Blast mitigation technologies: developments and numerical considerations for behavior assessment and design

T. Krauthammer

Department of Civil and Environmental Engineering, The Pennsylvania State University, University Park, PA 16802, USA
Email: tedk@psu.edu

Abstract

One of the last frontiers in structural dynamics is the behavior of structures under the effects of impact and explosions. Many serious difficulties exist in material modeling, load definition, and selecting effective approaches for addressing the behavior of complicated geometrical domains in a structure. This situation is especially difficult when considering structural concrete systems. Traditional computational tools may not be of much help, and special attention must be given to their application. Nevertheless, significant success can be achieved by including careful modeling of structural resistance mechanisms and insuring a physics-based approach in the numerical simulations. This paper addresses the development and application of some computational approaches (advanced SDOF, FE, FD, hybrid FE/FD, and combined symbolic-numeric) in support of behavior assessment and design of structural concrete systems.

1 Introduction and Background

A recent report by the National Research Council concluded that blast-hardening technologies developed for military purposes are relevant for civilian design practice. However, they must be adapted and expanded to be more specifically applicable, accessible, and readily. Additionally, it was noted that post-attack rescue and recovery operations can benefit from computer-based modeling and decision support systems. Finally, it was stated that barriers, including lack of
4 Structures Under Shock and Impact

professional education, exist to the effective transfer of relevant military technology to the civilian sector.

These findings might be surprising. After all, explosives have been used for several hundred years, and high explosives have been used extensively for about one hundred and fifty years. Since after WWII, the effects of both conventional and nuclear weapons have been well documented\(^2\,^3\). Consequently, scientists and engineers worked on the development of a better understanding of blast effects and how they can be mitigated. Therefore, it is only appropriate to review and discuss the state-of-the-art in computational support tools that can be used for behavior assessment and design of protective structures.

Explosive materials are designed to release large amounts of energy in a very short time\(^4\,^5\). This tremendous energy release causes the generation of shock wave in the surrounding media, which propagate away from the center of the explosion. The combined effects of pressure pulses and the corresponding particle velocities determine the characteristic local and global structural behavior.

Since after WWII, several sources were introduced which contained information on the nuclear threat and its mitigation. The last two publications in this group\(^6\,^7\) represent the state of the art in the design of protective structures to resist nuclear blast effects. Before the early 1970s, the nonnuclear explosion threat was treated less rigorously. The experiences in Vietnam and the real needs for explosive safety gradually shifted more attention to this issue, and a variety of related publications appeared. Similarly to the publications on the nuclear issue, most of these sources contain considerable amounts of empirical information and practical guidelines. Currently, the state-of-the-art in the design of structures to resist conventional and chemical explosions is represented by four publications\(^8\,^11\).

A computational support tool based on TM 5-855\(^8\) has been developed\(^12\), and it can be used effectively for conventional weapon effects calculations. Summaries and extensive descriptions of various other codes that can be used for a wide range of weapon effects and structural response calculations were published recently\(^13\).

Biggs\(^14\) provided a text on structural dynamics with special attention to blast effects and its mitigation. Although the primary emphasis was on the nuclear blast problem, the thorough treatment of the related dynamics problems enables also consideration of other cases. Baker et al.\(^15\) gave special attention to the issue of accidental explosions of various chemical compounds, and their book contains both scientific and practical treatments of related blast mitigation. The concept of Pressure-Impulse diagrams was presented and used to explain structural response to explosive loads, and the issue of blast resistant design was included.

Most of the available design manuals include analysis and design guidelines, but those are based primarily on simple single-degree-of-freedom (SDOF) considerations. Nevertheless, new resources are currently under development, and these are expected to include significant improvements and be made available to the technical community. The computational design aids that were developed in parallel to the evolution in design manuals are discussed next.
2 Computational Support Capabilities

The loading environments associated with many relevant threats (such as, impact, explosion, penetration, etc.) are extremely energetic, and their duration is measured in milliseconds (i.e., one thousand times shorter than earthquakes). Structural response under short duration dynamic effects could be significantly different from the much slower loading cases, and the designer must provide suitable structural detailing. Therefore, the designer must explicitly address the effects related to such severe loading environments, besides the general principles used for structural design to resist conventional loads. Due to the complexity of these phenomena, designers must employ appropriate computational tools in support of design activities.

