IMPROVING THE BLAST DAMAGE RESISTANCE OF COMPOSITES USING THREE-DIMENSIONAL WOVEN TEXTILES

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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).

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. [1]. The blast response of thermoset matrix laminates has been evaluated for both air and underwater explosive events. The deformation and damage caused to laminates by blast loading depends on several factors, including the overpressure and impulse of the shock wave, the boundary conditions, and the properties of the composite material. 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.

A common type of blast-induced damage to laminates 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. Various techniques have been developed to reduce the amount of delamination damage caused by explosive blast loading, including using a high toughness polymer matrix [2],[3], optimisation of the ply orientations [4], bio-inspired design of high-toughness ply layers [5], maximising the fibre volume content [6], and energy absorbent elastomer coatings [7][8].

An alternative approach to improve the delamination resistance of composite materials against an explosive blast is through-the-thickness fibre reinforcement. Mouritz [9],[10] proved 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. Tekular et al. [7] 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. Despite the studies by Mouritz [9],[10] and Tekular et al. [7] 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. There are two main types of 3D woven materials: 3D interlock woven and non-crimp 3D orthogonal fabrics. 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. Due to the z-binder yarns, 3D textile composites have high interlaminar fracture toughness properties [11]-[16] and consequently high resistance to delamination cracking caused by point impact loading [17]-[18]. 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%) were blast tested using plastic explosive charges. The composites were subjected to shock waves of increasing overpressure and impulse, and the amount and types of damage sustained was 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 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 Figure 1. The warp, weft and z-binder yarns consisted of two 800 tex (12K) carbon rovings (Tenax® STS40) combined to create a single 1600 tex (24k) roving. 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%).

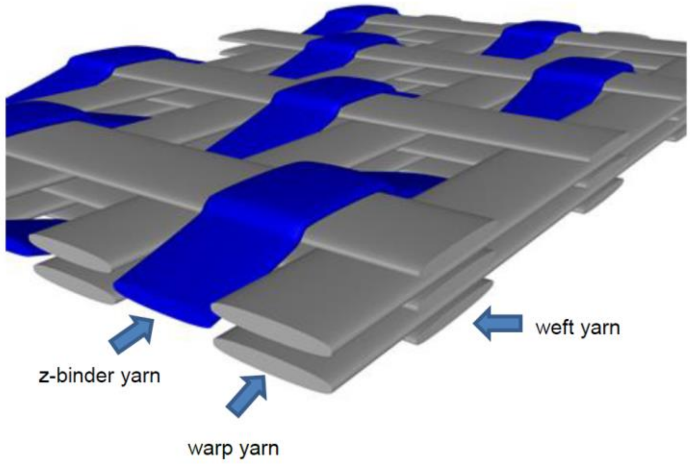


Figure 1: CAD image of the tow architecture to the non-crimp 3D orthogonal fabric.

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 hours. 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 (3K) 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.

2.2 Explosive blast testing

The experimental conditions used to perform explosive blast tests on the 2D laminate and 3D textile composites is shown in Figure 2. The tests were conducted inside a large blast chamber constructed of reinforced concrete lined with thick steel plating, and this is operated by the Defence Science and Technology Group, Department of Defence, Australia. The composite targets were flat square panels (180 mm x 180 mm x 2 mm thick) held within a rigid steel window frame (150 mm x 150 mm aperture) which was supported and restrained by a steel stand. The window frame was lined with soft rubber, and this allowed the composite panel to flex under the dynamic impulse load exerted by the shock wave. 100 g spherical plastic explosive charges (Type 4 RDX) were used to generate the shock wave that impulsively loaded the composite target. The charges were detonated using a 3.8 g EWB detonator (Type RP-80 produced by Teledyne RISI).

