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The influence of material type on the response of plates to air-blast loading

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A B S T R A C T

This article presents results from an experimental investigation into the influence of material properties on the response of plates subjected to air-blast loading. The failure of mild steel, armour steel, aluminium alloy and fibre reinforced polymer composite plates were investigated experimentally by detonating disks of plastic explosive at small stand-off distances. Permanent mid-point displacement increased linearly with increasing impulse for each material type, up to rupture. At higher charge masses, the mild steel plates exhibited ductile tensile rupture, while the armour steel plates (which ruptured at the same impulse) exhibited a more brittle type of failure. The aluminium alloy plates exhibited signs of melting and spraying radially outwards, resulting in material loss in the plate centre followed by rupture at higher impulses. The fibre reinforced polymer composite showed evidence of fibre fracture at lower impulses than the other equivalent mass materials. Non-dimensional rupture impulse was not found to correlate with tensile strength or material ductility, but was found to increase with increasing specific energy to tensile fracture (obtained from quasi-static tensile tests). Hence, the energy absorption capacity of the materials obtained from simple tensile tests could provide an approximate indication of their blast performance.

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1. Introduction

In recent years, there has been a concerted effort to improve the impact and blast protection of civil structures and transportation vehicles. One way to enhance protection is better materials selection, particularly in mass critical structures such as defence transportation vehicles. Often, the primary objective in defence applications is to improve ballistic performance, so high strength armour steels (such as Armox grades) are used to reduce the overall thickness of plating required for the same ballistic protection. Such steels provide much higher strengths and hardness (which are good for resisting projectile penetration) but at the expense of reduced ductility [1].

Another approach has been to examine the effect of layering on the ballistic performance of plates, in which the responses of multiple (thinner) layered plates are compared to the ballistic performance of a single monolithic plate of equivalent thickness. The results have been inconclusive, with improvements shown for layered plates under some conditions [2–5] (for example, for certain projectile geometries [2] or when the overall thickness exceeded a critical value [5]) but not in all cases [6–8]. The improvements evident in certain layered plate configurations (and some projectile geometries) could be attributed to an observed change in failure, from a more brittle failure such as shear plugging to a more ductile response [2]. Little is known about whether layering plates or using armour steels would have any significant influence on the blast performance of plates, or more generally, how altering the properties influences the blast performance of materials.

Nurick et al. [9–15] reported considerable experimental data on the response of steel plates to air-blast loading. Spatial loading distribution (localised versus uniform), explosive mass and shape, boundary conditions, plate size and shape, and plate thickness were varied. Non-dimensional analysis was used to collapse the data to a single trend-line which allowed for the prediction of permanent mid-point displacement [9]. This is discussed in more detail in Section 5. Langdon and co-workers [16–19] have, in other studies, reported the results from blast tests on other materials

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such as fibre reinforced composites [16] and fibre-metal laminates [17–19]. Fibre fracture, debonding, delamination, matrix cracking and shear cracking failures were evident in the panels [16–19], in contrast to steel plates which exhibit large plastic deformation followed by tensile tearing and shear failures at higher loading levels [10,12,13].

This paper reports the results of an experimental investigation into the air-blast loading response of plates manufactured from two mild steels, an armour steel, a fibre reinforced polymer composite, and an aluminium alloy. Two plate sizes were investigated, and the plate thickness varied such that plates with the same side length had the same nominal areal density. The aim of the work was to determine whether basic mechanical properties (such as tensile strength, ductility or specific energy to fracture) obtained from tensile tests could be used to as a first approximation to predict the behaviour of plates manufactured from different materials.

2. Experimental method

2.1. Materials and test specimens

Test specimens were manufactured using two types of mild steel, an armour steel known as Armox 370T, aluminium alloy 5083H116 and woven glass fibre reinforced polypropylene (GFPP, tradename: Twintex [20]). The plates with an exposed area of 300 × 300 mm had a nominal areal density of 23 kg/m^2. Some plates were tested with a larger exposed area of 400 × 400 mm and had a nominal areal density of 31 kg/m^2. Details of the test specimen dimensions and materials are given in Table 1.

Table 1
Details of specimens for blast testing.

