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Blast mitigation with fluid Containers: Effect of mitigant type

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ABSTRACT

The effect of filled external containers on the deformation induced in a steel plate under near-field blast loading has been investigated through a combined numerical and experimental study. Six different fill materials (mitigants) were considered for inducing near-field blast mitigation. The mitigants evaluated were bulk water, aerated water, sand, expanded polystyrene (EPS), a combination of EPS and water, and shear thickening fluid. The performance of the mitigants depended on their mass, with sand providing the best mitigation and EPS the worst for a given volume. Bulk water provided the greatest reduction of the peak deformation per unit of added mass. The mitigant material also had a significant effect on the deformation-time history of the steel plate. The sand and ½ EPS + ½ water containers were found to significantly delay the arrival of the pressure wave at the target surface due to their compressibility and low sound speed. Numerical analysis reveals that different mechanisms induce blast mitigation, and these are identified for each of the different mitigant materials.

1. Introduction

Recent conflicts have seen an increase in the use of buried IEDs, which are a serious blast threat to armoured vehicles. On-going research to combat these threats has been conducted in vehicle design such as hull geometry (Ie: v-shaped hulls) [1,2], energy attenuating foot-pads [3], material selection [4], active blast protection systems [5] and the use of water-filled containers [6,7].

Bornstein et al. [6,7] recently demonstrated the potential of external water-filled containers to reduce the deformation of a steel plate, representative of a section of an armoured vehicle, when loaded by a near-field explosive charge. The key blast mitigation mechanisms were identified as being rarefaction waves and shadowing. While Bornstein et al. [7] reported that rarefaction waves were a key mitigation mechanism; subsequent analysis by the same authors [8] has indicated that the rarefaction waves only make a small contribution to reducing target deformation. Shadowing is the process where the detonation products are deflected away from the container. This creates a low pressure 'shadow' region outside the container. The size of this 'shadow' region is dependent on the geometry of the container and not the type of mitigant within the container. As such there may be potential to enhance the blast mitigation efficiency provided by modifying the content of the container. The substitution of a compressible mitigant such as aerated water or sand in place of the water will lower the sound speed of the mitigant. The sound speed of aerated water with a 10% volume fraction of air is < 50 m/s [9], while the sound speed of sand was calculated to be ~ 265 m/s by Laine and Sandvik [10]. This reduction in sound speed may enhance the mitigation provided by allowing the structural response from the initial loading on the plate, which occurs outside of the container, to dissipate prior to loading at the centre of the plate. The compressibility of the mitigant also has the potential to reduce the deformation of the target by reducing the peak pressure delivered to the target. This effect was demonstrated numerically by McCallum and Townsend [11] who found that aerated water could significantly reduce the pressure of a transmitted shock wave when compared to bulk water. Kirkpatrick et al. [12] and Homae et al. [13] both reported that there may be benefits to using sand over water, identifying the benefits of porosity in reducing the peak incident pressure from an explosive event. Reducing the peak pressure at the target increases the duration of the loading, which according to the analytical models of Jones [14] for the dynamic response of plates has the potential to reduce target deformation. Whilst the use of mitigants such as water can provide near-field blast mitigation, care must be taken with respect to the location of the mitigant. Kirkpatrick et al. [12] observed that surrounding an explosive charge with water resulted in significantly greater loadings on target in the near-field.

Foam claddings are another blast protection technology that have been employed in scenarios involving water. Foam claddings have been used to reduce the impulse transferred to a target [15,16] through the fluid-structure interaction (FSI) effect. The FSI effect was analytically described by Taylor [17], and shows that when a plate is subjected to underwater shock loading the momentum transferred to the plate is

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influenced by its velocity. Lighter plates with a higher initial velocity are able to reduce the momentum transferred to them by a larger magnitude than heavier plates with a lower initial velocity. As such, the inclusion of a collapsible mitigant between the water and target plate, such as foam, may provide additional mitigation due to the FSI effect.

In this investigation, the blast mitigation performance of six materials is evaluated numerically and experimentally in terms of their ability to reduce the deformation of a steel plate subjected to near-field explosive loading. The mitigant materials evaluated are bulk water, aerated water, sand, expanded polystyrene (EPS), a combination of EPS and water, and shear thickening fluid. The materials were placed within a thin-walled polyethylene container located between the explosive charge and the steel plate, and their performance is compared to that of bulk water. The selected materials give a range of densities, sound speed values, and levels of compressibility in order to investigate the effect of these properties on near-field blast mitigation.

