blast analysis of structures, due to the difficulty of large tests, scaling is extremely important. Another useful tool is to ignore the explosion itself, and just focus on its impacts (similar to indirect analysis). In this paper, we will look into three types of controlled studies: shake table analysis, column loss analysis, and scaled blasts on structures.

6.1.1. Shake Tables

A shake table is a device which can vibrate at a frequency and amplitude determined by the researcher (Kurata 2003). The structure to be tested (usually a scaled, simplified model of a structure depending on the size of the shake table) is placed on the shake table. The vibration of the table acts as a dynamic (or if a short impulse loading as a static) loading on the structure, which then can be analyzed for deformation, strain, and other factors. For blast loading, the vibration can be designed to simulate a blast on the structure. Basic shake tables move with one-degree-of freedom, however more advanced versions can move in up to six-degrees-of freedom.

6.1.2. Column Loss Experimentation

To measure the impact of a blast on a structure, one can remove/weaken the destroyed/damaged members from a model of the structure, and see the effects on the structural integrity (Johnson 1984). This is the principle behind indirect analysis, and also the column loss experiment. In this type of experiment, the impact of a blast on the structural members would be determined. Then, the members would either be removed, or replaced by weaker members to represent the damage done. Then, the loading on the building would be applied, and the structural integrity determined.

6.1.3. Scaled Blasts on Structures

While it is cheaper, easier, and safer to model a blast loading without a blast, sometimes it is necessary to include the explosion. These experiments generally look into the interaction between the structures and the explosions. For example, in Li (2012), we see an example of a model building with explosives inside of it at varying locations and of varying strengths, which looked into the effect of an enclosed explosion in terms of interior pressure and blast damage. Smith (1992) investigated the pressure of enclosed explosions with complex geometries by creating varying enclosures of different geometries, placing blasts at different locations and measuring the resulting pressure at different locations. In a latter work, Smith (2006) also performed analysis of façade failure's impact on exterior blast pressures by creating closed structures with missing segments to represent façade failure and measuring the resulting exterior pressure. The impact of shielding and channeling by creating different urban environments were provided with model buildings to simulate these effects, and then measured the pressure caused by an explosion at different locations.

6.2. Experimental Data

To successfully validate a modeling technique for use in "real-world" applications, laboratory testing sometimes isn't good enough (uncontrollable variables) or isn't feasible due to expense or logistics. It is also near impossible to perform blast experiments on un-scaled structures in complex urban environments due to cost and safety issues. To validate modeling techniques without these issues, one can model a real terrorist attacks or accidental explosion, and compare them to the results from the event. Such was the technique used by Luccioni (2004). Luccioni validates his model of a blast load's impact on a structure by modeling the AMIA building terrorist attack, and comparing the predicted damage to the actual damage.

This type of analysis can also be performed post-attack/post-accidental explosion to better understand the type of explosion and/or why a structure performed the way it did. Explosion forensics is performed in Pape et al (2010c), when determining the cause of a restaurant explosion and an explosion on a table. By comparing the actual damage caused to damage caused by different types of explosions, the cause of explosion in each incident was determined. In the case of building performance, one can model the blast/damage to a structure, and determine why it performed as it did, and what would have been necessary for the structure to either fail or not fail (depending upon the instance). This is the case in Warn et al in regards to a structural column in 130 Liberty Plaza being struck by a beam from World Trade Center 2 and not collapsing, and in Sozen et al's (1998) report on why the removal by explosion of a structural column in the Murrah building lead to the building collapsing.

7. Protection against Blast Loading

While blast loading on a building can have destructive affects, there are methods which can be undertaken to mitigate the damage done. Some of the available methods are discussed in King et al. Blast retrofits generally attempt to strengthen the structure to resist the blast, shield the structure from the blast, or limit the damage caused by hazardous debris.

For cladding blast protection, an economical approach is to "to allow the plastic deformation of the cladding without failure, and hence increase the energy absorbed by the cladding without failure" (King et al. 2009). For concrete cladding, four retrofits are improving the cladding connections, reducing member spans, bonding reinforcement polymers to the member, and/or increasing the concrete's thickness. For unreinforced masonry cladding, you can increase the strength by reducing the member span and/or increase the wall thickness; you can increase the ductility by adding reinforcing steel and/or adding tension-carrying surface treatments to the member; and to limit debris damage one can install a catch system in case the wall fails. In the case of metal cladding, the strength can be increased by increasing connection capacities to develop tension membranes, reducing panel spans, and/or increasing panel thickness. Shield structures can also be built around the structure for protection purposes.

Another form of failure from a blast involves failure of the frame. It is important that frames respond in a ductile manner to blast loads, which can be done by designing connections to take the ultimate strength of the structure, designing redundant load paths, designing the structural frame capacity to be greater than the cladding and other framing capacities, and by avoiding non-ductile failure modes long unsupported spans, long cantilever beams.

8. Future work

Future work in this field includes developing post-terrorist attack analysis techniques of a structure in near-real time. Some research areas include developing appropriate sensors for the unique challenges created by a terrorist attack with high sampling ratio and amplitude. Computational analysis techniques to date need to be strengthened with extensive experimental data. In addition, decision making procedures considering uncertainties and errors would also be required.

9. Conclusion

The impact from a terrorist attack against a structure can be devastating, causing damage to nearby people, and to the structure itself, up to a progressive collapse. Instances of this include the 9/11/01 attack on the World Trade Center and the bombing of the Murrah Building. One key to better understanding the impact of a terrorist attack on a building is to understand the nature of the attack. To that end, different types of explosions, including physical, chemical, electrical and nuclear were provided in this report. These explosions cause various types of damage, some major ones being overpressure, thermal, and projectile. Numerous methods, both analytical and experimental, provided the opportunity to understand the impacts from an explosion. With this knowledge of an explosion the damage to a structure can be approximately determined, or detailed models could be developed to calculate the damage done.

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