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Explosive blast damage resistance of three-dimensional textile composites

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ABSTRACT

The damage resistance of 3D textile composites when subjected to shock wave loading caused by an explosive blast is experimentally investigated. Non-crimp 3D orthogonal textile carbon-epoxy composites with different volume contents of through-thickness z-binder yarns are subjected to explosive blasts of increasing intensity, and the resultant damage is compared to a 2D woven carbon-epoxy laminate. At high blast impulse, the 3D textile composites are highly effective at resisting large delamination crack growth, and display superior damage resistance compared to the 2D laminate. The delamination resistance of the 3D textile composites at high blast impulse increases with their z-binder yarn content, and this correlates with higher modes I and II interlaminar fracture toughness properties. Furthermore, the 2D laminate completely shatters under high blast impulse whereas the 3D textile composites remain intact, which is also evidence of higher explosive damage resistance.

1. Introduction

Fibre-reinforced polymer matrix composites are used extensively in a wide variety of military assets, including fighter aircraft, naval ships and submarines, and armoured land vehicles, which all require high damage resistance against an explosive blast. Similarly, composites are used in civil and commercial applications such as passenger aircraft, rail carriages, buses and buildings, which have been attacked by terrorists using improvised explosive devices. Composites are potentially more susceptible to damage from an explosive blast than the metals used in military and civil structures (e.g. steels, aluminium alloys). High strength, ductile metals can absorb a large amount of impulse energy imparted by an explosive shock wave via large strain plastic deformation and work-hardening before rupturing [1]. In contrast, composites may damage more easily due to their much lower failure strain, low strength and fracture toughness of the polymer matrix, and relatively weak strength of the fibre-matrix interface.

Many modelling and experimental studies have investigated the deformation and damage to composite materials subjected to explosive blast loads, as reviewed by Langdon et al. [2]. The blast response of thermoset matrix laminates has been evaluated for both air and underwater explosive events [3–17]. The deformation and damage caused to laminates by blast loading depends on several factors, including the overpressure and impulse of the shock wave [3–5,7,8,10,11,13], the boundary conditions [7], and the properties of the composite material [2,10,16,17]. Damage often initiates as fine-scale microstructural damage (e.g. fibre-matrix interfacial cracks, short matrix cracks), and then develops into more extensive damage (e.g. long delamination cracks, fibre breakage) leading to complete rupture with increasing shock wave pressure [3–7,9–11,16,17]. The blast response of sandwich composites with thin face skins covering a thick core of polymer foam, metal foam, metal lattice or balsa wood have also been assessed [14,18–25]. The damage to sandwich composites also depends on several factors, and can include skin-core debonding, core cracking and core crushing [14,22–25].

A common type of blast-induced damage to laminates and the face skins of sandwich composites is delamination cracking. Delamination cracks reduce the structural integrity of composites by lowering the post-blast mechanical properties such as stiffness, failure stress and fatigue life [3–5,16,17]. Various techniques have been developed to reduce the amount of delamination damage caused by explosive blast loading, including using a high toughness polymer matrix [26,27], optimisation of the ply orientations [9], bio-inspired design of high-toughness ply layers [28], maximising the fibre volume content [29], and energy absorbent elastomer coatings [30–32].

An alternative approach to improve the delamination resistance of composite materials against an explosive blast is through-the-thickness fibre reinforcement. Mouritz [33,34] proved

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experimentally that the amount of delamination damage to glass fibre laminates caused by an underwater shock wave can be reduced by through-thickness reinforcement using aramid stitches. The stitches increase the interlaminar fracture toughness of the laminate, and thereby make it more difficult for delamination cracks to grow under blast loading. Tekalur et al. [30] assessed the explosive blast response of a sandwich composite consisting of 3D woven laminate face skins and stitched polymer foam core. They discovered that stitching increased the damage tolerance against high pressure shock waves which cause core crushing. However, Guan et al. [35] found that stitching was not effective at increasing the blast damage resistance of sandwich composites. Finite element analysis by Guan and colleagues of stitched sandwich composites under different blast loading conditions revealed that most of the shock wave energy was absorbed by the skins and core, and the stitches absorb a much smaller percentage of the total wave energy. Despite the studies by Mouritz [33,34], Tekalur et al. [30] and Guan et al. [35] into stitched materials, much remains unknown about the efficacy of through-thickness fibre reinforcement of composites on their explosive blast damage resistance.

Three-dimensionally woven composites containing through-thickness z-binder yarns have high delamination resistance and therefore may potentially be highly resistant to damage caused by an explosive blast. 3D woven composites are already used in applications requiring impact damage resistance [36]. There are two main types of 3D woven materials: 3D interlock woven and non-crimp 3D orthogonal fabrics [37]. 3D interlock fabrics are woven by interlacing the warp, weft and z-binder yarns to create a fully interlocked fibre structure. Non-crimp 3D orthogonal fabrics consist of warp and weft yarns that are stacked as separate ply layers (without being interlaced by weaving), and are held in place with z-binder yarns woven in an orthogonal (through-thickness) pattern. This 3D fabric architecture avoids crimp of the warp and weft yarns, and thereby avoids significant reductions to the in-plane mechanical properties. Due to the z-binder yarns, 3D textile composites have high interlaminar fracture toughness properties [38–43] and consequently high resistance to delamination cracking caused by point impact loading [44,45]. However, the improvement (if any) to the blast damage resistance of 3D woven composites due to the through-thickness z-binder yarns is not known.

