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Blast protection of infrastructure with fluid filled cellular polymer foam

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Abstract

Full field blast experiments were performed to assess the potential of fluid filled polymer foam for blast mitigation. The experiments involve air blast loading of clamped mild steel plates covered with fluid filed polymer foam for blast protection. The deformation profiles and maximum deflections of plates are compared with and without foam protection. The experimental results indicate a reduction in the plate deflection up to 50% with foam protection.

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Keywords:

1. Introduction

The blast protection of people and structures against the devastating effects of blast waves has assumed utmost importance in the wake of increased terrorist attacks on civilian and military infrastructure all over the world. For instance, the US Department of State has reported that there were more than 13,400 terrorist attacks worldwide in 2014, resulting in more than 32,700 deaths and 34,700 injuries[1]. Due to the enormous magnitude of the problem, newer materials and technologies for blast protection have been under active research. This paper proposes a blast mitigation method using open cell polymer foam impregnated with water. Since any method of blast mitigation

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requires field experiments to verify it effectiveness and limitations over a wide range of loads, free field air blast experiments are performed to verify the proposed concept.

This paper begins with a brief review of the physics and properties of blast waves that are important in the design of any blast mitigation technology. Next, a review of different blast mitigation methods is given. This is followed by the discussion on the experimental procedure and the results.

2. Properties of blast waves

Detonation of a high explosive in air releases the stored chemical energy in to the surrounding air in the form of detonation products at high pressure and temperature. The detonation products expand and travel in the air creating a blast wave, which is characterized by a steep pressure front with expanding gases behind it. As the blast wave expands further, the peak over pressure decreases and its duration increases. The variation of blast wave pressure with time at a fixed location away from the point of detonation is as shown in Fig. 1. The pressure above the atmospheric pressure is called the overpressure. After a steep rise, the pressure quickly falls to the atmospheric pressure at the end of the positive phase, which typically lasts for a few milliseconds. The pressure further falls below the atmospheric pressure during the negative phase due to the suction created by the momentum of the expanding gases. After the end of the negative phase, which is generally longer than the positive phase, the pressure finally returns to the ambient value. When a blast wave encounters an obstacle in its path, it is partly reflected. The magnitude of the reflected pressure could be up to 8 times the incident pressure (for blast waves resulting from detonation of conventional explosives) depending on the magnitude of the incident overpressure and the angle of incidence. The time integral of the pressure-time history gives the specific impulse of the blast wave.

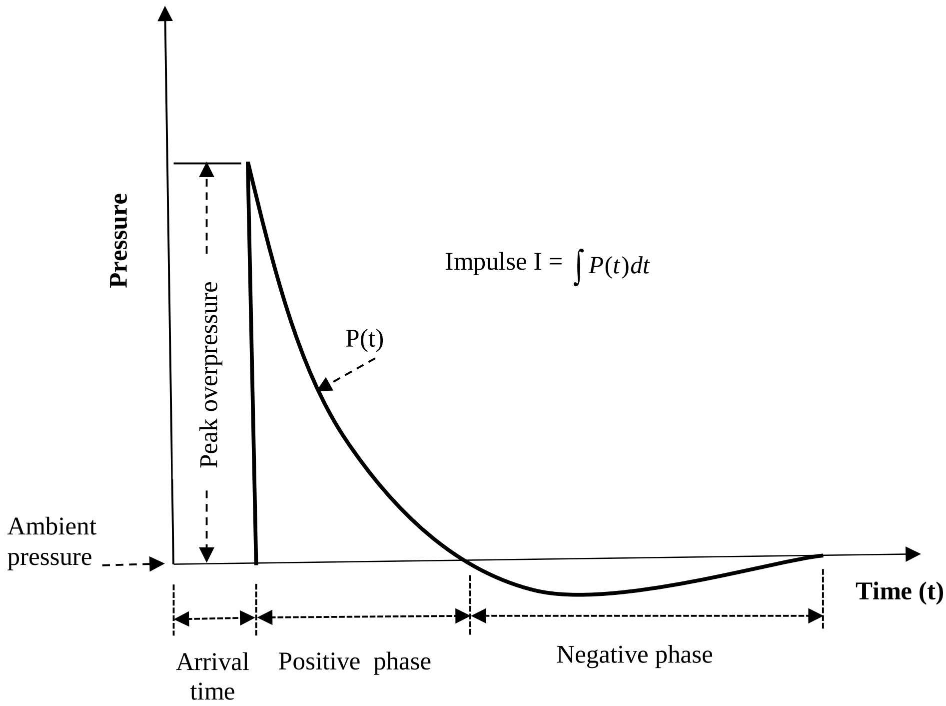

Fig. 1 Variation of blast pressure with time at a fixed location away from the center of detonation.

