BLAST AND IMPACT EFFECTS ON STRUCTURES

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1. Introduction

Blast effects of an explosion are in the form of a shockwave composed of a high-intensity shock front which expands outward from the surface of the explosive into the surrounding air. As this wave expands in the air, the shock front eventually envelopes an entire structure with shock pressures that are typically higher than those of conventional construction design. Conventional weapons that are detonated within close proximity of a structure can produce air blast loads that have major design implications for protective measures. Impact loads also have a local and global effect on structures. Local breach and penetration may have hazardous consequences if applied to key structural components such as perimeter columns, and may lead to progressive collapse and catastrophic failure. Considerations for blast and impact design revolve around protection of people and assets of significant value (sensitive equipment, storage, etc).

Blast and impact design measures call for considerable and careful design efforts towards strengthening a structure to resist these extreme loading cases. High-rate impulsive loads such as impact and shock cause different material responses than conventional building loads. A steel structure will respond differently from a concrete or masonry structure, and the design engineer needs to have a good background knowledge and understanding of the unique properties of materials that are needed for the design of structural resistance to extreme loads. Dynamic response limits of structural members are compared to set damage criteria that are defined in military and specific agency handbooks. These performance limits are usually set in terms of rotation, ductility and fragmentation for glazing.

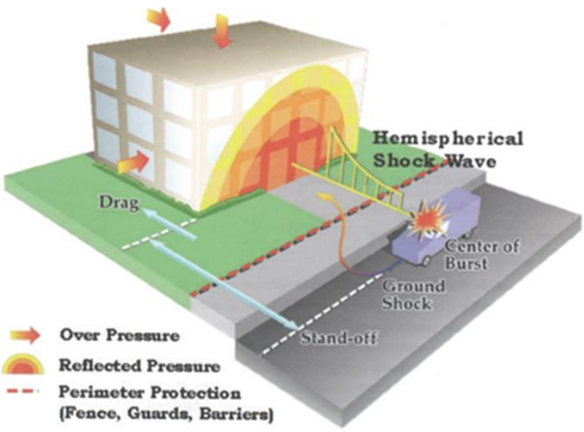
Prudent understanding and application of dynamic analysis techniques is required for obtaining the responses of the structural element in question. Equivalent single-degree of freedom (SDOF) model analysis is the most economical analysis technique and lends itself to be relatively easy to set up for analysis. Another analysis technique includes a multi-degree of freedom (MDOF) nonlinear dynamic methodology, which usually is a three-dimensional finite element modeling approach. Regardless of the sophistication level of the analysis, the designer will need to carefully consider the material behavior of elements and load types the element will encounter. For example, the element in consideration will first need to be sized and checked for conventional static loading before extreme dynamic loads are applied. Differences in load factors such as time duration and impulse shape and load distribution also play an important role in the response of the element. Material behaviors such as energy absorption in the form of strain hardening, material and structural damping, mass, and geometric properties like cross-sectional area and linearity are also important factors that influence dynamic responses.

The purpose of this chapter is to provide the designer with a basic understanding of the characteristics of air-blast and impact loading. Applications specific to various structural elements are explained to give the designer a good understanding of intent for design. This chapter begins by explaining the explosive effects of blast on structures and discusses different methodologies of analysis. Outlined design guidance for structural elements such as reinforced concrete, steel, masonry, and glazing is also considered. The information presented here forth is meant to give the engineer a basic foundation in the techniques and process of blast and impact mitigation on structures for the safety of occupants and valuable assets.

2. Blast

2.1. Explosion Effects

An explosion is an extremely rapid release of energy in the form of light, heat, and sound accompanied by a shock wave. The shock wave consists of highly compressed air traveling radially outward from the source at supersonic velocities (Figure 1). As the shock wave expands, pressures reduce rapidly with distance, and when it meets a surface in line of sight of the explosion, it is reflected and amplified by a factor of up to thirteen.



