ORIGINAL PAPER

A Critical Review of Blast Wave Parameters and Approaches for Blast Load Mitigation

P. A. Shirbhate[1] · M. D. Goel[1]

Abstract

Casualty analysis of major terrorist attacks in recent decades shows an enormous increase in fatalities and economic losses. Due to frequent terrorist attacks and failure of engineering structures under blast load, this issue has gained the attention of scientists and structural engineers. Recently, threat due to explosions is considerably raised owing to the availability of small size explosive devices with powerful and high range explosive materials. Thus, there is an immediate need for the structures, vulnerable to such tragic events, to be analysed and designed to resist these extreme loading conditions. To predict the behavior of structure under explosion loads, blast load analysis needs to be done. The effective blast parameters such as standoff distance, angle of incidence, explosive type and charge weight with its damaging effects discussed by various researchers have been overviewed in the present work. Further, it is uneconomical to harden the structure to resist the blast load. Therefore, certain strategies which can be adapted to mitigate the effect of blast pressure have also been analysed, and discussed different analytical models for prediction of blast loads. The paper present basics of blast for beginner researchers and structural engineers to understand such complex loading scenario.

1 Introduction

During recent decade, intensity of terrorist attacks have been increased and it has been observed that there is sharp rise in death tolls due to these frequent attacks, and its impact can be seen on the whole world. As per global terrorism index 2018, three trends (i.e. First, second and third trend between 2002–2007; 2007–2011; and 2011–2014, respectively) since 9/11, showed that there is a consistent increase in intensity of terrorist activities. Figure 1 indicates the number of countries which experienced at least single death from terrorism in a year. And it can be observed that the number of countries affected due to surge of terrorism is increasing. Terrorism leads to economic loss due to structural damage, and more importantly loss of precious lives. Figure 2 shows impact of terrorism and loss due to deaths which accounts for 72% of the economic impact of terrorism, 25% GDP losses, 2% property destruction and 1% injuries.

The casualty analysis of some major terrorist attacks such as Mumbai bombings (March 1993), Alfred P.

Murrah Federal building in Oklahoma City (April 1995), US Embassy building (August 1998), collapse of world trade center (WTC) in New York (September 2001), the tragic events in Bali (October 2002), Mumbai railway bombings (July 2005), Siege of Mumbai (November 2008) have been carried out and is represented in Fig. 3. The loss of lives and injuries occurred in the respective terrorist incidents have also been quantified in the chart. Among these attacks, the number of casualties and economic loss in twin tower attack (also known as 9/11 attack) was huge. It is seen from the casualty analysis of these attacks that terrorism is a threat to every nation. Therefore, important buildings such as government organisations, hospitals, public gathering places, shopping malls, theatres, mass transport systems, stadiums etc. should be designed to withstand such dynamic loads due to blast.

Blasting is basically a technology of exploding explosive material having both positive as well as negative perception. If the explosive is exploded intentionally then it is called blasting and if exploded accidentally then it is an explosion. Explosive is the storage of an enormous amount of energy, which upon explosion releases large amount of energy instantaneously. Usually, it is thought that explosives have been used for war or terrorism, but they are also used effectively for mining purposes. Blasting is used for building

✉ P. A. Shirbhate
  payalshirbhate@students.vnit.ac.in

1 Department of Applied Mechanics, Visvesvaraya National Institute of Technology, Nagpur 440 010, India
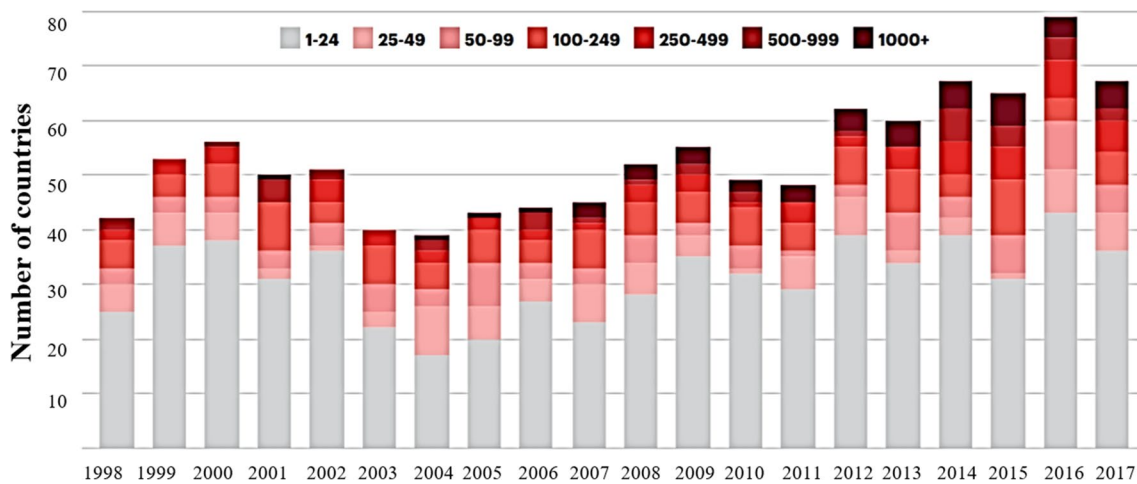
Fig. 1 Deaths from terrorism and number of countries affected, 1998–2017 (Global Terrorism Index, 2018)
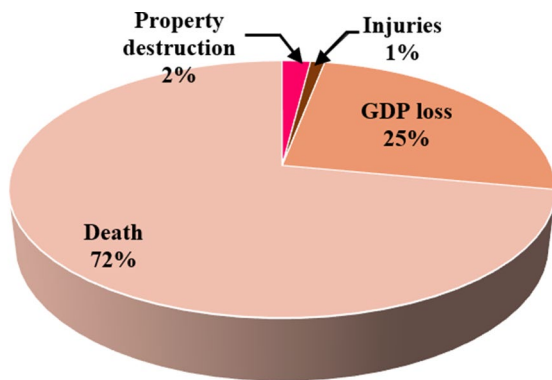

Fig. 2 Economic impact of terrorism, 2017 (Global Terrorism Index, 2018)

demolition, excavation of rock material and in the geological exploration. Seismic wave is generated to extract geomaterials such as oil, minerals, etc. from the earth's crust. During these operations there is a possibility that fragments of charges may hit the surrounding structure e.g. tunnel, natural rock, blast in mining etc., resulting in dust particles in flow. Consideration of effect of dust gives precise pressure value and the damage may be reduced [1]. Terrorist groups use the same techniques of blasting to create violence and to threaten the people. Along with people, the structural components also get badly affected by the impact of explosion, the same has been dealt with in the present paper.

The present paper focuses on the phenomenon of blast wave, blast load analysis and ways to mitigate the effect of blast overpressure. Usually, response of the structure is investigated with simplified single degree of freedom system

[2, 3]. Blast numerical models, such as Eulerian, Lagrangian, ALE, MMALE etc. to predict the blast response have been summarised. Various terms which one needs to understand before actually computing the blast pressure and the same are briefly discussed in the subsequent sections.

2 Effect of Blast on People and Structural Component

The effect of blast pressure on human body and structural components have been evaluated in several research works, and the same has been studied. The pressure ranges corresponding to injuries and structural damage are briefly presented in this section. The intensity of blast pressure and duration has a significant influence on people and structure. During the explosion, blast overpressure results in blast wind which causes injuries and casualties. The injuries are classified as primary, secondary, tertiary and quaternary injuries which are elaborated in Fig. 4 with pictorial representation [4]. Injuries due to initial blast waves, ignoring after burning effects have been discussed in the figure. Causes of death due to blast pressure are categorised as impact on head, impact on whole body and lungs damage [5].

