Blast: Characteristics, Loading and Computation—An Overview

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Abstract This paper presents the state of the art for blast load characterization, loading pattern and its computation for the analysis of engineering structures. Various empirical relations available for computation of blast load in the form of pressure-time function are presented in concise form for easier understanding. Based on this study, functions are suggested for computing the pressure-time load history for a structural response. Explanation is presented for empirical, semi-empirical and numerical methods for prediction of the blast load. Different numerical simulation techniques for modelling the blast load are presented. Various material models available in hydrocodes are also discussed for modelling advanced structural materials to be used in blast response mitigation.

Keywords Blast wave · Empirical relations · Friedlander wave equation · Peak pressure · Impulse

1 Introduction

In last 20 years, majority of terrorist attacks on civil buildings and structures are carried out using high explosive devices. The reason is that, high explosives results in devastating effects and meagre survivability of structure and its occupants. It is September 11, 2001 attack, which lead to change in focus of research in particular to analysis, design and protection of buildings against blast. More and more research emphasis is put towards making building/structures safe against such manmade devastating attacks.

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Explosion is categorized into three main categories i.e. physical, nuclear and chemical explosion. Example of physical explosion include failure of gas cylinder, eruption of volcano or mixing of two liquids at different temperature or the mixing of a hot particulate material with a cool liquid. In nuclear explosion, energy is released from formation of different atomic nuclei by redistribution of protons and neutrons within the interacting nuclei. Whereas, a chemical explosion involves rapid oxidation of fuel elements (carbon and hydrogen atoms) contained within the explosive compound. Chemical explosion is major source of terrorist attacks all over the world. Most of explosives are condensed, which means that these are either solid or liquid. There are two terms associated with the explosion (a) detonation and (b) deflagration. When explosive material decomposes at a rate much below the speed of sound in material, process is known as deflagration, whereas, detonation is the form of reaction of explosive which produces a high intensity shock wave and is the main characteristics of high explosives. Explosives are classified on the basis of their sensitivity to ignition and named as primary or secondary explosives. Primary explosives like mercury fulminate and lead azide can be easily detonated by simple ignition from spark, flame or impact. Secondary explosives such as TriNitroToluene (TNT) and Ammonium Nitrate Fuel Oxide (ANFO) when detonated create blast/shock waves and result in large scale damage to the surrounding [1].

1.1 Reference Explosive

There exist wide range of explosives and energy release after the explosion for each type of explosive is different. TNT is referred as standard explosive and all other explosives are expressed in 'Equivalent TNT' by using a conversion factor based on their mass specific energy. These factors are presented in Table 1 for some of the commercially available explosives and can be used for conversion to reference explosive for analysis purpose [2]. Explosion results in very high pressure blast wave propagating away from the centre of explosive source. This blast wave will load the structures or any obstruction to a very high magnitude of loading. The major characteristic of blast wave is short duration and high magnitude. In order to safeguard the structure against such loading, first requirement is to isolate the structure and secondly, structure should be designed to resist such high magnitude and short duration loading. This can be only be achieved by understanding the loading pattern and behaviour of structure in this complex situation. Hence, it is of prime importance for a structural designer to understand the blast and blast loading. This is the main focus of present paper to explain in a very simple way about the blast and blast loading.

Table 1 TNT equivalence of commercially available explosives [2]

S. No.	Explosive	Mass specific energy Q_x (kJ/kg)	TNT equivalent (Q_x/Q_{TNT})
1	Torpex (42 % RDX, 40 % TNT, 18 % aluminium)	7,540	1.667
2	Nitroglycerin (liquid)	6,700	1.481
3	PETN	5,800	1.282
4	HMX	5,680	1.256
5	Semtex	5,650	1.250
6	RDX (Cyclonite)	5,360	1.185
7	Compound B (60 % RDX, 40 % TNT)	5,190	1.148
8	Pentolilte 50/50 (50 % PETN 50 % TNT)	5,110	1.129
9	TNT	4,520	1.000
10	Tetryl	4,520	1.000
11	Blasting gelatin (91 % nitroglycerin, 7.9 % nitrocellulose, 0.9 % antacid, 0.2 % water)	4,520	1.000
12	60 % Nitroglycerin dynamite	2,710	0.600
13	Amatol (80 % ammonium nitrate 20 % TNT)	2,650	0.586
14	Mercury fulminate	1,790	0.395
15	Lead azide	1,540	0.340