Depending on the ratio of the blast wave positive phase duration and the natural time period of the structure, the response of a structure to blast load is governed by the peak overpressure alone or the impulse alone[2].In general, protection can be achieved by increasing the standoff distance between the source of explosion and the target. However this is not always possible in many practical situations and hence there is a need for reducing the harmful effects of blast waves on people and structures. The blast protection measures modify the parameters of the blast wave to reduce its harmful effects. This involves the use of various materials and techniques to reduce the peak overpressure and /or increase the duration of the blast wave. By modifying these blast wave parameters, the blast load would be deprived of its dynamic character and changed to quasi-static load for which the structure could be easily designed with static analysis methods. In the next section, the various techniques explored by the researchers for blast mitigation is presented.

3. Blast mitigation techniques.

Many researchers have explored various blast mitigation methods using different materials and techniques [3-6]. Among the materials investigated over the years, the use of soft condensed matter and water in various forms (water mist, aqueous foam, or bulk mass of water) has received considerable attention. Nesterenko [7, 8] investigated the application of heterogeneous granular materials, saw dust, porous copper-powder, metal-foam laminated structures, and polymer foams for blast protection of structures. It was found that density, porosity and relative geometrical size of the so-called ‘‘soft’’ condensed matter are the main parameters determining the effectiveness of blast wave mitigation. Gelfand *et al*.[9] experimentally studied the blast mitigation properties of water contained in an elastic shell for ground explosions of 0.1 kg and 1 kg TNT. They concluded that the ratio of high explosive mass to the mass of liquid and shell is the dominating factor in attenuation of blast over pressures. The principal mechanism of attenuation is attributed to the kinetic acceleration of the liquid facilitated by elastic properties of the container while heat removed from the explosion products and expended in in heating and possible evaporation of liquid contribute little to attenuation of blast waves. Shin et al. [10]used one-dimensional spherically symmetric numerical model to study mitigation effect of water shield in contact with explosive. Reduction of peak overpressure and delay in arrival time were computed for different radii of water shield. They found that with the spherical water shield radius equal to the spherical explosive radius, the peak pressure is reduced by 40% and the arrival time is increased by 75% at a scaled distance 1 $m/kg^{1/3.}$ Further, There is 10 % overpressure reduction at a scaled distance 1.5 $m/kg^{1/3}$ and 2% at a scale distance of 2 $m/kg^{1/3}$. Chong et al. [11] numerically simulated the blast mitigation process by water using a three- dimensional model. Results from their numerical simulations showed good agreement with experimental data for the cases with and without water shield. The peak pressure was reduced by more than 50% with water in comparison with the case without water. Apart from the use of bulk water, the application of water mist for suppressing the overpressures produced by explosions has been explored by many researchers. Willauer *et al*.[12] experimentally demonstrated the blast pressure suppression capabilities of water mist for TNT explosions in a confined space. The impulse, the initial blast pressure and the final quasi static pressures were reduced by 40%, 36% and 35% respectively by spraying the water mist. They proposed that the latent heat absorption by evaporation is the primary mechanism and the momentum transfer plays a secondary role. Other researchers have found the momentum transfer to be the main mechanism of blast mitigation. For instance, using numerical simulations, Schwer et al.[13] investigated the importance of different mechanisms of blast wave mitigation by water mist, namely, reduction of blast overpressure by energy abstraction via vaporization, reduction of the shock-front strength through momentum abstraction, and quenching of secondary reactions by the water mist. Their simulations indicate that water mist does not penetrate the flame front but mitigation effect does take place due to energy and momentum transfer by drag and vaporization. It is also found that vaporization, droplet size and mass loading play only secondary role in the mitigation process and the total amount of water is the most important parameter for effective blast mitigation.

The application of polymer foam filled with liquids of varying physical properties such as water, glycerin, and silicone fluids has been investigated at MIT (USA),among others, by Dawson [14] , Schimizze et al.[15], and Deshmukh and Mc Kinley [16]. The analysis of Dawson [14] shows that several fold reduction of blast overpressure from 100 ton high explosive placed at a 15 m standoff distance from the structure by the use of 100 mm thick foam filled with water or glycerin. Schimizze et al.[15] have studied blast mitigation properties of vinyl-nitrate foam filled with water, glycerin, glass beads, and aerogel. Samples were subjected to blast load in a shock tube at a 12-inch standoff distance. It was shown that these materials shape the incoming blast wave by reducing the peak pressure and increasing the duration of the blast wave. In the low density materials such as Army helmet pad and Det-Tex foam, the mode of mitigation is stretching and/or tearing of the solid material surrounding a collapsible pore while in high density materials such as water, glycerin and glass beads, the mode of mitigation is reflection of blast wave due to impedance mismatch. Deshmukh and Mc Kinley [16] have explored the application of adaptive energy absorbing field responsive fluid filled cellular solids for blast mitigation. The fluids studied include magneto rheological fluid or a shear-thickening fluid which were used to modulate the mechanical properties of a cellular solid.

