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REVIEW PAPER

Blast Valve Design and Related Studies : A Review

P.K. Sharma[*,!], B.P. Patel[#], and Harbans Lal[!]

[!]*Centre for Fire Explosive and Environment Safety, Delhi - 110054, India*
[#]*Indian Institute of Technology Delhi, New Delhi - 110 016, India*
[*]*Correspondence e-mail: pankaj.drdo@gmail.com*

ABSTRACT

The protective structures required for performing critical operations are vulnerable to the blast and shock loads of advanced weapons. A blast valve is an important component of such structures for ventilation during normal conditions and for protection from blast/ shock during explosion. In this paper, various aspects of blast valve design and related studies are briefly reviewed. The concept and effects of blast wave, blast impact, numerical modelling and deformation of circular plate (one of the critical components of blast valve) have been discussed. The merits and demerits of sensing mechanisms viz. remote and direct sensing are discussed. The leakage of blast pressure during finite closing period of the valve (one of the critical problems) and the shock tube as a major experimental facility for testing of blast valves are briefly discussed.

Keywords: Blast valve, wave, leakage, closure mechanism, shock tube

NOMENCLATURE

a, b	Loading parameter
d	Distance covered by closure plate in complete closure of blast valve
$f(t)$	Dynamic pressure force acting on the closure plate
F_0	Maximum amplitude of load pulse
H	Plate thickness
I_s	Specific impulse (impulse per unit surface area)
k	Spring stiffness
m	Mass of the closure plate
M_0	Plastic collapse moment per unit width
p_c	Static collapse pressure
p_0	Reference pressure
$p_{\max}$	Maximum incident pressure
$p_{\min}$	Minimum value of pressure below reference
$p(t)$	Blast overpressure as a function of time
R_0	Radius of central uniformly loaded region
R	Plate radius
t_a	Shock arrival time
t_c	Blast valve closing time
t_{d+}	Positive phase duration of blast wave
t_{d-}	Negative phase duration of blast wave
β	Plate parameter
σ_0	Minimum yield strength of plate material

1. INTRODUCTION

Blast valve or blast closure valve is used to prevent the stream of high pressure and flow of harmful contaminants into the hardened structure[1] during an explosion through ventilation ducts as shown in Fig. 1. On the impingement of blast wave, spring loaded circular plate starts moving downstream and closes the passage during positive phase of the blast. During negative phase of the blast, the plate starts moving in forward direction, closes the passage and prevents washing out of fresh air from the shelter. The spring is designed such that it permits flow of fresh air during normal operating conditions.

It appears that the blast valve development has started soon after WWII after experiencing the disasters of nuclear explosions at Hiroshima and Nagasaki in 1945[2]. Most of the valve development took place during 1950 to 1965 and the designs kept on improving during cold war era in order to safeguard civilian population from conventional and non-conventional explosions[3-8]. The development of blast actuated valve over remote actuated valves, the use of a bypass ventilation duct in blast actuated valves and development of chemical warfare valve using filters were some of the improvements. U.S. Army Chemical Warfare Laboratories initiated the development of 100 psi overpressure M1 valve under the operation greenhouse in 1950 and tested it successfully at the Nevada test site during 1951-52[3]. US Department of Defence patented a number of different designs of blast valves during 1960-1971[4-12].

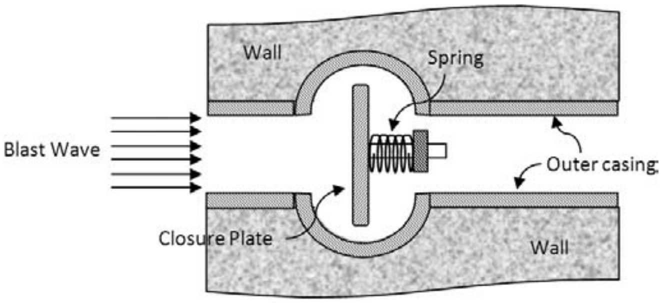

Figure 1. Schematic of blast closure valve.

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Blast valves may be either remote-actuated (closed mechanically by actuator on receiving signal from remote sensors) or blast-actuated (closed by the pressure wave itself). Both types can be non-latching which opens under negative pressures or latching which can only be reopened manually. A blast-actuated double-acting valve closes the passage against the positive as well as negative blast pressure and reopens at normal pressure. Fig. 2 shows the brief classification of blast valves. A similar device which operates on static pressure and widely used in industrial circulating fluidised bed (CFB) boilers is known as blast cap[13].

