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# The effects of blast-induced fragments on cellular materials

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ABSTRACT

This paper presents the results of an experimental study to characterise blast-induced fragments and to understand how different cellular materials alleviate the damage caused by the blast-induced fragment. In the experimental arrangement, a front plate, 106 mm in diameter, is subjected to a localised blast load to generate a cap fragment (Mode IIc failure) to impact a rear plate of similar dimensions, located parallel and offset from the front plate. Different charge diameters and masses are used to create fragments of different sizes and masses (4.1 g to 12.5 g) propelled at different speeds (244 m/s to 741 m/s). Various cellular materials (aluminium foam, aluminium honeycomb, balsa wood, Corecell M80 foam, Divinycell H200 PVC foam and polyurethane 200 foam) of thicknesses 40 mm and 60 mm are placed in front of the rear plate to act as energy absorbers. The damage caused by the fragment and the protective performance of the cellular materials are quantified by means of the maximum deflection of the rear plate. The results indicate that the cellular materials alleviate the damage incurred to the rear plate, with different materials absorbing different amounts of impact energy. For the range of experiments carried out and foam investigated, the Divinycell foam provided the best protection while Corecell foam offered the least resistance to damage.

## 1. Introduction

Fragments released upon the detonation of either improvised explosive devices (IED's) or ordnance or explosion can be classified as either *primary fragments* that are generated by the casings or containers which surround the explosive source or *secondary fragments* that are formed by nearby pieces of structures where the explosion occurred. Over the past few years, the number of global IED incidents has risen [1,2], whereby casualties and damage to structures are caused by the release and impact of blast-induced fragments. These fragments are typically generated and propelled in an unpredictable and uncontrollable manner from the source.

A number of studies have been conducted on the phenomenon of fragmentation to provide guidance for the prediction of fragment loadings on structures as a result of accidental explosions in or near the structures based on open field tests, for example References 3,4. Arnold and Rottenkolber [5] presented experimental data on the fragmentation of thin aluminium and steel spherical shells subjected to internal blasts by studying the speed distribution of the generated fragments. Between 2800 and 5000 fragments travelling between speeds of 2700 m/s and 3000 m/s were observed for the various sizes of the spherical charges (66 mm–180 mm diameter range). With refined physical and mathematical models of fracture, several authors [5–9] have developed and improved numerical simulation procedures to predict the initial speeds and size distribution of fragments generated by the shattering of munition casing under the blast wave propagated by the explosive it contains. In some cases, close correlation was found between the predictive model and the actual experimental findings.

Generally, fragments generated from objects in contact with the detonating explosives differ in mass, size, shape and velocity. Although irregular in geometry, there have been numerous attempts to statistically classify the 'uncontrolled' fragments in terms of mass distribution and velocity [3,10,11]. The generation of blast-induced fragments, however, can be "designed" to be more controlled in terms of the size and mass of the fragments, based on the quantity and size of the explosive. Nurick et al. [12,13] undertook investigations on the response of circular and square thin mild steel plates to blast loads over the entire area of the plate. Disc fragments were generated from the exposed area of the plate by means of Mode II (tensile tearing at the boundary) and Mode III (transverse shearing at the boundary) failure modes. Subsequently, when subjected to localised blast loads, fragmentation in the form of capping (Mode IIc failure mode – the ejection of a cap fragment from the central region of the plate where the load was applied) was attained [14–16]. The damage caused by these "capped" fragments was studied by Nurick et al. [17,18] whereby mild steel square tubes were subjected to localised blast loading. The opposite faces of the

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**Nomenclature**

| | |
|---|---|
| $\delta$ | (rear) plate maximum deflection |
| $d$ | plate diameter |
| $d_f$ | fragment diameter |
| $\varepsilon_d$ | onset strain of densification |
| $E_{Abs}$ | energy absorbed in quasi-static loading |
| $E_k$ | (fragment) kinetic energy |
| $m_f$ | fragment mass |
| $\eta$ | energy absorption efficiency |
| $\rho$ | density |
| SEA | specific energy absorbed |
| $\sigma_0$ | static yield stress |
| $\sigma_{pl}$ | plateau stress |
| $v_f$ | fragment speed |

square tubes were assumed to behave as two parallel rectangular plates. The charge was applied on one side of the tube and the damage as a result of the generated fragment was assessed by the deformation of the opposite side of the tube. The observations in the experimental study [17] showed that the fragment caused inelastic deflection on the opposite face, while fusion of the fragment onto the opposite face was observed at higher impulses. In the validated numerical model [18], the speeds of the fragments were predicted to be up to 835 m/s.