The composites were tested for three explosive conditions termed 'low', 'medium' and 'high', and these are defined in Table 1. Only one sample of each composite material was tested for each blast condition. Incident and reflective pressure gauges were used to measure the primary shock wave and any wave reflections from the walls/floor/ceiling of the blast chamber. The gauges were located at the same stand-off distance from the explosive charge as the composite target. Overpressure–time curves for the shock waves generated for the low, medium and high blast test conditions are shown in Figure 3. The overpressure rose instantaneously to the peak value with the arrival of the primary shock wave, and then decayed exponentially over a very short time (within ~0.5 ms). There were no significant secondary waves caused by reflection of the primary shock wave from the chamber surfaces. The peak overpressure and impulse of the shock wave was increased by reducing the stand-off distance between the composite panel and explosive charge. The impulse is defined by the area under the overpressure-time curve. The peak overpressure and impulse values for the low, medium and high explosive blast test conditions are given in Table 1.

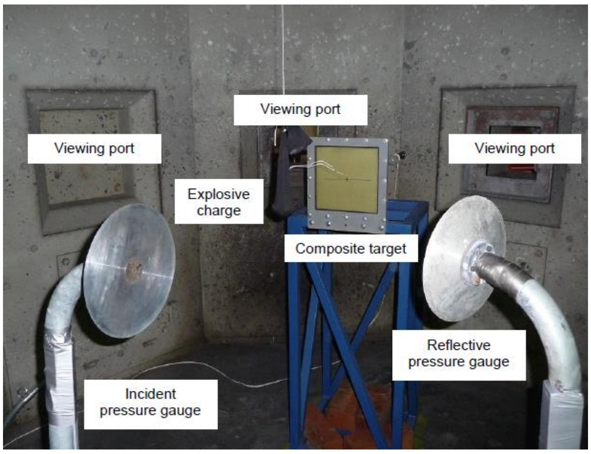


Figure 2: Experimental set-up for the explosion tests.

Blast Intensity	Explosive weight (g)	Stand-off distance (m)	Peak shock wave pressure (kPa)	Shock wave impulse (Pa.s)
Low	100	0.8	987 ± 64	151 ± 4
Medium	100	0.6	2238 ± 318	252 ± 28
High	100	0.5	3656 ± 1200	399 ± 44

Table 1: Explosive blast test conditions. The scatter values represent one standard deviation.

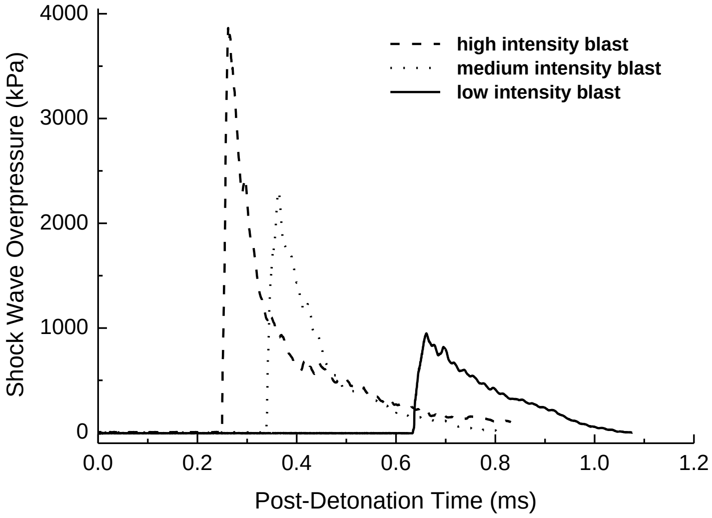
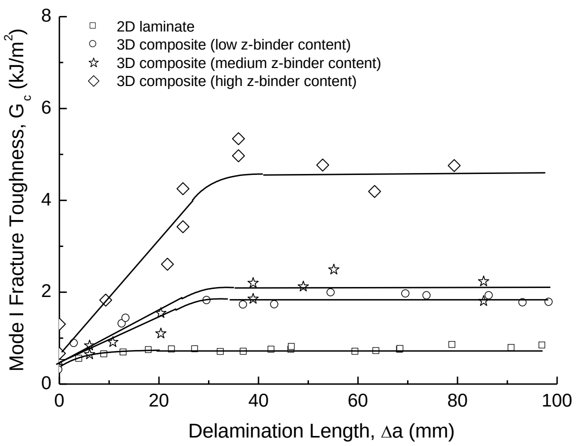


Figure 3: Overpressure-time curves for the shock waves for the three blast test conditions. The curves were measured using the reflective pressure gauge.