ID	Material	Planar dimensions of exposed area (mm × mm)	Nominal thickness (mm)
MS3	Mild steel	300 × 300	3
GFPP	Glass fibre reinforced polypropylene	300 × 300	11.5
AA5083H116	Aluminium alloy 5083 H116	300 × 300	10.5
MS4	Mild steel	400 × 400	4
A370T	Armox 370T	400 × 400	3.8

2.2. Blast test arrangement

The plates were clamped along the periphery between two square clamp frames, leaving a square exposed area free to deform. The clamp frames were mounted to a pendulum, via the corners as shown in Fig. 1a, so that the impulse imparted to the plates could be determined from the pendulum swing. Further details on blast testing using a ballistic pendulum to calculate impulse are provided in Ref. [9]. Air-blast loading was generated by detonating circular disks of PE4 plastic explosive at the centre of the plates. The charge mass was varied by changing the height of the explosive and the diameter of the disk (either 50 mm or 75 mm). The charge mass ranged from 7 g to 50 g to obtain a range of responses in the plates. The PE4 disks were located using a polystyrene bridge arrangement, as shown in Fig. 1b. Two stand-off distances were used, 25 mm and 38 mm, and were set by varying the lengths of the bridge legs.

3. Material characterisation

The quasi-static material properties were determined by performing uni-axial tensile tests on “dog-bone” specimens cut from the same sheets used to manufacture the blast test plates. The aluminium alloy and mild steel specimens were tested on a Zwick/Roell 1484 Tensile Tester at the Centre for Materials Engineering, University of Cape Town. The armour steel tests were performed at Imperial College. The armour steel tests were performed at a constant engineering strain rate of 6 × 10^{-3} s^{-1}, while the mild steel and aluminium alloy tests were performed at a constant engineering strain rate of 1.67 × 10^{-3} s^{-1}. A summary of the results is given in Table 2, and some typical stress–strain curves are shown in Fig. 2. As expected, the mild steel specimens were highly ductile (with elongations to failure in the 40–50% range) and low yield strengths. The MS3 sheeting exhibited considerable plastic hardening, with an ultimate tensile strength (UTS) of 369 MPa (48% higher than its 250 MPa yield strength). In contrast, the MS4 had a UTS of 399 MPa, which was only 20% greater than the 330 MPa yield strength of MS4.

The armour steel (Armox 370T) was much stronger, with a yield strength of 1.15 GPa. It displayed less hardening in the plastic range (UTS increased by only 10% of the yield strength) and exhibited little ductility, with elongations to failure between 5 and 7%. The aluminium alloy exhibited no distinct yield point (which is typical of aluminium alloys) so the 0.2% proof strength was used to compare to “yield strength”. In this case, the aluminium alloy displayed a relatively low proof strength (210 MPa), but showed considerable hardening in the plastic range (UTS of 325 MPa, which is an increase of 55%) and was more ductile than the armour steel (with an elongation to failure of approximately 20%).

4. Blast test results

The results from 58 air-blast tests, with material, charge mass, charge diameter, impulse and mid-point displacement, are listed in Tables 3 and 4. It is observed from Tables 3 and 4 that, for a given material and exposed area, the permanent mid-point displacement increased as the impulse increased, as expected.

4.1. Plates with a 400 mm exposed side length (armour steels vs mild steel)

The mild steel and armour steel plates exhibited large plastic deformation typical of locally blast loaded plates, with plate profiles having a central dome located atop a global dome, similar to responses reported by Nurick et al. [13,16] for mild steel plates. Selected cross-sections are shown in Fig. 3. As might be expected, the Armox 370T plates exhibited lower permanent deflections than the mild steel due to their greater tensile strength and the greater levels of elasticity. A graph of permanent mid-point displacement versus impulse is shown in Fig. 4.

Interestingly, the 370T Armox steel and the mild steel exhibited rupture under the same loading conditions – that is the same charge mass, stand-off distances and same load diameter. This indicates that the two materials have similar rupture threshold impulses, which was unexpected. Photographs of the ruptured plates are shown in Fig. 5, and it is observed that the mild steel plate exhibited tearing failures [14] that were more ductile in nature while the Armox 370T failure resembled a brittle cracking failure mode. While these results are not comprehensive, meaning that it cannot be assumed that mild steel can provide equivalent protection to Armox 370T in every blast scenario, it does indicate the important role of ductility in blast protection. At higher charge masses, the mild steel plates exhibited petalling failures, as observed by others [14,21].

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