

ACI 370R-14

Report for the Design of Concrete Structures for Blast Effects

Reported by ACI Committee 370



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Report for the Design of Concrete Structures for Blast Effects

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Report for the Design of Concrete Structures for Blast Effects

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This report addresses the design of structures to resist blast effects due to explosions. It describes the state of the practice for the guidance of structural engineers charged with the design of civil facilities that may be subjected to blast loads. This report addresses the steps commonly followed in this practice, including determination of the threat, calculation of structural loads, behavior of structural systems, design of structural elements, design of security windows, design of security doors, and design of utility openings. These steps can applied to the design of new structures or to the retrofitting of existing structures.

Keywords: blast; blast analysis; blast-resistant buildings; blast-resistant design; ductility; dynamics; explosions; retrofit for blast; shock; overpressure.

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CHAPTER 1—INTRODUCTION

The design of concrete structures for blast resistance has been of great interest to the military and other federal agencies for several decades. In addition, certain specialized segments within the engineering community have also had to consider blast loads on structures as a result of potential accidents. For example, the petrochemical industry has designed for blast resistance in their facilities for many years. Even though there is considerable history in the design of structures to resist blast effects resulting from accidents or intentional acts, it is only recently that the general structural engineering community has shown a strong interest in the response of structures subjected to explosions and other high-rate loading phenomena, such as impact.

Following the attacks on the World Trade Center in New York and the Pentagon in Washington, DC, on September 11, 2001, the vulnerability of the nation's infrastructure to terrorism became a top priority for many state and federal government agencies as well as private consulting engineers. Though the significance of these attacks greatly increased engineering interest in the design of structures to resist extreme loads, statistics show that US interests have been targeted by terrorists with increasing frequency during the last several decades (U.S. Department of State, 2003), leading to significant financial and personal losses. As a result, the engineering community has learned important lessons that have allowed for improved methods of analysis and design to be developed. For example, lessons learned from the Oklahoma City bombing in 1995 and the U.S. embassy attacks in Tanzania and Nairobi in 1998 shaped present design guidelines for prevention of progressive collapse.

While the field of blast- and impact-resistant design is not as mature as other fields, such as seismic-resistant design, historical events such as those described are important to note because they help shape current practice and research interests. Just as the field of seismic-resistant design has advanced by learning lessons from past incidents, engineers working in protective design can similarly benefit from being aware of historical events and corresponding data. Although such information is typically outside the scope of work routinely undertaken by design engineers, awareness of these issues is important for understanding potential threats and associated loads that may result. While historical data can be used with reasonable confidence for predicting natural loads such as earthquakes and floods, the same claim cannot be made for man-made loads associated with potential terrorist threats. Thus, the intent of the discussion herein is to bring awareness to engineers and designers that many factors can influence the loads to which a structure may potentially be subjected, and it is only through awareness and consideration of the factors that affect the threat environment that engineers can estimate design loads.

1.1—Overview of report

Given the trends in terrorism and the required protection of building occupants at petrochemical facilities, it is clear that structural engineers must be able to design structures

to resist the blast effects due to explosions. Drawing on research and engineering practice, the goal of this document is to compile essential information on the design of concrete structures to resist blast effects. Information is gathered from research reports, military design guidelines (when publicly available), and expertise from the petrochemical industry to provide a thorough introduction to the design of concrete structures to resist blast effects.

Several of the chapters in this report address topics that are nonstructural. When designing for blast effects, engineers must take into consideration that the loads that act on structures are strongly dependent on the distance between the structures and potential blast locations. In addition, there is a chapter on windows and openings because glass fragments from a blast typically contribute to injuries and fatalities. Thus, in designing structures to provide a safe environment for the inhabitants, structural engineers must consider other design issues that fall outside of their usual responsibilities when designing structures for more typical loads. Accordingly, it is important that engineers become familiar with these topics and play an active role in the decision-making process used to site buildings and select a façade system, doors, and windows.

Providing standoff is often the most cost-effective solution for mitigating the hazards associated with a blast load. In many cases, however, it may not be possible to provide sufficient standoff distance for a structure to eliminate the need for considering structural response to blast effects. Under these conditions, structural hardening is likely required. If consideration is given to structural modifications during the design stage, the costs of hardening can be minimized, and the aesthetic impact on the structure under consideration can, in many cases, be completely eliminated. As a retrofit, structural hardening can be expensive, although necessary for the safety of a building and its occupants. To address these design challenges, significant guidance is provided in this document on the selection of structural systems for blast resistance, methods of analysis, and design considerations. In addition, an entire chapter is dedicated to describing methods of retrofitting structures to achieve adequate blast resistance.

Although this report provides great breadth in the topics it addresses, it is not intended to be a stand-alone volume for practicing engineers. The purpose of this report is to provide a well-organized introduction that will serve as a starting point for identifying key issues associated with the design of concrete structures to resist blast effects. For engineers looking to familiarize themselves with this topic, it will serve as a concise guide. If more detailed information is needed, an extensive list of references has been provided.

1.2—Background and history

To develop an appreciation of the extent to which terrorists have targeted U.S. assets, it is helpful to review several previous events. The events described in the following are not intended to be an exhaustive list of attacks against U.S. interests. Rather, the intent of the discussion is to allow engineers unfamiliar with these incidents to gain an

appreciation of the threat environment that they may have to design against, which will dictate the loads that they must consider. Reasonable estimates of design-basis loads can only be developed once the potential threats and sources of loading are understood. Further discussion on threat environment is provided in [Chapter 3](#), whereas [Chapter 4](#) includes a discussion on hazard assessment and risk analysis. In Chapter 5, readers can find a description regarding how to predict blast loads for a given threat.

On February 26, 1993, an explosive device was detonated in the parking garage of one of the World Trade Center towers in New York City. As a result of this attack, six people were killed, and 1042 were injured. Damage was observed over seven floors, and property damage was over 500 million dollars. According to the FEMA/ASCE accident investigation ([McAllister 2003](#)), the compartmentalized layout of the building structure was credited with minimizing the propagation of damage and preventing progressive collapse.

Two years after the bombing of the World Trade Center, the Alfred P. Murrah building in Oklahoma City was attacked on April 19, 1995. As a result of a large truck bomb, 169 people were killed, over 500 were injured, and damages exceeded \$100 million. From an engineering perspective, there was great concern over the structural configuration of the Murrah building. This nine-story structure incorporated a transfer girder at the third floor that allowed the column spacing from the floors above to be doubled from 20 to 40 ft (6.1 to 12.2 m) for the bottom three stories. Because the bomb blast likely caused the failure of three of the columns that supported the transfer girder, the high loads from the floors above could not be redistributed to the remaining columns. As a result, the Murrah building failed due to progressive collapse. Because of this event, research into progressive collapse has become a great concern to the structural engineering community, and engineering guidelines to resist progressive collapse have been developed by the Department of Defense ([UFC 4-023-03](#)) and the General Services Administration ([PBS-P100](#)).

These events that took place on U.S. soil are quite familiar to much of the population, yet several other events in recent years have shown that U.S. assets all over the world are susceptible to terrorist attacks. Though it is not necessary to describe all of these events in great detail, it is helpful to discuss the incidents that have implications related to structural engineering. One such event includes the bombing of the Khobar Towers in Saudi Arabia on June 25, 1996. This facility was used to house U.S. and allied forces. There were 19 fatalities and approximately 500 U.S. personnel wounded in the attack. Other events that raised awareness of the need to protect against terrorist activities took place on August 7, 1998. On this date, two U.S. embassy buildings were bombed in Africa. As a result of these attacks, 11 Americans were killed, and over 30 were injured. The response of the two embassy buildings differed greatly. The embassy building in Tanzania fared quite well, and damage was limited. The Nairobi embassy building, however, suffered severe damage and underwent a partial collapse in a progressive fashion as the Murrah building.

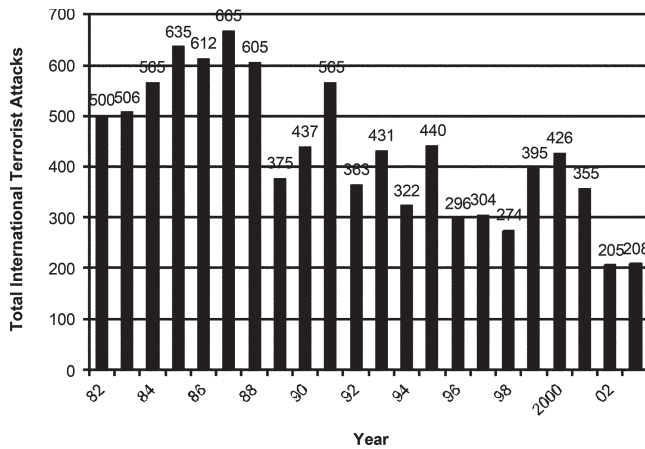


Fig. 1.2a—Total international terrorist attacks, 1982-2003 (U.S. Department of State 2003).

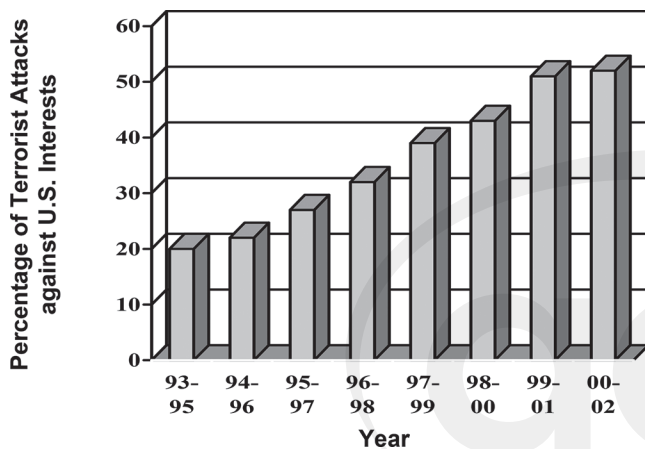


Fig. 1.2b—Terrorist attacks against U.S. interests as percent of total world attacks (Knight and Murphy 2004).

Unlike natural disasters such as earthquakes or hurricanes, terrorism is the result of a man-made act, and past events do not necessarily indicate the probability of risk that engineers must contend with in the future. Nonetheless, a review of trends in terrorist activities helps put in perspective the importance that must be assigned to the design of structures to resist blast. Based on an analysis of terrorist events between 1982 and 2003 (U.S. Department of State 2003), the number of attacks that took place worldwide does not show a clear trend (Fig. 1.2a).

The total attacks against the U.S. interests as a percent of total world attacks in a year, however, has increased steadily over the last decade (Fig. 1.2b). Statistics show that the vast majority of terrorist attacks against U.S. assets are against businesses and not aimed at the government or military, which might be more expected (Fig. 1.2c). For these terrorist events, the preferred method of attack is through the use of explosives. More than 65 percent of the attacks that take place involve the use of bombs and other explosive devices (U.S. Department of State 2003).

Vapor cloud explosions (VCEs) resulting from accidental release of flammable products within industrial facilities also continue to be a significant threat to building occupants due

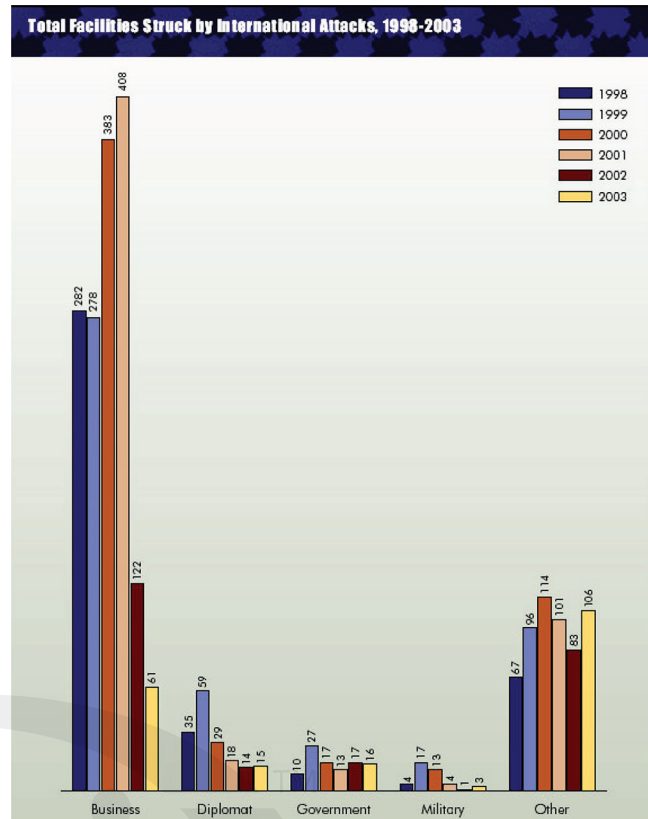


Fig. 1.2c—Total facilities struck by international attacks (U.S. Department of State 2003).

to the significant blast loads they produce (for example, Mina Ahmadi, Kuwait, in 2000; Toulouse, France, in 2001; Texas City, TX, in 2005; Big Spring, TX, in 2008; and Salt Lake City, UT, in 2009). VCE events have consistently resulted in fatalities throughout the world where hydrocarbons are processed. Industry standards require that building occupants be protected from postulated VCE events using a reasonable consequence basis or from an acceptable risk vulnerability basis (API RP752).

