BLAST RESISTANT DESIGN with STRUCTURAL STEEL

COMMON QUESTIONS ANSWERED

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Got questions about blast-resistant design? Check out this handy tear-out reference!

Strategies for blast protection have become an important consideration for structural designers as global terrorist attacks continue at an alarming rate. Conventional structures, particularly those above grade, normally are not designed to resist blast loads; and because the magnitudes of design loads are significantly lower than those produced by most explosions, conventional structures are susceptible to damage from explosions. With this in mind, developers, architects and engineers increasingly are seeking solutions for potential blast situations, to protect building occupants and the structures themselves.

The questions and answers that follow offer some explanation of explosions and the potential dangers they present to steel-framed buildings. The authors take a look at the historical response of steel-framed structures to blast situations and which types of structural frames, connections and steel shapes best resist blast loads. They also examine strategies designers can use to implement heightened building security and greater structural resistance to blast threats. Design specifications, code requirements, progressive collapse, seismic requirements and composite construction also are considered. Lastly, a list of references on the topic of blast protection is provided, along with information about computer software programs that can aid designers.

GENERAL EXPLOSION SCIENCE (SEE REF. 1,2,3)

What is an explosion? What are some common types of explosions?

An **explosion** is a rapid release of stored energy characterized by a bright flash and an audible blast. Part of the energy is released as thermal radiation (flash); and part is coupled into the air as airblast and into the soil (ground) as ground shock, both as radially expanding shock waves.

To be an explosive, the material:

1. Must contain a substance or mixture of substances that remains unchanged under ordinary conditions, but undergoes a fast chemical change upon stimulation.
2. This reaction must yield gases whose volume—under normal pressure, but at the high temperature resulting from an explosion—is much greater than that of the original substance.
3. The change must be exothermic in order to heat the products of the reaction and thus to increase their pressure.

Common types of explosions include construction blasting to break up rock or to demolish buildings and their foundations, and accidental explosions resulting from natural gas leaks or other chemical/explosive materials.

What is a shock wave?

The rapid expansion of hot gases resulting from the detonation of an explosive charge gives rise to a compression wave called a **shock wave**, which propagates 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 just ahead of the wave to full pressure just behind the wave is essentially zero.

If the explosive source is spherical, the resulting shock wave will be spherical. Since its surface is continually increasing, the energy per unit area continually decreases. Consequently, 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 can be treated as a sound wave.

Behind the shock wave front, the pressure in the wave decreases from its initial peak value. At some distance from the charge, the pressure behind the shock 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 or suction phase**.

What is a deflagration? How does it differ from a detonation?

A **deflagration** is an exothermic reaction (a moving flame front), which propagates from the burning gases to the unreacted material by conduction, convection and radiation. In this process the combustion zone progresses through the material (flammable mixture) at a rate that is less than the speed of sound in the unreacted material. In contrast, a **detonation** is an exothermic reaction characterized by the presence of a shock wave in the material that establishes and maintains the reaction. A distinctive characteristic of detonation is that the reaction zone propagates at a speed greater than the speed of sound.

Under proper conditions, flammable and combustible gases, mists or dusts suspended in air or another oxidant can burn when ignited. This could cause a **deflagration-induced explosion** to occur when the following conditions are met:

1. The presence of fuel mixed in proper proportions with the atmosphere (oxidant). Most gaseous fuels have lower- and upper-flammability limits for their concentrations in the air; and the concentration must be within these limits for a deflagration to occur.
2. The presence of air (oxygen) or other oxidant. Higher oxygen concentrations accelerate the rate of combustion, and low concentrations of oxygen reduce it.
3. The presence of an ignition source with energy output sufficient to initiate deflagration. Ignition can result from a hot surface, flame or spark. Location of the ignition source at the geometric center of a confined fuel-oxidant mixture results in development of the highest pressure and rate of pressure rise.
4. The combustion of a gas must generate a pressure greater than the structural capability (strength) of the confining structure. An explosion occurs when the enclosing structure ruptures.