Various ranges of blast overpressure corresponding to standoff distances along with fatalities/injuries and damages to component caused due to blast wave are illustrated in Fig. 5. As it can be observed in the figure, in the nearest range where the pressure is approximately 1373 kPa the blast wave can inflict fatal injuries to human resulting in death. As the standoff distance increases the magnitude of overpressure decreases as well. A pressure of 245 kPa and more can result in collapse of lungs whereas, 98 kPa of pressure can damage the eardrums. The blast pressure at higher standoff distance will have slight effect on the structure, such as
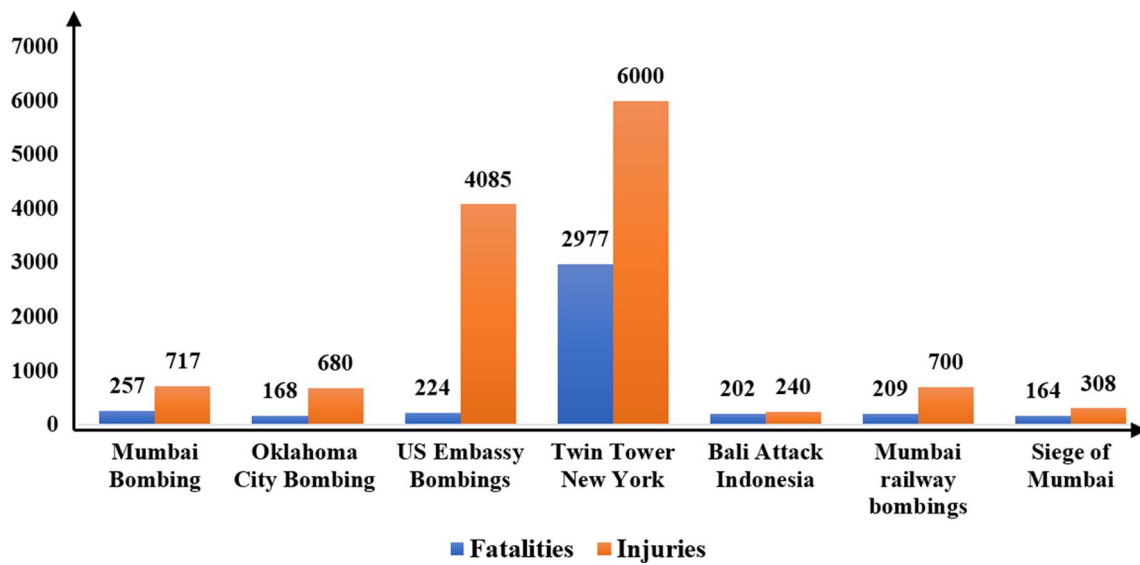
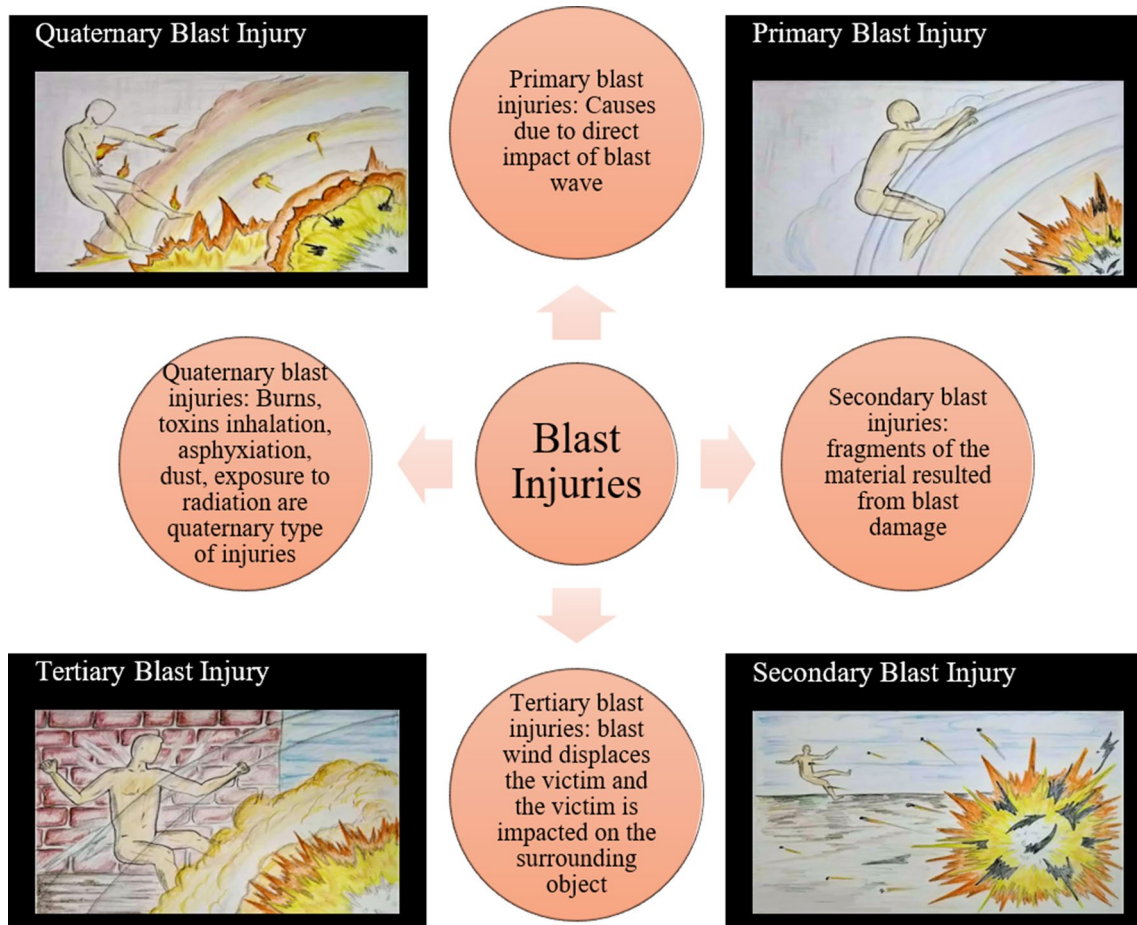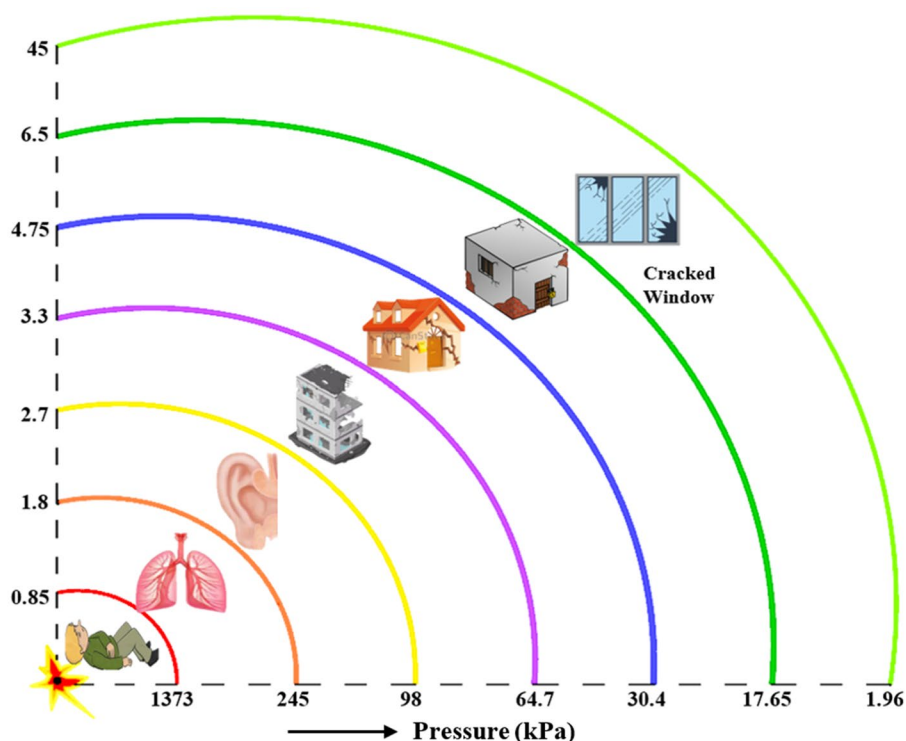**Fig. 3** Fatality and injury statistics of terrorist attacks

Fig. 4 Classification of blast injuries during blast event

Fig. 5 Blast injuries corresponding to overpressure ranges and respective standoff distances

cracks observed in the window. In case of component damage criteria for structure, it can be seen from the figure that, at certain pressure range and distance only cracks in the slab are observed. Whereas, in some cases, components such as columns, beams and walls get damaged and in extreme case of high overpressure at the least distance overall structure or some part of the structure can collapse.

3 Blast Phenomena

Either high explosives detonate or low explosives get deflagrated, depending on the type of explosive. When condensed high explosive such as TNT gets triggered, it generates hot gases. The explosive gases compress the surrounding air and in front of these gases, compressed air wave/blast wave forms. This whole process of formation of blast wave is termed as blast phenomenon [6].

Blast wave consists of shock wave with high pressure and high-speed wind, and the combined effect of these two is known as blast wave. The air moving behind the shock front with some pressure difference is termed as blast wind [7]. The parameters related to the blast phenomenon such as explosives, TNT equivalence, angle of incidence and standoff distance are explained in the upcoming subsections. Also the detonation process, Mach stem formation, diffraction and its effect on structure including scaling laws have been illustrated to understand the basics of the blast.

3.1 Detonation Process

If the decomposition rate is lower than the velocity of sound in the material, then it is termed as deflagration. When low explosives undergo chemical reaction, then deflagration takes place which results in rapid burning and flames [6, 8]. Whereas, detonation produces a high-intensity shock wave as a result of chemical reaction of high explosive material [6]. The shock wave travels at the speed greater than speed of sound in air i.e. at supersonic velocity with respect to explosives that are undetonated or unreacted. A shock wave driven by a chemical reaction of a high-performance explosive is called a detonation wave [7]. The velocity at which detonation wave passes through the detonated explosive is referred to as detonation velocity and it varies from 5 to 8 km/s [9]. High explosives produce effects other than heat including release of large amount of energy and strong blast waves. The initial detonation energy is lost in compression, breaking and acclerating the debris [10]. Dust generation and afterburn effects are important factors in modelling the precise situation in numerical modelling of the detonation process [1, 11]. Thus, the effect due to detonation is only dealt with in the present paper.

3.2 Explosives

Explosive is a chemical compound material or a device which releases large amount of energy in the form of heat, light, sound and shock wave when triggered. It is essential

Table 1 Estimated quantities of explosives in various vehicles [40]

Vehicle type	Charge mass/kg
Suitcase	10
Compact car trunk	115
Trunk of a large car	230
Closed van	680
Closed truck	2270
Truck with a trailer	13,610

for the explosive to be detonated, to produce effect other than heat. Explosives are easy to produce, compact and powerful therefore, commonly used in terrorist attacks as weapons. Hand delivered and vehicle weapons are the main sources of threat due to explosives [12]. But these days vehicle-borne improvised explosive device (VB-IED) and suitcase bomb became popular weapon for terrorist attack [13]. Quantity of explosives used during explosion depends on the carrier and the capacity of vehicles. Capacities of different vehicles to carry explosive are as given in Table 1.

Blast load gets influenced by the properties of the explosive material and therefore, it is necessary to know about types of explosives with their physical characteristics. Charge weight, material, shape and distance of the explosives from the structure are important characteristics of the blast wave and its effect on the structure [14]. Further, energy release rate and detonation velocity greatly affect the performance of the explosives [7].

Based on physical state, explosives are classified as solid, gas or liquid. The explosives are further categorized as military and home-made explosive. Fertiliser-fuel mixture or Ammonia Nitrate Fuel Oil (ANFO) are the types home-made explosives [15]. The military explosives are classified as high or low explosives on the basis of energy produced, and time taken for detonation or deflagration [13, 16]. Propellants, flammable chemicals, liquids or gaseous explosives materials are the types of low explosives [12, 14–16]. Moreover, based on the sensitivity of the explosives to ignition, they are classified as primary or secondary explosives [17]. To increase the energy release, aluminium particles are mixed into explosives or solid propellants. These particles can burn under high temperature and pressure condition behind blast wave. Thus, for accurate analysis of heavily aluminized high explosives it is important to evaluate after-burning effects on detonation of TNT [11].

3.3 TNT Equivalence

Blast load primarily depends on energy output of the explosives. Explosive energy of the detonating materials is determined with respect to equivalent weight of Trinitrotoluene (TNT). In addition to explosive energy, TNT equivalence

depends on charge shape (cylindrical, spherical, flat, square etc.), charge weight, confinement of explosive (casing, containers etc.) and the range of the pressure (close-in, intermediate or far ranges etc.) [12, 14, 16].

To know the energy output of explosion, one reference explosive TNT is used as standard explosive known as explosion bench mark. Conversion factor based on specific energy of explosive is multiplied to the specific energy of TNT to get the energy output of explosive under consideration and these factors are reported in Table 2 [8, 18].

In case of unconfined explosions, charge weight of explosive under consideration is calculated with reference to weight of TNT explosive and is represented by Eq. (1):

$$W = \frac{Q_x}{Q_{TNT}} W_x \tag{1}$$

where W represents effective charge weight in TNT; W_x is weight of explosive; Q_x is the mass specific energy of the explosive; Q_{TNT} is the mass specific energy of TNT and the ratio Q_x/Q_{TNT} represents TNT equivalent based on detonation heat [14].

3.4 Angle of Incidence

When the explosive charge gets detonated, incident blast wave is generated and it strikes the ground surface at an angle of incidence. The angle made by tangent to the blast wave and the ground varies from 0° to 90° and is known as angle of incidence [19–21]. Incidence angle influences blast pressure variation and impulse pattern on the structure. It also affects the reflection process and the value of reflection pressure. Reflected pressure reaches to maximum value when the reflected surface is perpendicular to the blast

Table 2 Type of explosives and TNT equivalent [7]

Explosive type	Mass specific energy Q_x (kJ/kg)	TNT equivalent Q_x/Q_{TNT}
Compound B (60% RDX 40% TNT)	5190	1.148
RDX (cyclonite)	5360	1.185
HMX	5680	1.256
Nitroglycerien (liquid)	6700	1.481
TNT	4520	1.000
Blasting gelatin (91% Nitroglycerin, 7.9% nitrocellulose, 0.9% antacid, 0.2% water)	4520	1.000
60% Nitroglycerine dynamite	2710	0.000
Semtex	5660	1.250
Pentolite 50/50	5860	1.129
PETN (90/10)	6406	1.23
Pentrite	6400	1.13

wave whereas, reflected pressure reduces to minimum value if the reflected surface is parallel to the blast wave. Reflected pressure will be moderate for an angle of incidence ranging between 40° and 55°. Within this range of angle of incidence, a coalescent wave resulting to Mach stem could be formed [22, 23].