2 Brief History of Blast Analysis

Herein focus is on high intensity blast waves which are the characteristics of high explosives. Their characterization in free air by experimental methods has a long history dating back to World War II [3]. Stoner and Bleakney [4] reported results of free air experiments conducted with small TNT and Pentolite charges of various shapes. Goodman [5] compiled the free air blast measurement conducted after World War II. Baker [6] provides an excellent historical summary of the blast experiments. Kingery [7] complied and analysed the blast wave properties from ground burst of large hemispherical TNT charges. Dewey et al. [8], Jack [9], Wenzel and Esparza [10] measured normally reflected pressure and proposed their relationships with the incident blast pressure. A good description of the characteristics of blast wave has been provided by Baker [6], Swisdak [11], and Glassstone and Dolan [12]. U.S. Army conducted several such experiments and presented a standard document, which was having a set of standard curves for free-air detonation and surface detonation [1]. These curves are based partly on experiments, and partly on the analyses and computer code computation. However, all these documents were for the defence purpose mainly and were not easily accessible to structural designers.

Later on, Brode [13], Henrych [14], Kingery and Bulmash [15] and Smith and Hetherington [16] based on modelling and experimental results recommended expression for blast generated peak overpressure for free air explosion for a given standoff distance and TNT equivalence. Formby and Wharton [17] conducted experiments for various explosives detonated at ground level and reported the results. Chapman et al. [18] carried out blast wave simulation using commercially available hydorcodes and results were compared with those obtained with experiments conducted by earlier researchers. Remennikov and Rose [19] carried of numerical simulation by modelling blast loads on buildings in complex city geometries and studied the effect of adjacent buildings on shadowing or enhancement of the blast. Jankowiak et al. [20] modelled pressure distribution after explosion using commercially available code. Similarly, many researchers throughout the world, particularly in academia, are using commercially available codes for simulation of blast in order to reduce the experimental load and for deep understanding of the complex physics involved in blast phenomenon. The various relationships proposed by these researchers have already been reported in detail by the author in his earlier paper [21]. Therefore, in the present manuscript emphasis is on the most commonly used relations for blast loading and their numerical modelling and simulation using available codes.

3 Blast Wave

After the explosion, there is sudden release of large amount of energy and it moves outward from the centre of explosion. This outward movement of energy causes the surrounding air to get compressed and move forward with a velocity front. This wave profile experienced by any object is dependent on type of explosive and its distance from source. Generally, most of high explosives results in ideal blast wave profile as shown in Fig. 1 [21]. Blast wave is characterized by instantaneous increase in pressure from ambient atmospheric pressure (P_0) to a peak incident overpressure (Ps_0). The peak incident overpressure decays exponentially with time and return back to ambient air pressure in time t_0, which is known as positive phase duration. This is followed by a negative pressure wave with duration, t_0^-, which is approximately 2–5 times of the positive phase in duration. In most of the hardened structure design, this negative phase is ignored being very small. The blast wave profile is described by Friedlander's equation as follow for spherical charge detonated in free air:

$$P(t) = P_{so}\left[1 - \frac{t}{t_0}\right] \exp\left[\frac{A \times (t - t_a)}{t_0}\right] \qquad (1)$$

where, $P(t)$ is the pressure at time, t (kPa); Ps_0 is the peak incident pressure (kPa); t_0 is the positive phase duration (ms); and A is the wave decay coefficient (dimensionless). In order to account for hemispherical blast, above equation is multiplied by a factor of 1.8 to take into account the reflection from ground [16]. The impulse of incident pressures associated with blast wave is obtained by integrating area under pressure-time curve as follow:

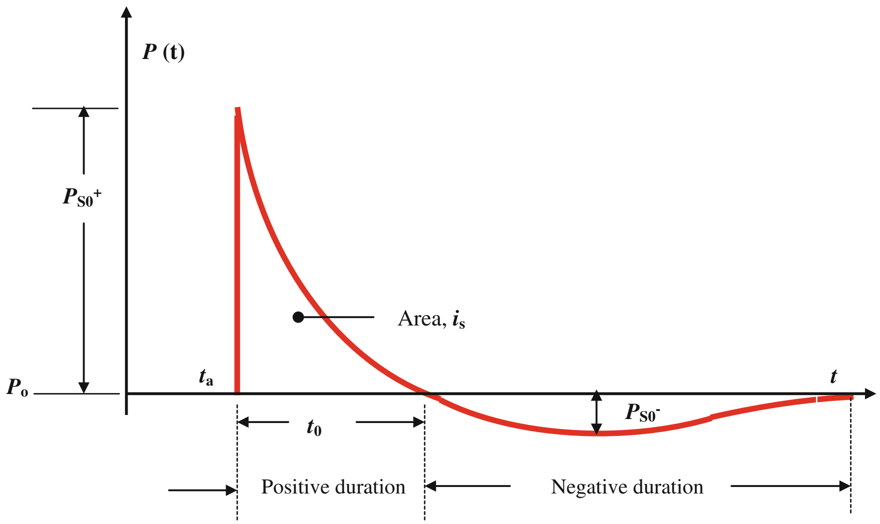

Fig. 1 Blast wave pressure—time history from ideal explosion (i.e. blast wave profile) [21]

$$i = \int_{t_a}^{t_a + t_0} P(t)dt \tag{2}$$

here, t_a is the arrival time (ms).

3.1 Blast Wave Scaling Law

According to this law "self-*similar blast waves are produced at identical scaled distances when two explosive charges of similar geometry and of the same explosive but of different sizes are detonated in the same atmosphere*". Most commonly used scaling laws are those proposed independently by Hopkinson [22] and Cranz [23]. Hopkinson and Cranz scaling law is commonly described as cube root scaling law. Figure 2 shows concept of this scaling law. Scaled distance, Z (=$R/W^{1/3}$) is commonly used for expressing the distance in equivalent form, where, R is expressed as distance from charge centre in 'm', and W is the charge weight in 'kg' of TNT.