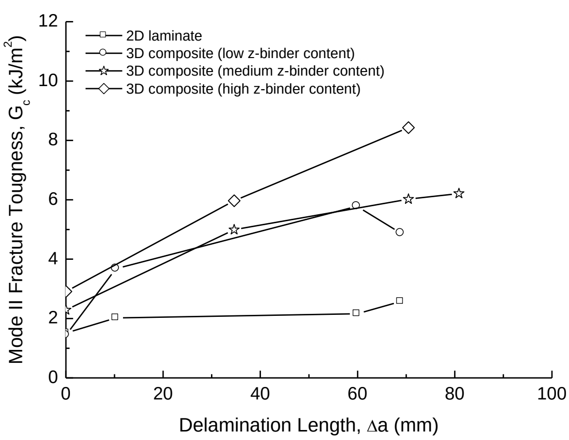
3 RESULTS AND DISCUSSION

3.1 Fracture toughness properties of 3D textile composites

The interlaminar fracture toughness properties of the 2D and 3D textile composites were determined to assess their resistance to delamination cracking caused by blast loading. The modes I and II interlaminar fracture toughness properties of the composites were determined using DCB and ENF tests, respectively, which are described in [16]. Modes I and II delamination crack growth resistance (R) curves for the composites are presented in Figure 4. The mode I R-curve for the 2D laminate shows a small increase to the interlaminar fracture toughness over the initial 10 mm of delamination growth due to the formation of a fibre bridging zone, and then the toughness remained constant at longer crack lengths. The R-curves for the 3D textile composites show that the mode I fracture toughness increased progressively over the initial 30-40 mm of crack extension and then reached a quasi-steady state toughness value. This was due to the formation of a bridging zone by the z-binder yarns along the delamination crack. The R-curves measured for the 3D textile composites under mode II showed different trends to mode I. The mode II interlaminar fracture toughness of the 3D textile composites increased continuously with increasing delamination crack length and (unlike the mode I condition) a steady-state crack growth condition was not attained for lengths up to ~70-80 mm. This is because the z-binder yarns did not develop a full-matured crack bridging process zone, even at the longest crack length.



(a)



(b)

Figure 4: (a) Mode I and (b) mode II crack growth resistance curves.

The effect of the z-binder yarn content on the modes I and II interlaminar fracture toughness values is shown in Figure 5. The mode II values are taken at the crack length of 60 mm, which is approaching the longest length that could be obtained in the ENF test. Both the mode I and mode II fracture toughness values (G_c) increased with the z-binder content, and this is because a greater number were bridging the delamination crack. The amount of toughening achieved by the z-binder yarns was similar or greater than that reported for other types of 3D textile composites [11]-[15].

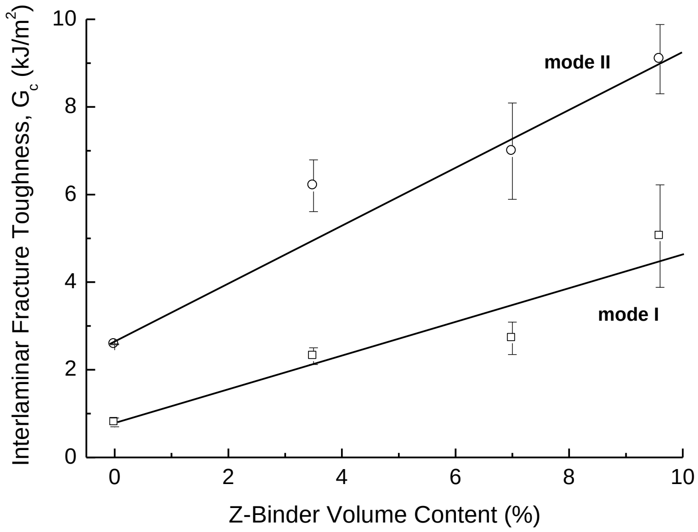


Figure 5: Effect of volume content of z-binder yarns on the mode I and II strain energy release rates.