3.5 Standoff Distance

The direct, unobstructed distance between asset and midpoint of charge weight is termed as the standoff distance and is shown in Fig. 6. The main purpose of standoff distance is to keep the threat away from the structure. With increasing standoff distance, the intensity of blast overpressure reduces [24, 25]. Standoff distance is not a fixed quantity but it is dependent on the type of explosion, type of structure to be protected and the protection level to be achieved. Standoff distance is an important and most economic parameter of blast mitigation strategy, as the intensity of blast overpressure can be reduced with provision of more standoff distance. The standoff distance can be created by proper entry control point, vehicle barriers, fencing, planters, knee walls, bollards and other physical barriers [13, 23, 26].

3.6 Types of Explosion

Webster defined explosion as "a large scale, rapid and spectacular expansion, outbreak, or other upheaval". Either high explosives are detonated or due to intense rise in local temperature, huge quantity of energy is rapidly released exerting pressure on the surrounding medium and it results in the phenomena known as explosion [6, 23]. Explosions are classified as physical, chemical, electrical and nuclear based on their nature. Physical explosion occurs due to explosion of compressed gas cylinders, it includes physical gas dynamics and thermodynamic effect. Exothermic reaction and fuel elements such as carbon and hydrogen atoms rapidly oxidises to release energy which results in chemical explosion. In nuclear explosion, redistribution of proton and neutrons will release explosion energy by the formation of atomic nuclei. Whenever there occurs failure of electrical circuits, electrical energy gets instantaniously released resulting in electrical explosion [16, 17, 25, 27]. Confinement of explosive is also an important parameter affecting the blast load, and the classification of explosions based on confinement are briefly discussed in Fig. 7.

Unconfined explosions are grouped as air burst, free air burst and surface burst based on where the explosive is located with reference to ground surface. In case of air burst, the explosion takes place at certain height from ground level and the Mach stem can be formed at certain paint, this can be observed from Fig. 8a. However, when the explosive detonates high above the ground surface in free air, then it can be categorized as free air burst as in Fig. 8b. And if the explosion takes place at the ground surface, then it is termed as surface explosion and is represented in Fig. 8c. Confined explosions are further classified depending on the extent of venting (i.e. fully vented, partially vented and fully confined explosion [27–29]. In confined explosions the pressure amplifies due to reflections, and can be observed from the Fig. 9a–c.

3.7 Mach Stem Phenomenon

Reflection is important in case of blast loading as it amplifies the intensity of blast pressure. Reflections are of two types, regular and Mach reflection and these will be governed by incidence angle. In regular reflection, incident and reflected waves are distinct and they intersect at the reflecting surface, the angle of incidence is zero in this case. Ernst Mach discovered the phenomenon of Mach stem experimentally which was validated by Von Neumann in 1941 with analytical criterion. When explosion takes place above the ground (Fig. 10a), the blast wave expand and strikes the ground surface, it gets reflected to form second shock wave (Fig. 10b) which travel behind the incident blast wave. Incident wave

Fig. 6 Standoff distance of the explosion from the structure
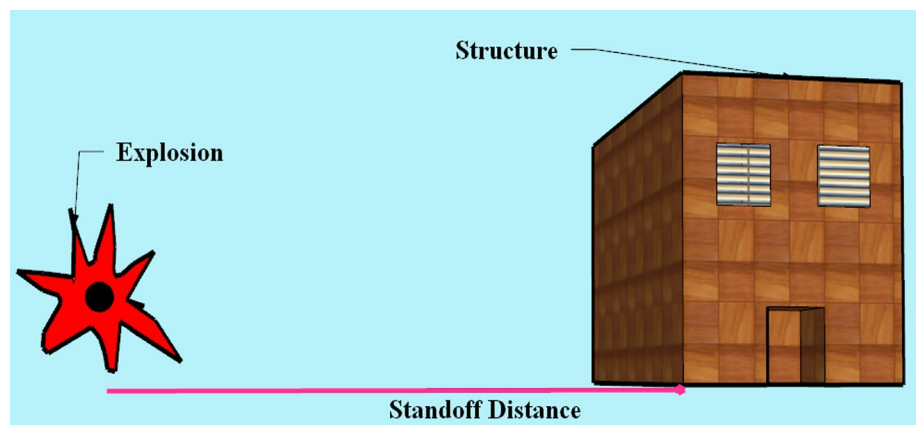
**Fig. 7** Type of explosion based on the confinement of explosive
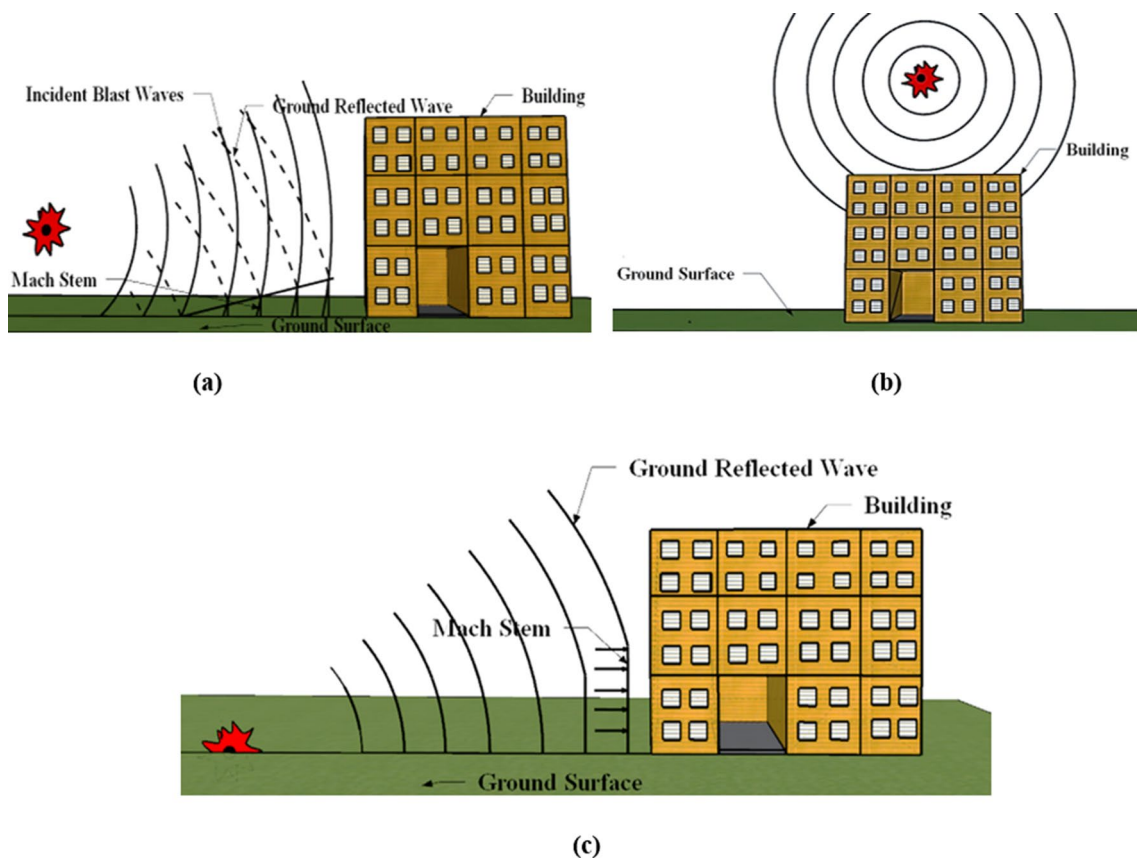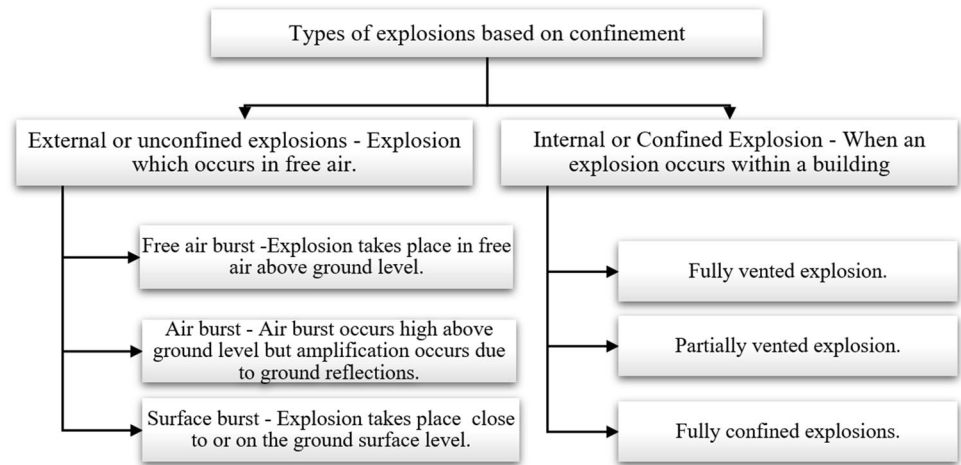
Fig. 8 Types of unconfined explosions based on location of explosive **a** air burst **b** free air burst **c** surface burst

travels slowly as it passes through air which is less dense. Whereas, the reflected wave travels faster than incident wave as it travels through denser medium. Thus reflected blast wave merges with the incident shock wave to form single wave known as Mach stem [19, 20].

The top of the Mach stem at which incident and reflected wave intersects is known as triple point. And if the multiple triple points are joined by a line, it indicates the path of triple point and is reported in Fig. 10c. The figure also illustrates whole phenomenon of regular as well as Mach reflection including terminologies involved. As Mach stem represent combined effect of incident and reflected pressure therefore, it is a high overpressure region [8, 26]. The design approach of the structure should be such that no explosion results in Mach stem.