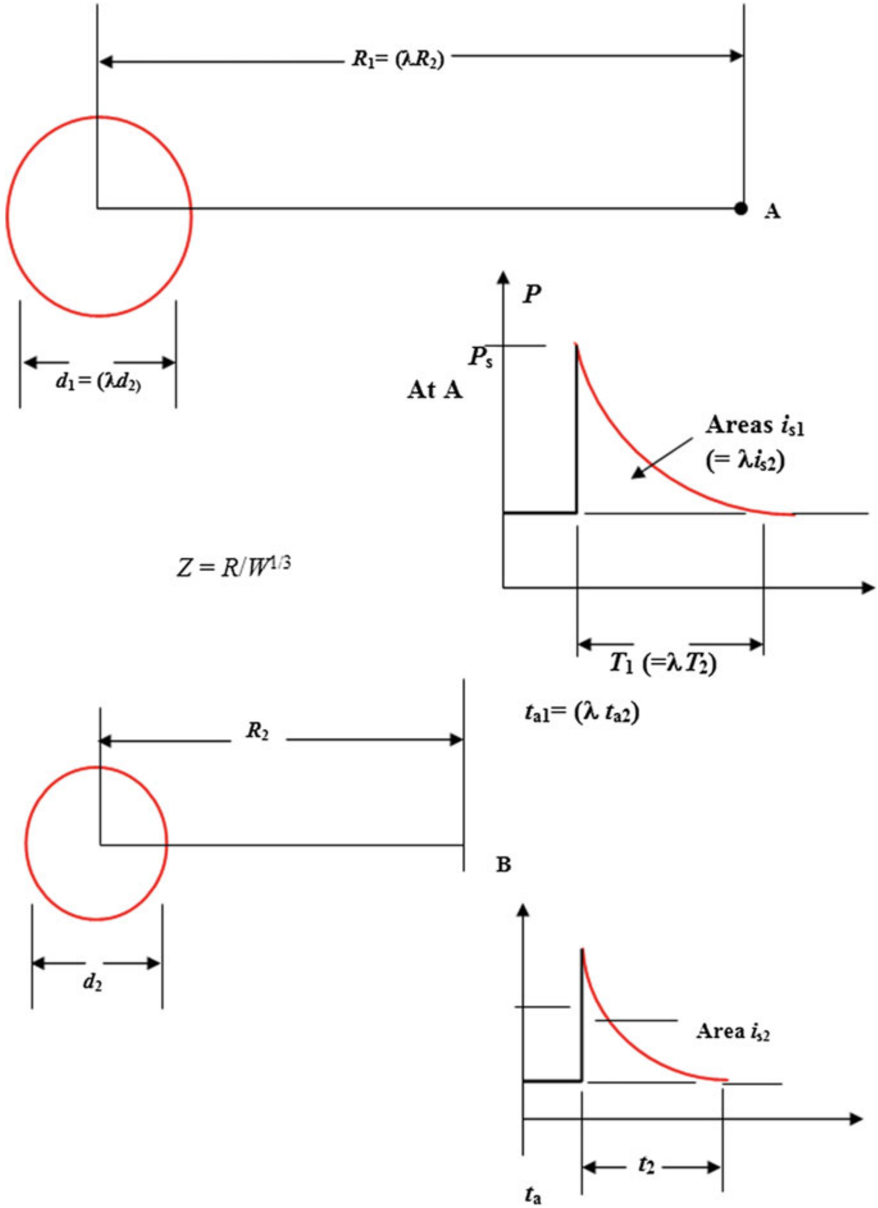

Fig. 2 Hopkinson-Cranz scaling laws [22, 23]

4 Blast Load Calculation

Blast wave parameters for conventional high explosive materials had been focus of a number of research studies during 1950 and 1960. Several researchers put forward their analysis during this period based of experimental work carried out by them [1–20]. These methods are divided into three basic categories for prediction of the blast effects on a structure:

(a) Empirical (or analytical) methods
(b) Semi-empirical methods, and
(c) Numerical methods.

4.1 Empirical Methods

These are essentially correlations with experimental data and are treated as outcome of the experimental work. Most of these approaches are limited by extent of underlying experimental database. The accuracy of all empirical equations diminishes in case of near field explosion. In this paper, most commonly used empirical method is presented in later section.

4.1.1 TM-5-1300 [1]

This manual was one of the most widely used documents available for both military and civilian sector for designing structures to provide protection against blast effects of an explosion before the UFC's manuals (Unified Facility Criteria). This manual presented the methods of design for protective construction used in facilities for development, testing, production, storage, maintenance, modification, inspection, demilitarization and disposal of explosive materials. The main objective of this manual was to establish design procedures and construction techniques whereby propagation of explosion or mass detonation can be prevented along with the protection for personnel and valuable equipments. Its secondary objective was the establishment of blast load parameters for design of protective structures, methods for calculating dynamic response of structural elements, constructional details and guidelines to obtain cost effectiveness in both planning and structural arrangements of blast resistant structures. It contained step-by-step analysis and design procedures including information on (i) blast loading; (ii) principles of non-linear dynamic analysis; and (iii) reinforced concrete and structural steel design.

The design techniques presented in this manual were outcome of the numerous full and small-scale structural response and explosive tests (of various materials) conducted. Several computer programs were included in this manual, which later formed the base of other related design manuals or programs. There exist total four categories of protection as per this manual namely protection category 1–4. The design curves presented in the manual give the blast wave parameters as a function of scaled distance for three burst environments: (i) free air burst; (ii) air burst; and (iii) surface burst. Figure 3a, b show the scaling chart for the positive phase blast wave parameters for a surface burst of spherical and hemispherical TNT explosion in free air at sea level [1]. Such scaling charts provide blast load pressures at a distance *R* (called the standoff distance) along the ground from a specific explosive. Using these charts blast load pressures and duration can be computed. To compute blast loads at points above the ground, a simplified approach is presented later in this paper.

4.1.2 TM 5-855-1 [24]

This manual presented the procedure for design and analysis of protective structures subjected to effects of conventional weapons. It was intended for structural engineers involved in design of hardened facilities. It includes air blast effects, blast loads on structures, and auxiliary systems (air ducting, piping, etc.). The manual provides closed-form equations to generate predicted air blast pressure-time histories.

This manual can also be used to evaluate blast loading on multi-storey buildings. Load-time histories for buildings and building components located at some height above the ground can be calculated according to the methodology presented in TM5-855-1. The basic steps are outlined as below:

1. Divide a surface into sub-sections and evaluate a pressure-time history and impulse for each small zone.
2. The total impulse applied to the surface is then obtained by summing up the impulses for each sub-section.
3. The total load-time history is then defined to have an exponential form with a peak calculated assuming an average peak pressure applied over all the surfaces.