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A	=	cross-sectional area
ao	=	speed of sound in undisturbed air, in./s (mm/s)
C	=	damping coefficient
C_d	=	drag coefficient
C_e	=	load reduction factors
Co	=	speed of sound in air, in./s (mm/s)
C_{ra}	=	ratio of reflected pressure to free-field pressure
c	=	material's cohesion
d	=	distance from the extreme compression fiber to the centroid of the longitudinal tension reinforcement
d_c	=	distance between the centroids of the longitudinal compression and tension reinforcement
E	=	combustion energy, in.-lb
E	=	initial tangent modulus of elasticity of the undamaged material

E_o	=	uniaxial initial tangent modulus
E_s	=	uniaxial secant modulus
$F(t)$	=	applied dynamic load
$F'(t)$	=	equivalent time dependent loading function
f_d	=	dynamic stresses
f_s	=	static stresses
I	=	moment of inertia
I	=	impulse
i_+	=	positive phase impulse, psi-s (MPa-s)
K	=	structural stiffness
L	=	span in the direction of the blast wave travel
L_w	=	blast wave length
M	=	bending moment
M	=	mass
M_f	=	mach number representing speed of wave front
P	=	axial force on the member acting at the plastic centroid of the cross section
P	=	pressure
P_o	=	atmospheric pressure
P_{so}	=	peak positive side-on overpressure
P_r	=	peak reflected overpressure
Q	=	shear force
q	=	distributed dynamic load transverse to beam length
q_o	=	dynamic pressure
R	=	radial distance from center of explosion, in.-lb
T	=	positive phase duration
t	=	time
t	=	glazing thickness
t_a	=	time of arrival
t_c	=	time to clear the surface
t_d	=	positive phase duration
t_d	=	negative phase duration
t_e	=	idealized duration
U	=	shock front velocity
V_f	=	volume, ft ³ (m ³)
W	=	TNT charge weight, lb (kg)
w	=	transverse displacement of the midplane of the beam
X_m	=	maximum door displacement
X_y	=	yield displacement for an equivalent elasto-plastic single degree of freedom model of the door
x	=	distance along the beam
x	=	displacement of the structure at time t
$\dot{x}$	=	velocity of the structure at time t
$\ddot{x}$	=	acceleration of the structure at time t
β	=	rotation of the cross section due to bending
ϵ	=	strain
$\dot{\epsilon}$	=	strain rate
ϵ	=	uniaxial strain
ϵ_c	=	uniaxial strain corresponding to σ_c
ϵ_u	=	ultimate uniaxial compressive strain
ϕ	=	angle of internal friction
γ_{xz}	=	shear strain
ϕ	=	curvature of the cross section
ρ	=	material mass density
σ	=	normal effective stress on the failure surface
σ	=	uniaxial stress
σ_c	=	maximum uniaxial compressive stress

σ_{max}	=	maximum allowable stress
σ_t	=	uniaxial tension cutoff stress
σ_u	=	ultimate uniaxial compressive stress
τ	=	shear stress on the failure plane
ω	=	accumulated internal damage

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <http://www.concrete.org/Tools/ConcreteTerminology.aspx>. Definitions provided here complement that resource.

access control—any combination of barriers, gates, electronic security equipment, or guards that can deny entry to unauthorized personnel or vehicles.

ammonium nitrate fuel oil—industrial explosive made by mixing ammonium nitrate with approximately 6 percent fuel oil.

computational fluid dynamics—numerical algorithms that enable calculation of fluid flow and shock wave propagation in fluids.

curtain walls—thin, protective, exterior, non-load-bearing building wall supported by the structural elements of a building and usually made of glass and light metals.

electronic security—security measures involving the use of interior and exterior sensors, closed circuit television systems, electronic entry control systems, data transmission media, and alarm reporting systems for the purpose of surveillance, intrusion detection, and screening.

fenestration—architectural term referring to any opening or arrangements of openings (normally filled with glazing media) for admission of daylight within a building’s exterior façade (for example, windows or doors).

level of protection—degree to which an asset is protected against injury or damage from an attack.

overpressure—pressure caused by an explosion over and above normal atmospheric pressure.

physical security—area of security concerned with measures and concepts designed to safeguard personnel; eliminate espionage, sabotage, damage, and theft; and prevent unauthorized access to equipment, installations, material, and documents.

polymer-bonded explosive—explosive material in which the explosive powder is bound together in a matrix using small quantities of a synthetic plastic.

progressive collapse—chain reaction failure of building members triggered by local failure of a primary structural component leading to the collapse of adjoining members, which in turn leads to the collapse of all or a large part of a structure.

scaled range—means of scaling blast energy that allows prediction of blast parameters using blast curves created with normalized test data. Normally denoted by Z , scaled range is computed as $R/W^{1/3}$, where R is the distance (ft) from the charge to the point of interest and W is the charge weight (lb) ($1 \text{ ft/lb}^{1/3} = 0.185 \text{ m/N}^{1/3}$).

shock front velocity—speed at which a shock front travels in the medium in which it propagates. The shock velocity decreases with distance from the explosion source.

single degree of freedom—mathematical model used to compute the dynamic response of a structural component in which the motion can be completely characterized by a single deformed shape.

standoff distance—distance maintained between a building or portion thereof and the potential location of an explosive detonation or other threat.

vulnerability—any weaknesses that can be exploited by an aggressor or, in a nonterrorist threat environment, make an asset susceptible to hazard damage.

CHAPTER 3—DESIGN PHILOSOPHY

This chapter introduces a number of basic topics and terms integral to blast-resistant design and discusses how these topics are treated. Detailed information is provided in subsequent chapters.

3.1—Explosions and fragments

The common denominator to all nonnuclear threats is an explosive material that generates overpressure upon detonation and may produce fragments as well. Some basic descriptions are given in the following of the major phenomena involved.

3.1.1 Explosions—An explosion may be defined as the fast transition of a material from its original solid or liquid state to a gaseous state, within a very short duration, while producing a steep overpressure front that propagates radially as a shock wave releasing a vast amount of energy. This fast transition is also known as a detonation. Some explosive materials are sensitive to low energy external effects that can initiate an explosive detonation. Other materials are insensitive to external effects and initiation requires special devices. Therefore, an explosion may be controlled and initiated at the required time and location, or may be accidental and uncontrolled.

In populated locations, both explosion scenarios are harmful, and precautions should be taken to minimize the chances of occurrence, control explosive characteristics, and protect the surrounding environment from any resulting damage.

3.1.2 Primary fragments—An explosive material is generally contained in a casing. Upon detonation, a shock wave is formed and gas is produced. The casing is dynamically sheared into many fragments. There can be thousands of fragments sheared off from a single explosive casing. In some cases, such as hand-grenades, fragment shapes and sizes are predefined, but in most cases, fragment shape and size is unknown. Commonly, there are a few large fragments and many small fragments and the size distribution may be determined in special experiments and formulated in appropriate distribution functions. Each fragment gains kinetic energy due to entrapped momentum, and fragment initial velocities may be greater than 1 mile/second (1.6 km/second).

3.1.3 Secondary fragments—Loose or unsecured objects in the path of an external blast wave can be swept up due to the interaction with the blast pressure and accelerated to velocities high enough to cause impact damage to the

surroundings. Secondary fragments could also result from structural elements not specifically designed for blast. An analysis of secondary fragments (**DDESB TP-13**) will require an estimate of fragment size, distance from the blast source, and characteristics of the explosion.

3.1.4 Explosion propagation—Energy produced from an explosion creates a pressure wave that propagates away from the source at a high velocity, the magnitude of which is dependent on the level of the overpressure. Most explosive materials will produce a pressure wave velocity that exceeds the speed of sound, thus creating a shock front. The shock front speed is pressure dependent, the higher the pressure, the higher the shock speed. The shock front pressure decays with distance. Because the shock front expands in three dimensions, the peak pressure decay is proportional to the cube of the distance from the explosion source.

An explosive detonated well above the ground or other reflecting surface is referred to as an air blast. The pressure-time history is characterized by a sharp rise in pressure from ambient, positive phase duration, and a negative pressure-time history (**5.1**).

The sharp rise in pressure is termed the peak, or side-on, overpressure. The positive phase is characterized by peak overpressure and duration. The area under the pressure-time curve is a measure of the total force exerted by the blast and is termed impulse. The negative pressure-time history, overexpansion at the center of the explosion, follows the positive phase.

Obstacles in the path of a shock front form a disturbance to free blast wave propagation. The result is a pressure increase acting on obstacle surfaces facing the shock front. This pressure increase is known as reflected overpressure and is illustrated in **Fig. 3.1.4**. The reflected pressure is largest when the obstacle surface is perpendicular to the propagation direction and is at the magnitude of the side-on pressure when the surface is parallel to the propagation direction. The pressure acting on inclined surfaces is larger than the side-on overpressure at angles larger than approximately 45 degrees, and approaches the reflected overpressure at 90 degrees. The angle is defined as the difference between the direction of propagation and the inclined surface (**5.7.2**). These pressure characteristics are more severe when acting on large surfaces than on limited surfaces.

An internal explosion results when an explosion occurs within a space surrounded by confining walls, floor, and ceiling. In this case, reflections from the surrounding surfaces occur, and the resulting shape of the pressure-time history is more complicated. Where openings are very limited in the confining surfaces, the blast overpressure may not decay to ambient quickly because the explosion gas products fail to vent. The resulting gas overpressure decays to ambient slowly enough to be considered a static pressure.

3.1.5 Fragment distance—A fragment's high initial velocity and irregular shape are the major parameters that dictate its travel distance. The irregular fragment's shape produces relatively high drag forces that cause a rather high deceleration and rapid velocity drop. The travel distance

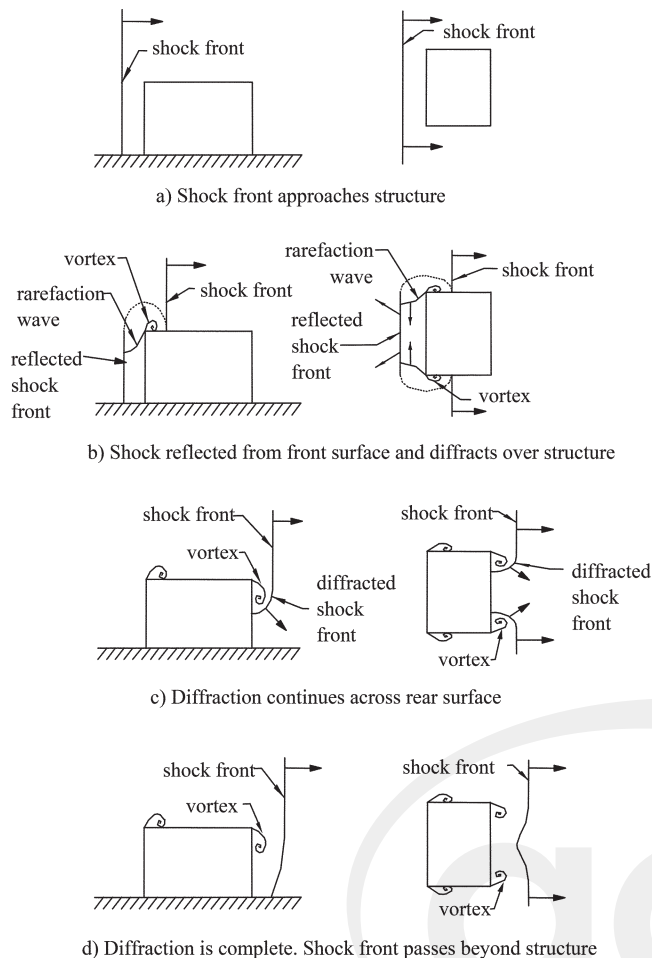


Fig. 3.1.4—Reflected overpressure (Krauthammer et al. 1999).

fragments is relatively limited as a result, commonly within several hundred feet (note: 100 ft = 30.5 m).