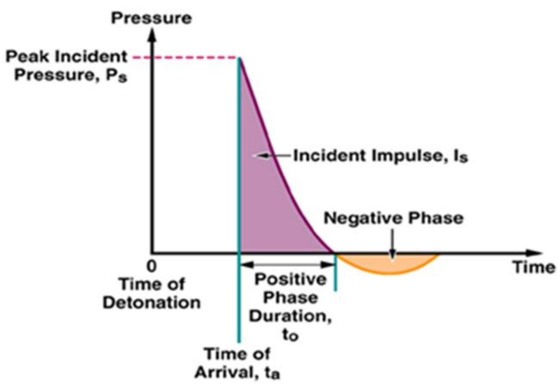


Figure 1. Schematic view of air-blast pressures acting on a building and pressure-time history of loading

The differences in pressure loads can be related to the type of explosion a structure experiences. Explosive charges can be classified into two main categories: unconfined and confined. Unconfined explosions can be described as being air-burst explosions, which are spherical in shape, and surface-burst explosions that are hemispherical. Air-burst explosions have a center of burst located at a distance above the ground that allows the ground reflections of the initial wave to arrive before the blast wave. Surface-burst explosions occur on or near the ground and cause an amplification of the initial shock due to ground reflections. Confined explosions occur adjacent to, or very near a structure such as a barrier, fully confined room, or partially confined room with one or more surfaces open to vent to the atmosphere. Due to the proximity of the explosion, the pressure loads will come from internal shock and gas pressure build-up—which lessens with more ventilation. Structures experiencing unconfined explosions usually just experience reflected pressure loads.

The magnitude of the reflection factor is a function of the proximity of the explosion and the angle of incidence of the shock wave on the surface. Air blast pressures decay rapidly with time, (i.e. exponentially), and their duration is typically measured in the thousandths of a second, or milliseconds. Diffraction effects are caused by corners of the building, which may act to confine the air-blast, prolonging its duration. Late in the explosive event, the shock wave enters a negative phase, creating suction. Behind the shock wave, where a vacuum has been created, air rushes in, creating a high-intensity wind or drag pressure on all surfaces of the building. This wind picks up and carries flying debris in the vicinity of the detonation. In an external explosion, a portion of the energy is also imparted to the ground, creating a crater and generating a ground shock wave analogous to a high-intensity, short-duration earthquake.

For an explosive threat defined by its charge weight in equivalent pounds of TNT, W, and its distance or standoff from the target, R, the peak pressure and impulse of the shock wave are evaluated using charts available in military handbooks. The impulse is defined as the area under the pressure versus time curve (i.e., the integral of pressure with respect to time). The impulse is an indicator of how long the air-blast acts on the target, which is needed for evaluating its response. The duration of the loading, t_d, is defined as the duration of a linearly decaying function having the peak impulse, I, and pressure, P, of the air-blast (i.e., $t_\mathrm{d} = 2I / P$). Because this duration differs somewhat from the actual duration (which is based on an exponentially decaying function), it is referred to as an “equivalent” duration.

Explosive pressures are many times greater than any other loads for which a building is designed, so the goals in blast engineering are modest by necessity. It should be accepted that some building damage may occur and the building may not be useable after an incident. The primary goal for high population buildings is to save lives. In order of priority, this is accomplished by:

- preventing the building from collapsing,
- reducing flying debris ,
- facilitating evacuation and rescue/recovery efforts, and
- preventing the building from collapsing is the most important objective. Historically, the majority of fatalities that occur in terrorist attacks directed against buildings are due to building collapse. This was true in the Oklahoma City Bombing in 1995 when 87% of the building occupants were killed in the collapsed portion of the

Alfred P. Murrah Building. Preventing collapse is important regardless of the attack modality used. For instance, in the September 11, 2001 attacks, nearly 3000 people were killed in the collapse of the World Trade Center twin towers, which was caused by the impact of commercial aircraft and not bombings.

Reducing flying debris generated by failed exterior walls, windows and other components can be highly effective in reducing the severity of injuries and the risk of fatalities. For new buildings, this may be done through choice of materials to encourage a more graceful failure and the balanced design of supporting members to ensure the least amount of failure. For an existing building the solution may be a catch system on the interior face of walls and windows to hold the fragments together and/or increase the strength capacity.