Major limitations of this simplified method lies in neglecting the true physics of the blast wave-structure interaction phenomena. It assumes that load-time history is applied to all parts of surface at the same time which is not experimentally true. This assumption provides a poor approximation particularly for near field blast. To overcome the above limitation, another algorithm has been developed in which total load on a surface at a particular time is computed by summing up load on each sub-surface at that time. Thus, calculation predicts a load-time history that has same total impulse as estimated by TM5-855-1 procedure, but with a different load versus time relationship.

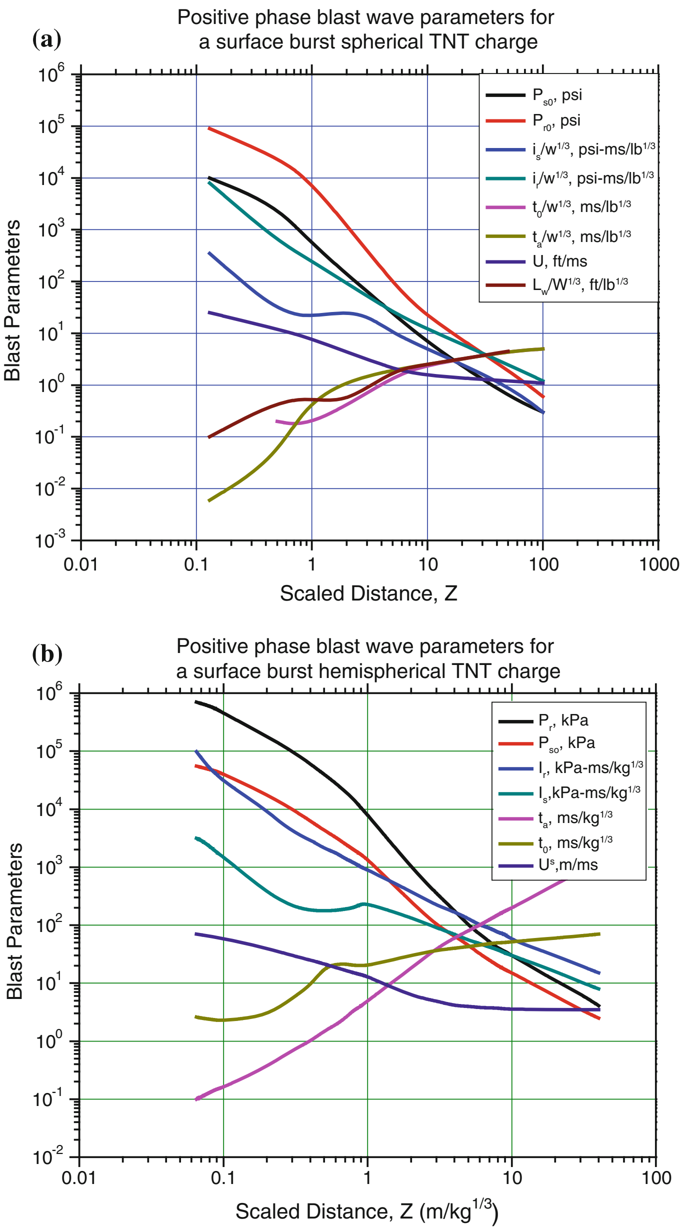

Fig. 3 Blast wave parameter. **a** Surface burst spherical charge. **b** Surface burst hemispherical charge [1]

4.1.3 CONWEP Airblast Load Model [25]

Kingery and Bulmash [15] developed equations to predict the air blast parameters from spherical air bursts and hemispherical surface bursts. These equations are widely accepted as engineering predictions for determining free-field pressures and loads on the structures. The Kingery-Bulmash equations have been automated in the computer program CONWEP [25]. Their report [15] contains a compilation of data from explosive tests using charge weights from less than 1 kg to over 400,000 kg. They used curve-fitting techniques to represent the data with high-order polynomial equations, which were incorporated in CONWEP program. These equations can also be found in TM5-855-1 but in graphical form only.

Unlike TM5-855-1, where an approximate equivalent triangular pulse is proposed to represent the decay of the incident and reflected pressure, CONWEP takes a more realistic approach assuming an exponential decay of the pressure with time using Friedlander' wave equation. The airblast parameters in above equation (peak incident and impulse, positive phase duration, and time of arrival) are calculated using the equations proposed by Kingery and Bulmash [15]. Using the peak pressure, impulse and duration, the program iterates to find the wave decay coefficient. The program then uses the Friedlander's wave equation to find blast pressure values at various time steps. Thus, finally a pressure-time history is applied on the structure directly using this model.