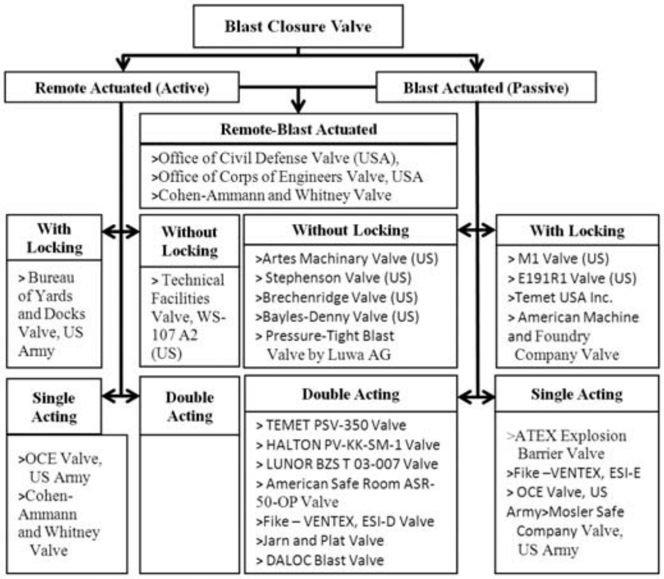

Figure 2. Classification of blast closure valve[2,5,6,8,11,14,15,19-24].

The internationally available designs of blast valves include flow rate capacities ranging from about 0.14 m^3/s to 16.5 m^3/s. It is also evident that the pressure loss across these valves at the rated air flow are normally less than 25 cm of water column. The common valves are generally designed for incident pressure ranging from 3 bar to 7 bar. The recognised companies working in the area of design and development of these blast valves are TEMET[14], American Safe Room[15], Halton Marine[16], etc. The pressure capacity of TEMET PVE-1-150 blast valve is up to 3 bar and operating temperature range is between -20 °C to 80 °C[17]. The pressure capacity of heavy duty TEMET PSV-250 valve is about 20 bar for long duration (peak positive duration, $t_{d+} > 60$ ms) and 60 bar for short duration ($t_{d+} < 5$ ms)[18]. The HALTON's PV-KK-SM Blast valve is designed to operate between -40 °C to 200 °C[19]. For the explosive protection valves from Lunor Company at Zurich, closing time is less than 2 ms[20].

2. BLAST WAVE AND ITS EFFECT

The sudden release and transformation of potential energy into kinetic energy during a conventional explosion generates hot gases up to 30 MPa pressure and a temperature of about 3000 °C – 4000 °C. High pressure gases move at very high velocity (7000 m/s) away from the centre of explosion and create blast wave in the surrounding medium[25]. A moving shock wave with decaying strength is called blast wave. The blast wave propagation is a nonlinear phenomenon with velocities greater than sonic[26]. The product gases with high pressure and temperature expand outward by generating pressure waves leading to shock wave. Due to very high velocity and very high temperature, the boundary layer effects are confined in a very narrow region and the flow of gaseous products is assumed to be inviscid. Thus the viscous forces are not considered for the explosive modelling[27].

The explosion in air at a considerable height from ground is known as free-field air blast with spherical waves. The key features of the free-field air blast wave[28], are shown in Fig. 3. The specific impulse (I_s) during positive phase is given by

$$I_s = \int_{t_a}^{t_a+t_{d+}} p(t)dt \tag{1}$$

Blast loading on a structure depends on the mass of explosive in terms of TNT equivalent and stand-off-distance. One important scaling parameter called 'Scale distance' is obtained by dividing stand-off-distance with cube root of equivalent mass of TNT. The blast scaling is done using Cranz-Hopkinson or cube-root scaling law[29]. It states that 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. The mathematical equations to calculate different blast parameters are given by Goel[26], *et. al.* describing the available formulae for pressure-time history useful to simulate blast-structure interaction with a fare degree of accuracy.