3.2 Explosive blast resistant properties of 3D textile composites

The 2D and 3D textile composites were subjected to shock wave loading under the conditions given in Table 1, and then any damage was assessed via visual inspection, ultrasonics, scanning electron microscopy and X-ray computed tomography (CT). Photographs of the composite panels after blast testing at the different shock wave impulse levels are presented in Figure 6. The images show the panel surface exposed directly to the blast.

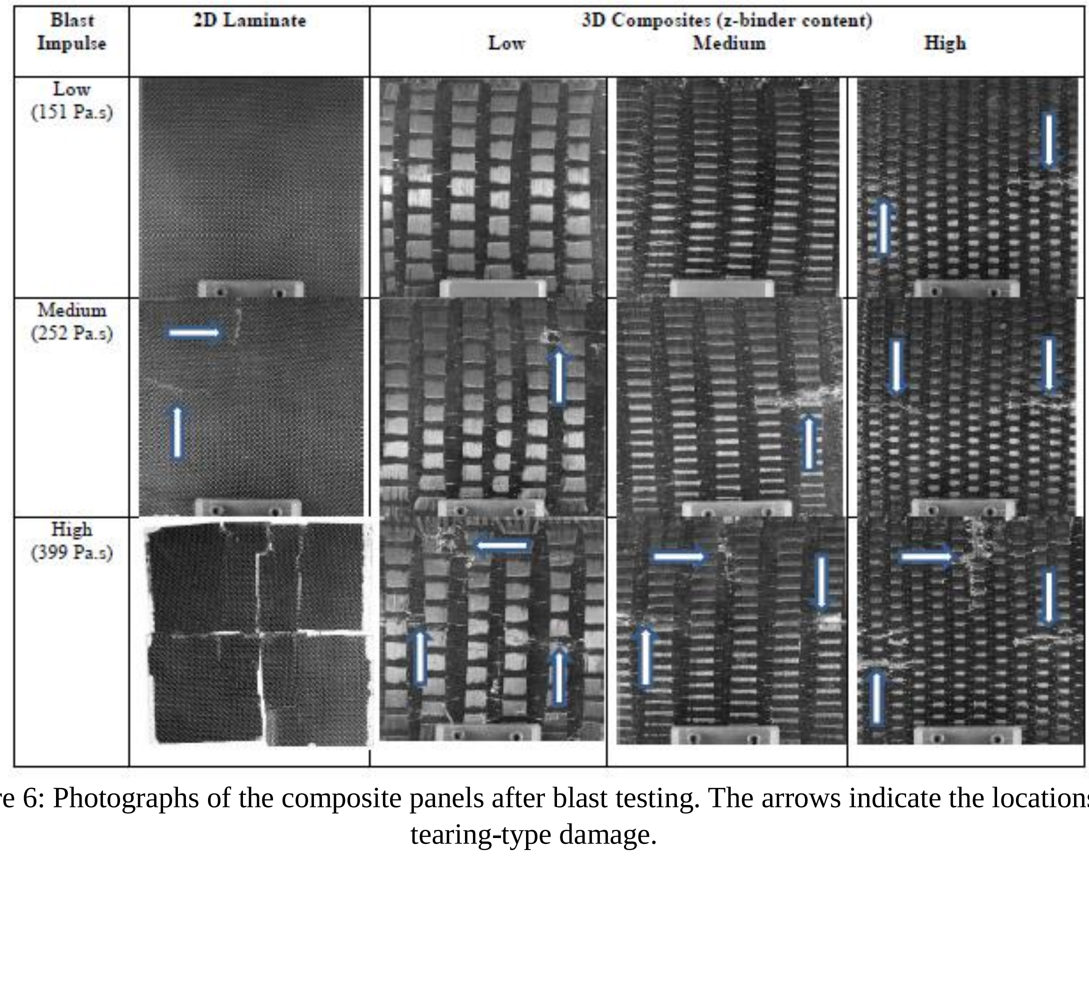


Figure 6: Photographs of the composite panels after blast testing. The arrows indicate the locations of tearing-type damage.

At the lowest shock wave impulse, the 2D laminate showed no visual signs of damage; however fine-scale interfacial cracking between the carbon fibres and epoxy matrix did occur. Comparatively, for the same low impulse, the 3D textile composites experienced more types of microstructural damage; namely fibre-matrix interfacial debonding, transverse cracking within the carbon tows, and matrix cracking within the resin-rich regions. These types of damage are the first to develop in composite materials under blast loading, and are caused by interlaminar and membrane (flexural) stresses generated when the panel bends under the shock wave impulse. At the low blast impulse, the 3D textile composites also experienced minor tearing-type cracks radiating from the sides, as indicated by the arrows in Figure 6. These cracks were caused by localised through-thickness rupture of the panel due to complete fracture of the carbon yarns (Figure 6). Under the lowest blast loading condition, it is possible that the 3D textile composites experienced more types of damage due to microstructural differences compared to the 2D woven laminate. Due to the larger size of the warp and weft tows as well as the z-binder yarns in the 3D textile composites, these materials had a less uniform distribution of fibres. The 3D textile composites also have larger resin-rich regions surrounding the warp, weft and z-binder yarns. Consequently, higher, more non-uniform and variable internal stresses may be generated within the 3D textile composites compared to the 2D laminate when subjected to the same blast loading condition. This may be responsible for the 3D textile composites experiencing fibre-matrix interfacial cracks, intra-tow cracks and matrix cracks within the resin-rich regions whereas the 2D laminate only experienced fibre-matrix cracking.

