BLAST BASICS


Anatol Longinow

AUTHOR BIOGRAPHY

Anatol Longinow, PhD, PE is an Adjunct Professor of Civil Engineering at Illinois Institute of Technology (IIT), Chicago, Illinois and at Valparaiso University (VU), Valparaiso, Indiana. Prior to his current affiliations he was a member of the firm of Wiss, Janney, Elstner Associates, Inc. (WJE) for 16 years. There he specialized in evaluating the effects of accidental explosions, vibrations, wind and seismic loadings on buildings. Before joining WJE, he was on the faculty of the Department of Civil Engineering at IIT and prior to that at VU. He spent 20 years with the IIT Research Institute (IITRI) where he specialized in the evaluation of the effects of nuclear weapons, HE weapons, wind and seismic loading on structures.

ABSTRACT

This article (a primer on blast effects) begins by identifying general military and most commonly used commercial explosives. The manner in which explosives release their energy is described and the primary blast parameters for explosions in air are identified. The emphasis is on blast from surface explosions. This is followed by a brief discussion of the interaction of the blast wave with building structures. Strength of buildings when subjected to blast effects of high yield (nuclear) explosions is quantified. This is followed by a brief discussion of internal explosions. The final topic is a brief presentation of results of studies dealing with casualties in buildings produced by external blast.

INTRODUCTION

The purpose of this article is as a primer on the basic aspects of explosion phenomena as this applies to the effects of high explosives (military and commercial) and effects of accidental explosions from commercial substances such as natural gas, propane, and liquid fuels, etc., on structures and people.

EXPLOSIVES

Deliberate explosives come in two general categories, i.e., military and civilian or commercial. Military explosives include cased explosives such as bombs, mortar shells, bullets, etc., each designed for a specific form of delivery. This category also includes uncased explosives such as various plastic explosives used for demolition and other functions. These are referred to as high explosives. Low explosives include such products as propellants.

Commercial explosives include such products as dynamite, TNT (trinitrotoluene) and Ammonium Nitrate among others. Ammonium Nitrate is an essential ingredient in nearly all commercial explosives. Its predominant use is in the form of AN prill, a small porous pellet with fuel oil. More than two million pounds of these mixtures, commonly referred to as ANFO (Ammonium Nitrate Fuel Oil), are consumed each year. They account for approximately 80% of the domestic commercial market.

ANFO products have found extensive use in a variety of blasting applications including surface mining of coal, metal mining, quarrying and construction. Their popularity has increased because of economy and convenience. The most widely used ANFO product is oxygen balanced free-flowing mixture of about 94% ammonium nitrate prills and 6% No. 2 Diesel fuel oil.

Items which are capable of exploding, but whose primary function is not to act as explosives, include natural gas, propane, liquid fuels such as gasoline and many other chemicals. These are generally referred to as low explosives (Longinow, A., Alfawakhiri, F., 2003)

EXPLOSIONS

High explosives release their energy by a process called detonation, and low explosives, such as propellants, natural gas, propane, etc., by the process of rapid burning. The time required for the detonation of a quantity of high explosive is much less than that for the burning of a like amount of propellant. With high explosives, the rate of detonation is not markedly affected by the particle size; with propellants, grain size is all-important. The shattering effect of a high explosive detonation is great, that of low explosives much less so. These distinctions are not completely clear-cut, however.

A number of so-called low explosives can be made to detonate--even black powder, under great pressure, and proper conditions. The military (and terrorist) use to which high explosives are put depend on their great shattering power and their high rate of detonation.

Some high explosives, such as mercury fulminate for example, are very sensitive to heat and shock and can be easily detonated by a spark or other local application of heat. These types of explosives are used to initiate less sensitive explosives and are called primers. Other explosives less sensitive to heat and shock than primers are used as boosters, i.e., intermediates between the primer and the main body of the explosive. These are capable of being initiated by the former and of initiating the latter.

The quantities of these three types of explosives in a given weapon differ greatly. 1) A very small quantity of primer, usually less than one gram, is used; 2) the booster weight is ordinarily of the order of a pound to a few pounds; and 3) the bulk of the explosive content of a weapon, the insensitive part, may constitute over 99% of explosive.

The explosion of a booster gives rise to a compression wave in the main explosive. If detonation in the main explosive does not occur, this compression is propagated as a wave, at approximately the speed of sound, through the explosive. However, if the compression is sufficient, chemical reaction of the explosive will take place as the result of the elevated pressure and temperature in the compression wave. This chemical reaction is very rapid, and the products of the reaction have a very high pressure and temperature. This zone in which the chemical reaction takes place, called the detonation wave, is propagated through the explosive at a speed considerably in excess of the speed of sound in the explosive and is preceded by the compression wave which it supports.