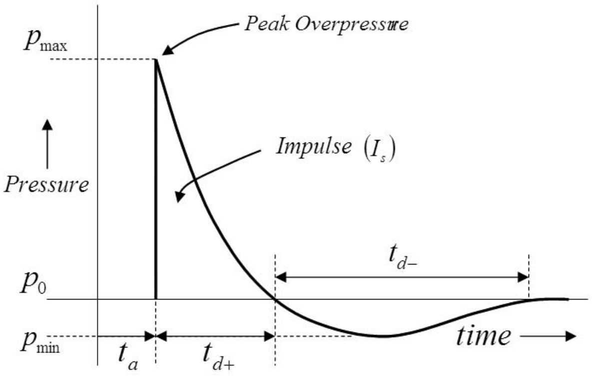

Figure 3. Ideal blast wave profile also known as Friedlander profile[26].

For preliminary investigations of blast-structure interaction, the structures subjected to blast loads may be considered as an equivalent single degree of freedom (SDOF) system[30], and a stepped triangular blast load. The dynamic response of stiffened orthotropic plates subjected to the stepped triangular blast profile is investigated by Alisjahbana and Wangsadinata[31] and the effects of stiffener arrangement and blast loading duration on the plate failure were examined. The use of a single stiffener passing through the centre and parallel to one of the edges leads to 30 per cent – 50 per cent reduction in absolute maximum dynamic deflection (as compared to a normal plate) while with two stiffener arrangement, the percentage reduction is only 5 per cent – 20 per cent (compared to a single stiffener arrangement) for damping ratio up to 10 per cent. Thus the use of single stiffener can be considered as the optimum arrangement.

3. LEAKAGE OF SHOCK AND BLAST PRESSURE

The simple and cost-effective method for minimising pressure leakage across a protective structure is to reduce the number and size of intake and exhaust openings or by using a blast valve. If the leakage pressure cannot be reduced to allowable limits or if the toxins are released inside the protected area during an explosion, there may be damage of the life or the key ammunition stored inside the structure. The leaked blast pressure and the rate of rise of this pressure inside protected area are the key parameters of design. A blast damper (a type of blast valve) with 1500 mm^2 x 1500 mm^2 cross-sectional area was tested using a shock tube, and the leakage pressure downstream of the blast damper was obtained[32]. The key findings were:

(a) shock tube was capable of generating long duration impulsive loads of 20 kPa-s with peak pressure up to 100 kPa,
(b) the leakage pressure exceeded the 20 kPa design limit, and
(c) the closing started at 35 ms after impingement of pressure pulse on the blades and completed till 70 ms with some vibration and rebound.

To overcome this problem, the blade opening angle was reduced from 45° to improve the closing of valve thereby controlling the leaked pressure within the design limits.

Data from several physiological studies and experimentations reveals that if the incident overpressure of 100 psig (≈ 7 bar)[33] or 30 psig - 40 psig[34] reaching ventilation port of a hardened structure can be attenuated such that the leakage into the structure does not cause an interior peak overpressure more than 5 psi (≈ 0.34 bar), the occupants will uphold slight or no blast injury[33]. The type of valve used for a specific installation depends on the duration and intensity of blast loading. For short-duration blast loadings, equipment such as baffles and mufflers with plenums are partially effective. Although the negative phase and positive phase durations for high yield (megaton) weapons are of the order of 30 ms and few seconds respectively, the peak negative pressure is never greater than about 3 psi (≈ 0.2 bar)[2].

4. BLAST VALVE ACTUATION MECHANISM AND LEAKAGE PROBLEM

Remote-actuated valves receive signal from external sensing devices (pressure/flash/radiation sensors) which trigger the closure mechanism such that the valve closes before the arrival of the blast wave. For greater reliability, three types of sensors (blast pressure, flash and thermal radiation) can be used together to actuate the valve closure mechanism on receiving the signal from either of them. However, cost of the system will be higher. Thus, for complete closure before blast arrival, the valves shall be designed for remote-sensor triggering and shall be power-operated.

To compensate for time delays of the electromechanical equipments of the remote actuated valve and to achieve the complete closure, the sensors must be placed along the periphery of a predetermined radius from the valve location (closer to ground zero). Thermal and flash sensors are used together to detect the characteristic pulse emitted by an explosion and to filter pulses from other sources such as lightning, fires etc. Problem against multibursts protection is one of the main drawbacks of remote-actuated valves. Hardenability and suitability of exposed sensors against multiburst is often necessary to initiate reopening of the valves as soon as the hazardous pressure has settled[24]. The remote-actuated valves may not close immediately to be effective in situation such as the explosion very near to the structure between the blast valve and sensing device. This is due to the fact that the blast wave will take smaller time to arrive at the structure compared to the time of activation of electromechanical control equipments.