Fig. 9 Types of confined explosions based on extent of venting **a** fully vented; **b** partially vented; **c** fully confined


(a) (b) (c)
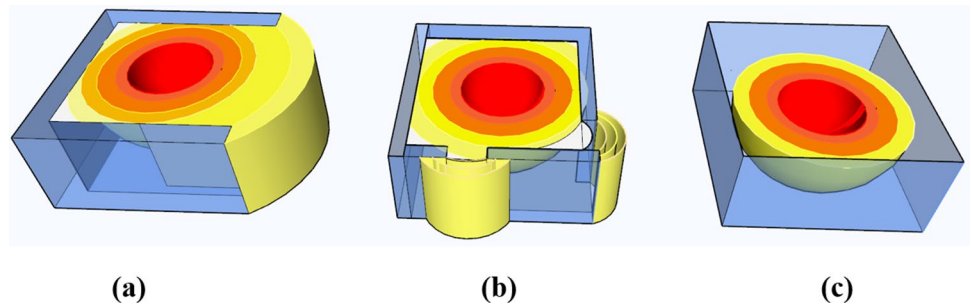
Fig. 10 Regular reflection and Mach stem formation **a** incident shock wave; **b** regular reflection; **c** Mach reflection

(a) (b)

(c)
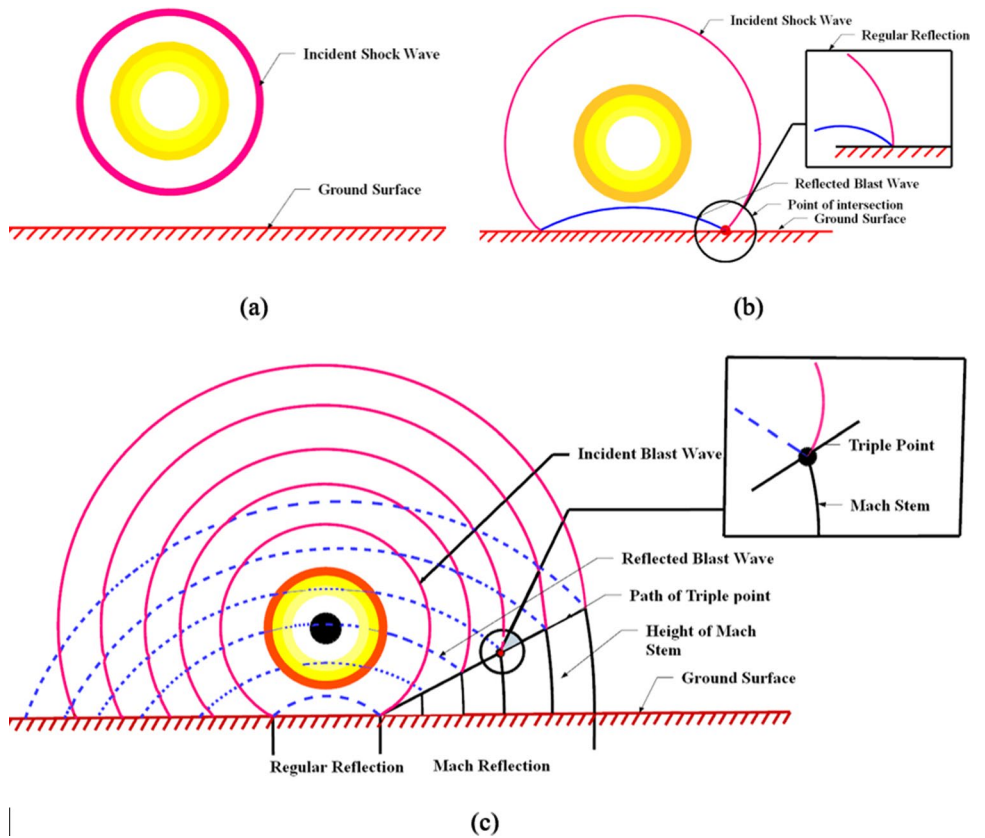
3.8 Diffraction

When the incident blast wave strikes the object, there occurs three phases such as reflection, rarefaction and diffraction [15]. Reflection of blast wave amplifies the incident waves due to coalescent effect of incident and reflected wave. Although, in some cases, incident waves pass over the object and diffracts around the object as shown in Fig. 11, reducing the intensity of blast overpressure behind the object. Height of the barrier influences diffraction effect on structure [30, 31]. Geometry of the structure and its components also have important role in intensity of blast pressure. Curve shaped structure such as domes, choirs, columns reflect the blast wave whereas columns and piers diffract them [32]. Whereas, re-entrant corners of the building are
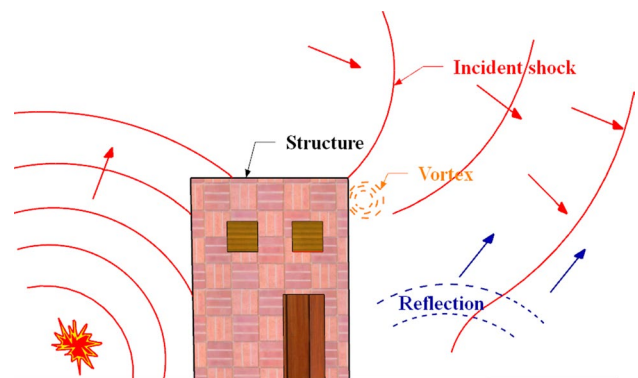
Fig. 11 Blast wave diffraction

more susceptible to diffraction effect and hence, increases the duration of air blast [15].

3.9 Blast Scaling Laws

The basic idea behind explosive scaling is to evaluate the effect of overpressure of different TNT explosives at different distances. The effect of small explosion at small distance will be same as that of large explosion at larger distance and is well explained from Fig. 12 [8]. It is elaborated from the figure that, 10 kg TNT at 32 m standoff distance creates the same blast effect which 100 kg TNT creates at 68 m standoff distance. Scaling laws correlate particular explosion and standard charge with parametric relationship [17]. These laws are developed to analyse the blast wave parameters and their effect. To predict explosions of large-scale for variable distances and energies, scaling law is used. Tests conducted at small scale explosions are used for prediction of large-scale explosion, using scaling laws [8, 16, 33]. Scaling laws given by Hopkinson, Sache and Taylor, Von Neumann and Sedov are briefly explained in this section.

Hopkinson used same explosive with two different weights and observed that at some common scaled distances the effect of both of them as same. Based on this Hopkinson proposed blast scaling law also known as cube root scaling, and the same is represented in Eq. (2). In the year 1915, Hopkinson communicated this law, it is the most commonly used scaling law and is referenced by [8, 33, 34].

$$Z = \frac{R}{W^{\frac{1}{3}}} \qquad (2)$$

where W is the weight of charge; R is the distance (range) from the explosive charge center.

Sache used similar experimental data as used by Hopkinson and proposed the scaling law in 1944. As per this law, pressure, time, impulse and other parameters can be defined with unique function of scaled distance as reported in Eq. (3) [8, 33, 34].

$$R = \frac{R\rho_o^{1/3}}{E^{1/3}} \qquad (3)$$

where R = Distance (Range), ρ_o = ambient pressure and E = energy of the explosive charge.

To resolve the issue of blast structure interaction, Taylor and Von Neumann studied the influence of explosive energy and distance between structure and explosion. Taylor from England [35, 36], Von Neumann from United States [37] and Sedov from Soviet Union [38] worked independently on scaling laws beyond traditional scaling laws. Their individual work was later combined which is known as Taylor-von Neumann Sedov (TvNS) theory [39]. The laws derived are based on global invariants, dimensional and self-similarity analysis [40].

4 Blast Analysis

To resist or mitigate the impact of blast on structure, it is essential to know how to predict the blast load. Blast load and its computation techniques are briefly overviewed in this section. For this, it is important to first understand characteristics of blast wave, blast pressure resulting from air blast and the methods discussed by various researchers to calculate blast overpressure. During explosion large amount of energy gets spontaneously released along with the production of gas which expands at high velocity, generating a blast wave which imparts pressure as well as momentum to the structure. Incident pressure or ambient overpressure is the primary effect of blast wave which occurs when blast wave propagates and compresses the surrounding air. Whereas, dynamic or pressure due to drag load accounts for secondary effect of blast wave [15].

Figure 13, represents blast wave profiles such as real pressure blast wave profile which is approximately normalized to draw ideal and idealized pressure curves. To simplify the load calculation, the curved portion of the blast wave is modeled as triangular pulse, and is also represented in

$$Z = \frac{R\,(m)}{\sqrt[3]{W\,(kg)}} = \ldots m/kg^{1/3} \quad Z = \frac{68\,m}{\sqrt[3]{100\,kg}} = 15\,m/kg^{1/3} \qquad Z = \frac{32\,m}{\sqrt[3]{10\,kg}} = 15\,m/kg^{1/3}$$

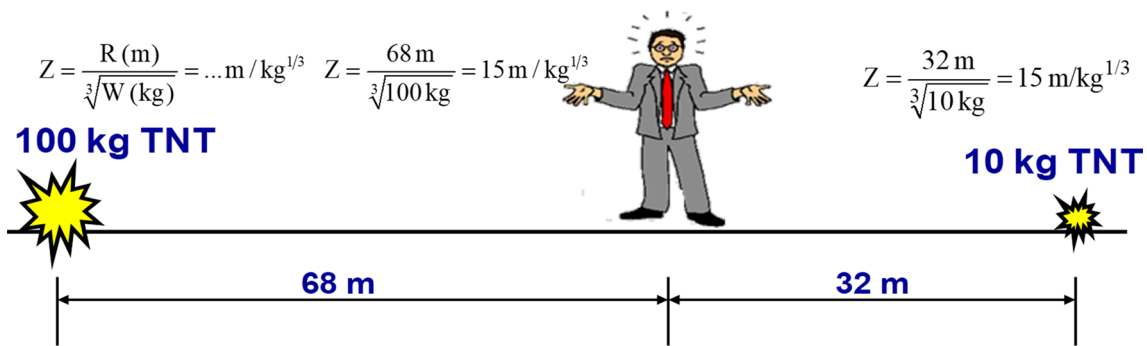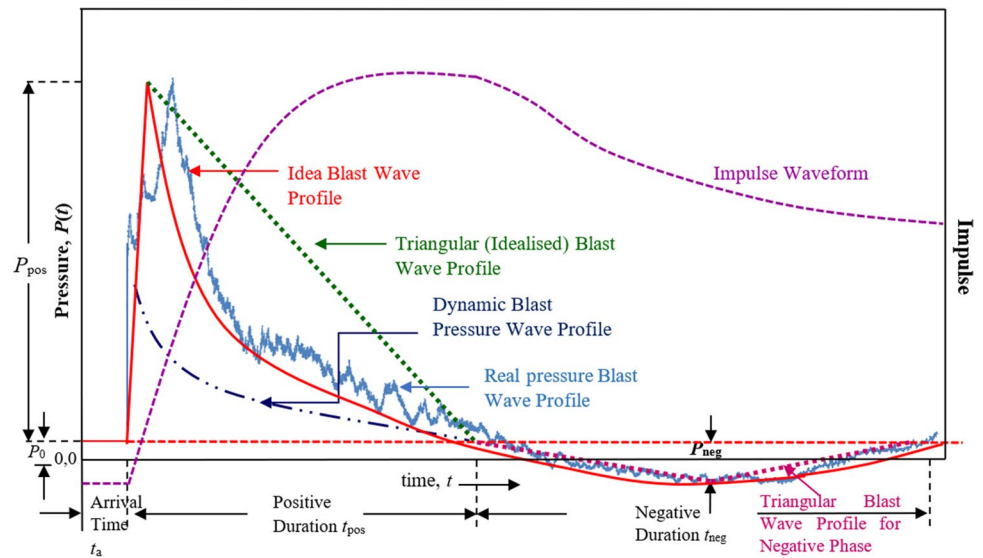**100 kg TNT**   **10 kg TNT**

68 m   **32 m**

Fig. 12 Scaled distance of different charge weights and standoff distances

Fig. 13 Blast wave profiles and impulse waveform diagram

the same figure along with impulse and dynamic pressure profile. Usually, the magnitude of dynamic pressure is very low compared to positive overpressure and it lasts for longer duration, this can be noticed from the dynamic pressure curve presented in figure.