3.1.6 Blast wave effects—When a blast wave impacts a structural element or a structural system, the blast wave imparts momentum to the structural system, and a dynamic response of the latter then starts. The blast wave's peak overpressure and positive phase duration, and the structural element's resistance and natural period are used to assess the dynamic response. The same blast will cause an entirely different response and damage to different structural systems.

3.1.7 Fragment effects—When a fragment hits a structural element, it may penetrate into the element. This is the case when the fragment's velocity vector is nearly normal to the surface of the structural element. If the structural element is relatively thick, the fragment decelerates and is stopped. Only impact surface damage signs are observed on the structural element—spalling, scabbing, and cracking in brittle materials. If the structural element is relatively thin, the fragment may pass through the element (perforation) and retain a residual velocity. In addition to the impact surface damage described for thick elements and a penetration hole, exit surface damage includes cratering, a shear plug, and scabbing (in brittle materials).

3.2—Threat scenario

A threat scenario, considering all specific explosives and conditions for which the structure is being designed to resist, must be determined.

3.2.1 Threat scenario description—A threat scenario should be fully described. It is important to state the explosive type, quantity, shape, and casing characteristics, controlled/uncontrolled initiation conditions, storage conditions, and details. Casing characteristics include geometry, thickness, material properties, location, and orientation with regard to any obstacles, and relative position with regard to targets of concern. Vapor cloud threats will be based on postulated release scenarios, locations, and levels of confinement and congestion. With the complete threat data, the explosion event can be analyzed and the pressure-time history at any location on structural elements can be evaluated. Also, the fragment distribution may be calculated and an interaction analysis with the target may be performed.

3.2.2 Threat probability—A threat can be fully defined sometimes, such as the explosive type, quantity, and distance from an obstacle or, in other cases, threats may be partially defined and some parameters are probabilistic. A warhead may include different amounts of explosives and may be detonated at different distances from a building. In such cases, the threat should be characterized in probabilistic rather than deterministic terms.

3.2.3 Threat envelope—To assess the overall effects on a structure, an envelope of all relevant threat scenarios should be prepared and the structure's response to each threat scenario, as well as to threats acting simultaneously, should be evaluated. All threat scenario results are then compared and extreme or worse cases are identified. The complete definition of threat and protection criteria will provide the basic information for design.

3.3—Protection criteria

Protection criteria determine the blast resistance required for a particular structure and depend on the allowable damage level, regulatory requirements, functional and safety requirements, cost aspects (costs of alternatives and cost versus benefits), client preferences, and acceptance standards. Minimization of injuries, loss of life, and property damage is the primary goal and is expressed through the allowable damage level. Consideration of each of these factors, combined with the complete definition of threat, will lead to the determination of appropriate blast resistance for a particular facility or structure. Major parameters such as the threat, damage level, and cost aspects are discussed in other sections of this chapter. The other parameters are explained in some detail in the following.

3.3.1 Regulatory requirements—Present national or local requirements may not state specific blast resistance requirements for civilian facilities, although insurance agencies do specify requirements for certain industrial facilities. U.S. government agencies have clearly defined guidelines for office buildings, military facilities, and embassies under their respective jurisdiction. The U.S. Occupational Safety and Health Administration (OSHA) regulations

do not specify blast-resistant requirements, though the regulations do indicate that measures shall be taken to provide a safe workplace. Experience from post-explosion OSHA investigations usually indicates that blast protection should have been considered. With these experiences, OSHA has introduced regulations in [29 CFR 1910.119](#).

3.3.2 Functional requirements—The function of a building or structure may determine the required level of blast resistance. Government facilities, public buildings, defense facilities, and industrial facilities each have specific considerations. For example, industrial facilities may require a blast-resistant control room to provide protection of control equipment and thus provide for a safe shutdown of essential plant equipment, as well as to provide for the safety of operational personnel.

3.3.3 Owner preferences and acceptance standards—Government organizations and other owners have determined their preferences and standards of acceptance. From the results of an informal industry survey, it is apparent that there is no uniform standard for acceptance among different industrial clients.

3.4—Balanced design

A balanced design implies a consistent level of protection throughout the structure and that a failure of the weakest element causes the least damage. This approach is recommended when considering the response criteria, or allowable damage, used to design the structural components that make up the building. The exposed building components should be designed to incur the same level of damage ([Dusenberry 2010](#)) throughout the building's load path. Some deviation from this balanced design approach is to allow a higher level of damage for the components that face the potential explosion source, or serve as the reflected surface where the blast load is amplified, as long as the components do not fail and create hazardous debris or allow leakage blast loads to pass through.

Another form of a balanced design approach deals with the design of the individual structural components themselves. It is important that the level of flexural capacity be limited so that the component's shear capacity is not exceeded. This is also true with component connection designs, where the connection capacities should comfortably exceed the inbound (in the direction of the blast load) and rebound (opposite the blast load direction) flexural capacity of the component. These component and connection balanced design recommendations should be applied even when the maximum estimated flexural response does not reach yield.

3.5—Global design

Blast-resistant design should aim to withstand the anticipated threats, minimize damage, and protect people. It is not just a structural engineering problem to withstand blast loads, nor is it a materials problem of providing better performance, but it is a continuous view of the whole structural system and the activation by all means to achieve the goal. It is a problem of global design, where the location of the structure is important, as well as its orientation, shape,

openings, architectural details, and structural details. Gates, walkways, obstacles, and fences surrounding the structure are also important design elements that can provide a greater standoff distance.

3.6—General principles of structural design

A structural system that is activated by a given threat responds both locally and globally. The local response may be due to the direct hit of a fragment, and is characterized by penetration and local damage, as previously described. The global response is the dynamic behavior of the structural elements and the overall structure due mainly to blast overpressures. In this section, the global response is considered.

3.6.1 Vibratory nature of response—A structural element subjected to a blast load responds dynamically in a vibratory type of motion. As a result, deflections, velocities, accelerations, and internal forces vary from positive to negative. Reinforcement is required on both sides of a concrete element that responds in bending. Velocities away from the acting load precede velocities in the opposite direction. The reversed velocity toward the acting load is termed rebound. During this phase, amplitudes decrease and required reinforcing to ensure bending resistance is commonly somewhat smaller than the amount required for the positive phase.

3.6.2 Natural periods of vibration—Structural elements that are characterized by a larger mass and smaller stiffness have longer natural periods than elements with smaller masses and higher stiffness. The dynamic response of a structural element to a given blast loading depends on its natural period. Larger inelastic deformations are expected in elements with similar resistance but with a relatively shorter natural period.

3.6.3 Dynamic reactions—The blast action on a structural element develops considerable dynamic reactions. Dynamic reactions that exceed the static shear reactions for a reinforced concrete slab can result in shear failure. Attention to dynamic reactions is required to prevent brittle shear failures.

Dynamic reactions develop in both directions because of the vibratory response. Consideration should be given to ensure a structural element's shear capacity in both directions as well as the supporting member's capacity (shear and flexural) in both directions.

3.6.4 Indeterminacy—Indeterminacy requires the development of more than one plastic hinge to achieve the bending capacity. Indeterminacy is a favorable characteristic of a structure that is intended to withstand blast forces. Indeterminacy provides higher overall resistance and stiffness due to flexure, more sections undergoing inelastic deformation, and energy dissipation.

3.6.5 Confinement—Reinforcement provided to enhance bending resistance is not sufficient to prevent brittle failure of concrete in compression, unless it is confined by closely spaced closed stirrups that enhance compression resistance, ductility, and delay brittle failure.

3.6.6 Strain rate effect—In many materials, very rapid rates of loading that occur under blast loading lead to higher values of tension and compression strength. Such materials are known as rate-sensitive materials. Reinforcing steel and concrete are rate-sensitive materials. The increase in strength depends on the rate of loading, the type of loading (compression, tension, or shear), and characteristics of the material. In general, an element made of rate-sensitive materials exhibits higher dynamic resistance than static resistance.

3.6.7 Blast resistance and earthquake resistance—Earthquake action on a building starts with motion of the underlying geotechnical material, where the building is called to follow the ground's motion. The building then vibrates accordingly. Earthquake vibrations last for approximately 1 minute or less. The whole building vibrates and induces inertia forces that are larger at higher stories. Blast action on a building starts with blast pressures acting on the building façades, commonly lasting only for a period of several hundredths of a second. Pressure distribution varies with distance from the source and decreases rapidly with time. Thus, an explosive that is placed on the ground will produce significant blast pressures to a certain height of the building. Higher stories will sense significantly smaller blast pressures.

In a blast response, many structural elements respond to both the direct action of blast overpressures and to the overall structural response. In earthquake loading, only the overall structural response is applicable.

Though a building's response to earthquake and blast loads is entirely different, they have in common the overall lateral dynamic vibration of the building. In both cases, buildings require a structural system to resist lateral loading. If a building is designed to withstand earthquake loads, it may already incorporate several essential components for its global blast resistance. Quantitatively, earthquake resistance may not be sufficient, and blast resistance should be checked, as well as all structural elements that respond locally.

3.7—Analysis and design

Analysis and design procedures for blast-resistant design are the central consideration, though not the only consideration, for the structural engineer. A discussion on several important topics is presented.

3.7.1 Conceptual design—The conceptual design is a major contributor to the success or failure of a blast-resistant structure. In the early stage of design, where architectural schemes and structural engineering concepts are blended, there is much importance to the deep understanding of blast-resistant design concepts and their proper implementation by the architect, the structural engineer, and by all other professionals involved in the project.

Proper conceptual design will consider the shape of the structure, its location and orientation, and its relationship with all surrounding structures. In the following stage of design, the conceptual design will be carried out jointly by the architect and the engineer to yield a solid structure that

can withstand the different actions and maintain the required performance.

3.7.2 Analysis—A structure that is subjected to blast-resistant loads responds dynamically and its behavior is more complicated. Hence, a detailed analysis is needed to follow dynamic behavior and identify locations where extreme load concentrations develop. The concept of damage-based design makes an analysis essential, as the analysis should be able to determine the deterioration of cross sections, structural elements, and of the whole structure.

3.7.3 Complexity and accuracy of calculations—A blast analysis may be performed at different levels of precision and complexity. Often, simple single-degree-of-freedom (SDOF) models are sufficient to estimate values of plastic deformation and evaluate ductility demand. Other times, more advanced computational tools are required to follow the response of different components, to identify damage growth, to evaluate the effect on overall behavior, and to follow dynamic characteristics at different locations.

There is no direct correlation between the complexity of computational tools and accuracy. The accuracy of calculations depends very much on the proper understanding and modeling of the structure. The calculation should cover the structural scheme, the assumptions, and the material models. Simple models that are based on understanding of the problem can yield better results than complex tools that are used without a clear understanding of their use.

3.7.4 Detailing—Detailing follows the structural design and analysis, and is often an important link that may determine the structure's resistance and damage. Careful detailing will ensure that the anticipated dynamic response will materialize. Detailing should pay attention to constructability and solve potential conflicts between construction requirements and structural integrity. Careful detailing of weak points, such as joints and at construction discontinuity points where damage and failure develop first, is imperative.

3.8—Energy absorption

Excluding inertia resistance, the amount of energy imparted by an explosion to a structure is usually very large. Although it is possible to design structural elements and the structural system to respond elastically, the resulting design will yield a heavy and expensive structure. The limitations of such a structure both from a performance and economical point of view require an examination of a controlled damage-based design philosophy.