4.1.4 UFC 3-340-02 (Unified Facility Criteria) [26]

This document presents methods of design for protective construction used in facilities for development, testing, production, storage, maintenance, modification, inspection, demilitarization, and disposal of explosive materials. Further, it provides design procedures and construction techniques whereby propagation of explosion (from one structure or part of a structure to another) or mass detonation can be prevented and personnel and valuable equipment can be protected. This document is revised version of TM 5-1300.

4.2 Semi-empirical Methods

These are based on simplified models of physical phenomena. Herein, attempt is made to model the underlying important physical processes in a simplified way. These methods rely on extensive data and case studies. Their accuracy is generally better than that provided by the empirical methods.

4.3 Numerical Methods

These methods are based on the mathematical equations that describe basic laws of physics of the problem. These principles include conservation of mass, momentum, and energy. The physical behaviour of materials is described by constitutive relationships. These models are commonly used in Finite Element Analysis (FEA) coupled with computational fluid dynamics (CFD) approaches. FEA has capability of predicting distribution of internal stresses and strains that are difficult to be measured experimentally. Also, FEA can be employed to understand how structures fail and to identify critical parameters. With the advancement in computational techniques finite element offers possibility to evaluate response of impulsive loading on structure using commercially available software packages as it is very difficult to conduct the field test. Some of the commonly used such packages are presented in Table 2. In the next section most commonly and widely accepted relation for computing the blast time history is presented.

4.4 Blast Pressure Calculation

Based on numbers of experiments and analysis carried out, several researchers proposed various empirical relationships as reported by author elsewhere in detail [21]. However, most commonly accepted relations are those proposed by Kinney and Graham due to their close proximity with the experimental results [27]. The peak positive overpressure and positive phase duration are computed using the following relations:

Table 2 Examples of computer programs used to simulate blast effects

S. No.	Name	Purpose and type of analysis
1	BLASTX	Blast prediction, CFD code
2	CTH	Blast prediction, CFD code
3	FEFLO	Blast prediction, CFD code
4	FOIL	Blast prediction, CFD code
5	SHARC	Blast prediction, CFD code
6	DYNA3D	Structure response with CFD (coupled analysis)
7	ALE3D	Coupled analysis
8	LS-DYNA	Structure response with CFD (coupled analysis)
9	Air3D	Blast prediction, CFD code
10	CONWEP	Blast prediction (empirical)
11	AUTO-DYN	Structure response with CFD (coupled analysis)
12	ABAQUS	Structure response with CFD (coupled analysis)
13	SHOCK	Blast prediction (empirical)

$$\frac{P_s}{P_0} = \frac{808\left(1+\left(\frac{Z}{4.5}\right)^2\right)}{\sqrt{\left(1+\left(\frac{Z}{0.048}\right)^2\right)} \times \sqrt{\left(1+\left(\frac{Z}{0.32}\right)^2\right)} \times \sqrt{\left(1+\left(\frac{Z}{1.35}\right)^2\right)}} \quad (3)$$

$$\frac{t_s}{W^{1/3}} = \frac{980\left[1+\left(\frac{Z}{0.54}\right)^{10}\right]}{\left[1+\left(\frac{Z}{0.02}\right)^3\right] \times \left[1+\left(\frac{Z}{0.74}\right)^6\right] \times \sqrt{\left[1+\left(\frac{Z}{6.9}\right)^2\right]}} \quad (4)$$

Once, peak positive overpressure, positive phase duration is known blast wave front parameters are computed using following relations [28],

$$U_S = \sqrt{\frac{6P_S + 7P_0}{7P_0}} * a_0 \quad (5)$$

$$P_0 = \frac{6P_S + 7P_0}{P_S + 7P_0} * \rho_0 \quad (6)$$

$$q_S = \frac{5P_S^2}{2(P_S + 7P_0)} \quad (7)$$

$$P_r = 2P_s\left\{\frac{7P_0 + 4P_s}{7P_0 + P}\right\} \quad (8)$$

where, a_0 is the speed of sound in air at ambient pressure, ρ_0 is the density of air at ambient pressure ahead of blast wave, ρ_s is the air density behind wave front, U_s is the blast wave front velocity, and q_s is the maximum dynamic pressure.