This blast wave lasts only for some milli or micro seconds and results in blast load which is dynamic in nature, having very high magnitude and very high frequency. Blast load is impulsive in nature i.e. high magnitude pressure for short duration. The parameters which govern the blast load include peak positive pressure (P_{pos}), positive phase duration (t_{pos}), under pressure (P_{neg}), negative duration (t_{neg}), wave decay parameters (*b*) and impulse (*I*). Blast loading on the structure can be defined using blast wave parameters and reflected pressures [26, 32, 41, 42].

When incident blast wave interacts with the structure, it reflects back producing reflected pressure which is always more than incident pressure, and it depends on incidence angle. The incident pressure is multiplied by appropriate reflected pressure coefficient, to obtain reflected pressure pulse [23, 43]. Blast pressure time history is mainly divided into positive and negative phases. These phases and the computation of governing parameters associated to blast load has been explored in detail in the subsections.

4.1 Positive Phase Blast Wave

The process starts with detonation of high explosives. Once the explosive gets detonated, the shockwave will travel along, the time elapsed between detonation and the time at which shockwave strikes the structure is known as arrival time (t_a). Initially, the pressure of the blast wave will remain equal to the ambient atmospheric pressure, it increases and reaches peak pressure instantaneously, known as peak positive overpressure

denoted as (P_{pos}). Time required to reach peak positive pressure is almost negligible, and is assumed to be zero. Once the pressure reaches peak pressure, it starts decaying exponentially, and reaches atmospheric pressure. Duration in which pressure is either above, or equal to atmospheric pressure is known as positive duration denoted by (t_d) [16, 26, 41]. Different references have given several empirical expressions to evaluate positive overpressure, and are discussed here.

Positive phase of the blast wave profile is usually described by the Friedlander's equation, due to the simplicity of this equation. Baker proposed Friedlander's equation [34], and is expressed as:

$$P(t) = P_{pos}\left(1 - \frac{t}{t_{pos}}\right)e^{-b(t/t_{pos})} \tag{4}$$

Initially, atmospheric pressure was not considered in the blast pressure calculation. Therefore, this equation was further modified considering ambient atmospheric pressure and thus becomes,

$$P(t) = P_0 + P_{pos}\left(1 - \frac{t}{t_{pos}}\right)e^{-b(t/t_{pos})} \tag{5}$$

This is equation is known as modified Friedlander equation and is widely used due its accuracy. The other most widely used approach to obtain blast pressure (P_t) on the basis of these equations was proposed by Kingery and Bulmash [44]. Based on this equation, U.S. Army developed the code known as Conventional Weapons Effects Program (CONWEP). The equation takes the following form,

$$P_t = P_r \cos^2\theta + P_i\left(1 + \cos^2\theta - 2\cos\theta\right) \tag{6}$$

The equation is applicable for $Z < 40$ (m/kg$^{1/3}$), having P_r and P_i as reflected and incident pressures, respectively.

4.2 Determination of Blast Pressure

There exists different relationships and approaches proposed by various researchers for computation of the blast pressure. The focus has been given on the important, and commonly used empirical relations. Brode carried out analytical approach to categorize the expression for peak positive pressure into near field, and medium to far field condition. Based on differential equation formulations, Brode presented Eq. (7a) for pressure more than 10 bar and (7b) for pressure range between 0.1 and 10 bar [45]. Here, Z represents scaled distance in m/kg$^{1/3}$.

$$P_{so} = \frac{6.7}{Z^3} + 1 \quad \text{for} \quad P_{so} > 10 \text{ bar} \tag{7a}$$

$$P_{so} = \frac{0.975}{Z} + \frac{1.455}{Z^2} + \frac{5.85}{Z^3} - 0.019 \quad \text{for} \quad 0.1 < P_{so} < 10 \text{ bar} \tag{7b}$$

Kinney and Grahm, put up Eq. (8) using data from chemical explosions, and most of the computer based calculations uses this approach. The equation is based on experimental data, and is governed by scaled distance, Z and ambient pressure, P_0 [46].

$$P_{pos} = P_0 \frac{808\left[1 + \left(\frac{Z}{4.5}\right)^2\right]}{\left\{\left[1 + \left(\frac{Z}{0.048}\right)^2\right]\left[1 + \left(\frac{Z}{0.32}\right)^2\right]\left[1 + \left(\frac{Z}{1.35}\right)^2\right]\right\}^{0.5}} \tag{8}$$

Newmark proposed formulation (refer Eq. 9) for computation of peak overpressures for surface blast. Where, P_{so} is the pressure in bars, W is the charge mass in metric tons ($=1000$ kg) of TNT and R is the distance of the surface from the center of a spherical explosion in m [47].

$$P_{so} = 6784\frac{W}{R^3} + 93\sqrt{\frac{W}{R^3}} \tag{9}$$

4.3 Computation of Arrival Time and Positive Phase Duration

Kinney and Graham, presented empirical relations for prediction of arrival time (t_a) of the blast wave front from the centre of explosion and suggested Eq. (10) which takes following form [46]:

$$t_a = \frac{1}{a_0} \int_{r_c}^{R} \left[\frac{1}{1 + \frac{6P_s}{7P_0}}\right]^{1/2} dR = \frac{1}{a_0} \int_{r_c}^{R} \left[\frac{1}{M_x}\right]^{1/2} dR \text{ (ms)} \tag{10}$$

where a_0 is the speed of sound in undisturbed atmosphere, M_x is the Mach number and r_c is the charge radius. The precision of given integration equation is less when compared to numerical calculation.

The portion above ambient pressure is known as positive phase with its duration termed as positive phase duration, and its computation is discussed here. The duration of the positive phase of blast wave depends on standoff distance. As standoff distance increases, duration of the positive pulse increases but with reduced amplitude [17, 41].

In the year 1979, Henrych presented Eq. (11), to predict positive over pressure duration and is represented as [48]:

$$t_{pos} = e^{(-2.75 + 0.27 \log_{10} Z+) + \log_{10} W^{1/3}} \tag{11}$$

Kinney and Grahm proposed Eq. (12) to compute positive overpressure duration with scaled distance (Z) and charge mass (W) as variables [46].

$$t_{pos} = W^{1/3} \frac{980\left[1 + \left(\frac{Z}{0.54}\right)^{10}\right]}{\left[1 + \left(\frac{Z}{0.02}\right)^3\right] \times \left[1 + \left(\frac{Z}{0.74}\right)^6\right] \times \sqrt{\left[1 + \left(\frac{Z}{6.9}\right)^2\right]}} \text{ (ms)} \tag{12}$$

Later on, in 2004 Sadovskiy reported Eq. (13) for determination positive over pressure duration having, W is charge mass and R is the charge radius [49],

$$t_{pos} = 1.2\sqrt[6]{W}\sqrt{R} \text{ (ms)} \tag{13}$$

4.4 Positive Phase Impulse

Impulse is the area under pressure time curve of air blast, and it greatly influences the performance of the structure [50]. Impulse of the incident pressure is a measure of energy from an explosion, or it is the pressure associated with the blast wave. Both positive as well as negative phases of the pressure time waveform contribute to impulse. Positive phase impulse, (i_s) is evaluated as per Eq. (14), [15, 16, 23, 41].

$$i_s = \int_{t_a}^{t_a + t_0} P_s(t) dt \tag{14}$$

where P_s is the peak incident overpressure; t_0 is the positive phase duration, t_a is the arrival time of the blast wave.

4.5 Wave Decay Parameter

Once the positive pressure reaches the peak values, it starts decaying and is represented by wave decay parameter (b). The shape of blast pressure profile depends on wave decay parameter, and it is a dimensionless parameter that governs the negative phase of blast wave. Based on pressure impulse ratio, various methods could be used to compute wave decay parameter. The parameter (b) can be calculated through area under pressure–time curve of the blast wave [16, 41]. The correlation between blast impulse and wave decay parameter presented by Kinney and Graham can be expressed as:

$$\frac{i_s}{A} = \int_0^{t_d} pdt = P_s t_d \left[\frac{1}{b} - \frac{1}{b^2}\left(1 - e^{-b}\right)\right] \tag{15}$$

## 4.6 Negative Phase of Blast Wave

Most of the literature neglects effect of negative phase on the structure. But flexible structures such as doors, windows, connecting nails, light cladding and glazing panels experience the impact of negative phase pressure. And among very few known facts, main effect of negative phase depends on angle of incidence. But nowadays, due to growing awareness for minimizing the structural damage, and injuries to the inhabitant during explosion, negative phase has gained the attention of many researchers and structural designers. Over expansion of previously compressed air and inertial effect, results in negative pressure phase of blast wave [21, 43].

The impact of negative phase on the surrounding elements is elaborated with reference to Fig. 14. The first point (1) indicates initial condition i.e. condition before explosion. Second point (2) signifies positive pressure phase, and the surrounding elements are affected with compressed blast wave. The overpressure decays exponentially, and at point (3) it reaches to zero pressure. As a result, the elements are back in their normal shapes with damaged effects on components. The pressure further reduces and goes below ambient pressure therefore, the suction effect of blast wave can be seen from point (4) of the figure. It can also be noticed that during negative pressure phase, everything is blown away in opposite direction to the incident blast wave. Finally, once the negative phase is over, the pressure reaches back to normal atmospheric pressure condition and everything is back in normal position which can be observed from the point 5.