What are the damaging effects of explosions to structures? (see Ref. 5)

Conventional structures, in particular those above grade, are susceptible to damage from explosions, because the magnitudes of design loads are significantly lower than those produced by most explosions. For example, design snow loads in the Midwest range from about 5 psf to about 50 psf. The peak pressure in the blast pulse produced by 10 lb of TNT at a range of about 50’ is approximately 2.4 psi (which is 348 psf!) with a duration of the positive phase of 7.7 ms. Conventional structures are not normally designed to resist blast loads.

Recent terrorist attacks demonstrate the types of damage that can be produced. The 1993 terrorist attack on the World Trade Center in New York City removed several thousand square feet of concrete floor slabs in the general area of the explosion and severely damaged several buildings’ communication, transportation and utility systems. Due to the inherent redundancy of the steel frames, the structures did not collapse.

The 1995 attack on the Alfred P. Murrah Federal Building in Oklahoma City revealed the vulnerability of conventional structural designs when subjected to blast loads. When a weapon is located at street level, the blast shock wave acts up against the underside of the floor slabs at upper stories. Floor slabs are not designed for this magnitude and direction of load—for this direction of load, the reinforcement is in the wrong place.

PHYSICAL SECURITY

What are the general objectives of defensive design involving a terrorist attack?

The main objective of defensive (protective) design of a civilian facility is to minimize casualties and damage. **Life safety** should be the primary design parameter. In certain situations it is also necessary to provide for the functional continuity of the facility. For example, a hospital must function after an attack in order to provide services for critical patients. Similar requirements apply to fire and police stations. While it is impossible to design all buildings against all threats, it is possible to design some buildings to be resistant to some threats. Defensive design often conflicts with aesthetics, accessibility, fire safety regulations and budgetary constraints.

What defensive strategies can be employed to reduce risks of terrorist attacks involving explosions?

The first step in the defensive design process is to establish the probable risk and the parameters of the threat to a facility. Risk of “collateral damage” to nearby buildings should also be considered. It is then possible to consider countermeasures (defensive strategies) to the threat. Common external blast threats are car, van or truck bombs. Internal blast scenarios involve a smaller explosive charge packed in a letter or a brief case, or a car bomb in a parking garage.

One way to protect a building from a possible attack is to make weapon delivery difficult. A set back distance and a secure fence around the building can serve this purpose. However, this approach often is not viable in a city where buildings adjoin other buildings along busy streets. In these cases, measures such as surveillance, limits on traffic movement and guards can enhance protection.

In the design of upgrades and retrofits of existing facilities, countermeasures that involve establishing a defensive perimeter (fences, bollards, etc.) and positioning the building at some distance from this secure perimeter often are not possible. Instead, threat countermeasures include the relocation of important functions to safer areas of the building. Other measure include hardening the mail area, moving people from external walls to inner offices, replacing or strengthening windows and window frames, hardened safety rooms, hardening portions of the building, or moving the entire operation to a more secure facility. In all circumstances, defensive strategies must incorporate some measures of facility-access control, contingency planning and emergency training for all occupants.

Open-Source References on Blast Design

The following list includes documents specific to the question asked as well as documents that are useful as background information on explosions, blast-resistant structural design and survivability of building occupants in blast environments.

Textbooks and Manuals

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

Norris, C. H., Hansen, R. J., Holley, M. J., Jr., Biggs, J. M., Namyet, S., Minami, J. K. *Structural Design for Dynamic Loads.* McGraw-Hill Book Company, 1959

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

"Fire and Blast – Criteria and Loading," Technical Committee 8, Planning and Design of Tall Buildings, International Conference on Planning and Design of Tall Buildings, Lehigh University, Bethlehem, Pennsylvania, August 21-26, 1972

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

"Design of Structures to Resist Nuclear Weapons Effects," ASCE – Manuals and Reports on Engineering Practice – No. 42, 1985