Self-acting blast valves may address the problem of delayed closing of remote-actuated valves during high yield explosion but a portion of blast wave can enter the protected structure during closure time due to inertia of the movable mechanical components[2]. They can be automatically closed during positive phase of blast loading. Protection against washing out of fresh air available in the room during negative phase of blast can be achieved either by a valve with latching mechanism or a double acting valve. An automatic latching mechanism closes the valve as soon as the positive phase of blast reaches the valve and remains in closed position until opened manually. A double acting valve automatically closes the opening during the negative phase and reopens it automatically once the blast wave passes out.

Thus, the best type of actuation (blast actuation or remote actuation) depends partly on the design pressure with respect to reaction time and operational considerations. For extended arrival times (low pressure), a remote-actuated mechanism can close the valve before the blast arrival whereas leakage may take place for a blast-actuated valve. At higher pressure (short arrival time), the remote-actuated valves may take longer time to close as compared to the arrival time[24]**.** However, the leakage pressure may not result in significant increase of the shelter's ambient pressure away from the valve, there may be a jetting effect resulting in very high pressure rise in the immediate vicinity of the valve. Generally, a plenum chamber is provided just after the valve opening to nullify the jetting effect. A plenum chamber is a room where a relatively small duct opens and pressure attenuates by sudden expansion preventing the jetting effect[24]**.** The ratio of the area of the chamber cross section to that of the valve outlet should be preferably greater than 4:1 so as to disseminate leaked flow as fast as possible[24].

Although the time delays are of the order of milliseconds for most of the valves, enough flow to cause injury may pass the port openings for certain valve designs and pressure levels. Thus the closing of the valve, at both high and low pressure ranges, must be checked. The amount of blast leakage to the shelter depends on the closing time of the valve which, in turn, depends on the mass of the moving parts, closure disk diameter, the pressure distribution on both faces of the closure disk and support stiffeners. The leakage can be reduced either by increasing the distance travelled by the blast wave in a bypass duct prior to complete closure of blast valve fitted in main duct[35] or by reducing the mass of moving parts. For closing time calculations, the circular plate with supporting springs can be modelled as a single degree of freedom (SDOF) spring mass system as shown in Fig. 4 with the stepped impulsive

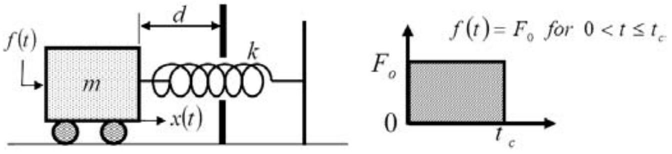

Figure 4. Closure plate and impulsive force model for closing time calculations[33].

loading profile[33].

The closing time t_c required to cover the distance *d* by closure plate of mass *m* under dynamic load *f*(*t*) is given by:

$$t_c = \sqrt{\frac{k}{m}} \cos^{-1}\left[1 - \frac{kd}{F_0}\right] \tag{2}$$

where *k* is the spring stiffness and F_0 is the maximum amplitude of the load pulse.

The closing time can be reduced satisfactorily by increasing the triggering pressure force to moving mass ratio, decreasing the length of the travel before closure, minimising the deceleration of moving mass during closure. One study was carried out at Lawrence Livermore National Laboratory where Plutonium (Pu) and high explosive (HE) were kept together in a Device Assembly Facility (DAF) fitted with three Temet (USA) blast valves in order to contain Plutonium, inside the DAF in case of an explosion of HE. Consequences of Plutonium leakage (outside the DAF) due to non-latching of blast valves during accidents were analysed involving three different combinations of high explosives and Plutonium kept in the assembly cell[36]. The amount of Pu leakage due to roof lift, non-latching valve and other means were obtained with respect to time. If the pressure impulse bypassed during the closure of a blast actuated valve is large enough, it can cause the air filters to rupture. A long duration overpressure of 0.136 bar might be taken as typical of that causing filter damage[37].