Negative pressure is calculated as per Eqs. (16, 17) as proposed by Krauthammer and Altenberg [43] and is reported as:

Fig. 14 Effect of blast pressure associated with positive and negative phase
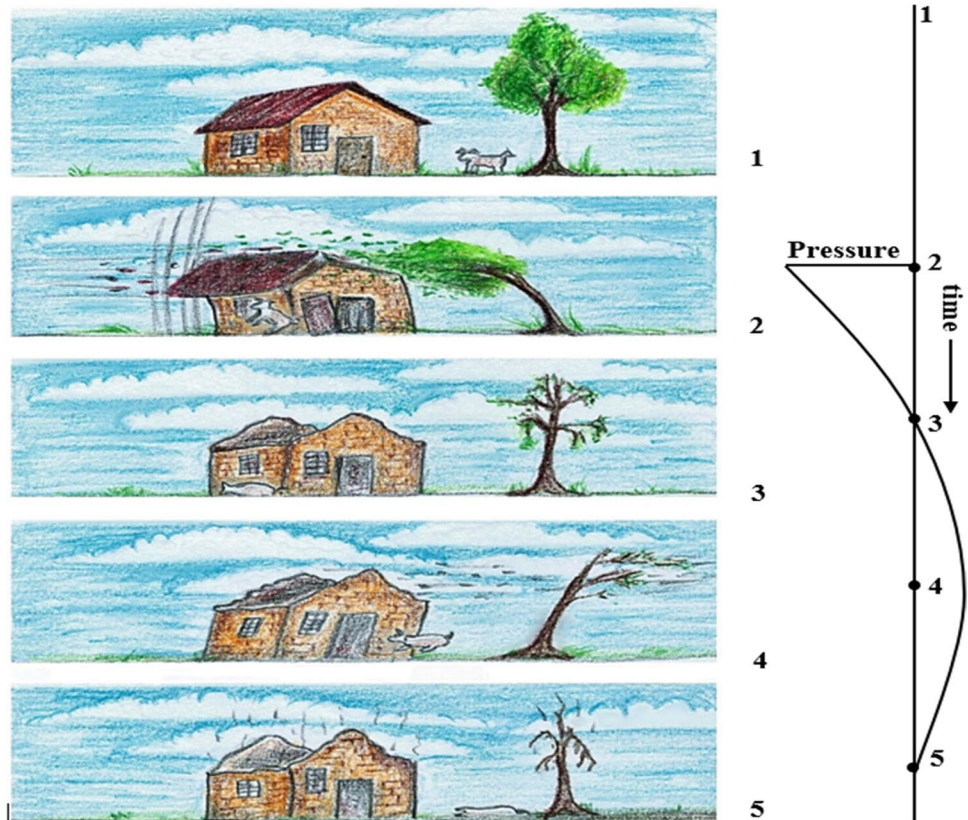
$$P_{neg} = \frac{0.35}{Z} 10^5 \, \text{Pa} \quad \text{for} \, (Z > 3.5) \tag{16}$$

$$P_{neg} = 10^4 \, \text{Pa} \quad \text{for} \quad Z < 3.5 \tag{17}$$

Negative phase duration is computed as described by Krauthammer using three different Eqs. (18, 19, 20) based on ranges of scaled distances, and are represented as [43]:

$$t_{neg} = 0.0104 \times W^{1/3} \quad \text{for} \quad Z < 0.3 \tag{18}$$

$$t_{neg} = (0.003125 \times \log(Z) + 0.01201) \times W^{1/3} \quad \text{for} \quad 1.9 \geq Z \geq 0.3 \tag{19}$$

$$t_{neg} = 0.0139 \times W^{1/3} \quad \text{for} \quad Z \geq 1.9 \tag{20}$$

The negative phase impulse is defined as area of the pressure time curve for negative phase, and is predicted based on the Eq. (21), recommended by Teich and Gebbeken [51].

$$i_s^- = \frac{P_s t_d}{b^2} e^{-b} \tag{21}$$

4.7 Modeling Techniques

Loading conditions generated by blast can be simulated with several approaches. These approaches are discussed briefly in this section. Using numerical simulation, entire explosion event can be analyzed, and the response of the structure can be determined. Various methods of analysis are available in different software (e.g. LS-DYNA, ABAQUS, AUTODYN, ANSYS AUTODYN, Air3D, DYNA3D, BLASTX, ALE3D etc.) for simulating the response of the structure subjected to blast load. Some recent methodology consisting coupling of finite element method (FEM) and the discrete element method (DEM) technique is used for effective analysis of crack pattern in blasting problems in tunnel [52]. For analysis of complex problems such as blast structure interaction can be solved using 3-dimensional FEM-FCT technique [53, 54] with embedded mesh, immersed body and body-fitted approaches [55]. Löhner et al. [55] worked to evaluate the accuracy of these embedded techniques under blast loads. It becomes uneconomical to perform experimental tests every time therefore, numerical techniques are used to minimize number of tests [56, 57].

In *Lagrange* simulation, the mesh is embedded with the material, and the mesh moves along with material. In this technique, computation of the air blast is done with CONWEP, referred as load blast enhanced (LBE) method. Lagrangian simulation has base of large experimental data [56, 58, 59]. Purely Lagrangian method is computationally economical, as air is not modeled explicitly with explosive and structure. This method is comparatively less accurate, as load blast feature does not consider shadowing effect as depicted in Fig. 15, and the pressure calculated will be incorrect.

Poor solution is obtained in Lagrangian technique due to mesh distortion at high strain rate. In order to tackle this distortion problem, frequent remeshing with the help of interpolation needs to be done, which increases computational time [60–63]. Pure Lagrangian formulation with high mesh deformation can be observed from Fig. 16.

In *Eulerian formulation* the mesh is fixed in the space, and the material moves through the mesh. Interface tracking

Fig. 15 Shadowing effect in load blast enhanced method
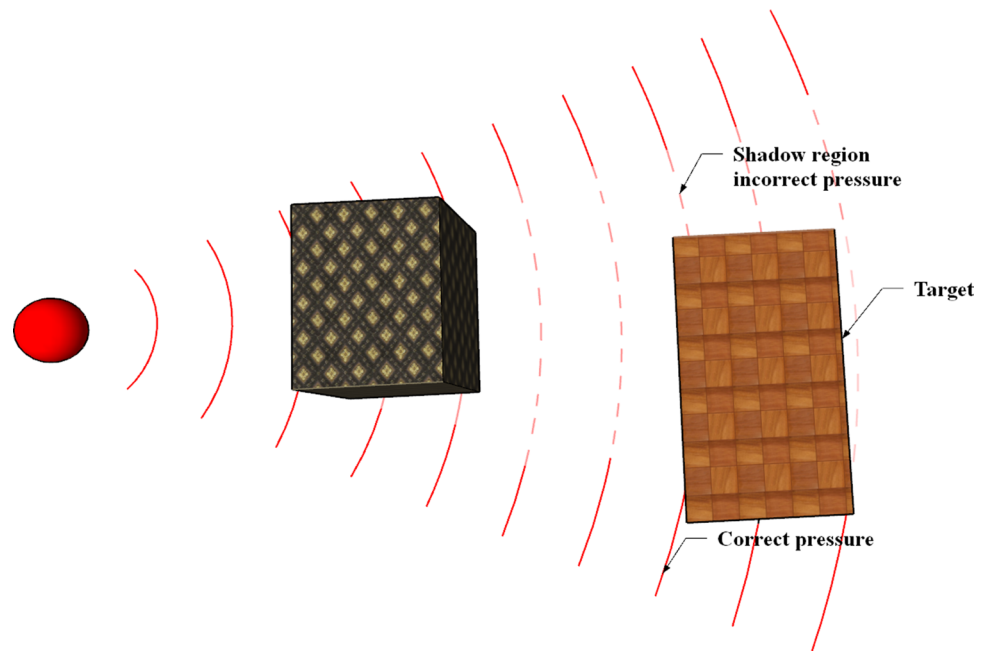
Fig. 16 Pure Lagrangian formulation
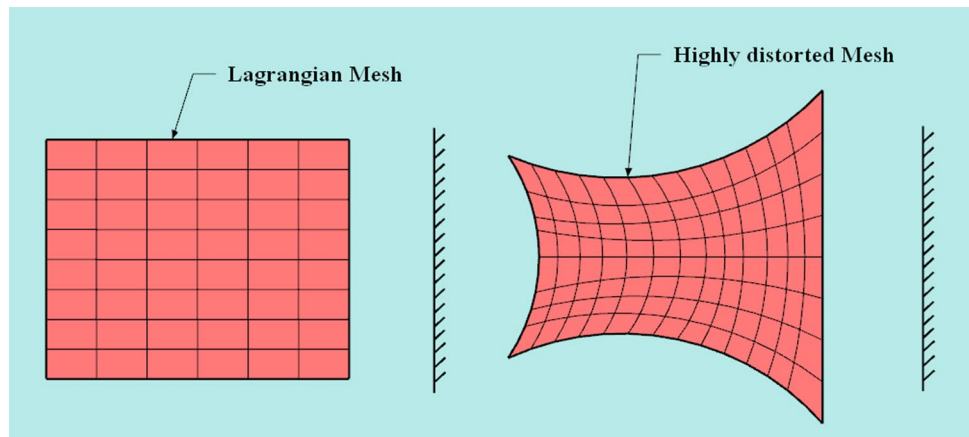
is needed in Eulerian formulation, as material moves through the fixed mesh [59, 63]. There is no distortion of mesh in this formulation, which makes it more advantageous to handle large deformation. Computational time is reduced as compared to the Lagrangian formulations, as remeshing is not required to be done [63]. Eulerian formulation can be observed from Fig. 17, with fixed mesh and material deforming through this fixed mesh.

Arbitrary Lagrangian–Eulerian (ALE) method is a fusion of Lagrangian and Eulerian techniques. The mesh can be fixed as in Eulerian method, or it may move along with the material as per Lagrangian manner [56]. Large distortion issue of Lagrangian formulation has been resolved in this technique. The feature also accounts for shadowing as well as focusing effect of blast or air (fluid) in pressure computation [60, 62].

In *Multi Material Arbitrary Lagrangian Eularian (MM-ALE)* approach, air domain and explosive need to be modeled explicitly [56]. Both air as well as explosive should be meshed for air blast analysis using MM-ALE formulation [64]. MM-ALE is more precise formulation, as complete process of explosion including detonation of high explosive can be modeled using algorithm [65].

Lucy (1977) developed the method of *smooth particle hydrodynamic (SPH)* which was later implemented in LS-DYNA. The method is based on equations of fluid motion [62]. SPH method uses mesh less Lagrangian technique and can be used to predict the response of the Light Armored Vehicle (LAV) for military use and other structures [65]. Absence of mesh has advantages to evaluate the problem with irregular geometry. The issue of large deformation and mesh tangling in high velocity problem has been resolved in this method [66].

5 Blast Mitigation Techniques

Insufficient protection capability leads to loss of lives, as well as economic loss due to structural damage under blast loads. Therefore, various mitigation strategies to safeguard the structure from primary and secondary damages need to be rectified. In the present section, the main focus is to identify different blast mitigation strategies. The aim of blast mitigation strategy is to minimize structural damage and to increase the capability of structure to function even after the blast. Standoff distance is one of the important and most

Fig. 17 Pure Eulerian formulation
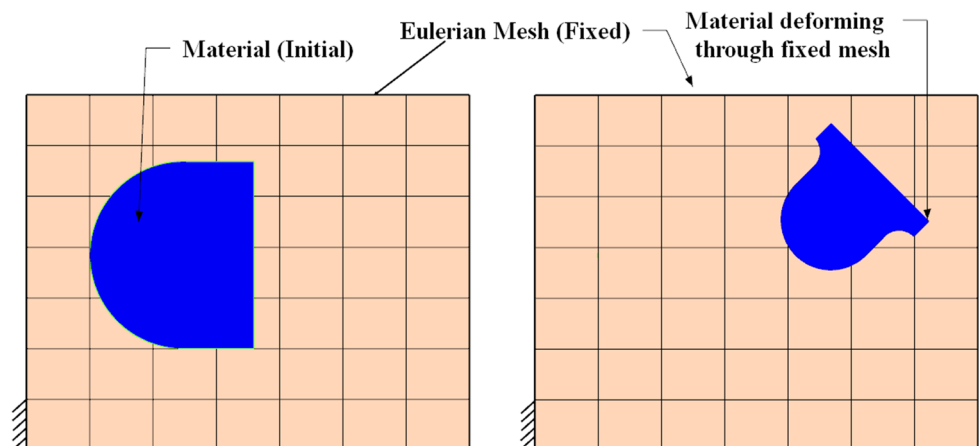
economical parameters in mitigation strategy, as pressure due to blast wave decays rapidly with standoff distance. When it is not possible to provide standoff distance, structure needs to be hardened which makes the structure uneconomical. Sometimes building need to satisfy design criteria for both seismic as well as blast load on structure, which needs light weight and energy absorption material. Thus, there is need of some lightweight energy absobing materials to be invented [15, 25, 26, 67].

