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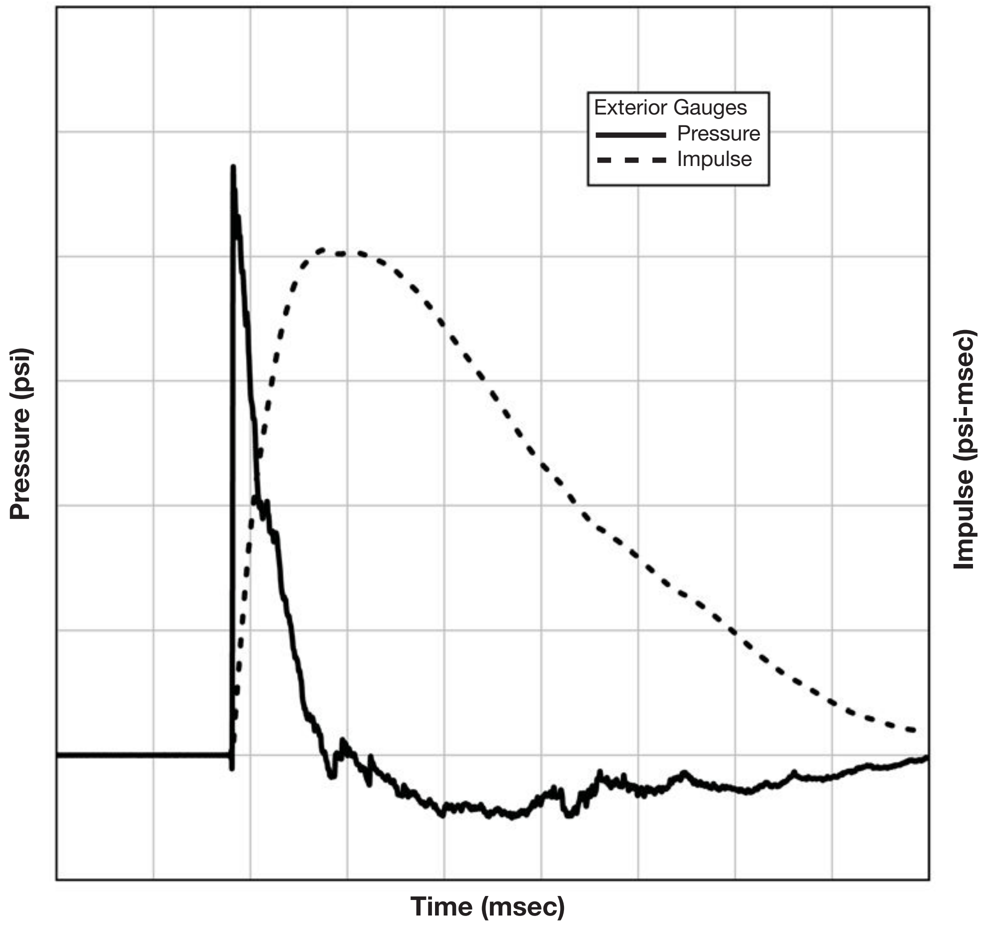
Steel Design Guide

Design of Blast Resistant Structures



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Design of Blast Resistant Structures

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Preface

This Design Guide provides guidance for the design of blast resistant structures and progressive collapse mitigation. Background information and some basic principles are reviewed, as well as the presentation of design examples. The goal of this Design Guide is to provide enough information for a structural engineer to effectively interact with a security or blast consultant.

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Chapter 1
Introduction

The purpose of this guide is to disseminate knowledge of blast resistance and progressive collapse mitigation to the structural engineering community, presenting basic theory with design examples so engineers and architects can achieve simple and effective designs.

Presently, security consultants with the assistance of the owner evaluate the particular vulnerabilities of a given facility and determine the appropriate and acceptable level of security risk. The risk assessment study determines the location and the size of the explosive threat. The blast consultants then calculate the blast pressures and review the design produced by the engineer of record. If the design is found to be insufficient, the blast consultant recommends upgrading the design and these revisions are incorporated into the construction drawings. It is advisable to involve the security consultant and blast consultant as early as possible in the planning and design process.

There is enough information provided in this guide to allow practicing structural engineers with a background in structural dynamics to interact with blast consultants to produce effective designs. The engineer of record can then proceed with the structural design based on the blast pressures given by the blast consultant. As it is with any unusual design, a peer review is a good idea and it is suggested that the final design be reviewed by a qualified blast consultant with experience in the design of blast resistant structures.

This guide is divided into the following chapters:

Chapter 2 addresses external blast explosions and is focused on the shock wave—not on fragment or projectile loading. The chapter does not cover the loads generated by a large blast in close proximity to the structure.

Chapter 3 addresses the evolution of documents related to the design of buildings for blast loading and provides guidance on the relevant factors in protective building design.

Chapter 4 addresses methods of dynamic analysis, simplifying multiple degrees of freedom into single degree of freedom systems, and determining the dynamic response to defined loads. It also explains the use of general structural engineering software to solve simple multiple degree of freedom problems.