Closed-form solutions are limited to simple geometries, simple loading and support conditions, and linear materials. Therefore, these methods will not be addressed herein. Approximate, simplified, methods are based on assumed response modes, and it is recommended to use such methods with data from computer codes that are based on current design manuals. Advanced numerical methods require significant resources, and they cannot be used effectively for typical design activities. Nevertheless, these approaches could be used in the final stages of detailed structural analyses for obtaining design guidelines and/or for the detailed evaluation of the anticipated structural response. Furthermore, structural response calculations may not be valid for scaled ranges less than 1 (ft/lbs), and structural breaching calculations must be done separately from structural response analyses. However, breaching calculations require the use of advanced computational tools (e.g., hydro-codes).

2.1 Simple approximate computational approaches

When subjected to extreme loads, structures may fail in a variety of ways. Depending on the characteristics of the loading, the proximity and intensity of the blast to a structural member, the response of the structure will determine the resulting mode of failure. Contact, or close in, explosions produce a cratering effect on the near side of the element, and spalling on the opposite face. These two damage mechanisms weaken the section and when the zone of spall overlaps the cratered region the section is breached. The capacity of different materials to resist cratering, spalling and ultimately breach, dictate the thickness required to maintain structural integrity. Typically, the material behavior dictates the modes of deformation and the resulting patterns of failure. Other modes of local failure that may result from direct blast involve shear failures. Typically, concrete materials are weak in tension. When subjected to a principal tension that exceeds the tensile capacity of the material, the reinforcing steel crossing the failure plane holds the aggregate together allowing shears to be transferred across the section. When the capacity of the reinforcing steel is reached, its ability to hold the sections together across the failure plane is diminished and the ability of the section to resist shear is lost. Similarly, flat plate slabs must transfer the loads to the columns through shear at the column slab.
interface. Although the area of this interface may be increased by means of drop panels, dowel action and shear heads, the capacity of the slab to transfer the load to the columns is limited by the shear capacity of the concrete. Extreme loads on short deep members may result in a direct shear failure before the development of a flexural mode of response. This direct shear capacity is typically associated with a lower ductility and a brittle mode of failure.

Each of the preceding modes of failure is associated with a fundamental frequency of response and therefore influences the characteristics of the load that the member feels. The dynamic response of the structural element to the transient blast loads will determine how much deformation the element undergoes. The highly impulsive loads are no longer acting on the structure by the time the structure reaches its peak response and the system may be idealized by a spring mass system set into motion by an initial velocity. Stiffer structural elements, or modes of deformation associated with higher frequencies of response, may respond to the same blast environment with a greater dynamic amplification factor. However, the characteristics of the higher frequency system will determine the peak deformations associated with the transient loading. Therefore, considering an elastic plastic single degree of freedom analogy for each of the various modes of failure will provide a reasonable means to determine the dynamic response of the element and its ability to deform within prescribed limits. Each analogy, however, depends on the proper detailing of the section to guarantee the capacity can be achieved and the ultimate deformation can be withstood.

The relationship between load and response under static conditions for a single-degree-of-freedom (SDOF) mass-spring-damper system is well known. One must know well both the load and the characteristics of the structure. Impulsive loads are loads with short duration compared with a characteristic time T (e.g., period) for the loaded structure. Such loads are often generated by high explosives or detonating gases. Blast effects, especially from explosive devices, are often accompanied by fragments, and the combined effect (i.e., loads) is not well defined. Blast parameters from spherical high explosive charges in open air are well known, and they can be found in various handbooks and technical manuals, cited above. When an air blast is reflected by a non-responding structure, a significant pressure enhancement is achieved (could be between 2 to 8 times the incident pressure), and such reflected pressures should be used as the load on the structure. For detonations in complex, and/or non-responding structural geometries, accurate determination of such parameters can be achieved with available computer programs. There are currently no fully validated computer programs for the prediction of explosive loading parameters for cases in which the medium-structure interaction exhibits a significant structural response. The equation of dynamic equilibrium for a linear SDOF system is shown below:

$$ F(t) = M\ddot{x} + C\dot{x} + Kx $$

In which, F is the magnitude of the applied load, K is the structural stiffness, M is the mass and C is the damping coefficient, respectively. \( \ddot{x} \), \( \dot{x} \) and x are the acceleration, velocity, and displacement, respectively.
The differences between the static and dynamic cases arise from the effects of inertia, $M\ddot{x}$, and damping, $C\dot{x}$, that do not participate in the static response. Usually, the effect of damping is small, but the inertia effect could be significant and it may dominate the response whenever loading durations are much shorter than structural response times. Furthermore, unlike the static case where the magnitudes of force and stiffness determine directly the corresponding deflection, in the dynamic domain the response (i.e., deflection, velocity and acceleration) is obtained by solving the given differential equation. The system response will depend not only on the magnitude of the force, but also on the relationship between the dynamic characteristics of the force and the frequency characteristics of the structure. Various design manuals\cite{6,7,8,9,10,11} contain dynamic response charts and tables that are based on SDOF considerations, and these can be used for design.