Raising the shock wave impulse to the medium and highest levels increased the volumetric density of damage within the composites. That is, the amount of fibre-matrix interfacial cracking as well as cracking within the crack tows and matrix phase increased with the shock wave impulse. Furthermore, the number and length of tearing-type cracks also increased. Of particular significance, at the highest shock wave impulse the 2D laminate completely shattered whereas all the 3D textile composites remained intact, and this is indicative of superior blast resistance.

The amount of delamination cracking to the composite panels was measured using through-transmission ultrasonics. C-scan images are presented in Figure 7 for the 2D laminate and the 3D textile composite with the medium volume content of z-binder yarns. It was not possible to ultrasonically inspect the 2D laminate following testing at the high shock wave impulse because it shattered. The dark regions in the images indicate the location of delamination cracks due to complete attenuation of the ultrasound signal. The delamination damage did not occur within a single region, but instead developed at multiple locations concurrently. The percentage area of delamination damage to the composites was measured from the C-scans where the ultrasound signal was completely attenuated. Figure 8 shows the effect of increasing shock wave impulse on the percentage area of the composite panels that sustained delamination damage. At the low and medium impulses, the amount of delamination damage was relatively low (under 10%), and there was no significant difference between the 2D and 3D textile composites. When the damage was so small, the delamination cracks were relatively short (typically under ~10 mm). The R-curves presented in Figure 4 show that the modes I and II interlaminar fracture toughness properties of the 3D textile composites are only slightly higher than the 2D laminate at short crack lengths ($\Delta a < 10$ mm). This is because the delaminations are too short to develop a fully matured z-binder bridging zone, which is needed to promote high interlaminar toughness in the 3D textile composites. At the high shock wave impulse, however, Figure 9 shows that the 3D textile composites were more resistant to blast-induced delamination damage than the 2D laminate, which was completely shattered. Furthermore, increasing the z-binder yarn content of the 3D textile composites reduced the amount of delamination cracking at the high blast impulse.