The propagation velocity of the detonation wave depends on the chemical and physical properties of the explosive and, to some extent, on the dimensions of the explosive and the degree of confinement.

When the detonation wave reaches the interface between the explosive and the air that surrounds it (unconfined charge), the products of the detonation, largely gases, expand with high velocity, pressure and temperature. The boundary between the air and the hot compressed gases is sharply defined. Behind this layer the pressure and temperature at a short time interval later decrease rapidly to lower values toward the interior of the charge. The rate of expansion of the luminous zone (the burnt hot gases) continually decreases. Eventually another discontinuity emerges from the luminous zone and leaves it behind. This is the shock wave, a sharp discontinuous rise in pressure propagating through the air surrounding the explosion products.

If the charge is confined by a metal case, such as a steel case of a bomb, the pressure of the hot gases expands the case. At first the metal flows plastically, until the volume of the case has been increased considerably (about twofold for steel cases) and than it ruptures. The resulting fragments of the casing are propelled at a high speed, and since they are not at first retarded, they precede the shock wave over a great distance from the charge. The acceleration of the fragments requires energy, and the fragments may carry a considerable fraction of the detonation energy of the explosive away. For this reason, the energy and the pressure of the shock wave from a confined charge are considerably less than that from an uncased explosive charge (Longinow, A., Alfawakhiri, F., 2003; Glasstone S., Dolan, P. J., 1977)

PROPAGATION OF SHOCK WAVE IN AIR

As mentioned earlier, the rapid expansion of the mass of hot gases resulting from detonation of an explosive charge gives rise to a wave of compression called a shock wave, which is propagated through the air. The front of the shock wave can be considered infinitely steep, for all practical purposes. That is, the time required for compression of the undisturbed air ahead of the wave to the full pressure just behind the wave is practically zero.

If the explosive source is spherical, the resulting shock wave will be spherical, and since the surface is continually increasing, the energy per unit area continually decreases. As a result, as the shock wave travels outward from the charge, the pressure in the front of the wave, called the peak pressure, steadily decreases. At great distances from the charge, the peak pressure is infinitesimal, and the wave, therefore, may be treated as a sound wave.

Behind the shock wave front, the pressure in the wave decreases from its initial peak value. Near to the charge, the pressure in the tail of the wave is greater than that of the atmosphere. However, as the wave propagates outward from the charge, a rarefaction wave is formed which follows the shock wave. At some distance from the charge, the pressure behind the shock-wave front falls to a value below that of the atmosphere, and then rises again to a steady value equal to that of the atmosphere. The part of the shock wave in which the pressure is greater than that of the atmosphere is called the positive phase, and immediately following it, the part in which the pressure is less than that of the atmosphere is called the negative phase.

The pressure in the shock front and the pressure, temperature and composition of the undisturbed medium uniquely determines the speed at which the shock propagates. The greater the excess of peak pressure over that of the atmosphere, the greater the shock velocity. Since the pressure at the shock front is greater than that at any point behind it, the wave tends to lengthen as it travels away from the charge. In other words, the distance between the shock front and the part at which the pressure in the wave has decreased to atmospheric continually increases.

The time elapsing between the arrival of the shock front and the arrival of the part in which the pressure is exactly atmospheric is called the positive phase duration (see above). The quantity of interest in application of blast measurements is positive impulse, which is the area under the positive phase duration curve.

For each pressure range there is a particle or wind velocity associated with the blast wave that causes a dynamic pressure on objects in the path of the wave. In the free field, these dynamic pressures are essentially functions of the air density and particle velocity. For typical conditions, standard relationships have been established between the peak incident pressure, the peak dynamic pressure, the particle velocity, and the air density behind the shock front. The magnitude of the dynamic pressure, particle velocity, and the air density is solely a function of the peak incident pressure and, therefore, independent of the yield of the explosion. The following table (Table 1) lists particle velocities for overpressures in the range of 2 psi to 20 psi.

TABLE 1
OVERPRESSURES AND CORRESPONDING PARTICLE VELOCITIES

Overpressure (psi)	Velocity (feet/sec)	Velocity (miles/hour)
2	103	70
3	195	102
4	195	133
5	239	163
6	280	191
8	358	244
10	431	294
15	594	405
20	737	502

At very great distances from the charge, the wave becomes acoustic, i.e., the pressure rise, temperature rise, and particle velocity are all infinitesimal, and as mentioned above, the velocity of the wave is that of sound (Glasstone S., Dolan, P. J., 1977).