Chapter 5 addresses the overall response of a building's structural system to blast loading.

Chapter 6 addresses member design, failure modes and design criteria including breaching, shear failure and bending.

Chapter 7 addresses steel connection design for blast loading.

Chapter 8 addresses basic progressive collapse concepts. Progressive collapse design is independent of blast design because progressive collapse may be caused by other possible events such as fire, accident, impact, etc. Examples demonstrating the determination of the structural response to progressive collapse are included.

The guide addresses only the behavior of structural steel under blast loading. It does not cover doors, windows, or any other structural material.

1.1 HISTORY OF INCIDENTS

In years past, blast resistant design was typically only used for facilities that either housed (or were in close proximity to) explosive material or were known as potential targets for attack. Munitions plants and storage facilities, strategic military and government facilities, and natural gas and petroleum refineries are a few examples of facilities that might have been designed specifically to resist blasts. However, the threat of bombings has increased in recent years. The incidents described in the following are closely associated with the evolution of the different security design criteria described in Chapter 3.

1.1.1 Blast Incidents

While numerous bombing events have occurred throughout the world, a small number of these events over the past three decades has had the largest impact on how the U.S. prepares for, and responds to, such events.

Notable events include:

- April 18, 1983—A suicide car bomber attacked the U.S. Embassy in Beirut, Lebanon, killing 63 people, 17 of whom were Americans.
- October 23, 1983—The U.S. Marine barracks in Beirut, Lebanon, were attacked by a suicide truck bomb killing 241 American military personnel.
- December 1983—Suicide truck bombers attacked the U.S. and French embassies in Kuwait killing 5 and injuring 86.
- September 20, 1984—The annex of the U.S. embassy in Beirut, Lebanon, was attacked with a truck bomb killing 24 and injuring the ambassador.
- December 21, 1988—A terrorist bomb destroyed Pan Am Flight 103 over Lockerbie, Scotland, killing 270 people.

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- February 26, 1993—The car bombing of the World Trade Center in New York, NY, resulted in the deaths of six and injuries to over 1,000.
- April 19, 1995—The A.P. Murrah Federal Building in Oklahoma City, OK, was attacked using a truck bomb, killing 168 people and injuring more than 500 others.
- June 25, 1996—Khobar Towers in Dhahran, Saudi Arabia, was truck-bombed, killing 19 airmen.
- July 27, 1996—Pipe bombing of Centennial Olympic Park in Atlanta, GA, during the 1996 Olympic Games.
- January 16, 1997—Double pipe-bombing at the Sandy Springs Professional Building in Atlanta, GA.
- February 21, 1997—Double pipe-bombing at the Otherside Lounge in Atlanta, GA.
- January 29, 1998—Pipe-bombing of the New Woman All Women Health Care Clinic in Birmingham, AL.
- August 7, 1998—Truck bombing of the U.S. Embassies in both Kenya and Tanzania. 224 people were killed in the two events, while nearly 5,000 sustained injuries.
- October 12, 2000—The USS Cole was attacked by a suicide boat while docked in the port of Aden, Yemen.
- September 11, 2001—Attacks on both the Pentagon in Washington, DC, and the World Trade Center in New York, NY, killed thousands and injured many thousands more. While these attacks did not involve the use of explosives, the airplanes involved were used as guided missiles that had explosive effects upon their targets (impact, deflagration and fire).
- May 12, 2003—Suicide bomb attacks on housing killed 34 people in Riyadh, Saudi Arabia.

Similar significant attacks in England, Russia, Spain, the Middle East, and other countries could be added to this list.

1.1.2 Progressive Collapse Incidents

The American Society of Civil Engineers (ASCE) standard ASCE/SEI 7-10 (ASCE, 2010a), Commentary Section C1.4 defines "progressive collapse" as "the spread of an initial local failure from element to element, resulting eventually in the collapse of an entire structure or a disproportionately large part of it." Although some experts may disagree, the following events are generally regarded as progressive collapse failures. Some are also examples of improperly designed or built structures that failed completely.

Notable progressive collapse events include:

- Quebec River Bridge, 1907. Bridge collapsed during construction killing 82 workers; compression members were observed to be distorted by up to 2¼ in., indicating incipient buckling. Improper design of lattice compression braces caused total failure of the partially constructed bridge.
- Ronan Point, 1968, UK. Small kitchen explosion caused partial collapse of 20 stories of a corner of an apartment building.
- Hartford Coliseum, 1978, Hartford, CT. Long-span space frame collapsed under a moderate snow load (less than 20 psf). Compression members had been improperly designed and the failure propagated through the entire arena.
- L'Ambiance Plaza, 1987, Bridgeport, CT. Collapse of two adjoining buildings that were under construction using the lift slab method. Triggered by loss of support of a slab at a column. 28 workers killed. Collapse propagated because final connections had not yet been made.
- Hyatt Regency Walkway, 1981, Kansas City, MO. Revised connection of hanger rods to framing had not been designed by a structural engineer. One connection failed and the lack of redundancy caused the complete collapse of both levels of walkways. Killed 114 people.
- World Trade Center 6, September 11, 2001, New York, NY. Several floors collapsed due to fire. The collapse was arrested by floors that were not on fire.
- World Trade Center 7, September 11, 2001, New York, NY. A fire caused the failure of a key structural member that resulted in the collapse of the entire building.