For most cases, where low-probability high-intensity explosions are considered, a damage-based design philosophy should be adopted. It is then accepted that a structure would undergo inelastic deformations due to blast loads. Resulting dimensions of the structural elements are modest compared to those limited to elastic behavior. Inelastic deformations are accompanied with energy absorption as a response to the energy imparted to the structure.

It is not always possible to allow an inelastic response. There may be cases where a structure may be damaged or experience blast loading repeatedly, and a damage-based

design would result in accumulated damage, structural deterioration, and increasing levels of damage. In such cases, structures should be designed elastically.

3.9—Ductility

Ductility is the capability to maintain structural resistance while sustaining energy-absorbing inelastic deformations. Ductility is a natural property of certain materials such as metals, and should be considered for use in structural elements such as blast-resistant doors. Ductility is absent in brittle materials such as unreinforced masonry and unreinforced concrete, and should not be used unless special measures are taken to enhance ductility. Reinforcement is not an automatic remedy to produce ductility and care should be given to the location, quantity, shape, and details of the reinforcement.

3.10—Damage control

Damage may occur due to local actions such as fragment impact. Typical damage due to fragment impact has been described in 3.1.6. For global blast overpressure action, the entire structure responds as well as individual components. Damage may occur in certain elements and even at certain locations of these elements. Thus, local damage may be a result of a local or a global action.

Damage may occur in elements of the primary structural resisting scheme or in secondary elements. Damage to secondary elements may have a relatively minor effect on the overall resistance (such as infill walls), or may have no contribution to the overall resistance (such as windows and glazing). Damage may occur to equipment due to loss of stability or due to an intolerable dynamic response.

Damage may occur to a structure's inhabitants due to partial or complete collapse, external fragment penetration, fragments formed from a fractured wall or glazing, local dynamic characteristics of acceleration, velocity and displacement that a human body cannot tolerate, or falling objects as a result of the overall response.

In the following, damage to structural components will be discussed.

3.10.1 Damage parameters—Damage may be defined as a weakness in a structure's integrity that is caused by loading. Damage may be amplified through brittle cracking, through inelastic rotations, or through degraded stiffness.

3.10.2 Design to predefined damage level—The amount of energy imparted to the structure may be resisted by the structure elastically and inelastically. Inelastic resistance sacrifices the structure's integrity and produces damage through which energy is dissipated. Inelastic resistance requires that a structure be designed to demonstrate sufficient ductility without collapse. The larger the inelastic deformation due to a given threat, the larger the expected damage to the structure and the more modest the resulting structural elements. Economic considerations encourage larger inelastic deformations. Performance and safety considerations encourage constraints to inelastic deformation.

A structure's ductility provides the reserve for unpredicted effects and covers the range of probabilistic threats that may occur. If an explosive detonates closer to a structure than had been considered, a ductile structure will resist the explosion through the development of somewhat larger inelastic deformations, whereas a nonductile structure may collapse.

In every case, all relevant considerations should be used to define the allowable damage level.

3.10.3 Damage propagation and progressive collapse—

When a structural element loses its resisting capacity, loads seek an alternative path. If an alternative path is available, then a load redistribution develops to resist the external actions. If an alternative path is not available, then a collapse occurs. Explosions may occur at different locations and cause damage to different elements. Each explosion scheme will require an alternative load path. A more general approach is to tie structural elements to each other, enabling the development of different alternative paths. In all cases, a design should localize damage and the propagation of damage should be prevented by a structural system that provides a stable alternative load path.

3.11—Construction

The selected structural system and materials of construction should consider the method and sequence of construction. For higher blast loads, cast-in-place reinforced concrete construction is the preferred method. In some countries, precast concrete is preferred; however, special attention should be provided to connection detailing to provide ductility. Precast concrete wall panels in combination with other supporting materials, such as structural steel, are also used. With the proper selection of materials and methods, construction time and cost are reduced. Reinforced concrete block walls are often used in facilities with smaller blast loads. The constructed cost of such facilities is lower; however, they may not be preferable in performance.

In blast-resistant facilities, construction details are of major importance. Reinforcing details may affect the mode of failure and dictate the amount of ductility that a structural element may develop. Construction joints might yield weaker cross sections where premature failure may occur. Other construction issues such as anchor bolt embedment and structural steel connections are also important. Details should cover structural as well as nonstructural elements. Nonstructural elements should not dislodge due to inadequate connections and become secondary missiles causing damage and injury. Higher strength concrete may yield advantages, yet care should be given to avoid brittleness. Quality of construction should be monitored to avoid weak elements in the structure.

3.12—Cost effectiveness

Costs of facilities and structures vary with location and selected level of protection. The level of protection affects the selection of construction materials, structural system, and member sizes. In many cases, 100 percent protection may not be feasible due to prohibitive costs and low probability of threat occurrence. Therefore, blast-resistant protection

criteria should be selected based on the probability of blast occurrence, degree of damage potential, and cost.

As the distance of a structure is increased from the blast source, the loading decreases significantly. This is important in facilities that cannot be made blast resistant such as office buildings where exposure to local damage exists due to windows and openings. In industrial facilities, distance increases the length and expense of control cabling necessary to control process equipment and provide for an orderly shutdown. For any facility, distance increases real estate requirements and the length of utility connections.

Reinforced cast-in-place concrete, reinforced masonry, reinforced precast concrete, or structural steel are suitable for blast-resistant facilities. For low blast resistance, prefabricated structural steel construction or reinforced masonry will be suitable and may be less expensive. For higher loads, reinforced concrete buildings are more effective. Hybrid structures with structural steel frames and concrete wall panels may also be suitable. The additional costs of blast-resistant structures may be 20 to 30 percent higher than conventional structures.

3.13—Decision making

In the decision-making process, all the factors described in this chapter should be considered. Alternatives should be developed based on the input from the architect responsible for facility layout, the environmental engineer responsible for determining regulatory requirements, the security consultant (or process engineer for accidental industrial situations) responsible for determining the blast potential/threat, the structural engineer responsible for engineering and design of the facility, and the owner responsible for providing overall preferences. Decision-making considerations include cost estimates of alternatives, technical and operational advantages and disadvantages, construction durations, and benefit versus risk potential. The provided information should lead to the optimal alternative.

CHAPTER 4—GENERAL PLANNING AND DESIGN METHODOLOGY

All too often, the structural strengthening of a facility to resist blast pressures is the final consideration, not the first. A hazard assessment and risk analysis is often used to determine if a facility needs further study and planning to evaluate safety, economics, and function. These assessments may dictate the implementation of other alternatives.

This chapter covers such general blast design methodology topics as blast design applications, basic objectives, hazard assessment, planning, and a basic sequence of structural design.

4.1—Applications

Though there are quite a number of structures of various types designed with some level of blast consideration, there are three fundamental applications for this specialized area of design:

1. Preventing terrorists from using destruction or injury as a tactic

2. Minimizing the effects of impulsive or energetic-based industrial accidents

3. Protecting defense facilities

These basic applications are covered in detail in the following sections.

4.1.1 *Minimizing destruction of terrorist tactics*—

Terrorist incidents are all too frequent in the news—indeed, one aim of the terrorist is the attention that is attracted. A handful of incidents have caused major damage in terms of life and property. Most incidents, however, typically cause much less damage. Targets are often selected that are symbolic of the terrorist's opposition. Such targets include government administration buildings, embassies, federal courthouses, national park monuments, trains, airport terminals, and aircraft. Other targets, selected somewhat more randomly, may include commercial office buildings or open public areas. Buildings adjacent to these potential targets are also at risk. The determination of which facilities to protect and how much protection to provide is an area of technical specialization that extends well beyond structural engineering. This type of risk analysis decision is typically made by the facility owner in cooperation with specialists experienced in this form of evaluation.

Complicating protection efforts against terrorism is the desire that potentially targeted facilities must appear normal, or architecturally open, while concealing blast-strengthening efforts. The primary reason is that people feel more uncomfortable working in a facility that resembles a fortress or that visibly presents itself as a potential target. A secondary reason for this is to make it more difficult for an attacker to evaluate the robustness of the target. In protection against terrorism, ordinary architectural features such as fences, barricades, or bollards are often used to maintain adequate distance between a potential terrorist and target, thereby minimizing exposure to blast effects.

4.1.2 *Minimizing effects of industrial accidents*—

Industrial facilities may be subjected to accidental explosions resulting from the manufacture, handling, and storage of hazardous substances. Such substances include fuel, petrochemicals, explosives, or grain. Bursting pressure vessels are also a significant hazard to building occupants. If the potential blast location is known, such as for grain silos or explosives storage chambers, protective barriers surrounding the source can be used to reduce blast wave propagation and fragment effects. If the potential blast location is inside an enclosed building, such as for chemical laboratories, frangible wall panels can be used to reduce the buildup of internal gas pressures. These panels open rapidly to allow blast pressures to vent outside. If the potential blast location is not defined, such as for vapor cloud releases, occupied buildings and essential facilities in the immediate area to a potential vapor release can be strengthened.

For industrial facilities, blast-resistant facilities typically have little need to appear normal. External esthetic concerns are typically minimal and are based on a facility's location within an industrial plant. Interior design is sometimes employed to compensate for the lack of external features and to enhance productivity. In this situation, workers

knowledgeable of the production process may actually feel safer within a visibly strengthened building.

4.1.3 Protecting defense facilities—Military installations consist of a wide range of facility types such as hardened hangars, personnel shelters, weapon storage bunkers, missile silos, and command centers. These facilities can be subject to deliberate attack with the intention of permanently preventing operation of the facility. The appearance of blast-hardening features is unimportant, although the facility itself may be designed to be hidden or obscured as to its purpose. A number of U.S. government publications address the design of military facilities ([UFC 3-340-01](#); [UFC 3-340-02](#); [UFC 4-023-03](#); [UFC 4-010-01](#)).

4.2—Objectives of blast-resistant design

The objectives generally used for blast-resistant designs include some combination of the following.

4.2.1 Eliminate or minimize personnel injury—The protection of building occupants and the public is always a prime objective for occupied facilities, though the exact intended degree of protection can vary.

Some industrial facility owners adopt the concept of neutral risk in the blast evaluation of buildings. Neutral risk is the concept that a person should not be at a greater risk of injury from being within a building than they would be outside the building. Many industrial explosions do not generate high blast overpressures that are lethal to someone standing in the open. These same blast overpressures, however, can be great enough to collapse conventionally constructed buildings. The implication is not to eliminate injury, but to eliminate additional injury.

Other facility owners may have reasons for providing greater protection. Operators in process control buildings may be expected to remain at their posts following the detection of a potentially hazardous situation. In this case, immediate evacuation is not intended so that the emergency may be directly dealt with and eliminated. In some facilities, certain buildings may be designated as safe havens or locations for assembly in the event of an evacuation order, and damage levels may be controlled to minimize fire and toxic release scenarios after a vapor cloud explosion.

4.2.2 Prevent disruption of operations—The minimization of downtime and repair of valuable or essential equipment is often a design objective, especially for equipment common to multiple operating units. The unnecessary disruption of activities at an industrial facility will result in lost production that often will have a severe financial impact. Otherwise unaffected sections of an industrial facility can be impacted from the use of a common control location that has been damaged from an explosion.

4.2.3 Prevent propagation of damaging effects—This objective is applicable to all types of blast design. In design against terrorism, progressive collapse mechanisms are analyzed to minimize building damage. In industrial design, the location and spacing of control facilities and utilities can greatly reduce the creation of secondary damage effects, such as release of toxic materials or flammables. In the design of ammunition bunkers, sufficient spacing or barrier

walls are provided to prevent sympathetic detonations from adjacent storage compartments.

4.3—Hazard assessment and risk analysis

The objective of a hazard assessment and risk analysis is to determine if any blast considerations are necessary. The assessment may also establish design criteria to mitigate the risk. Not all buildings need to be blast resistant, even where a threat exists. Some examples where blast-resistant design may not be required by the risk assessment include low occupancy structures, buildings housing nonessential equipment, or buildings remote enough from any blast source.

A hazard assessment is a rational and comprehensive study that identifies all potential explosion sources and considers the effect of preventative measures. The basic questions to be answered are: What is the explosion threat? Is it a realistic danger? What are the mitigating factors?