Based on these parameters following IS 4991-1968, pressure profile at different sides of structure can be computed and then structural analysis can be carried out [29].

5 Numerical Modelling and Simulation in Blast Analysis

In numerical simulation of blast load due to explosion and its effects on structures, analysis consists of basically two major parts,

(a) Modelling the blast load, and
(b) Modelling the material.

5.1 Modelling the Blast Load

The load that is being generated due to an explosion using numerical techniques can be modelled by following methodology:

5.1.1 Defining Pulse-Time Curve

The process of directly defining pulse-time curve is quite straightforward and is one of the easiest ways to model blast loads. Pressure-time history can be obtained using different models available as discussed already. However, coupling effects of loads and structures (such as the change of structural curvature and shock wave reflections) are not easy to consider in such modelling. Therefore, sometimes simulation results of this method are not satisfactory. But still this method provides the basic behaviour of the structures under such complex loading.

5.1.2 Defining Blast Loads Using Blast Pressure Functions

Blast loads can be conveniently calculated using blast pressure functions such as CONWEP [25]. CONWEP function produces non-uniform loads exerted on exposed surface of the structure. This blast function is used for two cases i.e. free air detonation of a spherical charge, and ground surface detonation of a hemispherical charge. The input parameters include equivalent TNT mass, type of blast (surface or air), detonation location, and surface identification for which pressure is applied. It takes into account the reflection from surface and then apply total blast pressure as computed based on the following equation,

$$P(t) = P_r \cdot \cos^2\theta + P_i(1 + \cos^2\theta - 2\cos\theta) \tag{9}$$

where, θ is the angle of incidence, defined by the tangent to the wave front and the target's surface, P_r is reflected pressure, and P_i is incident pressure. It can be seen that CONWEP calculates reflected pressure values and applies these to designated surfaces by taking into account angle of incidence of blast wave. It updates angle of incidence incrementally and thus account for the effect of surface rotation on pressure load during a blast event. The major drawback of CONWEP is that it cannot be used to simulate purely localized impulsive loads produced by explosive flakes or prisms.

5.1.3 Modelling Explosive as a Material

In this method, explosive is modelled as a material using equation of state (EOS) of explosives with help of CFD codes. When explosive is detonated, its volume expands significantly and interacts with the structure. Contact force between expanded explosive product and structure is then calculated. Expansion of explosive is defined by three parameters i.e. position of detonation point, burn speed of explosive and geometry of the explosive. Explosive materials are usually simulated by using Jones-Wilkins-Lee (JWL) high explosive equation of state, which describes pressure of detonation [30]. JWL equation is written as,

$$P = A\left(1 - \frac{\omega\rho}{R_1\rho_0}\right)e^{-R_1\frac{\rho_0}{\rho}} + B\left(1 - \frac{\omega\rho}{R_2\rho_0}\right)e^{-R_2\frac{\rho_0}{\rho}} + \frac{\omega\rho^2}{\rho_0}E_{mo} \quad (10)$$

where, P is the blast pressure, ρ is the explosive density, ρ_0 is the explosive density at the beginning of detonation process, A, B, R_1, R_2, ω and E_{mo} are material constants, which are related to the type of explosive and can be found in explosive handbook [30].

5.2 *Modelling of Materials*

Blast loads typically produce very high strain rates in the range of 10^2–10^4/s. This high loading rate would alter dynamic mechanical properties of target structures and, accordingly, expected damage mechanisms for various structural elements. For reinforced concrete structures subjected to blast, strength of concrete and steel reinforcing bars increases significantly due to strain rate effects. Figure 4 shows approximate ranges of expected strain rates for different loading conditions. It can be seen that ordinary static strain rate is located in the range: 10^{-6}–10^{-5}/s, while blast pressures normally yield loads associated with strain rates in the range: 10^2–10^4/s [31]. Commonly used material models for metals and concrete are discussed here in brief.