Evacuation, rescue and recovery efforts can be significantly improved through effective placement, structural design, and redundancy of emergency exits and critical mechanical/electrical systems. In addition, reducing the overall damage levels will make it easier it is for people to get out and emergency people to safely enter.

2.2. Building Damage Due to Explosions

The extent and severity of damage in an explosive event cannot be predicted with perfect certainty. Past events show that the level of damage to structures significantly varies based on specifics of the failure sequences. For instance, two adjacent columns of a building may be roughly the same distance from the explosion; but in the explosion, only one fails because a fragment strikes it in a particular way which initiates collapse. By chance, the other is not struck and maintains structural integrity. Similarly, glass failures may occur outside of the predicted area. Also, the details of the physical setting surrounding a particular building occupant may greatly influence the levels of injuries incurred. Moreover, the position of a person, seated or standing, facing towards or away from the event as it happens, can affect the severity of injuries received.

Despite these uncertainties, it is possible to give some general indications of the overall levels of damage and injuries to be expected in an explosive event, based on the size of the explosion, distance from the event, and assumptions of the construction of the building. Additionally, there is strong evidence for a relationship between injury patterns and structural damages.

Damages due to the air-blast shock wave may be divided into direct air-blast effects and progressive collapse. Direct air-blast effects are damages caused by the high-intensity pressures close in to the explosion. These may induce the localized failure of exterior walls, windows, floor systems, columns and girders.

The shock wave is the primary damage mechanism of an explosion (Figure 2). The pressures it exerts on building surfaces may be several orders of magnitude greater than the loads for which the building is designed. The shock wave also acts in directions for which the building may not have been designed, such as upward on the floor system. In terms of sequence of response, the air-blast first impinges on the closest point in the vicinity of the explosion: typically, this is the exterior envelope of the building which is also the weakest and most brittle part of the building. The explosion pushes on the exterior walls and may cause wall failure and window breakage. As the shock wave continues to expand, it enters the structure, pushing both upward and downward on the floors.

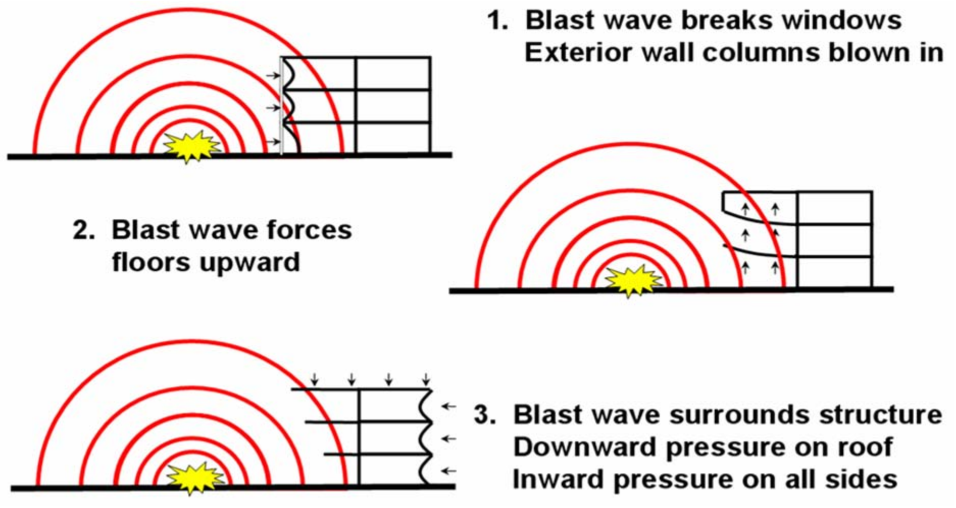


Figure 2. Damage pattern due to explosion

Floor failure is common in close-in vehicle weapon events. This is because floor slabs typically have a large surface area for the pressure to act on and a comparably small thickness. Also, they are not designed for upward loads, which are typical in explosion incidents. In terms of the timing of events, the building is engulfed by the shock wave and direct air-blast damages within tens to hundreds of milliseconds from the time of detonation. If progressive collapse is initiated, it typically occurs within seconds of the explosion.