BLAST LOADS FROM SURFACE EXPLOSIONS

An explosion from a charge located on or very near the ground surface is referred to as a surface burst. The initial wave is reflected and reinforced by the ground surface to produce a reflected wave. The reflected wave merges with the incident wave at the point of detonation to form a single wave, essentially hemispherical in shape. A Mach front is formed by the intersection of the initial wave and the reflected wave from the ground. The shock front can be considered as a plane wave over the full height of the Mach front.

The height of the Mach front increases as the wave propagates away from the charge. The increase in height with distance is referred to as the path of the triple point and is formed by the intersection of the incident, reflected, and Mach waves. A structure is considered as subjected to a plane wave when the height of the triple exceeds the height of the structure (Glasstone, S., Dolan, P. J., 1977).

INTERACTION OF SHOCK WAVES WITH BUILDINGS

When a shock wave strikes a non-rigid obstacle such as a building, the wave is reflected by the surfaces of the building. At the instant the wave strikes the wall, the wall is accelerated and continues to accelerate as long as there is pressure on its outer surface. At first, the deformation of the wall is elastic, so that for insufficient excess pressure or insufficient positive duration there may be no permanent displacement of the wall. If the blast intensity is sufficient, the wall eventually deforms inelastically and suffers permanent displacement. If, for the wall in question, the displacement is greater than some critical amount, the wall will collapse.

The essential characteristics of loading and building response for transient loads produced by explosions depend primarily on the relationship between the effective duration of the loading and the fundamental period of the structure on which the loading acts. When the effective duration is very short, say less than one third of the period, then the impulse due to the transient loading is of major importance, and the response of the structure can be based entirely on a consideration of impulse and momentum. On the other hand, when the duration of the loading is relatively long compared with the fundamental period, then a quasi-static design can be made.

The effective duration of loading for a blast from one megaton of TNT is about 1 sec., for a kiloton equivalent energy about 0.1 sec., and for one ton, about 10 milliseconds. The duration varies as the cube of the energy of detonation. For energies corresponding to gas explosions or other explosives, the same relationship can be applied as a first approximation. The fundamental relations for developing blast-resistant design procedures are given in TM5-1300, 1990; TM5-855-1, 1986; Biggs, J. M., 1964; Newmark, N. M., 1953.

STRENGTH OF BUILDINGS

Depending on the geographic location, buildings are designed to resist gravity loads, wind loads, and seismic loads. Few, if any, conventional buildings are designed to resist blast loads.

During the decades of the cold war there was an interest in the United States to identify the best available shelter space. A fair amount of attention was devoted by the U.S. Civil Defense to determine the protective capabilities of existing buildings. The threat was that produced by the effects of nuclear weapons, which included thermal radiation, initial radiation and blast. Table 2 is a summary of a study conducted to categorize the strength of conventional buildings subjected to the effects of blast from nuclear weapons (Pickering, E. E., Bockholt, J. L., 1971)

TABLE 2
FAILURE OVERPRESSURES FOR CATEGORIES OF BUILDINGS

	Building type	**Free Field Failure Overpressure, psi**	**Failure includes either one or a combination of the following conditions**
1	Single story framed residences, with or without basements.	2.9	Roof collapse, gross displacement, collapse of walls.
2	Single story masonry load bearing residences with or without basements.	4.0	Same as "1"
3	Two or three story framed residences, row houses, motels, etc., with or without basements.	3.0	Roof collapse, gross displacement, collapse of walls, large portion of siding removed, gross deflection from vertical.
4	Two or three story masonry, load-bearing wall residences, apartments, motels, etc., with or without basements.	4.0	Same as "1"
5	One and two story "store front" and small commercial masonry load bearing wall buildings.	4.9	Same as "1"
6	Two to four story commercial, residential and office masonry load bearing wall buildings	5.0	Same as "1"
7	Multistory steel framed apartment buildings (two to ten stories). Heavy exterior walls - Light exterior walls -	10.2 6.8	Exterior walls and interior partitions blown out. Severe distortion of frame. Severe distortion of interior core.
8	Multistory reinforced concrete frame apartment buildings, (four to ten stories). Heavy exterior walls - Light exterior walls -	10.0 6.8	Same as "7"
9	Multistory steel framed office buildings (four to ten stories). Heavy exterior walls - Light exterior walls -	10.4 8.0	Same as "7"
10	Multistory reinforced concrete framed office buildings (four to ten stories). Heavy exterior walls - Light exterior walls -	10.2 8.0	Same as "7"

11	Steel framed office buildings, more than ten stories. Heavy exterior walls - Light exterior walls -	10.2 6.8	Same as "7"
12	Reinforced concrete framed office buildings. Heavy exterior walls - Light exterior walls -	12.0 6.5	Same as "7"
13	One story masonry load bearing wall buildings (such as schools, libraries, etc).	4.6	Same as "1"
14	Monumental masonry buildings, two to five stories, with or without structural frames	10.8	Roof collapse, gross displacement, collapse of exterior walls.
15	Masonry load bearing wall industrial buildings, one story	3.8	Same as "1"
16	Light steel frame industrial buildings, one story	6.4	Failure of structural frame.
17	Heavy steel frame industrial buildings, one story	10.0	Failure of structural frame.