A risk analysis explores the likelihood of an explosion, vulnerability to occupants, and the consequences of various mitigation measures. Hazard and risk references for anti-terrorism-related design can be found in [Krauthammer et al. \(1999\)](#). For industrial facilities, refer to [API RP752](#).

4.4—Planning

The planning phase begins after a hazard assessment and risk analysis concludes that a hazard exists and must be dealt with. Planning includes considerations of building siting, alternative or redundant locations, orientation, plan size, height, location of entrances and exits, inclusion of barriers, and type of construction. Planning on a more detailed level also includes the number, location, and type of window and door fenestration.

Blast load decreases significantly with distance. Thus, increasing the distance between blast source and protected facility is often an effective way to mitigate risk. In resisting terrorism, the distance between the explosive device and the target can be increased by using fences or other obstacles to prevent the close entry of unauthorized vehicles or people. In industrial plants, occupied buildings can be located farther away from identified release sources. In the storage of hazardous materials, distances between storage containers can be increased to prevent propagating effects. The military will frequently use methods such as hiding, burying, or disguising a potential target.

4.5—Structural design process

This section provides a straightforward listing and discussion of the basic work flow in a blast-resistant design process. Each step involves choices that the owner and design professional must make to meet blast design requirements as well as achieve a cost effective design (refer to Fig. 4.5 for a generic work process, and 4.5.1 through 4.5.9 for discussion). For instance, there are a number of variations in the dynamic analysis, from a chart solution to a computer-based dynamic nonlinear finite element analysis (FEA). There are also choices to be made in detailing

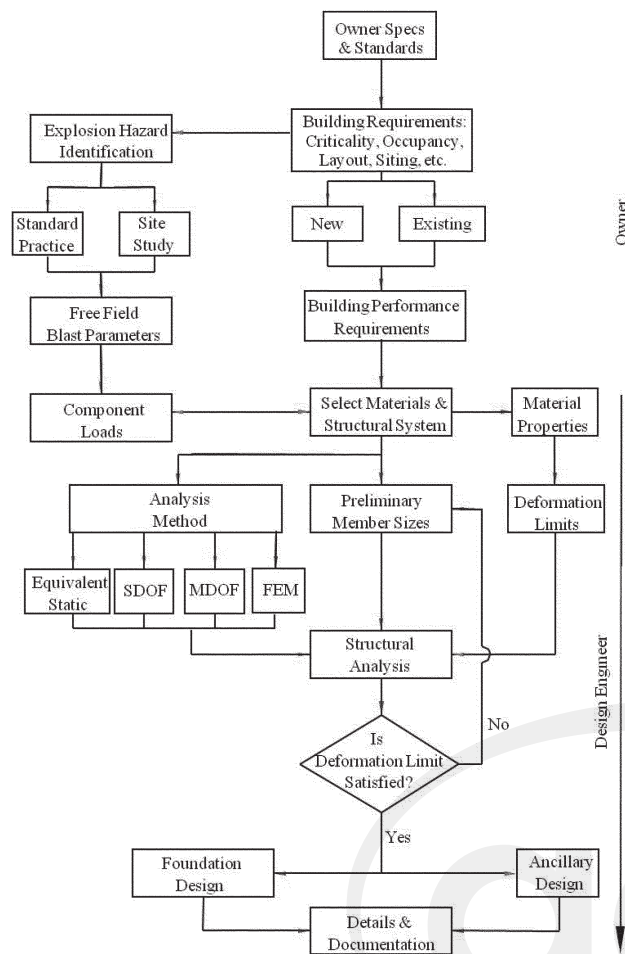


Fig. 4.5—Blast-resistant design work process (Krauthammer et al. 1999).

permissible level of damage. The preceding discussion on objectives should assist in determining the optimal solution.

4.5.1 Obtain design blast load—Depending on the type of explosion, the blast load may often be determined not by the structural engineer, but by a specialist familiar with the relevant nature of the explosive material. Considerations in this determination will include the specific type and amount of explosive, distance from the source of the explosion, prevailing wind direction, building orientation, and extent of intervening objects. The blast load is usually described in terms of an overpressure versus time relationship. Fragment loading criteria may also be included. In certain cases, a safety factor may be applied to the size of the charge. Refer to [Chapter 5](#) for a detailed discussion of this step.

4.5.2 Determine facility layout and type of construction—The facility layout will indicate the orientation and area of exposure for a building's blast-resisting walls. The orientation can have a significant effect on reflected blast wave effects. A building's height or existence of reentrant corners can affect the magnitude of blast loading. The type of construction will dictate the level of deformation a structure can sustain before failing. Wood framed and unreinforced masonry structures will generally have little blast capacity. Preengineered steel and reinforced masonry buildings will

generally have a somewhat greater capacity. Reinforced concrete buildings can be designed to sustain large blast loads. [Chapter 6](#) provides a more detailed discussion on types of building construction.

4.5.3 Determine structural response requirements—The permissible deformation is based on the extent of tolerable damage. A low permissible response, for example limited to the elastic range, equates to no structural damage; however, the material and construction cost may be prohibitive. A high permissible response can be achieved when a structure almost reaches the point of collapse, but there may be significant nonstructural damage. Based on achieving facility objectives, the tolerable level of damage can be determined. The structural response should follow from this determination because the structural response roughly equates to the level of expected damage. Refer to [Chapter 9](#) for further details.

4.5.4 Determine type of construction materials—The economic selection of blast-resistant building materials is based on estimated level of response. Dynamic properties are then based on the chosen materials. [Chapter 7](#) provides further details. Unreinforced masonry is considered a very brittle material because it will not sustain any resistance after reaching its ultimate capacity. Properly designed reinforced concrete, masonry, or structural steel buildings will be able to provide continued resistance after reaching their ultimate capacity.

4.5.5 Perform dynamic analysis—For structural elements or systems, an analysis is performed using trial dimensions and proportioning to determine their dynamic response. Calculation complexity and need for accuracy of results varies greatly and should lead to the most efficient calculation method. Available blast analysis methods include charts, equations, and single degree-of-freedom (SDOF) numerical integration. A structure can be analyzed as a series of SDOF structural elements using the simplest means, as a smaller series of minimally coupled elements using numerical integration, or fully coupled through the use of nonlinear dynamic FEA. Note that the level of analysis accuracy will typically not need to exceed the accuracy of the calculated load and assumed material properties. Refer to [Chapter 8](#) for further information on dynamic analysis alternatives.

4.5.6 Refine design—The first analysis of assumed materials and dimensional proportions will rarely result in an optimal design. Thus, revised trial dimensions and proportioning will be needed with a repeat of the analysis until the dynamic response fits within allowable response criteria. Supporting member forces and resulting sizes are generally minimized by designing for plastic response of the initial blast resisting elements. In other words, one should design up to the permissible response limits. The engineer's knowledge and experience is needed to obtain an optimal solution of building capacity, operability, and constructed cost. Refer to [Chapters 10](#) and [11](#) for possible retrofit approaches.

4.5.7 Design connections—Connections should not be allowed to be a point of failure. Connections are designed for the ultimate capacity of the supported

member. Some connections may be detailed in such a way as to relocate a plastic hinge point slightly away from the actual joint. This may be done to avoid a plastic hinge in a nonductile region or area of stress concentration. **Chapter 9** provides further details on connection design.

4.5.8 Design ancillary items—Ancillary items include doors, windows, and other architectural features. Though windows are important and necessary in office buildings, courthouses, and government buildings, they usually cause the majority of nonlethal personnel injuries, especially in low- and moderate-level explosions. Thus, windows are normally reduced or eliminated and designed to resist blast effects. Refer to **Chapter 11** for window design alternatives.

4.5.9 Construction phase—Blast design does not end with issued drawings. The intent of the design must be followed through fabrication and construction. The conventional wisdom used in many construction decisions may not apply to blast resistance. For instance, substitutions of stronger materials can lead to higher flexural capacity and higher forces on supporting members. The construction contractor should be selected based on his experience handling structures with similar details unique to blast-resistant design.

CHAPTER 5—BLAST LOAD PREDICTION

The purpose of this chapter is to familiarize the practicing structural engineer with the types of blast hazards likely to be encountered during analysis and design situations, as well as the subsequent blast loads that can result from these hazards. This chapter is not intended to be a how-to manual, but rather to direct the engineer to resources for performing load predictions. It is important for the structural engineer to know the key blast load parameters and to be aware of current blast prediction methodologies and their limitations. It is also important for structural engineers to be aware that the prediction of blast loads is one of the most important steps in a blast analysis or design, and it may be advisable to consult a knowledgeable blast-effects expert to ensure that explosion scenarios are properly defined and blast effects correctly predicted.

5.1—Blast load basics

5.1.1 Blast wave phenomena—An explosion is a sudden release of energy that creates a pressure wave of sufficient magnitude to cause damage or injury. In general, people think of explosions in terms of detonations of explosive charges, but there are many other explosion sources that have the same, or greater, potential to cause damage. For example, reactive chemicals may undergo a rapid reaction under certain conditions. These events are often referred to as runaway reactions. Flammable materials mixed with air can form flammable vapor clouds that, when ignited, can cause very large explosions. Not all explosions involve a chemical reaction. Physical explosions can result from any rapid release of energy that creates a blast wave, such as a bursting pressure vessel or a rapid phase transition of a liquid to a gas. Different blast sources produce different blast waves, and there are appropriate prediction methods to

properly characterize each type of explosion. No single blast prediction method can accurately predict the blast produced by all types of sources.

Blast loads resulting from an explosion are created by the rapid expansion of material creating a pressure disturbance or blast wave radiating away from the explosion source. This blast wave may be termed a shock or pressure wave depending on the amplitude and rate of pressure rise. A shock wave, characteristic of an explosive detonation or other intense explosion source, is a supersonic pressure disturbance with an instantaneous rise in pressure. Pressure waves, characteristic of slower-speed blast sources, have relatively long rise times and lower peak values than shock waves. As a pressure wave travels away from the explosion center, the pressure amplitude decreases and the duration of the blast wave increases. Overexpansion at the center of the explosion creates a vacuum in the explosion source region and a reversal of gas motion. The negative pressure region expands outward, causing a negative pressure (termed the negative phase) that trails the positive pressure (termed the positive phase). The negative phase is generally lower in magnitude but longer in duration than the positive phase for shock waves, but may be comparable or greater in magnitude of pressure and duration for pressure waves. A shock wave pressure-time history recorded during a high explosive detonation is shown in Fig. 5.1.1.

Expansion of the blast wave causes air particles to move outward during the positive phase and inward during the negative phase. The flow of air particles creates a pressure analogous to a wind. The pressure produced by this flow is referred to as the dynamic pressure. This pressure is lower in magnitude than the shock or pressure wave and imparts a drag load similar to wind loads on objects in its path.

As the shock or pressure wave strikes a wall or other object, a reflection occurs, increasing the applied pressure on the surface. This reflected pressure is considerably higher than the incident or free-field pressure wave. At the free edges of a reflecting surface, the discontinuity between the forward traveling incident blast wave and rearward traveling reflected blast wave creates a rarefaction, or pressure relief

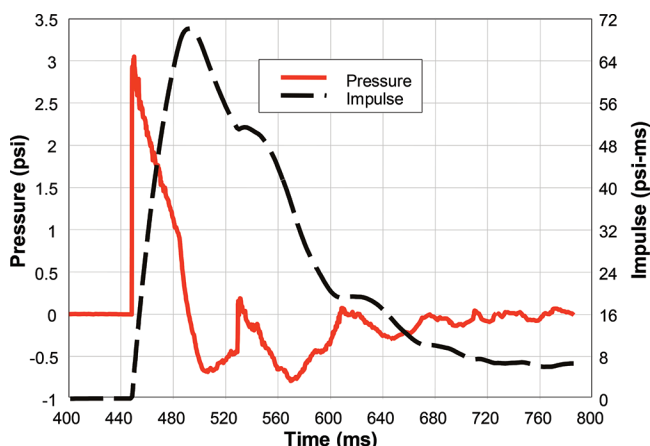


Fig. 5.1.1—Pressure transducer trace from high explosive detonation (UFC 3-340-02). (Note: 1 psi = 6.895 kPa)

wave. The rarefactions travel inward from the outer edges across the face of the reflecting surface. The rarefaction waves relieve the positive reflected pressure down to the side-on pressure plus drag pressure. The time required for the rarefaction waves to completely relieve the reflected pressure is termed the clearing time. It should be noted that a rarefaction wave does not instantaneously clear reflected pressure; rather, the relief is somewhat gradual and takes longer than the time required for the leading edge of the rarefaction to travel to the center of the reflected surface. If the clearing time exceeds the positive phase blast wave duration, clearing does not affect the positive phase loads.