Distance From Explosion	Most Severe Building Damage Expected	Associated Injuries
Close-In	Building Collapse	Fatality due to falling down floor levels and being crushed by falling structural components
Moderate	Exterior wall failure, exterior bay floor slab damage	Skull fracture, concussion
Far	Window breakage, falling light fixtures, flying debris	Lacerations from flying glass, abrasions from being thrown against objects or objects striking occupants

Table 1. Damages and injuries due to explosion effects

Severity and type of injury patterns incurred in explosive events may be related to the level of structural damage. A general summary of the relationship between the type of damage and the resulting injuries is given in Table 1.

2.3. Component Response Types

Depending on the design of the element and its configurations structural components respond to explosives effects in flexure, shear or breach.

2.3.1. Flexure

Flexure typically occurs in relatively flexible elements and provides a ductile failure mode. This is the preferred failure mechanism and provides most energy dissipation due to flexural yielding. Flexural response can be achieved by properly detailing elements in such a way that precludes shear failure modes.

2.3.2. Shear

Shear failure occurs when structural elements cannot be designed to yield in flexure before their shear capacity is exhausted. Shear failure is categorized as diagonal shear and direct shear.

Diagonal tension shear failure occurs when an element response reaches the diagonal tension resistance limit before the bending capacity is exhausted. Diagonal tension failure exhibits very little ductility capacity and therefore is brittle in nature. Because of this, diagonal tension failure should be avoided in blast-resistant design. One method to avoid diagonal tension failure mode is to decrease the flexural capacity of the element in such a way that element undergoes flexural yielding before shear capacity is exhausted. However, flexural resistance of the element should not be reduced when doing so will compromise desired level of protection. Alternatively, the diagonal tension capacity of concrete wall can be increased by increasing the thickness of the concrete or by placing shear reinforcement.

Direct shear occurs when explosion occurs very close the element. Direct shear capacity depends on friction resistance across the joints and dowel action of the longitudinal reinforcement. Direction shear strength generally exceeds diagonal shear strength. The direct shear failure mode is almost always very brittle and should be avoided. One way to avoid direct shear failure is to increase the standoff between the element and explosion source.

2.3.3. Breach

Breach occurs when the explosive source is located relatively close to the element and, when detonated, will cause shattering of material in the vicinity of the explosion. Usually breaching becomes of concern when explosion occurs closer than a scaled distance of 3.

Breach analysis is often conducted using computational fluid dynamic codes with appropriate equations of state or by experimental studies. Breach effects can be mitigated by material thickness, proper confinement and the application of anti-spall laminates such as FRP.

Spall typically occurs on the back side of the wall when a weapon is placed at the breaching distance but does not cause full breach. Spall occurs due to compression wave travel thru the thickness of the material. When reflected from back surface of wall this causes thru-thicknesses tensile stresses at the back face that can exceed the tensile strength of the material.

Both breach and spall will cause fragmentation on the back side of the wall. Spall can be mitigated by application of shielding (laminates) such as FRP or so called "catchment systems" such as geotextile fabric to stop fragments.

2.4. Structural Analysis Techniques

Structural calculations performed in this study are derived from first principles of structural dynamics using nonlinear generalized stiffness methods to predict response of structural components. Material behavior is modeled using idealized elastic, perfectly plastic stress-deformation functions, based on actual structural support conditions and material properties. The model properties selected provide the same peak displacement and fundamental period as the actual structural system in flexure. Response to shear is evaluated by comparing the demand on the element to its capacity. Maximum deflection is evaluated by solving the governing differential equations for the lumped mass system using numerical methods. Dead loads plus 25% of the live loads are combined with air-blast effects throughout the analyses. Design recommendations are to sustain the load combination.

Parameters considered in calculations include dynamic material properties, structural sections, span lengths, support conditions, existing loading conditions, structural damping, P-delta effects.