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

"Design of Blast Resistant Buildings in Petrochemical Facilities," ASCE Task Committee on Blast Resistant Design, 1997

UFC 4-010-01, *DoD Minimum Antiterrorism Standards for Buildings*, Department of Defense, 31 July 2002 (**www.tisp.org/files/pdf/dodstandards.pdf**)

Documents Pertaining to Blast Effects, Structural Design and People Survivability in a Blast Environment

Assheton, R. (Compiler). *History of Explosions – On Which the American Table of Distances Was Based, Including Other Explosions of Large Quantities of Explosives.* Bureau for the Safe Transportation of Explosives and Other Dangerous Articles, 1930

Longinow, A., Hahn, E.E., Bertram, L. A.,"Personnel Survivability in a Blast Wind Environment," *Journal of the Engineering Mechanics Division*, ASCE Proc. 103 (EM2), April 1977

Longinow, A., Chu, K. H., Thomopoulos, N. T., "Probability of Survival in a Blast Environment," *Journal of the Engineering Mechanics Division*, ASCE Proc. Paper 16991, April 1982

American National Standard for Estimating Airblast Characteristics for Single Point Explosions in Air, With a Guide to Evaluation of Atmospheric Propagation and Effects. S2.20-1983

Protection of Federal Office Buildings Against Terrorism. Committee on the Protection of Federal Facilities Against Terrorism, Building Research Board, Commission on Engineering and Technical Systems, National Research Council, National Academy Press Washington, D.C. 1988

"Structures for Enhanced Safety and Physical Security," Proceedings of the Specialty Conference sponsored by the Structural Division of the American Society of Civil Engineers, Arlington, Virginia, March 8-10, 1989 (Edited by T. Krauthammer)

Protecting Buildings From Bomb Damage—Transfer of Blast-Effects Mitigation Technologies From Military to Civilian Applications. National Academy Press, Washington, D.C., 1995

What is the difference between physical and operational security measures?

Physical security measures, also called passive security measures, include actions such as perimeter protection with walls, fences, bollards, planters and intrusion-detection alarms. It also includes actions like hardening the structure or portions thereof to mitigate blast effects if perimeter protection is not sufficient.

Operational security measures, also called active security measures, involve actions such as intelligence, surveillance and guards.

What specific blast effects are considered in defensive structural design?

As mentioned previously, in an explosion produced by a vehicle bomb, part of the energy is released in the form of thermal radiation, and part is coupled into the air as air blast and into the ground (soil) as ground shock.

For above-grade structures subject to surface attack and airbursts, air blast is the primary mechanism producing the potential for damage and casualties, and this is the loading that is used in design.

For buried or below-grade structures, depending on weapon yield, ground shock can be an additional design effect.

What is a "stand-off" distance? What is a "height of burst" (HOB)?

Stand-off distance refers to the direct, unobstructed distance between a weapon and its target. **Height of burst** refers to aerial attacks. It is the direct distance between the exploding weapon in the air and the target. For a bomb capable of being detonated above a target, an optimum height produces the maximum coverage by a given level of pressure, resulting in maximum damage. This is referred to as the optimum HOB.

How large are design blast loads? How are blast loads evaluated?

Selection of the blast charge size W is based on the perceived risk to the design building and any buildings nearby. Various factors play a role here, such as the social and economic significance of the building, security measures that deter terrorists, and data from previous attacks on similar facilities. The minimum standoff distance R is determined from the layout of a building's surroundings and reflects the expectation of how close to the building the design charge could explode.

W and R are two necessary inputs for the scaled distance parameter $Z = R/W^{0.33}$ that is used to determine "equivalent" design pressure impulses using published curves [see Ref.10]. For greater accuracy, computer programs such as *AT Blast* are available for free download at **www.oca.gsa.gov**.

Blast loads are applied to external building cladding if it is assumed to transfer the loads to structural elements. Where windows, doors and external walls are not expected to remain intact, blast loads also should be applied to internal structural elements. Floor slabs especially should be checked for uplift-pressure impulse. Blast loads usually are not factored and used in combination with unfactored gravity loads.