5.1.2 Key parameters—An idealized pressure-time history indicating the key parameters of a blast load are shown Fig. 5.1.2. The figure also shows a comparison between free-field or side-on and reflected pressure-time histories. The parameters shown in Fig. 5.1.2 are defined in [Chapter 2](#).

Free-field loads are those produced by blast waves sweeping over surfaces unimpeded by any objects in their path. This load is also referred to as side-on when the blast wave sweeps over a wall or other object parallel to its direction of travel. Side-on pressure terms are indicated by a “so” subscript in the figures in this chapter as well as in most references.

The most complete treatment of blast wave parameters and their relationships can be found in [Baker \(1973\)](#). Other useful references are [UFC 3-340-02](#) and [Baker et al. \(1983\)](#).

5.1.3 Scaling—Blast pressures, load duration, impulse, shock wave velocity, arrival times, and other blast parameters are frequently presented in scaled form. Research has shown that scaling laws can be applied to explosions, allowing data from one explosion test or simulation to be applied to a geometrically similar (larger or smaller) case. As a result, scaling has tremendous utility in blast predictions by allowing compilations of explosion test and numerical modeling data to be used to predict loads for any combination of explosion energy and standoff distance within the range of data. When making predictions, the scaling laws used to scale the data must be strictly followed. [Baker et al. \(1991\)](#) and [Baker \(1973\)](#) provide complete treatments of

blast scaling. The most common form of scaling is called cube root scaling, owing to the fact that many of the blast parameters (stand-off, duration, and impulse) are scaled by the cube root of the explosion energy. Both dimensional and dimensionless scaling is used, and care must be taken with all unit parameters to ensure the scaling is correctly applied for the blast curves being used.

5.2—Explosion sources

As mentioned previously, there are a wide variety of possible explosion sources. Types of explosions and their defining characteristics are discussed in this section. Explosions involving chemical reactions can be classified by their reaction rates into two primary groups: deflagrations and detonations. A deflagration is an oxidation reaction that propagates at a rate less than the speed of sound in the unreacted material. By contrast, a detonation propagates supersonically, usually many times faster than the speed of sound. Because pressure is closely related to reaction rate, detonation pressures are usually many times higher than deflagration pressures.

An explosion is an exothermic chemical reaction usually involving an oxidizer and a fuel. Explosion reactions can be produced by a wide array of materials. The reaction rate is dependent on the chemical and physical properties of the energetic material, the reactant proportions and homogeneity, geometry of the material, characteristics of the container in which the material resides, the method and energy of initiation, and other initial conditions. A deflagration may be initiated by a soft initiation source such as friction, spark, or open flame. Under certain conditions, a deflagration can transition into a detonation. Alternatively, detonations can be directly initiated in an explosive material that exceeds certain minimum geometry constraints if impinged by a shock source of sufficient strength.

Deflagrations and detonations may involve oxidizers and fuels that are oxygen deficient, or materials that may produce flammable gases as a product of reaction. In either case, the unreacted or flammable products may mix with air and result in secondary burning. The secondary burning does not contribute significantly to the blast pressures for external explosions, but can be a major consideration when predicting internal explosion blast pressures.

Industrial explosives, propellant, and pyrotechnic manufacturing provide a wide array of energetic material configurations and materials. These products may include gas generators for airbags, packaged general-purpose explosive charges, shaped high-explosive charges for cutting, or blasting agents used in mining. Materials used in these manufacturing processes may not be well characterized in terms of potential explosives hazards; therefore, the structural analyst should take care to understand the full range of blast loads that may be produced and designed with the appropriate factors of safety. Terrorist threats principally involve solid materials such as plastic explosives or improvised explosives such as ammonium nitrate and fuel oil.

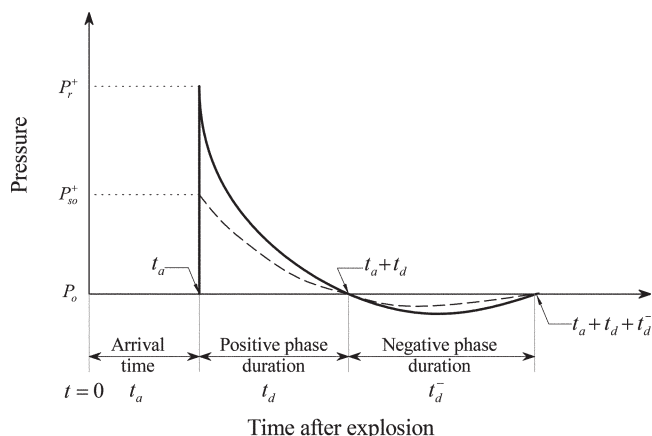


Fig. 5.1.2—Typical side-on pressure-time history for shock loads.

Explosions originating from a chemical reaction, the material involved and its state, the proportions of fuel and oxidizer (if applicable), the geometry of the material, the characteristics of the container holding the material, and method and energy of initiation are among the parameters that determine explosion characteristics. Explosive materials can be broadly categorized based on their state. Solid materials typically produce high pressure, short duration loads, whereas combustible gases of comparable energy produce lower pressure, longer duration loads. Energy output and standoff (separation) distance in the configuration of interest is key to accurately determining a structure's blast loads. Explosion sources are described by group in the following paragraphs.

5.2.1 High explosives—High explosives are materials that are intended to produce detonation events with supersonic reaction fronts. The reactions proceeding through the explosive are self-sustaining if the charge is of sufficient diameter and properly initiated. Reaction rate, or detonation velocity, varies with material type and is a key factor in detonation pressure for a material. Detonation velocities typically range from 0.6 to 5.6 mi/second (1 to 9 km/second). High explosives can be classified by their sensitivity to initiation into primary, secondary, and tertiary explosives. Primary explosives are very sensitive to initiation; an example is lead azide used in detonators. Secondary high explosives include trinitrotoluene (TNT), composition C4, and dynamite. Tertiary explosives are much less sensitive to initiation; that is, they require a powerful booster charge to initiate them. Blasting agents such as ammonium nitrate fuel oil (ANFO) is an example of a tertiary explosive.

For convenience in predicting blast pressures, the energy release of high explosives is commonly measured as a value relative to that of TNT. This TNT equivalence is used to determine a TNT charge weight capable of producing the same explosion energy, blast pressure, or blast impulse as the explosive of interest. The TNT equivalence is different for energy, peak pressure, and impulse, and separate TNT equivalent energy values are reported for many materials. Equivalencies for a number of these materials are published (UFC 3-340-02; DOE-TIC-11268; Baker et al. 1983) but, in some cases, they must be determined experimentally for a particular configuration.

Blast loads from high explosives may occur due to accidental or intentional detonations. Accidents involving high explosives can include explosives processing, handling, and transport events. Intentional detonations can include explosives testing, military weapons, demolition, specialized cutting or explosive forming, and terrorist threats. In the case of intentional detonations, structures may be required to withstand multiple events, such as a test structure.

Confined explosive charges will create gas pressures in the structure in addition to shock waves. If not adequately vented, these gas pressure loads may exceed the shock loads. Preliminary designs can often be performed based on the peak gas or quasi-static loads with subsequent checks for the combined shock and gas pressure loads.

High explosives come in many forms determined by their chemical and physical properties and intended use. Most explosives have additives to aid in stabilizing the material chemically or physically. Powdered explosives may be combined with a plastic binder to form plastic bonded or polymer bonded explosive. Extrudable explosives have a viscous form due to the addition of rubber resins to the explosive material. This addition allows the explosive to be molded or extruded to produce a particular shape.

Certain liquids, such as nitromethane, can also detonate. Nitromethane is relatively insensitive and must be initiated by a strong ignition source such as a high explosive booster. It does have safety advantages over other materials and may be handled as a simple flammable liquid in many cases. The shock front produced by nitromethane is well formed and produces blast loads with 100 percent TNT equivalence.

The selection of effective charge weights, safety factors on blast loads, and allowable response criteria will be dependent on whether accidental or intentional explosion threats are considered. Guidance on these selections is discussed in Baker (1973) and UFC 3-340-02.

5.2.2 Propellants and pyrotechnics—Propellants and pyrotechnics, also known as low explosives, are energetic materials that do not typically detonate and are used to produce gas, smoke, flash, or sound. Both solid and liquid rocket propellants, gun propellants, and black powder are examples of low explosives. Pyrotechnics includes many different materials such as fireworks, smoke grenades, flares, and the gas generator material in automobile air bags. The relatively low reaction rates of these materials result in low blast pressure output; although, in certain conditions, propellants and pyrotechnics may detonate. Fire hazards and gas generation concerns dominate the safety analysis in most cases, but detonations or deflagrations cannot be ruled out in all cases.

Predicting blast loads for these materials can be challenging. There is much less data available for propellants and pyrotechnics than for high explosives with respect to blast loads. In some cases, TNT equivalencies for these materials are used. While peak pressures for propellants and pyrotechnics may be low compared with high explosives, their impulses can be quite high and may exceed the energy equivalent high explosive values. TNT energy equivalencies may be quite high. Care must be taken when equivalencies are based on small-scale tests as large quantities may react in a more energetic manner. Additionally, when using TNT equivalent weights based solely on energy, the blast pressure will be overpredicted, but impulse and load duration will be underpredicted when compared with actual blast output from a pyrotechnic or propellant. The designer should insist on an adequate determination of TNT equivalency, including energy, pressure, and impulse equivalents.

5.2.3 Vapor cloud explosions—VCEs involve the release of a flammable material which, when mixed with air and given the proper conditions, forms an ignitable material potentially leading to an explosion. Only the fuel within flammability limits participates in the explosion, which is a minor percentage of the total quantity of fuel released.

(Baker and Baker 1991). The blast output of a vapor cloud explosion is highly variable and depends on the fuel, size of the flammable vapor cloud, presence of congestion (obstacles such as structural members, pipes, and vessels) in the flammable region, and presence of confining surfaces. Release of a flammable material into the open-air absent congestion or confinement typically results in a fireball that does not produce damaging overpressures. Confinement and congestion in the flammable cloud creates turbulence and accelerates the combustion, thereby increasing the flame speed. Peak overpressure is a strong function of flame speed; thus, a key element in vapor cloud explosion predictions is maximum flame speed. Vapor cloud detonations are rare and typically only occur with high-reactivity materials, strong ignition sources, and with confinement and congestion of the flammable vapor. The vast majority of VCEs are deflagrations. A particularly noteworthy characteristic of deflagrations is that high flame speeds only occur in confined/congested regions of the flammable cloud, and the flame decelerates outside of congestion. As a result, deflagration blast loads are produced in confined/congested areas rather than at the point of release or dispersion. In the rare case of vapor cloud detonations, the blast loads are produced by the detonable material and are typically considered to be centered in the dispersed cloud and not at the point of release.

The pressures produced by VCEs are substantially lower than those produced by high explosives. For example, a vapor cloud detonation may reach 16 to 18 atmospheres overpressure, compared with 100,000 atmospheres or greater for most high explosives. However, the energy of VCEs can be very large, making them among the most devastating accidents in history. The large energy term produces a commensurately large impulse. Blast predictions made using a TNT equivalent approach tend to be inaccurate due to the disparity between the pressure and impulse compared with high explosives. As a result, TNT equivalence analyses of VCEs are not recommended.

5.2.4 Vessel bursts—Vessels designed to contain materials under pressure have the potential to create hazardous overpressures and fragments if the vessel fails while under pressure. A vessel burst may occur at normal working pressure due to a mechanical integrity problem, weakening of vessel, applied external factors (such as impact), elevated pressure due to excessive pressurization from an external source, an uncontrolled internal chemical reaction, heating vessel contents with insufficient pressure relief, or other means. This type of accident results in loss of contents and may lead to a follow-up explosion when the contents subsequently mix with air and are flammable or pyrophoric.