Verification of the capabilities any potential blast mitigation method by conducting field experiments is crucial in order to gain confidence in its application to real life situations. The objective of this paper is to investigate and quantify the potential of the fluid(water) filled natural latex polymeric foam for blast protection by conducting field experiments.

4. Experimental procedure

The experimental program consisted of subjecting mild steel plates covered with water-filled foam to free field air blast loads. The 1 x 1 x 0.005 m mild steel specimen plates used in the experiments were cut from commercially available stock. The target plates were clamped at their boundary to a test rig with eight symmetrically placed bolts. The experimental set up is shown in Fig. 2. The test rig had a circular hole of 0.6 m diameter to expose the target plate covered with foam to blast load. The test specimen is covered with a block of polymer foam saturated with water. The foam used in the experiments is natural latex pin core foam manufactured by MM foam Ltd. Low temperature plastic explosive (LTPE) rolled into a sphere is held above the plate center by a wooden tripod. The TNT equivalency factor of LTPE is 1.17. An electric detonator placed at the center of explosive initiated the detonation. Experiments were also conducted on bare plates without foam for comparison. The experimental parameters are given in Table. 1. A photograph of the foam used in the experiments is shown in Fig 3. The density of the foam is 20 kg/m^3. The thickness of the foam is varied from 50 mm to 100 mm .

Fig. 2 Experimental set up in the field

Table 1 Experimental parameters and results

Test No.	Mass of LTPE (kg)	Standoff distance (m)	Test Condition	$\delta_{\text{exp with foam}}$ (mm) (a)	$\delta_{bareplate,\text{exp}}$ (b)	% change 100*(b-a)/b
1	0.3	0.145	100 mm foam-water	20	27	-26
2	0.3	0.300	50 mm foam-water	13.5	23	-41
3	1.5	0.500	100 mm foam-water	42	66	-36
4	1	0.350	100 mm foam-water	34	68	-50
5	1.5	0.350	100 mm foam-water	65.5	110	-40

Fig. 3 Pin core natural latex polymer foam used in the experiments. Foam density 20 kg/m^3.

5. Results and discussion

The deformation profiles of the plates with foam protection are compared with those without protection in Figs. 4-6 for select cases. The photographs of plate with and without protection for 1.5 kg charge mass at 0.5 m standoff are shown in Fig. 7. As it can be seen from these figures, the deformation profiles with protection are more gradual, and in the form of domes as compared to more sharp conical shape observed in the cases without protection. The drastic reduction of the plate midpoint deflection is quite noticeable. The reduction in plate midpoint deflection varied from 50% in the case of 1 kg explosive charge at 350 mm standoff distance to 22% reduction in the case of 0.3 kg mass at 350 mm standoff distance.

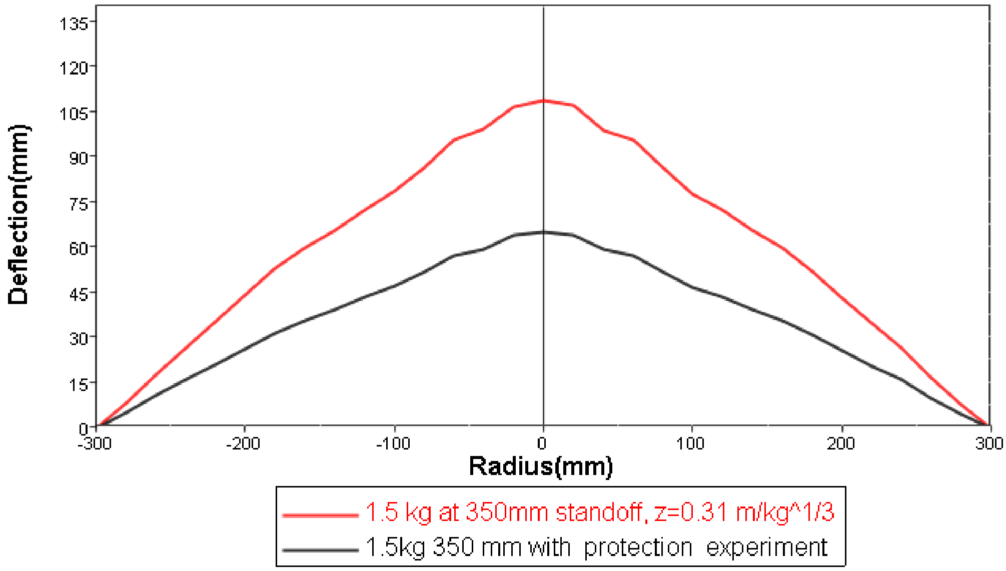

Fig. 4 Measured deformation profiles of target plate for 1.5 kg HE at 350 mm standoff, with and without protection