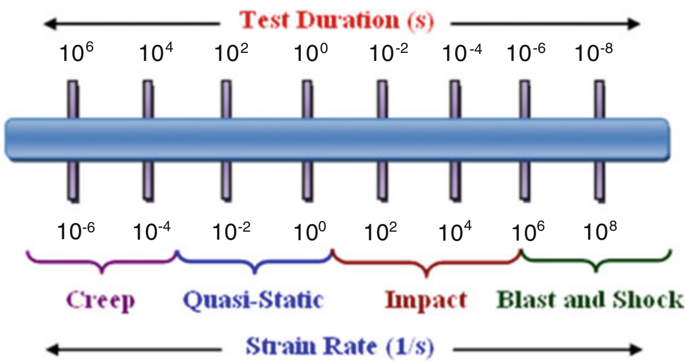

Fig. 4 Strain rate associated with different types of loading [30]

(a) The Johnson-Cook material model is a widely used constitutive relation, which describes plasticity in metals under strain, strain rate, and temperature conditions [32].

$$\sigma_y = (A + B\bar{\varepsilon}^{p^n})(1 + c \ln \dot{\varepsilon}^*)(1 - T^{*m}) \quad (11)$$

where A, B, C, m and n are used defined material constants; $\bar{\varepsilon}^p$ is effective plastic strain; $\dot{\varepsilon}^*$, being effective plastic strain rate, for $\dot{\varepsilon}_0 = 1\ \text{s}^{-1}$; and $T^* = (T - T_{\text{room}})/(T_{\text{melt}} - T_{\text{room}})$. The constants for a variety of materials are found in a book by Johnson and Cook [32].

(b) If only the strain rate effect is considered, the above model is equivalent to another famous material model i.e. Cowper-Symonds model, in which strain rate is calculated for time duration from start to the point, where strain is nearly constant from the equivalent plastic strain time history [33]. In Cowper-Symonds model, dynamic yield stress (σ_{dy}) is computed by,

$$\sigma_{dy} = \sigma_y \left(1 + \left|\frac{\dot{\varepsilon}}{D}\right|^{1/n}\right) \quad (12)$$

where σ_{dy} is the static yield stress and D and n are material constants.

(c) Concrete can be modelled using concrete damaged plasticity model available in various computer codes. The damage plasticity constitutive model is based on the following stress-strain relationship,

$$\sigma = (1 - \omega_t)\bar{\sigma}_t + (1 - \omega_c)\bar{\sigma}_c \quad (13)$$

where, $\bar{\sigma}_t$ and $\bar{\sigma}_c$ are the positive and negative parts of the effective stress tensor, $\bar{\sigma}$, respectively, and ω_t and ω_c are two scalar damage variables, ranging from 0 (undamaged) to 1 (fully damaged) [34].

6 Computer Simulation

Computational methods in the area of blast effects mitigation are generally divided into two major streams i.e. (a) for prediction of blast loads on the structure, and (b) for calculation of structural response to loads. Computational programs for blast prediction and structural response use both first-principle and semi-empirical methods. Programs using first principle method can be categorized into uncoupled and coupled analyses. Uncoupled analysis calculates blast loads as if the structure (and its components) are rigid and then applying these loads to a responding model of structure. Shortcoming of this procedure is that when blast field is obtained with a rigid model of structure, loads on structure are often over-predicted, particularly if significant motion or failure of structure occurs during loading period. For a coupled analysis, blast simulation module is linked with structural response module. In this type of analysis, computational fluid mechanics (CFD) model for blast load prediction is solved simultaneously with computational solid mechanics (CSM) model for structural response. By accounting for the motion of structure while blast calculation proceeds, pressures that arise due to motion and failure of the structure can be predicted more accurately. Examples of this type of computer codes are LS DYNA, ABAQUS AUTODYN, and DYNA3D [30, 34–36]. Table 2 summarizes a listing of computer programs that are currently being used to model blast-effects on structures. Prediction of blast induced pressure field on a structure and its response involves highly nonlinear behaviour. Comparing calculations to experiments must therefore validate computational methods for blast-response prediction. Considerable skill is required to evaluate output of computer code, both as to its correctness and its appropriateness to situation modelled; without such judgment, it is possible through a combination of modelling errors and poor interpretation to obtain erroneous or meaningless results. Therefore, successful computational modelling of specific blast scenarios by engineers unfamiliar with these programs is difficult, if not impossible and should be used carefully.

7 Conclusions

Kinney and Grahm's equations are most commonly used by researchers due to their close agreement with the experiments. The blast profile is exponentially decaying wave profile computed using Friedlander's wave equation. Using this profile reflected and dynamic pressure can be computed as suggested and used in the analysis. For detailed structural analysis use of coupled FE software is recommended.

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