Defense in depth is another important parameter, consisting several layers that terrorists need to cross before reaching the centre of the asset. Physical barriers such as blast wall, anti-ram barriers and vehicle barriers can also be constructed in standoff zone which impede access to protect the structure [15, 23, 26]. Orientation and shape of building, proper landscaping and architectural aspects to design the structure against blast threat attenuate the effective pressure [26, 68, 69].

5.1 Mitigation Systems

Basically, there are two types of mitigation systems as active and passive mitigation system. Active mitigation system activates appropriate system, whenever threat is detected and reduces the damage to landmine vehicles and occupants. In this way, active mitigation systems minimize the blast pressure, temperature, impulse and subsequently reduces destructive effects due to blast. But the main requirement of such system is that very short time (order of microseconds) is available to deploy the system, due to the availability of short distances in case of armoured vehicles. As per literatures, these types of systems are not easily available. Water deluge system is employed in mining sector as active mitigation system. In case of water deluge system, once the gas leakage is sensed, with immediate effect water droplets are sprinkled on the affected asset [70, 71].

Passive mitigation system does not consist of any sensors which required to be triggered. But it consists of structure with different geometries and materials placed in between threat and target. Impedance mismatching, sacrificial cladding, blast deflection, blast or shockwave disruption are the different ways of passive mitigation [70].

5.1.1 Impedance Mismatching

Impedance mismatching is done by placing layers of different materials between threat and object to attenuate the effect of blast or shockwave. Due to impedance mismatching there will be dissipation of pressure and will work as mitigative measure. One of the examples is cavity filled with water is kept in between blast wave and object [70, 72].

5.1.2 Sacrificial Cladding

In sacrificial cladding, multiple layers of different material and their stress strain characteristics are used to absorb energy. Sacrificial claddings represented by Fig. 18 consists of a stiff cover plate and core which transfer least impulse. The cover plate enhances the flexural capacity whereas, the core possesses energy absorption characteristics [73–75]. The purpose to use these layers of different material characteristics is to have plastic deformation. Metal plates, sandwich layers, blast wall, perforated plates, cellular and honeycomb type of structure can be utilized as sacrificial cladding. It has also been observed from literatures that sandwich panel is one of the types of sacrificial layer and is best mitigative measure, due to its superior strength and stiffness [26, 70, 74]. Inserts in sandwich panels could be
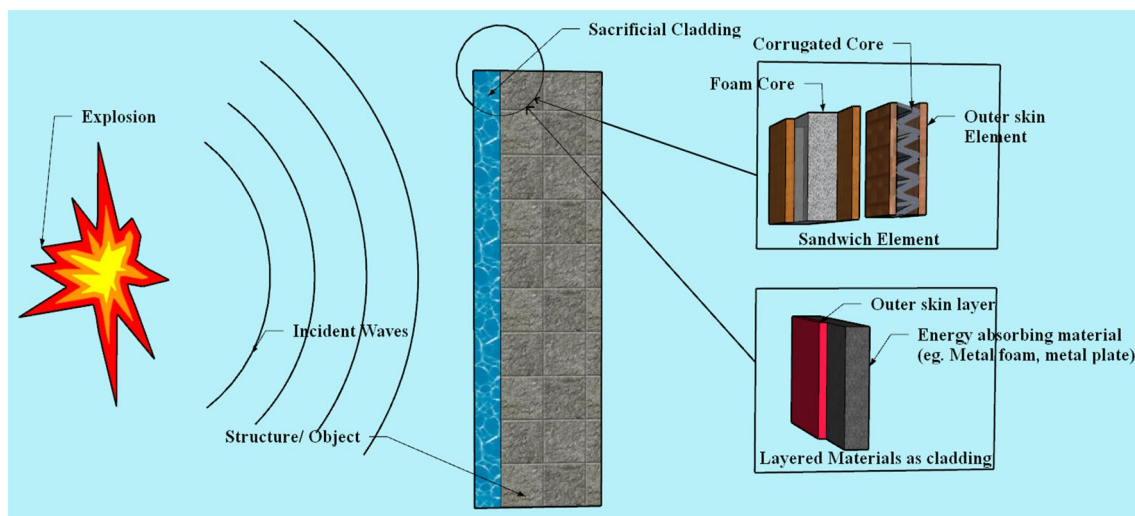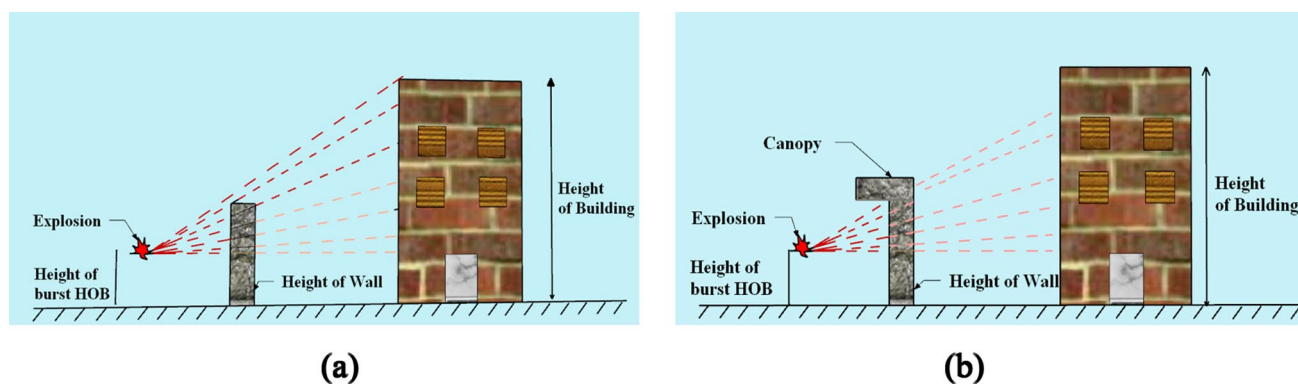

Fig. 18 Sacrificial cladding with different materials for blast mitigation

Fig. 19 Geometric configuration of blast wall **a** planar wall; **b** canopy wall

varied (e.g. ceramics, metal foam, lattice structure, honey-combs) and the higher energy absorbing and ballistic resistant material could be fidentified [70, 74, 76–79].

5.1.3 Sacrificial Blast Wall

A physical barrier that separates the explosive threat and asset to be protected acts as a mitigative measure which is relatively economical [80]. Standoff distance increases with the provision of blast wall between threat which has ability to minimize or eliminate the blast induced pressure [26]. The blast wall acts as obstacle to reduce the pressure and impulse behind the wall. The barrier will cause the wave to diffract, which weakens the blast wave intensity, resulting in reduced propagated energy behind the barrier [81]. Energy absorption and reflection of the wall depends on the design of the blast wall. Height of wall, thickness, orientation and positioning of wall with threat and asset are significant factors affecting the performance of the blast wall in blast pressure mitigation. These blast wall shields a structure or building by reflecting the blast wave from the surface of wall [26]. One of the important aspects in blast wall design is that the fragment load should not be produced due to complete (or partial) failure of wall. Canopy or overhang enhances the performance of the wall, as it redirects or alters the blast wave away from the target structure [26, 31, 80]. Figure 19a, b shows plain, canopy configuration of blast wall, respectively. Height of wall is same in both the figures, but wall with canopy offer comparatively more reduction in blast pressure as that of plane wall, this can be observed from figure [80, 82].

5.1.4 Blast Wave Deflection and Disruption

In this technique, the blast waves are redirected away from the asset to be protected. For example, hulls of V shape redirect the blast away from the hull. Whereas, in blast disruption type of mitigation system, the main focus is to disrupt the path of the blast wave by imparting some object in between threat and asset. Such systems could include granular filters, barriers, baffles etc. Perforated plates can also be incorporated in shock tubes to disrupt the path of blast wave so that effect of blast pressure can be mitigated [70].

6 Summary

The current scenario of the terrorist attacks and its impact on people as well as objects indicates the need to adopt blast resistant or mitigation measures. Therefore, main purpose of the present paper is to give concepts and terms involved in the phenomenon of blast, so that beginner researchers and structural designers could initiate their work in the field of blast. To minimize the risk of structural damage, different numerical approaches suggested by several researchers have also been summarized so as to compute the blast overpressure. The paper also covers the aspects of positive as well as negative phase of the blast wave. Blast parameters including, standoff distance, weight of explosive charge, Mach stem phenomenon considering the effect of angle of incidence have also been extensively overviewed in the present work. The more emphasis has been given on mitigation strategies, and the effect of lightweight material in reduction of the blast response on a structure. Physical barriers such as, sacrificial cladding, blast wall and other mitigation systems which can be adopted to reduce the blast pressure are discussed briefly in the present work.

Compliance with Ethical Standards

References

1. Soto OA, Baum JD, Togashi F, Löhner R, Frank R, Amini A (2016) The simulation of dust effects from fragmenting charges. Int J Numer Methods Heat Fluid Flow 26:999–1026

2. Ding Y, Chen Y, Shi Y (2016) Progressive collapse analysis of a steel frame subjected to confined explosion and post-explosion fire. Adv Struct Eng 19(11):1–17

3. Eskew EL, Jang S (2014) Damage assessment of a building subjected to a terrorist attack. Adv Struct Eng 17(11):1693–1704

4. Singh AK, Ditkofsky NG, York JD, Abujudeh HH, Avery LA, Brunner JF, Sodickson AD, Lev MH (2016) Blast injuries: from improvised explosive device blasts to the Boston Marathon bombing. Radio Graph 36:295–307

5. Larcher M, Valsamos G, Karlos V (2018) Access control points: reducing a possible blast impact by meandering. Adv Civ Eng 2018:1–12

6. Smith PD, Hetherington JG (1994) Blast and ballistic loading of structures. Butterworth-Heinemann, Oxford

7. Cullis IG (2001) Blast waves and how they interact with the structures. J R Army Med Corps 147:16–26

8. Neff M (1998) A visual model for blast waves and fracture. Master's dissertation, Department of Computer Science, University of Toronto

9. Remennikov AM (2002) Blast resistant consulting: a new challenge for structural engineers. Aust J Struct Eng 4:121–135

10. Baum JD, Soto OA, Togashi F, Löhner R, Giltrud ME, Bell J (2017) An investigation of stationary and moving cased charge detonations in stone lined pipes. In: 31st international symposium on shock waves, vol 1, pp 117–126

11. Togashi F, Baum JD, Soto OA, Löhner R, Zhang F (2012) Numerical simulation of TNT-Al explosives in explosion chamber. In: Seventh international conference on computational fluid dynamics (ICCFD7), Big Island, Hawaii, July 9–13, 2012