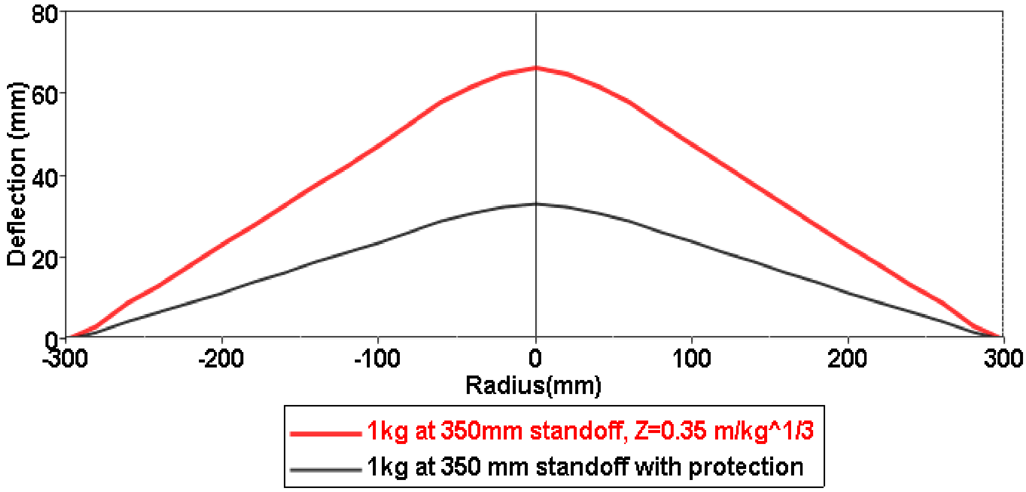

Fig. 5 Measured deformation profiles of target plate for 1 kg HE at 350 mm standoff, with and without protection

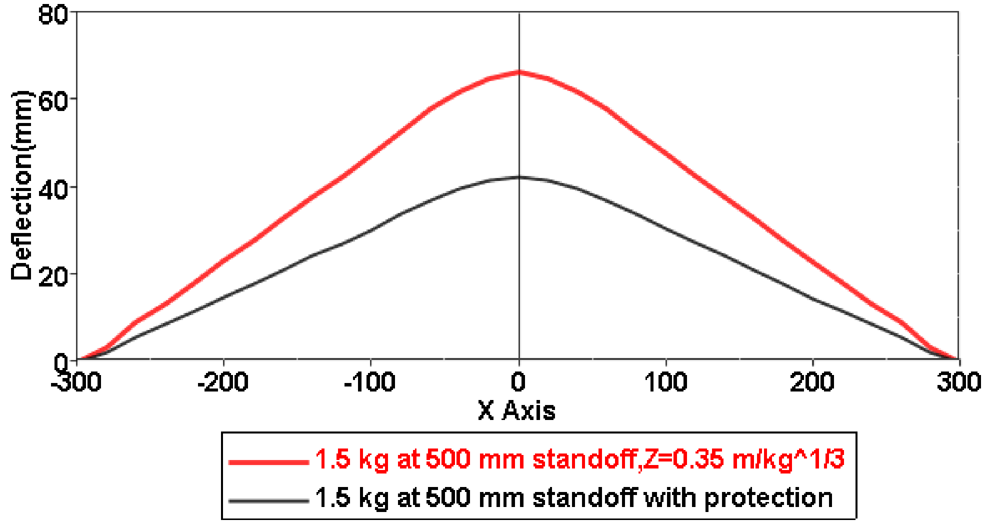

Fig. 6 Measured deformation profiles of target plate for 1.5 kg HE at 500 mm standoff, with and without protection

(a) without foam protection (b) with foam protection

Fig. 7 Photographs of plate (a) without foam protection and (b) with protection for 1.5 kg charge at 0.5 m standoff.

6. Conclusions

Free field air blast experiments were conducted to assess the potential of water filled open cell polymer foam for blast protection. The fluid-filled foam is used to cover the front face of the mild steel plates. The target plates were exposed to different intensities blast loads from detonation of high explosives in air. The experimental results show substantial reduction in the overall deformation of the plates with the proposed protection method. Potential applications of this blast mitigation technology include protection of vehicles against land mines, ships, and civil and military infrastructure against accidental explosions or terrorist attacks. Further experimental and numerical studies are in progress to further quantify the mitigation effect and understand the mechanism of blast protection by the fluid-filled foam.

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