Shown in Figure 9 are plots of the mode I and II critical strain energy release rates (G_c) against the amount of delamination damage sustained at the high blast impulse. The amount of damage decreases rapidly with increasing interlaminar fracture toughness. This is because many of the delaminations in the 3D textile composites were sufficiently long (Δa above ~20-30 mm) that a large-scale z-binder bridging zone developed during blast loading, and this impeded more extensive cracking. The z-binder yarns bridged the delaminations caused by the blast, and thereby suppressed large-scale crack growth. In some cases the z-binders themselves experienced splitting cracking and partial rupture, however they did not completely fail which enabled them to retain a strong crack pinning effect. This proves that 3D textile composites are highly effective at resisting large-scale delamination cracking caused by high intensity explosive blasts.

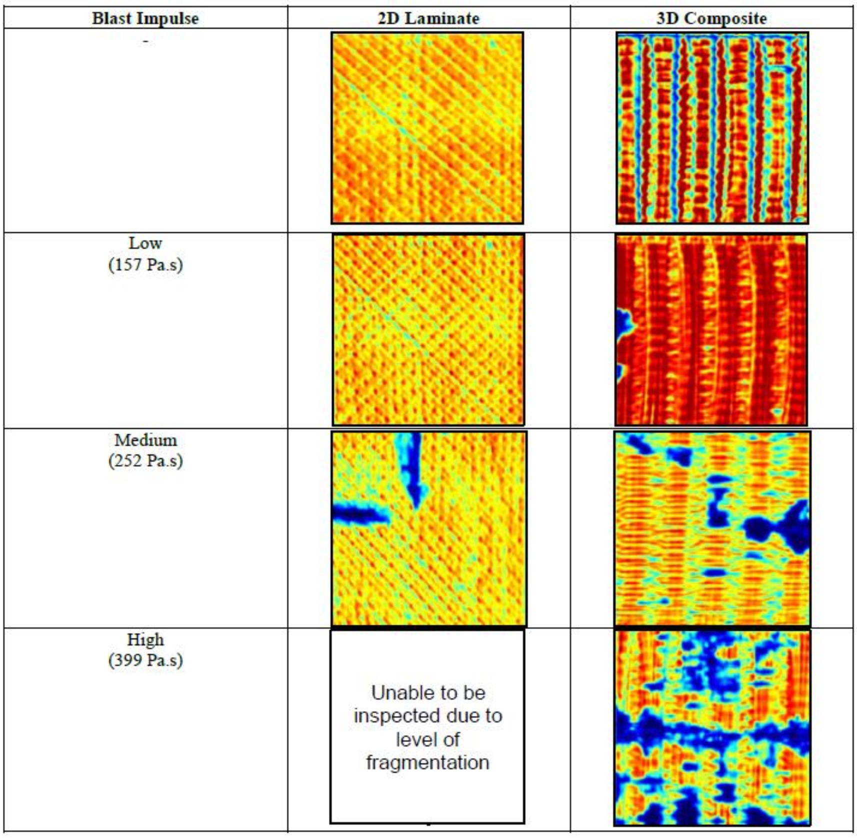


Figure 7: Ultrasound images of the 2D laminate and 3D textile composite with the medium z-binder yarn content before and after explosive blast testing. The dark blue regions indicate delamination cracking.