Four characteristic parameters must be known about the structure under consideration to employ an SDOF model of the structure: Equivalent load $F(t)$, mass $M$, and stiffness $K$ (damping $C$ that is valid in the elastic response regime is ignored in most design manuals). Mass and stiffness parameters for the structural system under consideration are selected based on the type of problem, load source, type of structure, and general conditions for load application to the structure. For example, localized load on a small part of the structure, a distributed load over a large part of the structure, etc., and the expected behavioral domain (linear elastic, elastic-perfectly plastic, nonlinear, etc.). Neither Biggs\cite{12} nor the design manuals provide information on the treatment of fully nonlinear systems by SDOF simulations. However, such approaches were presented in the literature, and they can be employed for analysis and design\cite{13,14,15,16}. The continuous structural element is represented by an equivalent single-degree-of-freedom (SDOF) system, which is a modified version of the previous equation:

$$\frac{F'(t)}{M'(x)} = \ddot{x} + 2\xi\omega'\dot{x} + \left[\frac{R(x)}{M'(x)}\right]x \quad (2)$$

In which $x$, $\dot{x}$, and $\ddot{x}$ are the displacement, velocity, and acceleration, respectively, of the point on the structural element that is being modeled. $M'(x)$ represents the equivalent mass of the system, $R(x)$ is the resistance function, and $\omega'$ is the damped natural circular frequency. $M'(x)$, $R$, and $\omega'$ are nonlinear numerical functions that depend on the state of deformation of the system. $\xi$ is the damping ratio of the system, given as a ratio of the critical damping (i.e., $\xi = C/C_c$). As noted earlier, the damping contribution, $2\xi\omega'\dot{x}$, may be ignored for non-elastic responses by setting $\xi = 0$. $F'(x)$ is the equivalent time dependent loading function. The nonlinear load-deflection relationship serves as the skeleton resistance curve, based on which the dynamic resistance function and the dissipation of energy are evaluated. The equivalent mass of the SDOF system is derived based on the deflected shape of the structural member. This approach bears similarities to previous methods\cite{5,8,10,12}. However, the derivation of nonlinear resistance functions for various structural behavior mechanisms and other parameters was discussed later\cite{16}.

One should distinguish between structural elements that are sensitive to pressure and those that are sensitive to impulse, as addressed in design manuals\cite{10}. This leads to the introduction of the pressure-impulse (P-I) diagram concept. The
basic idea of a pressure-impulse relationship is not new. It is a direct outcome of applying a pressure pulse to a linear SDOF oscillator\(^5\). One can compare the structural response of different elements with the ratio \(t_d/T\), in which \(t_d\) is the duration of the applied load and \(T\) is the natural period of the element. It should be noted that \(T=2\pi/\omega, \omega=(K/M)^{0.5}\), and \(K\) and \(M\) are the stiffness and mass for the equivalent SDOF, respectively. It has been shown that if \(t_d>T\), the structure will reach its peak displacement well before the load has diminished. Here, one can use the principle of energy conservation and show that the limiting peak displacement will be equal twice the static displacement \((x_{max}/x_{st} = 2)\). This behavioral domain has been called quasi-static or pseudo-static. If, however, \(t_d\ll T\) the load will diminish well before the structure will reach its peak displacement. Again, one can use the principle of energy conservation and show that the limiting displacement ratio will be \(x_{max}/x_{st} = 0.5 \omega t_d\). This behavioral domain is defined as impulsive. When \(t_d\approx T\), the behavior is defined as dynamic and one needs to perform a dynamic analysis for deriving the structural response values. Furthermore, one can combine the information presented above into a normalized pressure-impulse (P-I) diagram, and it can be used to define the type of expected response in the structure under consideration. The approach enables designers to select appropriate analysis and design approaches for a particular case. This basic concept can be expanded by selecting different linear oscillators, each representing a different type of structural element, for deriving specific P-I diagrams for each case. Then, each element in the structure under consideration could be evaluated independently, and such individual behavior characteristics could be used also for high explosive damage assessment.