Progressive collapse failures may be due, in part, to concrete punching shear. Concrete codes now have structural integrity reinforcement that addresses this type of failure. Examples of concrete structures that have collapsed are:

- 200 Commonwealth Avenue, 1971, Boston, MA. A 17-story concrete high-rise under construction. Four workers were killed and 20 injured.
- Skyline Plaza apartment building, 1973, Fairfax County, VA. Collapsed during construction killing 14 workers; 34 others were injured.
- Cocoa Beach Condominium, 1981, FL. Collapsed during construction, killing 11 workers, and injuring 23 others.

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1.2 CHARACTERISTICS OF BLAST EFFECTS

An air blast creates a supersonic shock wave, increases the ambient air pressure in the environment, and may generate high velocity fragments due to the destruction of the container that holds the charge. The explosion can happen in an enclosed or open space. In the open there is no confinement of the explosives; therefore, there is no increase of air pressure due to confinement and venting is not relevant. In an enclosed space, venting the explosion byproducts is important.

Blast loads are different from the typical loads familiar to structural engineers due to their large magnitude and short duration. The speed with which a blast load is applied exceeds the loading rate of an earthquake by several orders of magnitude. Blast pressure may exceed hundreds and even thousands of pounds per square inch, but last only a hundredth or even a thousandth of a second. The structure is designed to absorb the energy from the blast. Designers use plastic design with ultimate dynamic strengths without load factors, capacity reduction factors, or safety factors. Due to the nonlinear nature of the response, member failure is characterized by large deformations and/or rotation. Further, the engineer must ensure that failure of members closest to the blast will not cause a failure that propagates to elements outside the area directly affected by the air blast loading. If members outside the area fail, a progressive collapse of the structure may be generated. To prevent progressive collapse, the structure should be sufficiently redundant to allow for load redistribution or members must have sufficient strength to preclude failure.

The patterns of blast damage on a particular structure will vary greatly due to several factors:

- Type/variety of construction, including materials, mass and stiffness
- Type of explosive
- Standoff distance between the charge and the structure
- Orientation of the charge to the structure
- Orientation of other structures surrounding the targeted structure

Structural damage from a blast varies significantly with distance from the charge, robustness of the structure, and characteristics of the material. Blast pressure drops significantly with increased distance and the resulting response is correspondingly decreased. Structural damage also lessens with increased robustness and increased material ductility. An example of these effects is the bombing of the Murrah Federal Building in Oklahoma City, OK, where many nontargeted buildings in the vicinity of the targeted building sustained significant damage from the blast. During the event, buildings up to 800 ft away from the charge experienced varying levels of structural collapse, largely due to the lack of robustness. Damage varied significantly based on the building construction and the distance from the blast. In addition, windows were broken in many buildings throughout the downtown area within a 1½-mile radius from the charge. The occurrence of breakage decreased, in general, with increased distance from the blast.

There are many different types of explosives, but 1 lb of trinitrotoluene (TNT) is universally used as a standard measure of effectiveness of explosive materials. Homemade explosives such as ammonium nitrate with fuel oil (ANFO) are less powerful than TNT, and thus equivalent weights of other explosive materials would have less effect than TNT. Some military grade explosives, such as C-4 and pentolite, produce more powerful effects using the same weight of material. TNT equivalence is a commonly used metric due to the lack of detailed information available for other materials. TNT weighs about 100 lb/ft^3. This means that the volume of TNT corresponding to 10,000 lb is 100 ft^3, which can be visualized as a 6-ft by 2-ft closet in the average home ≈ (6 ft)(2 ft)(8 ft) = 96 ft^3.

When an explosive device is located very close to a structure, both localized and global damage to the structure may occur. Localized damage may consist of flexural deformation, breaching (e.g., the pulverization of the material), and collapse of primary structural elements and wall systems in the immediate vicinity of the blast. As the distance from the blast increases, localized damage transitions to more widespread damage consisting primarily of broken windows and failure of weaker building components comprising the building envelope.

Varying levels of damage to a structure may also be seen as the orientation of the charge to the structure changes. In a uniformly constructed building, the side of the building directly facing the blast will experience a higher load and more damage than the sides which are not facing the blast. The sides not facing the blast will experience an incidental loading from the blast, which will be lower than the direct reflected loading applied to the side facing the blast.

Structures in the vicinity of the targeted structure may also affect blast patterns but to a lesser extent than the items listed above. A structure located between the explosive charge and the targeted structure will reduce the peak reflected pressure on the target structure. However, it should be noted that only under ideal circumstances will the reduction be significant. In many cases, the shock wave will re-form (almost to its original strength) over the distance between the structures. In certain instances, surrounding structures may even reflect and amplify the loads seen by the targeted structure. In general, however, the first shock loading (not subsequent reflections) will control the level of damage.

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