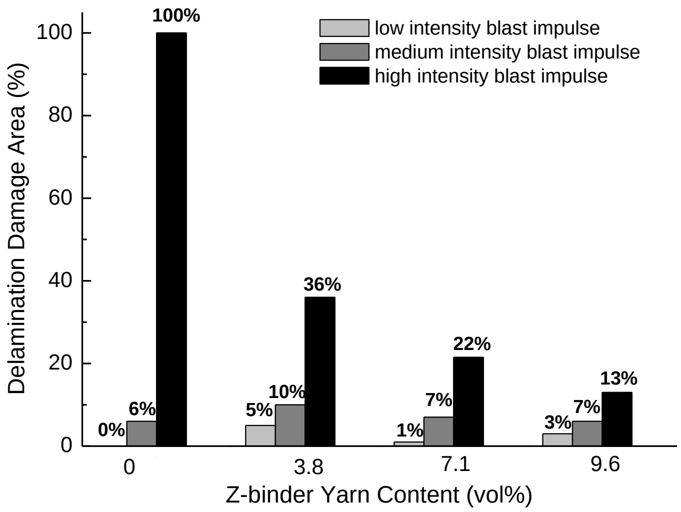


Figure 8: Effect of z-binder yarn content on the percentage area of the composite that delaminated due to blast loading.

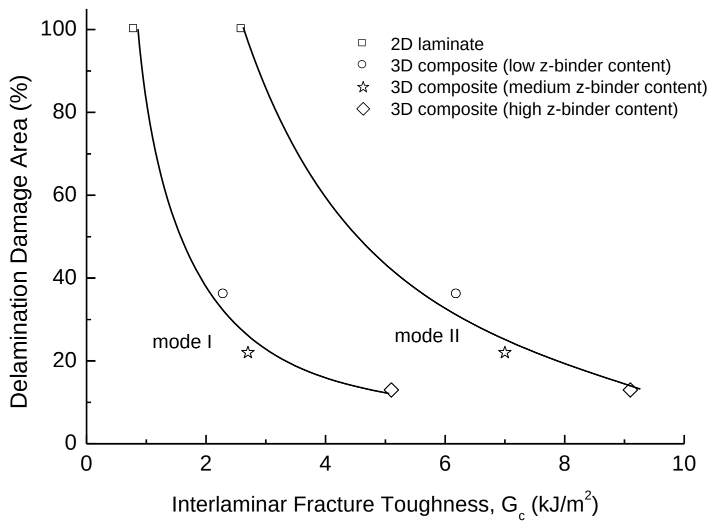


Figure 9: Plots of mode I and II interlaminar fracture toughness against the percentage area of delamination damage sustained by the composites when subjected to the high shock wave impulse. The lines are best-fit.

4 CONCLUSIONS

This study has proven that non-crimp 3D orthogonal textile composites have superior damage resistance compared to 2D woven laminate for certain explosive blast loading conditions. When subjected to an explosive blast with a relatively low impulse, 3D textile composites experience more types of microstructural damage compared to the 2D laminate. Under the low blast test condition, the 3D textile composites experienced multiple types of damage: interfacial cracking between the fibres and matrix, cracking within the tows, cracking within the resin-rich regions, and tearing cracks. In comparison, the 2D woven laminate only experienced fibre-matrix interfacial cracking. The 3D textile composites experienced more damage due to the more non-uniform internal stresses generated during dynamic deformation under the shock wave loading.

At the high blast impulse, the amount of delamination damage to the 3D textile composites is lower than the 2D laminate. The through-thickness z-binder yarns in the 3D textile composites generate bridging traction loads along internal delaminations formed by the explosive blast, thereby suppressing more effectively large-scale crack growth compared to the 2D laminate. Under the high blast test condition, the delamination damage sustained by the 3D textile composites decreased with increasing volume content of the z-binder yarns. The modes I and II interlaminar fracture toughness properties increased with the z-binder content, and this reduced the delamination damage caused by the high intensity blast. Furthermore, the 2D laminate completely shatters whereas the 3D textile composites remain intact.

Based on the research findings, it appears that non-crimp 3D orthogonal textile composites provide superior blast damage resistance, and this increases with the z-binder yarn content. However, the superior blast resistance only occurs when the shock wave impulse is high enough to cause the z-binder yarns to develop a large-scale crack bridging process zone that opposes extensive delamination damage.

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