In the far field, the blast load from a vessel that fails at high pressures (several thousand psi [note: 1000 psi = 6895 kPa] or higher) is similar to that caused by high explosives. In the near field (scaled range less than $3.0 \text{ ft/lb}^{1/3}$ [$1.19 \text{ m/kg}^{1/3}$]), overpressures are less than those produced by high explosives, and the use of TNT equivalent prediction procedures will overestimate pressure. The key parameters for estimating blast effects from bursting vessels are the volume of the material in the vessel, the failure pressure,

the composition of the contents, and the temperature of the contents.

Fragments represent an additional hazard from bursting vessels. Failure at working pressure or overpressurization at a relatively slow rate usually results in a small number of fairly large fragments. In some cases, one or both ends of a cylindrical pressure vessel may be propelled long distances by a rocketing mechanism, or other large fragments may be thrown as a result of the expansion of the vessel contents. Containment of these fragments may be required to provide adequate safety, which can be quite challenging. Fragment hazard prediction methods were developed by Wilfred Baker (Baker et al. 1977) and cited in numerous other references including the Center for Chemical Process Safety (1994), Committee for the Prevention of Disasters Due to Dangerous Substances (1992), and Baker et al. (1983).

5.2.5 Boiling liquid expanding vapor explosion—A special case of a vessel burst, a boiling liquid expanding vapor explosion (BLEVE), occurs when a vessel fails and a rapid depressurization of a liquid is above its boiling point for atmospheric pressure. Upon depressurization, a portion of the superheated liquid rapidly boils, and the expanding vapors contribute to the blast wave. Compressed gases in the vessel prior to failure also contribute to the blast wave as a bursting pressure, as described in the previous paragraph. A common BLEVE scenario is immersion of a pressure vessel in a fire, causing weakening of the vessel shell to the point of failure. A BLEVE may involve a flammable liquid, and mixing of the flammable material with air and subsequent ignition may cause a fireball. A detailed discussion of BLEVE events and simplified blast prediction methods is provided by the Center for Chemical Process Safety (1994).

5.3—Load prediction methods

5.3.1 Scope—This section describes the principal methods for predicting blast loads for explosion hazards with some discussion of practical applications and limitations. A more detailed treatment is given for high explosives and VCEs because these tend to be the most common design threats for protective construction. Applied loads on building structures are also covered in more detail because the task of translating free-field blast loads into applied loads may fall to the structural engineer.

5.3.2 Process—Prediction of blast loads on structures requires the following basic steps:

- a) Hazards definition
- b) Free-field load prediction
- c) Prediction of loads imposed on the structure

The selection of appropriate hazards for analysis requires knowledge of the process or potential hazardous situations. A process hazards assessment will aid in identifying potential explosion hazards but will not provide much guidance on selecting the magnitude of the hazard. For solid and liquid explosives, the quantity of participating explosives can be defined based on inventory with consideration of whether a detonation or deflagration could propagate to interconnected quantities (for example, through piping and vessels in a processing operation) or separated explosives. In some cases,

the explosive quantities to be used for analysis are mandated by government regulations. VCEs require an estimate of the quantity of material participating in the explosion, which frequently entails flammable material discharge and dispersion analyses. Vapor cloud explosion analysis also requires knowledge of the confinement and congestion in the flammable cloud, necessitating a site inspection by someone trained in vapor cloud explosion analysis.

Analysis and design for explosion events will typically include conservative estimates of material quantities and factors of safety that are applied to estimated charge weights. A factor of safety is recommended by **UFC 3-340-02** to account for uncertainty in blast loads and for potential construction flaws. The structural analyst should be aware of the significant factors involved in selecting the explosion energy or other parameters to help guide decisions about structural performance during the structural analysis and design process. Knowledge of the conservatism in the hazard definition can be used to guide the response criteria selection and application.

In many cases, blast load prediction is a multi-step process. Often, an initial estimate of blast loads will be made using simplified techniques and conservative estimate of explosion energy. It may become obvious at this point that the predicted loads are so low they are not a contributing factor in structural design or will not cause undue cost or complexity in the design, thus the initial loads are judged to be adequate for analysis or design, and more detailed blast load prediction to reduce conservatism is not necessary.

The basic approach involves predicting free-field loads using empirical or semi-empirical methods. Blast curves that relate explosion energy, standoff distance, and blast wave parameters are typically used in this initial load prediction step. These curves are readily available for high explosives and vapor cloud explosions. The free-field loads are then translated into applied loads for the structure or component of interest. Building size and orientation to the explosion are key parameters for computing applied loads from free-field values.

The applied loads are used in structural analysis of the building and components. If this analysis shows significant changes are required to meet the applied load, refinement of the blast load prediction may be warranted. A refined load prediction may include a more accurate estimate of explosion energy if the original estimation was too conservative, although all predictions should include a safety factor. Detailed load prediction may be needed, in which case, more sophisticated tools such as hydrocode or computational fluid dynamics tools should be used. The interaction of the blast waves with surrounding structures and equipment can be modeled to more accurately define the blast load environment and reduce conservatism in the load prediction by including shielding and wrap-around effects.

5.3.3 Resources—Technical manuals developed for the Department of Defense and other government agencies provide a wealth of information and guidance on the prediction of blast loads (**UFC 3-340-01**; **UFC 3-340-02**). These manuals cover a range of threats and hazards

including high and low explosives as well as bursting vessels. Many of these manuals have electronic versions and supporting software to aid in the implementation of the methods. Distribution of these tools is typically restricted to government agencies and their contractors.

5.4—High explosives

5.4.1 Empirical relationships (for example, *HE standard*)—A significant amount of data has been produced that quantifies the relationship between charge weight, standoff distance, and blast parameters for both positive and negative phases. Several technical manuals produced by the Department of Defense contain the relationships in the form of scaled blast curves (**UFC 3-340-01**; **UFC 3-340-02**). High explosive blast curves are also available in the public domain in references such as the **Center for Chemical Process Safety** (1994) and **Baker** (1973), as well as blast-prediction software.

5.4.2 External loads—The empirical blast parameter curves provided **UFC 3-340-01** and **UFC 3-340-02** plot air blast parameters versus scaled distance for both air burst (elevated charge) and surface burst configurations. A charge detonated on the ground will produce higher blast loads than an air burst due to the reflection of the shock by the ground surface. For unyielding surfaces with the charge located on the surface, the effect is a doubling of the apparent charge weight because the energy of the blast directed to the ground is fully reflected. For soft soils or charges located above the surface, the reflection factor is less because some of the energy is absorbed by the substrate. Some guidance for selecting the reflection factor is given in various government technical manuals, but it is conservative to assume a fully reflecting surface.

The most commonly used approach to present blast wave relationships for high explosives is the Hopkinson-Cranz, or cube root, scaling method (**Baker et al. 1983**). The cube root term results from geometric scaling laws in which charge diameter varies in proportion to all distances, and the charge weight is proportional to the cube of the charge diameter. To use these empirical curves, the scaled distance is computed by dividing the standoff distance from the charge to the point of interest by the cube root of the charge weight. Standard empirical curves for high explosives are based on conditions at sea level. Hopkinson-Cranz scaling is dimensional, whereas Sachs or energy scaling is dimensionless. Sachs scaling (**UFC 3-340-01**) inherently includes ambient pressure in scaling blast pressure, so Sachs scaling can be used to account for the effect of altitude.

Parameters that are a function of time, such as load duration and impulse, are reported in scaled terms that include charge weight or energy to account for scaling effects. Users are cautioned to read the correct axis and to unscale the parameters prior to application. These curves are based on equivalent weights of TNT. **UFC 3-340-01**, **UFC 3-340-02**, and **Baker et al. (1983)** provide TNT equivalence tables for various explosives. Figure 5.4.2 is a simplified version of TNT blast curves that provide positive phase

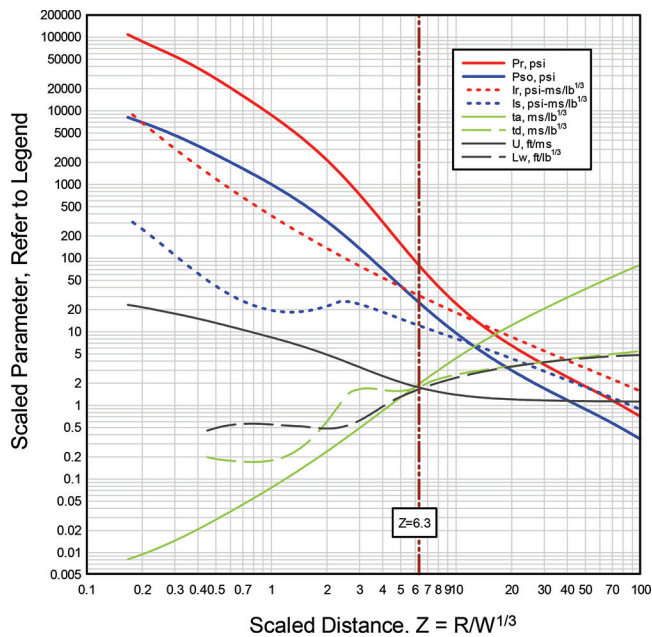


Fig. 5.4.2—Simplified version of TNT blast curves (UFC 3-340-02). (Note: 1 psi = 6.895 kPa; 1 psi/lb^{1/3} = 4.192 kPa/N^{1/3}; 1 ms/lb^{1/3} = 0.608 ms/N^{1/3}; 1 ft/lb^{1/3} = 0.185 m/N^{1/3}.)

parameters for charges located at ground level, as this is the most common situation.

5.4.3 Internal loads—Blast design for reinforced concrete structures often involves containment of internal explosion effects such as for explosives or propellant processing bays. Shock waves produced emanate from the charge, striking wall and roof components and reflecting to impact other surfaces. Each surface is subjected to multiple shock waves.

Internal explosions also produce gas and heat, which cause a pressure increase within the containment. The peak gas pressure developed is a function of the charge weight/free volume ratio in the containment. Empirical relationships for gas load prediction are covered in **UFC 3-340-01** and **UFC 3-340-02**. This pressure buildup is relatively slow compared to the load duration associated with shock waves. For simplicity, the peak gas or quasi-static pressure is assumed to rise instantaneously to the peak gas pressure but is not additive to shock pressures. A curve of peak gas pressures versus weight/volume is shown in Fig. 5.4.3.

Duration of the gas pressures is a function of the vent area available and the rate at which temperature decays in the containment area. This duration is determined by computing the gas impulse and solving for an equivalent charge weight. **UFC 3-340-02** contains predictive methods for gas impulse based on vent area and vent weight.

Two software packages have been developed by the Department of the Navy to compute interior loads. **SHOCK** computes shock pressures on a wall or roof surface including the effect of reflections. **FRANG** determines gas pressure durations by modeling venting and pressure decay. The Department of the Army and Defense Special Weapons Agency have developed a series of algorithms for internal load prediction culminating in **BLASTX**, which is capable

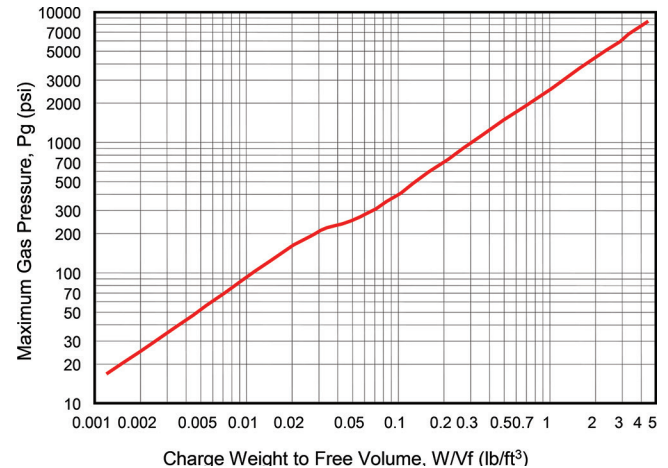


Fig. 5.4.3—Peak gas pressure for internal TNT detonations (UFC 3-340-02). (Note: 1 lb/ft³ = 158 N/m³; 1 psi = 6.89 kPa.)

of modeling shock and gas pressure propagation through multiple rooms.