Computer codes based on the P-I approach can provide an approximate method to determine building vulnerability to explosive events\(^21\). Damage calculations are made in two steps: First, damage in each structural component of the building is calculated (i.e., beams, columns, walls, etc.) using P-I graphs that define several damage levels (e.g., 0%, 30%, 60% and 100%). Such P-I curves are developed to predict component blast damage based on the element type, structural properties, and blast loading environment. Second, the damage calculated for each structural element is combined in a weighted manner to derive a percentage of building damage. Building repairability and reusability are computed in a similar process.

Multi-degree-of-Freedom (MDOF) approaches are generally similar to SDOF methods, but they include several masses, springs and dampers. Each mass may undergo motions (i.e., displacements, velocity and acceleration), and it represents the behavior of a particular location in a structure, or an attached system. Instead of solving a single equation of motion, one has to address a system of equations. The coupling between these individual equations depends on the structural complexity and the structural/mechanical coupling in the physical system. Obviously, one may envision cases for which a very large systems of equations would be required, and such approaches were used frequently in the 1950s and 1960s. However, these approaches were largely displaced by more general and useful finite element or finite difference codes.
2.2 Intermediate approximate computational approaches

SDOF methods can provide information for one point in the structural system under consideration. Although such information is valuable for supporting design activities, it could be a serious limitation when the structural behavior is under consideration. For such advanced design/behavior analysis, one may have to employ more detailed computational approaches. For example, one could employ Timoshenko beam or Mindlin plate formulations for the analysis of structural elements subjected to blast and shock. Therefore, such procedures could be defined as ‘intermediate approximate methods’. Recent developments in this direction showed their ability to obtain detailed behavioral information (considering several combinations of flexure, shear and axial modes), however, the required computational resources were very modest. Although such approaches are much more advanced than SDOF methods, they are limited to the consideration of single elements, or of simple structural systems. Despite their enhanced capabilities, as compared with SDOF models, these approaches have been used infrequently in support of facility design. However, they could become much more popular in the future.

2.3 Advanced approximate computational approaches

Advanced computational methods include various finite element, finite difference and hybrid codes. Such approaches, however, require large computational resources, they cannot be used effectively for typical design activities and they should be employed selectively. Nevertheless, they can be very useful for the assessment of structural behavior under the expected loading conditions and in support of design activities. Several recent examples for such applications can be cited for illustrating these capabilities. A hybrid (FE/FD) approach was used for the analysis of shallow-buried arch structures subjected to surface blast loads. Those analyses showed the evolution of damage for the medium-structure interaction and structural response phenomena. A similar approach was used to study the behavior of structural concrete beam-column connections, and to assess the influence of detailing parameters on their performance. An advanced finite element code was used to study the behavior of three-dimensional structural concrete connections, and the specific contributions of reinforcement details on the behavior.

2.4 Structural assessment support tools

Structural assessment following explosive loading events are essential tools in support of rescue and recovery operations. Under such conditions, personnel must decide quickly about demolition and evacuation, and on how best to apply the physical resources that would be available on a site. Unfortunately, such events are very stressful and decisions must be made without the ability to perform extensive analyses. Sometimes, the individuals who must decide may not have adequate technical background in the corresponding engineering fields. Such conditions are ideal for the application of coupled symbolic-numeric decision support tools that can
be used by trained personnel in performing the required damage assessment operations. Recent studies showed the effectiveness of such approaches. Furthermore, experiences from incidents in which buildings were severely damaged by explosive devices have shown that such decision support tools are urgently needed.

3 Conclusions and Recommendations

A vast amount of information on the behavior, design and construction of fortifications has accumulated during the last half century. Nevertheless, many design manuals and their supporting computational tools rely heavily on SDOF approaches. Typical SDOF approaches are based on linear, or very simple nonlinear, structural behavior assumptions. As a result, they may not provide efficient support for modern design activities. Modifications that enhance their nonlinear behavior simulations have been shown great promise, and gradually they are being adopted for such applications. It was noted that the best results are obtained when a structure is analyzed gradually by employing a range of validated numerical approaches from simple to advanced. Developing the appropriate design and construction technologies and the corresponding computational support tools, is important. However, developing the approaches for implementing them by the technical community is also important. Many aspects of such technologies have been developed by various military organizations. Nevertheless, their direct application in the civilian sector may not be simple. The civilian construction industry is using different materials and procedures than those employed for military fortifications. The structures are less massive, and they use many materials and components that were never considered under violent dynamic effects. There is an urgent need for research and development aimed at remedying this problem.

Education and training are central aspects of the required developments to enable the transition of such technology to the technical community. Such training and technology transfer should be handled collaboratively by professional societies, leading universities, and the research and development organizations that will continue to be active in this area.

References


12 Structures Under Shock and Impact