5. SHOCK TUBE

Generally, there are two experimental methods used to impart blast loading to a structure: real explosion and shock tube. In India, Storage and Transport of Explosive Committee (STEC) is regulatory and advisory body for explosive storage and handling. Shock tube is used to simulate blast wave of a particular pressure and Mach number in a laboratory with or without any real explosion. Explosion driven shock tubes are designed for small explosion inside the driver portion of the shock tube to obtain a blast/shock wave. Shock tube produces planar wave fronts and wave parameters that can be easily controlled. The blast parameters can be easily replicated as and when required with the help of a shock tube[38].

A large number of experimental studies have been carried out on structures using shock tubes. A small scale TNT explosion along with FEM simulation was done to analyse dynamic performance of aluminium honeycomb sandwich panels under air blast to examine the blast-resistance capability of square sandwich panels with hexagonal aluminium honeycomb cores[39]. Three parameters (deformation pattern, velocity-displacement histories of face sheets and total energy absorbed) were obtained and compared with the simulation results. It was concluded that the scale distance is the key parameter controlling the failure modes. In experimentation, scaled down models were preferred in order to reduce the cost. Based upon geometric, dynamic and kinematic similarity, the dimensional parameters were established and used to characterise prototype from model results[40].

Experimental study of carbon fibre sandwich panels subjected to three different blast loads were conducted in the 28″ square cross-section shock tube and results were compared with finite element model developed using commercial software ABAQUS[41]. The important features of loading profile such as rise time, exponential decay pattern, and peak overpressure very well matched with shock tube test results. The maximum strains at front and back central portions were obtained with good agreement between experimental and simulation results (maximum difference up to 12 per cent) and a difference of only 1.74 per cent was found for the peak overpressure. Testing and analysis of scaled down model of the piston-plate air-blast valve by Clark Valve Company was carried out using shock tube test facility[42]. Two sets of tests were conducted: the first one to understand the working principle and preliminary evaluation of design parameters and the second one to cater for performance evaluation of different components such as plate, sealing, etc. of the modified valve based on the test results of the first set. The key finding of second test was that the valve was insensitive to the ground shock and able to deliver required flow of air with designed pressure drop.

The simulations results obtained using DYSMA code were validated through a shock tube test for curved aluminium panels of three different radii[43]. The shock tube equipped with high speed photography and 3-D Digital Image Correlation (DIC) technique was used to obtain the deflection, velocity and strain parameters with high degree of correlation between experimental and numerical simulation results. Results show that blast mitigation capability of a panel increases as the radius of curvature increases. Same shock tube setup fitted with muzzle (driving bullet) was used to impart sequential impact loading on sandwich composite structures[44]. It was found that the damage was prominent at the exit face of sandwich composite in case of high velocity impacts. For low velocity impacts, it was confined to the front face and core only. The blast performance of composites subjected to high velocity impacts a priori was better than those subjected to low velocity high mass impacts. To study the blast mitigation properties to prevent traumatic brain injuries (TBI) of US Military soldier due to IEDs, the protective helmets made up of vinyl-nitrile foam shell filled with water, glycerin, glass beads, Der-Tex foam etc. were tested in explosive driven shock tube and were modelled in ABAQUS[45]. The linear shock-Hugoniot relation was used to model the filler materials in conjunction with the Mie-Grüneisen equation of state. The filler material, solid foam and fluid were modelled using Coupled Eulerian–Lagrangian (CEL) method, Lagrangian and Eulerian elements respectively. The peak pressure measured in the shock tube test was very well predicted by numerical simulations. It was also found that the foam like filler materials are better suited for shock absorption as compared to dense materials like water and glycerin.

A water shock tube test facility was used to simulate the effect of underwater explosion on clamped circular plate with peak pressures ranging from 10 MPa to 300 MPa to study the sensitivity of failure modes and to investigate the efficacy of finite element simulation to predict these failure modes[46]. Experimental results were obtained for failure modes corresponding to three different pressure ranges: 0 MPa - 64 MPa, 110 MPa - 120 MPa and 130 MPa - 135 MPa. It was observed that at lower pressure, the failure initiates at centre and then propagates to periphery whereas for high pressure range (130 MPa - 135 MPa), the plate shears at the inner periphery of circular clamps. Simulation results were able to capture the failure modes with fair degree of accuracy. An ultra fast blast simulator facility hydraulically driven by means of computer controlled actuators was setup and used at the University of California, San Diego, to test the full-scale structural models[47]. In a time span of 8 years, over 500 tests got conducted using this facility on several civil and military structures. The authors claimed that it can be viewed as an alternative to shock tubes.