What are the most popular and cost-effective methods for upgrading existing buildings for physical protection?

Some level of blast resistance is required for new Federal Buildings. Existing Federal Buildings undergoing expansion also must include blast resistance. In each case the General Services Administration (GSA) establishes design requirements. Specific actions can involve: protecting windows; installing a secure perimeter fence and/or hardening a portion of the building; and determining the likelihood of progressive collapse and designing against it. There is no comparable, universal guidance in the civilian sector. However, some of the guidance developed by the Federal Government is available to the general public.

BLAST RESISTANT STRUCTURAL DESIGN

What is the historical experience with steel-framed structures subjected to Blast?

A study of 17 British buildings hit by German bombs during World War II examined eight steel-framed buildings, five reinforced concrete buildings and four wall-bearing buildings (see Ref. 6). The steel-framed buildings included office, apartment and industrial buildings, and a two-story railway station.

The weight of bombs ranged from 110 lb to 3,100 lb. In each case the charge weight was approximately 50 percent of the bomb weight. With one exception all were internal explosions and the type of damage was fairly typical.

One example is the explosion damage to a seven-story apartment building. This building consisted of a concrete-encased steel frame (for fire protection). The floors were 6” hollow tile with 3.5” concrete topping, supported on steel beams and girders. Exterior walls consisted of 9” brick and tile facing. Interior walls were 3” brick with plaster surfaces.

A 1,100-lb bomb perforated the roof and three floors and detonated just above the fourth floor. Damage to the seventh floor consisted of a failed girder due to impact from the bomb and about 100 sq. ft of floor area removed. Damage to the sixth floor included a buckled girder with torn out connections, several deflected beams and approximately 190 sq. ft of floor area removed. On the fifth floor, one girder deflected about 7”. Several other floor beams were bowed. Approximately 650 sq. ft of floor area was demolished. On the fourth floor, one girder was blown down together with four beams. One column deflected 7” and twisted, and about 700 sq. ft of floor area was demolished. The fifth floor was blown up; the fourth was blown down. One bay on each of the first, second and third floors is believed to have collapsed due to weight of debris from above. There was no fire. Due to the sufficient redundancy of the steel frame, the building did not collapse.

Another example of a steel-framed building subjected to an internal explosion was the World Trade Center on Feb. 26, 1993. A van containing approximately 1,800 lb. of fertilizer-based explosives was parked on an exit ramp just south of column 324, one of the main steel columns supporting the 110-story tower structure. The column measured about 4’ by 4’ across. It and six adjacent columns lost their fireproofing and lateral restraint (the bracing provided by the concrete floors that were blown out around them), but otherwise were not damaged by the explosion. The fact that the column did not buckle from the significant increase in its effective length speaks well for the redundancy in a building that probably was not designed for blast loading.

How different are seismic and blast effects on structures?

The first difference is in the way a given structure is loaded. In the case of an earthquake the structure is subject to ground motions that shake the structure from the base up. In the case of an explosion produced by an air or a surface burst, the structure is loaded by means of a compression wave (shock wave) over some area. Since a portion of the blast energy is coupled into the ground, the structure is also subject to ground motions similar to an earthquake, though much less intense.

A second difference is the duration of loading. For earthquakes, the duration of induced motions (shaking) can range from seconds to minutes. Additional loadings are produced by “aftershocks,” which are generally less intense than the initial shaking. For conventional explosives, the duration of a pressure wave is on the order of milliseconds.