2. Experimental methodology

2.1. Explosion bulge die test

The experimental test set-up to determine the blast mitigation efficiency of the different materials is shown in Fig. 1. This test design is based on the original experimental research by Bornstein et al. [7] to assess the effect of water-filled containers of different dimensions on blast mitigation. A cylindrical 5.06 kg PE4 explosive charge (70 mm high and 248 mm diameter) was suspended 600 mm above the flat steel target plate, measured from the bottom of the charge to the top of the steel target. The steel target was 760 mm long, 760 mm wide and an average of 9.4 mm thick, with a quasi-static yield strength of 800 MPa. The steel plate was freely supported on an explosion bulge die (EBD), the dimensions of which are provided in Fig. 1. A laser displacement transducer (LDT) was used to record the transient (dynamic) deformation at the target centre during the blast tests. The LDT was a Micro-Epsilon ILD 2300-200 operated at a sampling rate of 30 kHz and displacement range of 200 mm. The permanent deformation measurements were taken by placing the deformed plates back into the EBD following the test and recording the deformation profile using a laser measurement device. The mitigants were placed within high density polyethylene (HDPE) containers with a length of 300 mm and a width of 300 mm. The containers were of varying height and had a wall thickness of 3 mm.

2.2. Material selection

2.2.1. Bulk water

A number of reference experiments were conducted on the bare steel target plate to provide a baseline level of performance against which the alternate mitigant materials were evaluated. In addition to providing a baseline using 100 mm high and 200 mm high water containers, an experiment was conducted where a 100 mm high water container was placed on top of an empty 100 mm high water container. This setup was used to exploit the shadowing effect with a reduced mitigant mass when compared to a full 200 mm high container.

2.2.2. Aerated water

The aerated water container is shown (without a lid) in Fig. 2(a). Aeration was achieved using a HAILEA ACO 328 air compressor with a flow rate of 70 L/min connected to air lines of ~10 m length to six Aqua Nova aquarium air stone walls (Fig. 2(b)). The air stone walls were attached to the container base and spread across the surface to create a uniform distribution of bubbles through the water. However, the volume fraction of air in the water was not quantified. Prior to the experiment the top of the original container was placed back onto the aerated water container.

2.2.3. Sand

The sand used as the mitigant had a bulk density of 1.34 g/cm^3, and thus a sound speed < 265 m/s can be expected based on the work Laine and Sandvik [10]. As was described for the aerated water, the reduction in sound speed when compared to water may increase the separation between the arrival of the shock wave on the target plate outside the container and the pressure wave directly below the container. In addition, the compressibility of the sand due to its porosity has the potential to reduce the peak pressure applied to the target and thus reduce deformation.

2.2.4. Expanded polystyrene (EPS)

An H-grade expanded polystyrene block (EPS) was used to maintain the shadowing effect of the container at a reduced weight: ~1.2 kg for the EPS filled container vs. ~19.6 kg for the water-filled container. The EPS used in the experiments had a compressive strength of 135 kPa at 10% strain based on a quasi-static loading condition [18]. The bottom of the container was removed to allow the EPS block to be bonded inside the container. Hence the top surface of the HDPE container interacted with the charge, but there was no HDPE container bottom in contact with the target.

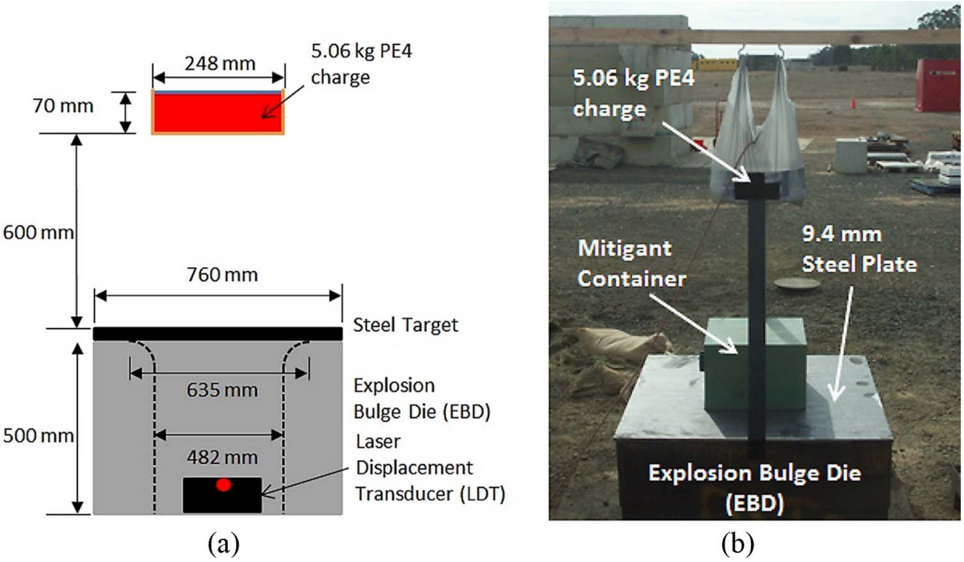

Fig. 1. (a) Schematic of baseline experimental setup. (b) Photograph of experimental setup for 200 mm high HPDE mitigant-filled container.

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