5.4.4 Analytical methods—Analytical methods have been developed to predict blast loads. These methods fall into two groups: semi-empirical and hydrocode. The semi-empirical approach uses a physics-based model to compute selected blast parameters with coefficients that are tuned to match test data. These models are limited to configurations and charge weight ratios for which data are available, but offer the advantage of quick run times compared with more detailed techniques. **BLASTX** is an example of this approach. Semi-empirical codes may offer limited abilities to model shock diffraction, shielding, and reflection. Semi-empirical methods have been developed primarily by defense-related agencies and are restricted to distribution to government and its contractors.

Hydrocodes use a grid of computational cells to track detonation propagation through an explosive charge and shock wave propagation through a medium based on models of material behaviors and fundamental thermodynamics and fluid dynamics to predict pressure, density, and other key parameters. Hydrocodes that have been developed by both government agencies and private industries are available to analysts developing loads for commercial projects. This type of analysis is much more complex than the use of empirical relationships. Some of the available tools have user interfaces that greatly simplify the analysis, especially for standard materials, but considerable effort and expertise is typically required to conduct a competent analysis.

Output from hydrocodes will be in the form of pressure-time histories for selected probes or nodes in the model. Application of these loads to the structural model can be tedious. If the structural analysis involves a time history calculation, the time-varying loads may be transferred into the structural analysis but the number of data points to be transferred may be excessive. Normally, a simplification is made to the applied load history by greatly reducing the number of load points to a series of lines approximating the

real curve. This reduced multi-point curve is more complex than the linear decay cube used for the empirical relationship analysis.

5.5—Bursting pressure vessels

Bursting pressure blast predictions are most commonly conducted in one of two ways: simplified analytical methods or computation fluid dynamics models. In either case, it is necessary to select the conditions under which the vessel would be expected to fail—overpressure/overfilling, runaway reaction, external heating, mechanical or impact load, corrosion, or other mechanisms. This selection is important because it determines the composition, pressure, temperature, phase, and energy of the vessel contents, all of which can have a significant effect on the predicted blast loads. In any case, as long as the vessel pressure is above 2 atmospheres at failure and the pressure is released abruptly, the resultant blast will be a shock wave (that is, suddenly applied).

The most recent simplified method was published by **Tang et al. (1996)** and consists of a series of nondimensionalized curves to predict the side-on pressure and impulse at a particular stand-off. These curves depict pressure and impulse as a function of:

- Pressure ratio (defined as burst pressure divided by ambient pressure)
- Ratio of specific heats of the vessel contents (a property of the gaseous contents of the vessel)
- Expansion energy potential of the vessel contents
- The temperature ratio (the ratio of the vessel internal temperature at failure to the ambient temperature)

The vessel energy term in this analysis should be corrected for ground reflection, liquid fraction in the vessel, and energy consumed by fragment production. In addition, the side-on pressures need to be modified to account for reflection and clearing effects; this is typically accomplished by using the methods outlined in **UFC 3-340-02**.

If more detail is necessary, a computational fluid dynamics model can be applied. These models can use their simplified physical models of thermodynamics and gas properties to compute the production and propagation of blast waves produced by a bursting vessel. It is important to note that there are complex interactions between the failing vessel and the fluid escaping the vessel that cannot be adequately modeled by any current program. In addition, the failure of the vessel is not wholly deterministic as cracks can propagate along microcracks and grain boundaries in a manner that cannot usually be predicted. As such, these numerical analyses will rely heavily on the experience and expertise of the analyst. The advantage of using a hydrocode is that it can directly produce load-time distributions on arbitrary surfaces and account for shielding and focusing effects produced by adjacent structures.

5.6—Vapor cloud explosions

The prediction of vapor cloud explosions (VCEs) is more complex than high explosives or bursting pressure vessels. The first step in determining blast load from VCEs is to

develop the release scenario for the flammable material. This selection process is typically done with input from process engineers and plant operations. Dispersion modeling is performed to model the release scenario and determine the size, shape, and concentration distribution of the flammable vapor cloud. This dispersion is overlaid onto areas of confinement and congestion to define the flammable mass that may participate in the explosion. In some cases, cloud dispersion is not evaluated and the confined/congested area is assumed to be filled with a stoichiometric mixture of flammable gas. This approach may be justified if it is evident that credible release scenarios can fill the area.

Blast loads may be determined using simplified methods consisting of graphs (blast curves) of pressure and impulse, or duration versus scaled standoff, or through more complex modeling using computational fluid dynamics (CFD).

In the blast curve method, the scaled standoff is computed by dividing the separation distance from the center of the explosion to the point of interest by the cube root of the energy content of the confined/congested flammable mass and multiplying by the cube root of ambient pressure. Reading pressure and impulse from the blast curves requires selecting from among the families of curves. The curves range from low flame speeds that produce almost negligible blast pressure to the supersonic flame speed of a detonation producing the highest pressure. Determination of maximum flame speed requires knowledge of the amount of confinement and congestion in the flammable portion of the vapor cloud, and the fuel reactivity. From this scaled

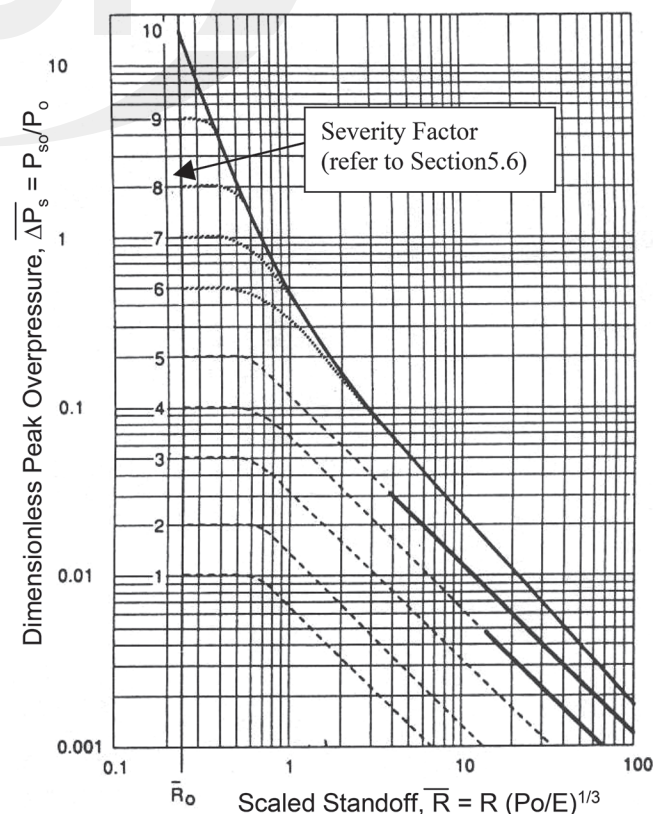


Fig. 5.6a—Overpressure versus scaled distance, TNT multi-energy method (Van den Berg 1965).

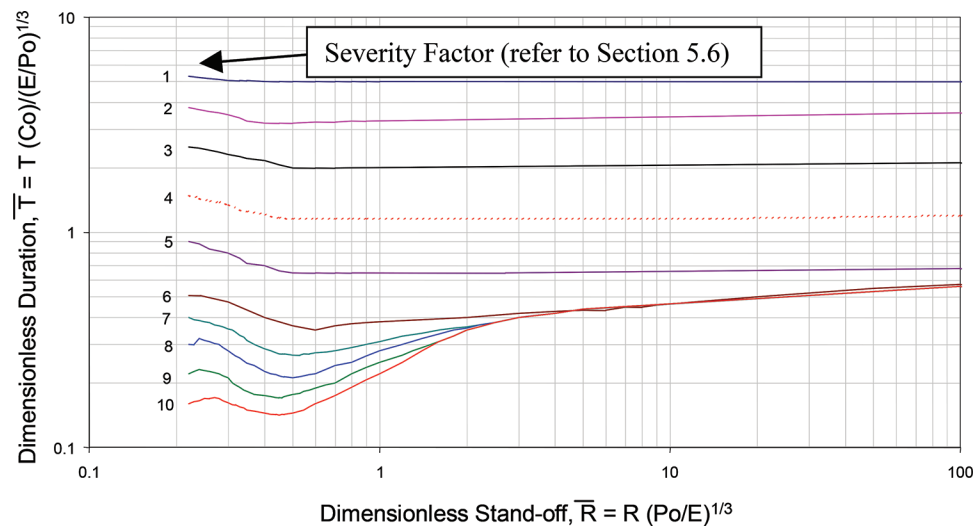


Fig. 5.6b—Duration versus scaled distance, TNO multi-energy method (Van den Berg 1985).

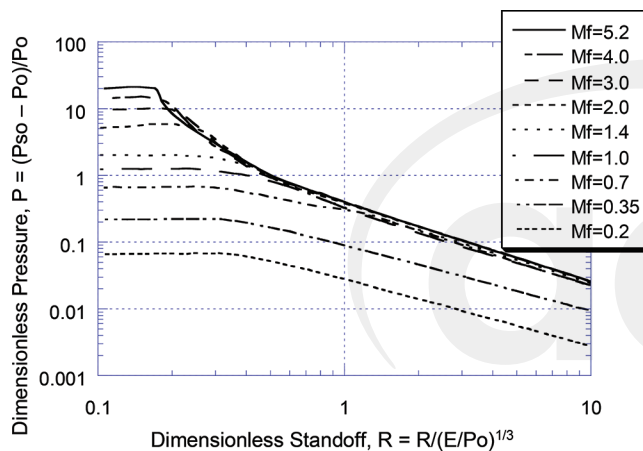


Fig. 5.6c—Overpressure versus scaled distance, Baker-Strehlow-Tang Method (Tang and Baker 1999).

standoff, scaled peak pressure and impulse (or alternatively duration) can be determined by selecting the appropriate explosion strength or flame speed. The two most commonly used scaled methods are TNO Multi-Energy method (Van den Berg 1985), most commonly used in Europe, and the Baker-Strehlow-Tang method (Tang and Baker 1999), most commonly used in North America. Both methods use a similar approach in which the severity factor (TNO Multi-Energy) or flame speed (Baker-Strehlow-Tang) is based on the degree of confinement and congestion as well as fuel properties. Van den Berg (1985) and Tang and Baker (1999) describe the methodology for selecting severity factor and flame speed. Figures 5.6a and 5.6b show the set of TNO Multi-Energy curves for overpressure and duration. Figures 5.6c and 5.6d show the Baker-Strehlow-Tang overpressure and impulse curves, respectively. Crowl (2003) and the Center for Chemical Process Safety (1994) give detailed descriptions for these methods.

A different approach is to develop a CFD model of the process area. A grid of computational cells is constructed

and the controlling combustion chemistry and gas kinetics equations are solved to track the progression of the reaction and resulting pressures. The end result is a pressure-time history at selected points. It is important for the structural analyst to know if the pressure-time plots are free-field or applied loads.

5.7—Load on structures

Free-field blast parameters obtained from the empirical relationships for high explosives and VCEs as described in the aforementioned methods must be modified to account for interaction with building surfaces before they are used in structural analysis. Additionally, other parameters become important that were not previously determined, including drag pressures, clearing times, and blast wave length.

5.7.1 Equivalent load shapes—The load and time history from a shock wave is of a shape similar to that shown in Fig. 5.1.2. This time history is typically simplified to a load time history with an instantaneous pressure rise and a linear pressure decay in the form of a right triangle. This simplified load is shown in Fig. 5.7.1. Peak pressure and impulse are preserved from the scaled shock parameters and an idealized duration t_e is computed by $t_e = 2I/P$. This simplified time history is readily applied to simple structural models to quickly determine response.

5.7.2 Reflected loads—A reflection occurs any time a surface impedes movement of a blast wave, and the reflected pressure on the surface is a function of the angle of incidence. Reflected loads are maximized when a blast wave impacts normal to the plane of the wall, termed normally reflected. These reflected loads can be determined directly from empirical blast curves using the P_r curve. Reflected blast loads are also produced when a blast wave strikes a surface at some oblique angle, although the pressure is less than normally reflected. Blast pressures applied when a blast wave propagates parallel to a surface are side-on or free-field.

The reflection coefficient C_{ra} , or ratio of reflected pressure