BLAST LOADS FROM INTERNAL EXPLOSIONS

An internal or confined explosion will produce shock loads and, in most instances, quasi-static gas pressure loads from the confinement of the products of the explosion. This pressure has a long duration in comparison to that of the shock pressure.

As in free air, blast loads on a given surface will be generated from the direct shock wave and from shock waves reflected from other surfaces.

Even light partitions that fail in an explosion are present for a sufficient length of time (a few milliseconds) to provide reflecting surfaces for the shock wave and partial confinement of the gas loads.

Three degrees of confinement are possible, i.e., a) fully vented, b) partially confined, and c) fully confined. A fully vented explosion is one in which the gaseous products can escape through openings before significant gas pressure and impulse can be developed. A partially confined explosion is one in which venting does not occur quickly enough to eliminate gas pressure buildup, resulting in relatively long duration gas pressure loads and significant impulse. Full confinement is associated with essentially total confinement of an explosion as by a hardened structure. In this type of explosion, the gas pressure decays very slowly (NFPA 68, 2002).

Numerous deflagrations (explosions) on the inside of buildings are produced due to the accidental release, accumulation and subsequent ignition of gases such as natural gas, propane, etc.

CASUALTIES PRODUCED BY BLAST

People in buildings subjected to blast would be tumbled in the direction of the flow terminating in impact with hard surfaces inside the building. Some would interact with debris from the break up of the building walls, partitions, furniture, other people, etc. Some would be blown out of the building, terminating in impact with the ground plane. The extent of casualties would depend on the type of building, the yield of the weapon and the range of the given building from the weapon.

In a study (Longinow, A., 1979) conducted for U.S. Civil Defense, estimates of casualties were made for different buildings and shelters when subject to a large weapon (1 MT). For framed buildings (steel and concrete), up to four stories with weak exterior walls (weak curtain walls, large glass windows, etc.) the following results were obtained.

Probability of Survival	10%	50%	90%
Reference Free Field Overpressure, psi	11	7	5

Casualty mechanisms included blast translation terminating in impact with hard surfaces and interaction with debris from the breakup of the building walls, partitions, furniture, etc. These results are representative of large weapons in the Mach region and provide an indication of casualties that would be produced in buildings by external high explosives of smaller yields

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this narrative was to provide a very basic and general primer on explosions produced by surface bursts and their effects on buildings structures and people. The information on which this is based may be found in the open literature as shown in the list of references.

It is noted that a great deal of information dealing with the response of structures and people when subjected to blast effects comes from that developed for nuclear weapons during the decades of the cold war. This is not to say that such information is not useful in the present case. A lot of it is. Nonetheless, there is clearly a need to develop data that is specific to high explosives.

REFERENCES

Biggs, J. M., “Introduction to Structural Dynamics,” McGraw-Hill Book Company, 1964

Glasstone, S., Dolan P.J., (Editors) “The Effects of Nuclear Weapons,” prepared and published by the U.S. Department of Defense and the U.S. Department of Energy, Third Edition, 1977, reprinted by the Federal Emergency Management Agency

Longinow, A. and Alfawakhiri, F., “Blast Resistant Design with Structural Steel – Common Questions Answered,” Modern Steel Construction, AISC, October 2003

Longinow, A., “Survivability in a Nuclear Weapon Environment,” DCPA Contract DCPA01-77-0229, for Defense Civil Preparedness Agency, Washington, D.C. 20301, May 1979

Pickering, E. E., and Bockholt, J. L., “Probabilistic Air Blast Failure Criteria for Urban Structures,” Contract DAHC20-67-C-0136, for Office of Civil Defense, Office of the Secretary of the Army, Washington, D.C., 20310, November 1971

Newmark, N. M., “An Engineering Approach to Blast Resistant Design,” University of Illinois Engineering Experiment Station, Reprint Series No. 56, 1953

TM 5-855-1, “Fundamentals of Protective Design for Conventional Weapons,” U.S. Department of the Army, November 1986 (http://www.military-info.com/MPHOTO/p021c.htm)

TM 5-1300 Structures to Resist the Effects of Accidental Explosions,” U.S. Departments of the Army, Navy and Air Force, November 1990 (http://www.military-info.com/MPHOTO/p021c.htm)