The delamination resistance of 3D textile composites to airborne shock waves generated by an explosive charge is studied experimentally. A 2D woven laminate and non-crimp 3D orthogonal composites with different volume fractions of z-binder yarns (3.8%, 7.1%, 9.6%) are blast tested using plastic explosive charges. The composites are subjected to shock waves of increasing overpressure and impulse, and the amount and types of damage sustained is quantified. Improvements to the blast damage resistance of the 3D textile composites are correlated with improvements to their modes I and II interlaminar fracture toughness properties. Via this work, this study aims to determine whether the explosive blast damage resistance of 3D textile composites is superior to the 2D woven laminates commonly used in military and civil structures.

2. Materials and experimental methodology

2.1. Composite materials

Explosive blast tests were performed on non-crimp 3D orthogonal carbon-epoxy composites. The non-crimp orthogonal fabrics had the tow architecture illustrated in Fig. 1. The warp, weft and z-binder yarns consisted of 1600 text (24 K) carbon rovings (Tenax® STS40). The rovings were aligned using a ribbon loom into non-crimp multi-layer fabrics consisting of two warp and three weft plies. The z-binder yarns were orthogonally woven into the fabric in rows aligned in the warp tow direction (as indicated in Fig. 1). By reducing the spacing between the warp-aligned rows of z-binder yarns it was possible to increase their volume fraction. In this way, 3D textile fabrics were produced with the volume content of z-binder yarn being low (3.8%), medium (7.1%) or high (9.6%).

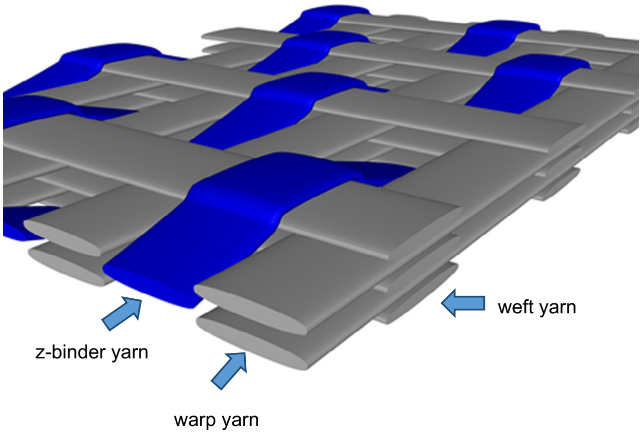

Fig. 1. CAD image of the tow architecture to the non-crimp 3D orthogonal fabric. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The typical cross-section profile of a z-binder yarn within a 3D textile composite is shown in Fig. 2. Because the 3D fabrics contained only five ply layers they were relatively thin (about 2 mm thick), and consequently the through-thickness segments of the z-binder yarns were inclined at a steep angle from the orthogonal direction. The average inclined angle (θ) of the z-binder yarns was 68°. The profile and inclined angle of the z-binder yarns was the same for the different volume contents.

The 3D fabrics were infused with liquid epoxy resin at room temperature using the vacuum bag resin infusion (VBRI) process. The epoxy consisted of a mixture of bisphenol A resin (SC8100 supplied by Lavender CE Pty Ltd) and diamine hardener (SD8824 from Lavender CE Pty Ltd). Following infusion, the resin was allowed to gel at room temperature for one day and then the 3D textile composites were cured at 60 °C for 8 h. The 3D textile composites were 2 mm thick and had a carbon fibre volume content (which includes warp, weft and z-binder yarns) of about 46%.

A 2D woven laminate was also manufactured to bench-mark the blast damage resistance of the 3D textile composites. The laminate was made using a plain woven fabric consisting of a 50–50 ratio of 200 tex (3 K) warp and weft carbon rovings. The fabric was supplied by Carr Reinforcements Ltd., Burnley, England (Type 38193). The carbon rovings used for the warp and weft yarns were much thinner than those used in the 3D textile composites (which were 1600 tex). The 2D laminate was made using the VBRI process with the same epoxy resin and cured under the same conditions as the 3D textile composites. The 2D laminate had the same thickness and similar fibre content (about 48%) to the 3D textile composites.

Top view photographs are shown in Fig. 3 of the 2D woven fabric and the 3D textile fabrics with the medium and highest z-binder yarn contents. Due to the tow size of the warp and weft yarns in the 2D woven fabric (200 tex) being smaller than those used in the 3D fabrics (1600 tex), the yarns are more closely spaced. The weave pattern is the same for the 3D fabrics containing the different volume contents of z-binder yarns; the only difference is the spacing between the z-binder yarns (as shown by com-