Report for the Design of Concrete Structures for Blast Effects

Reported by ACI Committee 370

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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.

CONTENTS

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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 similar progressive fashion as the Murrah building.

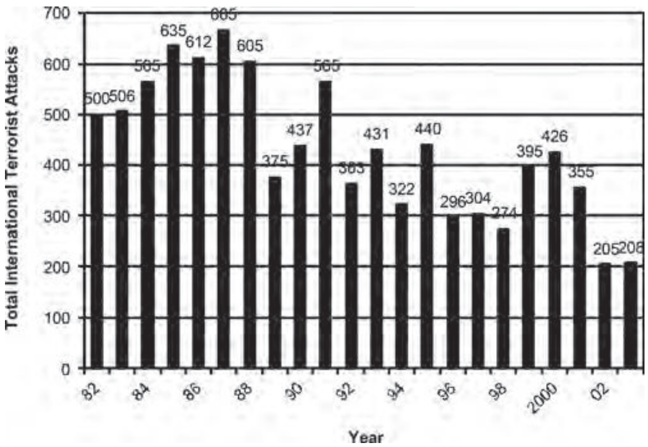

Fig. 1.2a—Total international terrorist attacks, 1982-2003 (U.S. Department of State 2003).

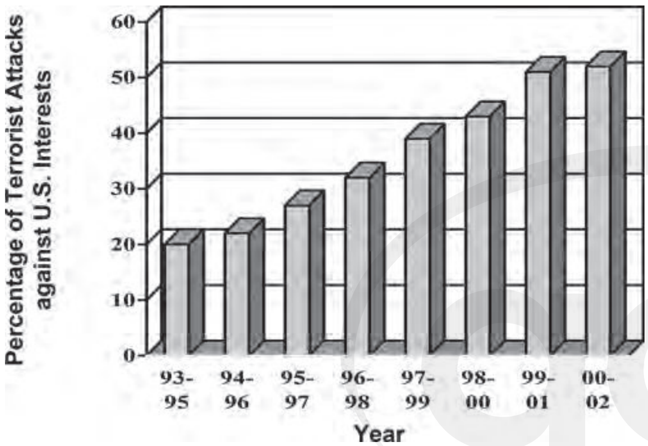

Fig. 1.2b—Terrorist attacks against U.S. interests as percent of total world attacks (Knight and Murphy 2004).

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

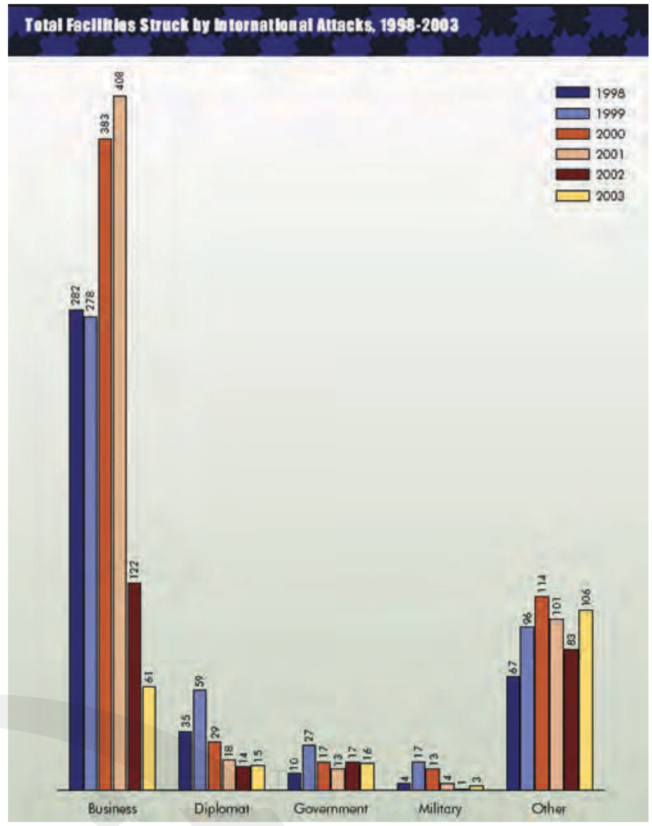

Fig. 1.2c—Total facilities struck by international attacks (U.S. Department of State 2003).

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)
$C_{r\alpha}$ = 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
$\bar{t}_d$ = 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
$\dot{\varepsilon}$ = strain rate
$^t\varepsilon$ = 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
$^t\sigma$ = 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
ϖ = 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 ft/lb$^{1/3}$ = 0.185 m/N$^{1/3}$).

shock front velocity—speed at which a shock front travels in the medium in which it propagates; shock front 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 of