With the threat posed by high velocity fragments to nearby structures and development of new materials, there are increased interests to seek ways to mitigate the impact that fragments may cause. The energy absorbing or impact resisting ability of different materials when subjected to impact by fragments or other projectiles has been widely reported. The response of natural fibre composites; comprised of flax, hemp and jute fabric – reinforced polypropylene composites subjected to impact by fragment-simulating projectiles was studied by Wambua et al. [19]. The dominant failure modes of the composites include fibre fracture, delamination and shear cutout. In terms of energy absorption, the composite hybrid structures performed better than mild steel and the plain composites. Ceramic armour system dissipated impact energy by cracking as reported by López-Puente et al. [20]. In an experimental study by Yungwirth et al. [21], pyramidal micro-architectured lattice (trusses) were used as cores of steel and aluminium alloy sandwich panels under projectile impact. The findings indicated that the panels exhibited similar failure patterns. The front face sheet failed by ductile hole enlargement while the rear plate failed by petalling as the projectile perforates through the material. The cores did not dissipate any significant amount of energy.

The most common energy absorbing materials used to alleviate damage from projectile impact are cellular materials in the form of foams (metallic and polymeric), wood or honeycomb. These materials with inherent cellular structures are often used as cores of sandwich panels to dissipate impact energy. Hou et al. [22] reported on investigations on aluminium foam sandwich panels under impact by flat, hemispherical and conical nosed projectiles. It was found that the front face sheet fails by circular hole formation with insignificant deflection, while the core is subjected to tunnelling during partial or complete perforation. Flexible polyurethane foam was subjected to projectile impact in an investigation carried out by Zaretsky et al. [23]. Beyond a projectile speed of 43 m/s, the polyurethane foam turned into powder form upon impact. Atas and Sevim [24] subjected sandwich panels with either polyvinylchloride (PVC) foam cores or balsa wood cores to impact from drop weights. Balsa wood was observed to be stiffer than PVC in impact but debonded from the face sheets easier than the PVC. Investigations on aluminium honeycomb sandwich panels subjected to out-of-plane projectile impacts were reported on by Hoo Fatt and Park [25]. It was found that during perforation, the incoming projectile sheared off a compressed plug of the sandwich panel (front sheet, core and back sheet).

Despite the numerous studies on the blast loading of structures reporting on capping, there is a need to gain insights for better understanding of the generation of capping as a method of fragmentation, its characteristics, the damage it may cause and how the damage can be alleviated. This paper presents the experimental results on the characteristics of blast-fragments which are blast-induced by explosive charges of different sizes and masses. The damage caused by the fragment is quantified by assessing the maximum deflection of a second witness target plate. The damage mitigation effectiveness of different energy absorbing cellular materials was also investigated via the comparisons of the deformation of the target plate after fragment impact.

## 2. Material characterisation

In the characterisation of cellular materials, the plateau stress and onset strain of densification on the compressive stress vs. strain curve are prime indicators of the energy absorbing ability of a material. While the plateau stress can be inferred from the stress-strain curve, there are different methods to determine the onset strain of densification as reported by Li et al. [26]. A more consistent approach to determining the onset strain of densification, as suggested by Li et al. [26], is based on the energy efficiency method (Eq. 1) that was proposed by Avalle et al. [27].

$$\eta = \frac{E_{Abs}}{\sigma(\varepsilon)} \tag{1}$$

$\eta$ is the energy absorbing efficiency, $\sigma(\varepsilon)$ is stress at strain '$\varepsilon$' and $E_{Abs}$ is energy absorbed from a strain of 0 to '$\varepsilon$'. The energy absorbed is essentially the area under the stress-strain curve from the original unstrained position to a generic strain '$\varepsilon$', as described by Eq. 2. The onset strain of densification is thus determined as the strain at which the energy absorbing efficiency is at its maximum.

$$E_{Abs} = \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon \tag{2}$$

In this study, six materials, as shown in Fig. 1: aluminium foam (relative density 8.5%), aluminium honeycomb (relative density 3.8%), balsa wood, Corecell M80 foam, Divinycell H200 foam (PVC foam)

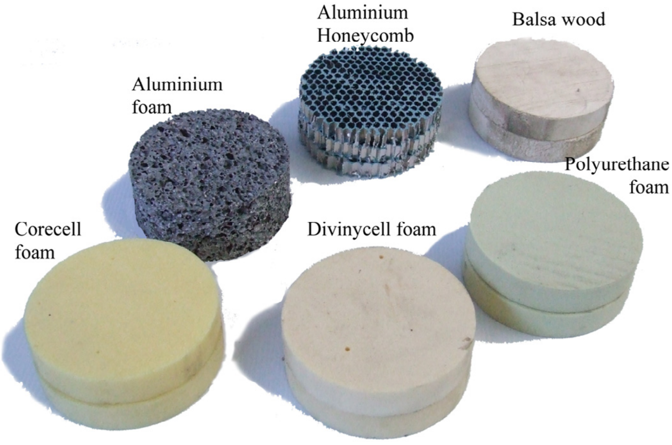

**Fig. 1.** Photograph of all the energy absorbing materials used in the study.