For example, in the Oklahoma City event, the yield of the weapon was approximately 4,000 lb TNT equivalent. The truck containing the explosive was positioned about 10’ from the building. The peak pressure at the face of the buildings was about 1,900 psi, and the duration of the positive phase of the pulse was approximately 3 ms. Judging by the size of the crater, a fair portion of the energy coupled into the ground, producing ground shock. However, judging by the damage, clearly air blast was the primary damage mechanism. Further, earthquakes shake an entire building, but produce mostly horizontal loads at floor-slab levels, concentrating in the specially designed, laterally stiffer structural systems. Blast usually does not attack the entire structure uniformly, but produces the most severe loads to the nearest structural elements, both vertical and horizontal, with little regard to their stiffness. Uplift pressure load on floors is also a specific blast effect.

What is the role of structural ductility in blast resistance?

The term **ductility** refers to the ability of the material to absorb energy inelastically without failure—the greater the ductility, the greater the resistance to failure. Blast-resistant designs often conservatively assume elastic response in order to simplify design, minimize permanent (plastic) deformations, and reduce post-blast repairs, especially where functional continuity of the facility is considered. Due to their highly ductile features, structural steel frames provide additional ultimate resistance for a blast event exceeding in severity the design blast.

Ductile inelastic structural response can be expected during both severe blast and severe earthquake events. However, it is generally recognized that plastic hinge zones and ductility demands in the two events do not necessarily match because of the differences in the loading patterns and effects.

Does the mass of the structural frame play a role in blast-resistant design?

Yes. The inertia, as measured by the mass of the structure or structural member, is an important factor in the response to a dynamic-impulse lateral load such as a shock wave. Because steel is the most dense construction material, heavy and robust steel members are especially effective in resisting blast loads. This is evident in the performance of heavy tanks and battleships, the ultimate blast-resistant structures.

Do building codes require structures to be blast resistant?

For ordinary buildings, like apartments, offices, and stores, building codes do not require blast resistance. For buildings that house hazardous processes, building codes require special safety considerations. For example, the Uniform Building Code states that "walls, floors and roofs separating a use from an explosion exposure shall be designed to resist a minimum internal pressure of 100 pounds per square foot in addition to other conventional loads."

Which is better at resisting blast load effects—a moment frame or a braced frame?

The lateral stability of a moment frame is dependent on the bending stiffness of rigidly connected beams and columns. Adequate diagonal bracing or shear walls at selected locations provide the lateral stability of a braced frame. Elements of lateral stability often are distributed more uniformly in moment frames, in which case each part of the building is more likely to be stable on its own. Therefore, moment frames are the better choice for blast-resistant design. In braced frames, the diagonal braces or shear walls can be knocked out by an engulfing blast wave, reducing the effectiveness of the braced frame, unless special features are included to mitigate this potential behavior.

PROGRESSIVE COLLAPSE

What is progressive collapse?

Progressive collapse is the propagation, by a chain-reaction, of a local structural failure into the failure of a substantial portion of the building, disproportionate in magnitude to the original failure.

What events caused progressive collapse incidents in the past?

The 1968 failure of one corner of a 23-story residential precast concrete building in London (Ronan Point) was caused by poor connection detailing and was triggered by an explosion from a gas deflagration. In the aftermath, the UK introduced building regulations addressing progressive collapse. In North America, some examples of progressive collapse include the 12-story steel-framed Union Carbide office building, in Toronto, 1958; a 16-story cast-in-place reinforced concrete apartment building, Boston, 1970; and a 16-story post-tensioned concrete lift-slab building in Bridgeport, CT, 1987.

The Alfred P. Murrah Federal Building in Oklahoma City was a dramatic example of progressive collapse of a weakly redundant reinforced-concrete building, with collapse triggered by the vehicle bomb near the front of the building. As mentioned earlier, the building had minimal resistance to upward loads generated by the blast at street level.

What is robustness? How can one add robustness to a building?

When referring to a building, the term **robustness** implies the strength and sturdiness to resist excessive loads. A highly redundant steel-framed building can be considered robust.

It is more difficult and expensive to add strength to an existing building than to consider this aspect in a new design, especially for high-rise buildings. One notable building that has undergone strengthening (an increase in its robustness) is the Citicorp Building in New York City. After the building was built, it was discovered that it would not likely survive a particular wind condition. The building was strengthened effectively, but at a significant expense.