12. Department of the Army, Navy, and Air Force (1990) Structures to resist the effects of accidental explosions (with addenda). Army Technical Manual (TM 5-1300) Washington, DC

13. Hao H, Hao Y, Li J, Chen W (2016) Review of the current practices in blast-resistant analysis and design of concrete structures. Adv Struct Eng 19(8):1–31

14. Department of Defense (2008) Unified facilities criteria: structures to resist the effects of accidental explosions. UFC 3-340-02. Washington, DC

15. Remennikov A, Carolan D (2005) Building vulnerability design against terrorist attacks. In: Proceedings of the Australian structural engineering conference, pp 1–10

16. Ullah A, Ahmad F, Jang HW, Kim SW, Hong JW (2016) Review of analytical and empirical estimations for incident blast pressure. KSCE J Civ Eng 21(6):1–15

17. Ngo T, Mendis P, Gupta A, Ramsay J (2007) Blast loading and blast effects on structures—an overview. EJSE Spec Issue 7:76–91

18. Jeremic R, Bajic Z (2006) An approach to determining the TNT equivalent of high explosives. Sci Tech Rev L VI 1:58–62

19. Eichinger WE (1985) Mach stem modeling with spherical shock waves. M.S. Thesis Airforce Institute of Technology, US army

20. Karzova MM, Khokhlova VA (2015) Mach stem formation in reflection and focusing of weak shock acoustic pulses. J Acoust Soc Am 136:436–442

21. Rigby SE, Fay SD, Tyas A, Warren JA, Clarke SD (2015) Angle of incidence effects on far-field positive and negative phase blast parameters. Int J Prot Struct 6(1):23–43

22. Lofquist C (2016) Response of buildings exposed to blast load. Master's Dissertation, Structural Mechanics, Lund University, ISSN 0281-6679:1-88

23. FEMA (2003) Risk management series: reference manual to mitigate potential terrorist attacks against buildings, 426, Washington, DC

24. Verma S, Choudhury M, Saha P (2015) Blast resistant design of structure. IJRET 4:64–70

25. Shadhar HM, Lakshmi S (2017) Study of response of RC tall buildings subjected to blast loads. Int J Eng Sci Comput 7:11137–11143

26. Goel MD, Matsagar VA (2014) Blast-resistant design of structures. Pract Period Struct Des Constr 19(2):1–9

27. Shukla PJ, Desai AK, Chentankumar MD (2018) The current practices of analysis of reinforced concrete panels subjected to blast loading. Int J Struct Constr Eng 12:935–943

28. Koccaz Z, Sutcu F, Torunbalci N (2008) Architectural and structural design for blast resistant buildings. In: Proceedings of 14th world conference on earthquake engineering at Beijing, China

29. Draganic H, Sigmund V (2012) Blast loading on structures. Tech Gazette 19(3):643–652

30. Baumgart CM (2014) The effect of advanced structural materials to mitigate explosive and impact threats. Masters Theses, Missouri University of Science and Technology, p 7320

31. Alsubaei FCF (2015) Performance of protective perimeter walls subjected to explosions in reducing the blast resultants on buildings. Electronic Thesis and Dissertation Repository, p 2976

32. Vannucci P, Masi F, Stefanou I (2017) A study on the simulation of blast actions on a monumental structure. HAL-01447783v3

33. Chock JMK (1999) Review of methods for calculating pressure profiles of explosive air blast and its sample application. Masters theses, Blacksburg, Virginia

34. Baker WE (1973) Explosions in air. University of Texas Press, Austin

35. Taylor GI (1950) The formation of a blast wave by a very intensive explosion I. Theoretical discussion. Proc R Soc A 201(1065):159–174

36. Taylor GI (1950) The formation of a blast wave by a very intense explosion. II. The atomic explosion of 1945. Proc R Soc Lond Ser A Math Phys Sci 201(1065):175–186

37. Neumann JV (1963) The point source solution. In: Collected works, vol. VI. Pergamon, London, p 218

38. Sedov L (1946) Propagation of strong shock waves (translated from Russian). J Appl Math 10:241–250

39. Barbier M, Villamaina D, Trizac E (2016) Microscopic origin of self-similarity in granular blast waves. Phys Fluids 28(8):1–16

40. Barbier M, Villamaina D, Trizac E (2015) Blast dynamics in a dissipative gas. Phys Rev Lett 115(21):1–5

41. Goel MD, Matsagar VA, Gupta AK, Marburg S (2012) An abridged review of blast wave parameters. Def Sci J 62:300–306

42. Karlos V, Solomos G (2013) Calculation of blast loads for application to structural components. JRC Technical Reports European Union 1-50

43. Krauthammer T, Altenberg A (2000) Negative phase effects on glass panels. Int J Imp Eng 24(1):1–18

44. Kingery CN, Bulmash G (1984) Air blast parameters from TNT spherical air burst and hemispherical burst. Technical report ARBRL-TR-02555. CRC Press, Taylor & Francis

45. Brode HL (1955) Numerical solution of spherical blast waves. Jpn J Appl Phys 26(6):766–775

46. Kinney GF, Graham KJ (1985) Explosive shocks in air. Springer, Berlin

47. Newmark NM, Hansen RJ (1961) Design of blast resistant structures. In: Harris, Crede (eds) Shock and vibration handbook. McGraw-Hill, New York, p 3

48. Henrych J (1979) The dynamics of explosion and its use. Elsevier, Amsterdam

49. Sadovskiy MA (2004) Mechanical effects of air shockwaves from explosions according to experiments. In: Sadovskiy MA

(ed) Selected works: geophysics and physics of explosion. Nauka Press, Moscow

50. Larcher M (2008) Pressure-time functions for the description of air blast wave. European commission

51. Teich M, Gebbeken N (2010) The Influence of the under pressure phase on the dynamic response of structures subjected to blast loads. Int J Prot Struct 1(2):219–234

52. Zárate F, Gonzalez JM, Miquel J, Löhner R, Oñate E (2018) A coupled fluid FEM-DEM technique for predicting blasting operations in tunnels. Undergr Space 3(4):310–316

53. Baum JD, Luo HJ, Löhner R (1993) Numerical simulation of a blast within a multi-room shelter. In: Proceedings of the MABS-13 conference. The Hague, pp 451–463

54. Löhner R, Camelli F, Baum JD, Togashi F, Soto OA (2014) On mesh-particle techniques. Comp Part Mech 1:199–209

55. Löhner R, Baum JD, Mestreau EL, Rice D (2007) Comparison of body-fitted, embedded and immersed 3-D euler predictions for blast loads on columns. Collect. Tech. Pap.—45th AIAA aerospace sciences meeting and exhibit, p 1133

56. Tabatabaei ZS, Volz SA (2012) Comparison between three different methods in LS-DYNA: LBE, MM-ALE, coupling of LBE and MM ALE. In: 12th International LS DYNA users conference, pp 1–10

57. Schewer L (2010) A brief introduction to coupling load blast enhanced with multi material ALE: the best of both worlds for air blast simulation. LS-DYNA Forum, Bamberg, pp 1–12

58. Miller D, Pan H, Nance R, Shirley A, Cogar J (2010) A coupled Eulerian/Lagrangian simulation of blast dynamics. In: Proceedings of the IMPLAST conference, Rhode Island 12–14 October, 2010

59. Soulie Y, Bouamoul A, Nguyen-Dang TV (2012) ALE formulation with explosive mass scaling for blast loading: experimental and numerical investigation. Comp Model Eng (CMES) 86(5):462–486

60. Slavik TP (2009) A coupling of empirical explosive blast loads to ALE air domains in LS-DYNA®. In: 7th European LS-Dyna conference

61. Slavik TP (2012) Blast loading in LS-DYNA. University of California – San Diego, San Diego

62. Toussaint G (2010) Comparison of ALE and SPH methods for simulating mine blast effects on structures. Defence R&D Canada—Valcartier, Technical Report, TR 2010-326

63. Aryal A (2014) A coupled Eulerian–Lagrangian extended finite element formulation for moving interface problems and damage transport in hyper-elastic media. Dissertation, graduate school of Vanderbilt University

64. Hilding D (2016) Methods for modelling air blast on structures in LS-DYNA. In: 14th German LS-DYNA forum Bamberg

65. Trajkoski J (2017) Comparison of MM-ALE and SPH methods for modelling blast wave reflections of flat and shaped surfaces. In: 11th European LS-DYNA conference, Austria

66. Lacome JL (2000) Smooth particle hydrodynamic (SPH): a new feature in LS-DYNA. In: 6th International LS-DYNA users, vol 7, pp 29–34

67. Schimizze B, Son S, Goel R, Vechart AP, Young L (2013) An experimental and numerical study of blast induced shock wave mitigation in sandwich structures. Appl Acoust 74(1):1–9

68. Gebbeken N, Doge T (2010) Explosion protection—architectural design, urban planning and landscape planning. Int J Prot Struct 1(1):1–21

69. Badshah E, Naseer A, Ashraf M, Shah F, Akhtar K (2017) Review of blast loading models, masonry response, and mitigation. Shock Vib 2017:1–15

70. Langdon GS, Nurick GN, Balden VH, Timmis RB (2008) Perforated plates as passive mitigation systems. Def Sci J 58:238–247

71. Mostert FJ (2018) Challenges in blast protection research. DST Def Technol 14(5):426–432

72. Rahimzadeh T, Arruda EM, Thouless MD (2015) Design of armor for protection against blast and impact. J Mech Phys 85:98–111

73. Guruprasad S, Mukherjee A (2000) Layered sacrificial claddings under blast loading part I analytical studies. Int J Imp Eng 24:957–973

74. Goel MD, Matsagar VA, Gupta AK (2014) Blast resistance of stiffened sandwich panels with closed-cell aluminium foam. Lat Am J Solids Struct 11:2497–2515

75. Ding Y, Wang S, Zhao K, Yang L, Yu J (2016) Blast alleviation of cellular sacrificial cladding: a nonlinear plastic shock model. Int J Appl Mech 8(4):1–24

76. Mondal DP, Goel MD, Das S (2009) Compressive deformation and energy absorption characteristics of closed cell aluminum-fly ash particle composite foam. Mater Sci Eng A 507(1–2):102–109

77. Goel MD, Matsagar VA, Marburg S, Gupta AK (2013) Comparative performance of stiffened sandwich foam panels under impulsive loading. J Perform Constr Facil ASCE 27(5):540–549

78. Goel MD, Altenhöfer P, Matsagar VA, Gupta AK, Mundt C, Marburg S (2015) Interaction of shock wave with closed cell aluminum metal foam. Combust Explos Shock 51(3):373–380

79. Codina R, Ambrosini D, Bordon FD (2017) New sacrificial cladding system for the reduction of blast damage in reinforced concrete structures. Int J Prot Struct 8(2):1–16

80. Smith PD (2009) Blast walls for structural protection against high explosive threats: a review. Int J Prot Struct 1(1):67–84

81. Zhao XQ, Hao H (2008) Prediction of airblast loads on structures behind a protective barrier. Int J Prot Struct 35(5):363–375

82. Palla S, Goel MD (2017) Performance assessment of curved steel wall under blast loading. Int J Eng Res Mech Civ Eng 2(3):406–411