6. EFFECT OF BLAST WAVE ON CIRCULAR PLATE

Circular plate is used for closure of the blast valve during blast loading. The plate is designed such that it has enough strength against impulse/blast loading and minimum inertia which are conflicting requirements. Due to inertia penalty to achieve strength, the valve closure time will increase leading to the increased rate of leakage pressure into the shelter. Thus, the study of effect of blast wave on the circular plate is important. A review of blast impact on metallic and sandwich structures has been reported[48] with a brief description of different experimental, theoretical and numerical methods. The working principle of a ballistic pendulum system and different sensors to record pressure, acceleration, displacement and impulse were also reviewed[48].

An analytical study has been carried out considering simply supported circular steel plate with rigid plastic material behaviour with localised blast loading function (Fig. 5) having constant pressure in central region ($p = p_0,\ 0 \le r \le R_0$) and exponentially decaying radial profile outside the region ($p = p_0 a e^{br},\ R_0 \le r \le R$) to simulate explosion of near-field charges such as buried land mines. The analytical results were compared with the numerical results obtained from ABAQUS and a good correlation within 15% difference was found[49]. The authors have derived the static plastic collapse pressure (p_c) of the circular plate as,

$$p_c = \frac{6M_o R}{\beta} \tag{3}$$

where R is the plate radius.

The plastic collapse moment per unit width (M_0) and the plate parameter (β) are given by:

$$\beta = R_0^2 \left(3R - 2R_0\right) - \frac{6a}{b^3}\left[e^{bR}\left(bR - 2\right) - e^{bR_0}\begin{pmatrix} b^2 R_0 \left\{R - R_0\right\} \\ -b\left\{R - 2R_0\right\} - 2 \end{pmatrix}\right] \tag{4}$$

$$M_0 = \frac{\sigma_0 H^2}{4} \tag{5}$$

where H is the plate thickness, σ_0 is the minimum yield strength of the plate material and R_0 is the radius of central uniformly loaded region. The loading parameters (a, b) can be obtained by regression technique using data obtained from commercial software such as AUTODYN. For uniform pressure distribution (a=1, $b \to 0$) the collapse pressure for all values of b is given by

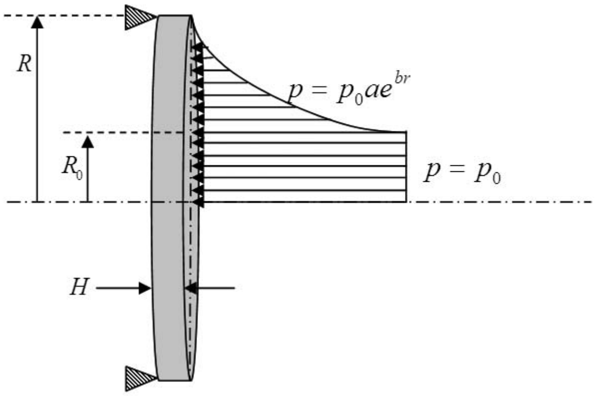

Figure 5. Simply supported circular plate with localised blast loading function.

$$p_c = \frac{6M_o}{R^2} \tag{6}$$

The mathematical formulation of dynamic behaviour of circular plates subjected to uniformly distributed ideal impulsive loading was carried out by Wang and Hopkins[50]. The key findings of this analytical solution were the time in which the plate comes to rest and the central deflection of plate at the instant. FEM was employed to analyse dynamic behaviour of circular plate under the influence of exponential impulsive forces[51]. Vibration characteristics of damped circular plate were obtained for different loading conditions.