What official design specifications exist for reducing the risk of progressive collapse?

The sector of our economy that researches the protection of government buildings from terrorist attack and mitigates progressive collapse of these buildings is the General Services Administration (GSA), Department of Defense (DoD) and their contractors. GSA and DoD have developed guidelines for the protection of buildings against blast effects. Civilian-sector engineering firms that work for GSA on Federal Buildings receive these guidelines as dictated by a particular project. Some of these are available to the general public.

The GSA's "Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects," is available for free download at **www.oca.gsa.gov**. Also, "DoD Minimum Antiterrorism Standards for Buildings," is available for free download at **www.tisp.org/files/pdf/dodstandards.pdf**.

STRUCTURAL MEMBERS AND CONNECTIONS

How does high-rate loading, as produced by blast loads, affect steel properties? (See ref. 8, 9)

The yield stress of low-carbon structural steel subjected to dynamic loads tends to increase. The ultimate strength is less affected. Elastic modulus remains the same. Steels with higher-static yield stresses achieve a lower percentage in yield-stress increase under dynamic loading, as do weaker steels.

For example, an experiment on structural steel members consisting of mild steel (static yield stress of F_y = 37 ksi) associated with time to yield, showed dynamic-yield stresses in the range of 45 ksi and 50 ksi (an increase in the range of 22 percent and 35 percent). In this series, the time to yield ranged from approximately 1 s to 1 ms, and the fundamental period of the respective structural members was approximately 100 ms. For structural members with fundamental periods of less than 100 ms, test results indicated a dynamic yield stress of more than 50 ksi.

What are the common ranges for steel-deck gages and concrete-slab thickness in floors designed for blast resistance? Can lightweight concrete be used in blast-resistant design?

The traditional reinforced-concrete slab on top of steel deck, composite and non-composite, is an efficient blast-resistant floor system. Concrete-slab thickness depends on the magnitude of design-blast pressure, and the span between supporting beams. Two layers of reinforcement usually are required to sustain upward and downward loads. Steel deck can effectively prevent concrete fragmentation. Steel-deck type and gage are selected to support construction loads during concrete placement. Lightweight concrete is less effective in resisting blast loads than normal-weight concrete.

In blast-design applications, what can be done to ensure that concrete floor slabs do not separate from structural steel beams when subjected to uplift blast pressures?

One approach is to weld slab reinforcement to connector studs (in composite floors) or directly to steel support beams. Another option is to design and cast the beams integrally with the slabs.

What structural shape is the optimal choice for beams in blast-resistant floors?

The choice of structural members supporting a slab depends on the load magnitude and where it is expected to act. If the blast load is expected only on the top of the slab, such as a slab over a basement, then either a W-shape or hollow structural section (HSS) is likely to be effective. If the maximum blast load is as likely to act on top of the floor slab as on its lower surface, then both shapes are likely to be effective. When the underside is loaded, the support beams will be loaded both on the bottom and on their sides. The net direct load on the webs of W-shapes is likely to be minimal. Where significant torsion effects are likely, HSS are preferred for their superior torsion resistance.

What types of column sections are preferred in blast-resistant design?

Military manuals for blast-resistant design base procedures on material properties increased by approximately 10% to account for strain-rate effects. Columns designed to resist high blast loads usually have sufficiently small slenderness ratios, and buckling occurs plastically rather than elastically. Also, because dynamic-impulse load tends to suppress the occurrence of buckling, it is conservative to adapt static formulas to the dynamic case. The choice of structural shape will depend on a number of factors, like whether the column is subjected to an axial load, or to flexural and axial load. Since in the latter case the load can come from any direction, it is useful to use a shape that has equal flexural strength in all directions, such as a round or square HSS.

What types of steel-frame connections are effective in mitigating blast and progressive collapse effects?