Response to large, close-in charges such as those having a scaled distance ($Z = R/W^{1/3}$) less than two, is not well defined throughout the blast industry. In the above expression, Z is the so-called scaled distance, W is the charge mass, and R is the distance from the charge to the target structure. The local breaching mode of failure may be described as shattering, or gouging out of the structural material. If this occurs, it will prevent engagement of the total section to resist the blast. The total column section must be engaged to resist overall blast effects before a local failure renders it incapable. At a scaled distance below two, the possibility of a breach through the concrete encasement and the steel column must be considered before the response of the overall member can be addressed.

2.4.1. Simplified Analysis Techniques

Balanced design is an iterative process that involves analysis of structural elements and determination of hierarchy of failures by comparing performance levels of elements in question and repeating the analysis until desired failure hierarchy is found. This approach is computationally very intensive and therefore selection of analysis procedures is very important to strike balance between accuracy, time and cost.

General methods to design elements for air-blast loads fall into three categories: 1) static, 2) Dynamic Single Degree of Freedom (SDOF), and 3) Dynamic Multi Degree of Freedom (MDOF) methodologies. Each methodology offers advantages and disadvantages in analysis difficulty, time, and accuracy.

2.4.2. Equivalent Static Analysis

A structural element subjected to dynamic loading exhibits higher strength than if subjected to a static load. While static analysis methodologies offer quick and simple solutions to air-blast loadings, the accuracy is dependent on the assumed structural properties and configurations such as stiffness and mass distributions, which may not be representative of the structural element undergoing analysis. In other words, static loads capture neither stiffness related nor inelastic behavior seen in air-blast events and as such their use may result in unpredictable performance. Since performance in static analysis methodologies cannot be easily predicted, balanced design that employs static methodologies usually result in grossly over-designed systems that may be neither economical nor constructible.

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Biographical Sketches

Shalva Marjanishvili, Ph.D., P.E., S.E., is a Technical Director at Hinman Consulting Engineers with two offices in San Francisco, CA and Alexandria, VA. He earned his BS and PhD in Structural Engineering from the Georgian Technical University, and an MS in Structural Engineering from Stanford University and has more than 20 years of experience in structural engineering. Dr. Marjanishvili is responsible for Hinman Consulting Engineer’s analytical capabilities including progressive collapse analysis of new and existing buildings, anti-terrorist design and analysis of air-blast response of existing and new structures He is a principal author of Hinman analysis software for evaluating structural response to explosive terrorist threats using new and innovative analysis techniques and cost effective design solutions to provide and improve reliability and robustness of structural systems against various threats and hazards, natural or man-made. His experience includes protective anti-terrorism design, progressive collapse mitigation, vulnerability and risk assessments of numerous federal office buildings including federal and state courthouses, embassy structures, airline terminals including airline control towers, military installations including command and control centers, commercial building including banks, pharmaceutical and petrochemical facilities. He served as Chair of ASCE/SEI Blast, Shock and Impact Committee, and is a registered civil and structural engineer in California.

Iman Alsharkawi is a Lead Technical Engineer at Hinman Consulting Engineers, working in the Alexandria, VA office. There, she participates in the design, analysis and evaluation of building structures to resist the effects of blast. She has been involved with projects from all across the country and world including embassies, child care development centers, federal buildings, VA hospitals and military complexes. Iman also aids in the development and documentation of analysis software that is used to enhance the design of structures to withstand blast. Iman has earned her BS in Mechanical Engineering and MS in Aerospace Engineering with a concentration on aircraft structures and computational fluid dynamics from The George Washington University in Washington, DC. She has three years of experience working in the aerospace industry and two years of experience in structural engineering and is a member of the Society of American Military Engineers (SAME), American Society of Mechanical Engineers (ASME), and American Institute of Aeronautics and Astronautics (AIAA). During times that she is not engaging in professional pursuits, Iman enjoys flying radio-controlled airplanes and ultralights and skydiving. She is an active member of the United States Ultralight Association (USUA) flying club of Virginia and United States Parachute Association (USPA) and currently holds a USPA A-License.