Hsieh[52], *et al.* have investigated the effect of stiffener arrangements of a rectangular door structure subjected to blast loading using FEM. In the static analysis, it was found that the increase in stiffener depth and web thickness of I-section increases its flexural strength. In the dynamic analysis for a door depth of 150 mm and blast load of 0.6 bar incident pressure with 7.0 ms duration, the rotational deformations at the hinged support were found within the design limits. A good agreement between numerical and experimental results was found. The dynamic response of steel stiffened plates under uniform blast loading was analysed using ABAQUS for different stiffener configurations[53]. The numerical model was verified with the published experimental results for a 50 mm thick and 1.0 m radius circular plate subjected to blast of 50 kg of TNT kept 0.5 m directly above the center of the plate. The polyurea coated and uncoated steel plates under different loading environments were investigated using self-developed CFD code PUMA2 and the LS-DYNA software[54]. The modified PUMA2 was verified for a planer shock-square cavity problem and good agreement was found. The CFD code was used to provide pressure field inputs to the LS-DYNA software to obtain stresses and strains. It was concluded from LS-DYNA results that the coating is able to stop fragmentation without any increase in structural stiffness. The effect of localised blast loading on circular steel plate was analysed numerically and validated experimentally to conclude that the simulated results can be used with certain degree of confidence if realistic and accurate mathematical models are used[55]. Modified Johnson Cook model for material modelling, Gurson porous elastic model for progressive ductile failure modelling and adiabatic thermal softening model were used in numerical analysis.

7. NUMERICAL MODELLING

Due to higher costs and difficulties involved in full-scale experiments, numerical tools such as finite element method (FEM) and computational fluid dynamics (CFD) are frequently employed. Generally Eulerian formulation is used to determine the blast load on a structure followed by a Lagrangian simulation to estimate the structural response. The Arbitrary Lagrangian-Eularian approach is used to analyse the simultaneous interaction between the blast and the structure. The computational time increases significantly from a pure Lagrangian to a fully coupled Eulerian-Lagrangian simulations. An analysis has been done by Borvik[56], *et al.* to explore the benefits and drawbacks of simulation while switching between pure Lagrangian formulation and more advanced methods such as the fully coupled Eulerian-Lagrangian formulation in a specified blast load problem of a 20 ft ISO container to be used in international operations. On comparison with available full-scale experimental test data, the fully coupled Eulerian-Lagrangian approach seems to be less accurate than Lagrangian approach. The various commercial softwares such as LS-DYNA, ABAQUS, AUTODYN, EUROPLEXUS, etc have modules to study the blast-structure interaction problem[56]. A computational fluid dynamics code CFX, validated against published experimental results is used to model detonation of a dense explosive for a 3-D simulation of overpressure wave propagation generated within a small-scale branched tunnel[57]. The arrival time of the blast front obtained using CFD simulations shows excellent agreement with experimental results, however the overall comparison shows that the CFD simulation can very well predict the blast hazard in confined spaces of complex geometry.

Fluid-structure interaction (FSI) modelling of a blast loaded structure using single degree of freedom (SDOF) model while accounting the detonation induced shock wave-structure interactions was reported by Deshpande and Fleck[58]. In addition to the finite element (FE) model, a lumped parameter approach was also adopted to capture FSI due to underwater shock involving large length scales. The sandwich structure containing compressible foam core between two face sheets was modelled by treating the face sheets as rigid lumped mass system and core as rigid plastic material. The net water pressure due to the incident and reflected waves was approximated using Taylor model[59]. Analysis shows that the lumped parameter model is able to predict the FSI effects accurately upto the occurrence of first cavitation. The shock wave impact on vehicle occupants was examined by Yang[60], *et. al.* using Eularian-Lagrangian based FSI code VTF to reduce the cases of traumatic brain injury (TBI) due to IED blast which accounted for at least 60 per cent of combat casualties in 2009 in Afghanistan and Iraq.

The shock/blast mitigating effect of a multi-arch double-layered panel was studied by Wensu and Hong[61] using LS-DYNA to optimise the use of heavy and solid masses for higher blast capacities**.** The effects of arch height, number of arches and sheet thickness on shock absorption capacity were studied. As the arch height, number of arches and arch thickness increase, the multi-arch panels perform better against impulsive loading. The reduction in longitudinal displacements of multi-arch panels obtained were 17.5 per cent, 18.7 per cent, and 27.4 per cent, respectively, for arch heights of 40 mm, 50 mm, and 60 mm. With five arches, the reduction in the permanent displacement of back layer plate is 12.0% while with six arches, the permanent displacement reduces by 51.3%. This is because a more uniform distribution of impact load on the back flat plate is achieved with increased number of arches. The simulation results were validated with the experimental ones obtained using pendulum impact test. A similar study was carried out by Spranghers[62], *et al.* to check the correctness of a pure Lagrangian FEM formulation of a thin aluminium plate fixed centrally on to a steel frame subjected to explosion of 40 g charge at a standoff distance of 25 cm with small-scale blast experiments. It was found that the FE model based on shell formulation is capable of simulating structural response however strain amplitudes prediction was less accurate. A steel plate with dimensions of 244 mm × 244 mm × 1.9 mm and two steel hollow disks were analysed using LS-DYNA to investigate the effects of explosive weight and plate thickness on the midpoint displacement[63]. The numerical results were compared with available experimental results.