Both bolted and welded connections perform well in a blast environment. If a welded connection can develop the strength of the connected elements (or at least the weakest of the connected elements), the connection will remain intact. The same is true for a bolted connection. However, welded connections need to be carefully detailed and constructed.

With large members (especially in moment frames), it can be difficult to develop member strength using bolts. However, certain bolted connections, such as those using top and bottom flange angles, can sustain significant inelastic deformations and sometimes are preferred in blast-resistant design.

ANALYSIS METHODS AND LITERATURE SOURCES

What analysis methods are used in blast-resistant design?

Most structures are complex in behavior even under static loads, and their response to dynamic loads might include additional complications from combinations of elastic and inelastic vibration modes.

A common approach to determine the dynamic response of a structure to some specific loading is to model the structure as a system of finite structural elements and masses connected together at a discrete number of nodal points. If the force-displacement relationships are known for the individual elements, structural analysis can be used to study the behavior of the assembled structure.

It is prudent for practical design purposes to adopt approximate methods that permit rapid analysis of complex structures with reasonable accuracy. These methods usually require that both the structure and the loading be idealized to some degree.

During the 1950s and 1960s, much work was done to develop simple methods for the design of structures subjected to blast loads produced by blast from nuclear weapons. [The book by J. M. Biggs (Ref. 12) which is a revision of an earlier book (Ref. 11) written by several authors including J. M. Biggs contains an excellent introductory presentation of such methods.]

What design/analysis software is available?

Blast design/analysis software for the general public is not available at this time. Software and design manuals exist in the U.S. Government and military sector, but these items generally are made available only to contractors doing work for U.S. Government agencies, such as the U.S. Army Corps of Engineers and the General Services Administration (GA).

As mentioned earlier, the software product *AT Blast*, deals with blast pressures and is available from the GSA website. There are programs available for the dynamic-response analysis of single-degree-of-freedom systems, such as *Nonlin*, which can be downloaded for free at:

www.app1.fema.gov/EMI/nonlin.htm

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REFERENCES

1. *Fire Protection Handbook.* National Fire Protection Association, Thirteenth Edition, 1969
2. Glasstone, S. and Dolan P. J. (Editors), *The Effects of Nuclear Weapons.* U.S. Department of Defense and the U.S. Department of Energy, Third Edition, 1977 Reprinted by the Federal Emergency Management Agency
3. *Guide for Explosion Venting.* NFPA 68–1978
4. Clayton S. White, “The Nature of the Problems Involved in Estimating the Immediate Casualties from Nuclear Explosions,” CEX-71.1, Civil Effects Test Operations U.S. Atomic Energy Commission, July 1971
5. Longinow, A., “The Threat of Terrorism – Can Buildings be Protected?” Building Operating Management, July 1995
6. “Effects of Impact and Explosion,” Summary Technical Report of Division 2, NDRC (National Defense Research Committee) Volume 1, Washington, D.C. 1946
7. *GSA Security Criteria.* Building Technologies Division, Office of Property Development, Public Buildings Service, General Services Administration, 1997
8. *Air Force Design Manual, Principles and Practices for Design of Hardened Structures.* Research Directorate, Air Force Special Weapons Center, Air Force Systems Command, Kirtland Air Force Base, New Mexico, December 1962
9. Crawford, R. E., Higgins, C. J., Bultmann, E. H. *The Air Force Manual for Design and Analysis of Hardened Structures.* Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, October 1974
10. “Structures to Resist the Effects of Accidental Explosions,” Dept. of the Army Tech. Manual, TM5-1300, Dept. of the Navy Pub. NAVFAC P-397, Dept. of the Air Force Manual, AFM 88-22, June 1969
11. Norris, C. H., Hansen, R. J., Holley, M. J., Biggs, J. M., Namyet, S., Minami, J. K. *Structural Design for Dynamic Loads.* McGraw-Hill Book Company, Inc. 1959
12. Biggs, J. M. *Introduction to Structural Dynamics.* McGraw-Hill Book Company, 1964 ★