The numerical study using ABAQUS and experimental study using ballistic pendulum were performed on circular steel plates for repeated uniform blast loads and excellent correlation is found for midpoint deflection and deformation profiles[64]. One similar fluid-structure interaction analysis was performed considering a spring-mass system (SDOF elastic structure) subjected to blast impulse generated by shock-tube to study the coupled response with FSI and without FSI[65]. The results show that FSI considerations lead to a damped periodic motion of the structure in comparison to the non FSI considerations and the difference between the displacements predicted using the two approaches increases as the ratio of structural velocity to the particle velocity increases.

A pure numerical simulation using in-house FSI code was used to study interaction between linear and non-linear one dimensional blast wave propagating in air and free-standing plate by Kambouchev[66], *et al.* The results have been verified with previously derived exact solution for different blast profiles and different plate thicknesses and a good agreement was found. Different elements of FSI modelling, viz. fast explicit coupling platform, finite volume solver for fluid with advanced shock capturing schemes and dynamic finite element solver for capturing structural deformations are described[67]. The simulation results for cubical and cylindrical structure were found to be in good agreement with the published experimental results. An experimental study of aluminium cylindrical shell structure containing varying fluid levels subjected to long duration blast wave was done at air blast tunnel (ABT) at Ministry of Defence Shoeburyness, UK. The localised buckling and deformation results were found to be in good agreement with those from the detailed non-linear numerical model comprising of remapped Lagrangian analysis[68].

8. CONCLUSIONS

The detailed literature review reveals that the leakage of blast pressure, being an important problem, has not been analysed in the open literature except a few reports published during 1950's by US Department of Defence. Thus there is a need to analyse different techniques for reducing the blast pressure leakage of a blast valve. It is also concluded from the literature review that the fluid-structure interaction analysis of complete blast closure valve has not been carried out. Only static and dynamic finite element analyses of square and circular plates for various support conditions have been reported. The FSI modelling and simulation of complete valve assembly need to be performed to analyse its structural response, stresses, and failure zones to optimally design a blast valve.

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CONTRIBUTROS

Mr Pankaj Kumar Sharma received his BTech.(Mechanical Engg.) in 2001 from CSJM University Kanpur, MTech (Thermal & Fluids) in 2008 from IIT Bombay and currently pursuing PhD from IIT Delhi. Presently working as Scientist 'D' at Centre for Fire Explosive and Environment Safety, Delhi. His areas of interest include : Heat transfer, CFD, FEM and fluid-structure interaction.

In current study, he has carried out the literature review and prepared the manuscript.

Prof. B.P. Patel received his BE(Mechanical Engg.) from APS University Rewa, in 1992; MTech (Mechanical) from IIT Bombay, in 1999 and PhD from MNNIT Allahabad, in 2005. Presently working in the Applied Mechanics Dept. at IIT Delhi. He has more than 20 years of teaching and research experience in nonlinear static/dynamic analysis of composite plates and shells, functionally graded structures, higher order shear deformation theories, solid-fluid interaction, buckling/postbuckling, continuum damage mechanics, multi-scale modelling.

In current study, he has contributed in the literature review and manuscript preparation.

Mr Harbans Lal received his MSc(Physics) from Panjab University, in 1978; MTech (Solid State Materials) from IIT Delhi, in 1980 and MBA from Panjab University, Chandigarh, in 1989. Presently working as Scientist 'G' at Centre for Fire Explosive and Environment Safety, Delhi. He has more than 30 years experience in free air explosion dynamics, underground and under water explosion effects, high speed instrumentation, scaled modeling, blast/shock resistant design of systems and structures, test validation of blast protective structures and systems, design and evaluation of blast resistant construction techniques, design validation of NBC shelters and hardened structures, damage and injury models, etc.

In current study, he identified blast valve design requirements, it's testing methods, etc. and also contributed in the literature review.