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Delamination toughening and healing performance of woven composites with hybrid z-fibre reinforcement

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A B S T R A C T

This paper presents an investigation of a novel three-dimensional (3D) hybrid fibre-polymer composite material that has the unique combination of properties to both resist the growth and self-heal delamination cracks. This hybrid fibre composite contains two types of through-the-thickness z-binders made of carbon fibre tows (for high delamination resistance) and thermoplastic filaments (for self-healing). The performance of this hybrid 3D composite is compared with 3D composites reinforced in the through-thickness direction with either carbon tows or thermoplastic filaments. The results show that the hybrid 3D reinforcements substantially improve the mode I interlaminar fracture toughness (~1200%) and self-reparability of the composite. To understand the toughening mechanism of the hybrid z-binders, a finite element analysis is conducted to simulate the crack growth resistance behaviour and the fracture properties of the composite materials in the as-manufactured and healed conditions. The model is able to predict with good accuracy the fracture toughness and healing properties, and is used to further study the effects of hybridization ratio of the carbon and thermoplastic z-binders on the fracture toughness and healing properties of the 3D reinforced composites.

1. Introduction

Three-dimensional (3D) fibre composite materials have great potential in applications demanding light-weight structures with high delamination resistance and damage tolerant performance [1]. Example applications for 3D fibre composites include the inlet blades of aircraft engines and the wind turbine blades used for power generation. 3D fibre composites consist of warp and weft yarns to provide high in-plane mechanical properties together with through-thickness z-binder yarns to provide high interlaminar fracture toughness [2]. The z-binder yarns are usually inserted by weaving, stitching, tufting or z-pinning in a repeating pattern, and their volume content can be adjusted (typically 0.5 to 5–10%) via the pitch and spacing.

3D fibre composites possess higher interlaminar fracture toughness [3–5,2,6,7] and fatigue resistant [2] properties compared to 2D laminates due to the through-thickness z-binders. The interlaminar toughening stems from the z-binders generating traction loads via bridging the delamination cracks over a long distance (typically 10–40 mm). As a result, the damage resistance of 3D fibre composites against hard body impact [8,9] or explosive blast loading [10] can be much higher than 2D woven laminates. However, the z-binder yarns can degrade the in-plane mechanical properties of 3D fibre composites by typically ~5–20% (and sometimes more), and the level of degradation depends on the size and volume content of the z-binders as well as the loading condition (e.g. tension, compression) [11]. This degradation can be attributed to the microstructural defects such as ply waviness and crimping, as well as breakage of in-plane fibres that occurs during the z-binder insertion process.

To date, all published studies on the delamination resistant properties of 3D woven composites have been performed on materials containing z-binders that are usually made of carbon [3,4,2,6,7] or glass [5] fibre yarns. While these 3D woven composites have high delamination resistance due to the high stiffness and strength of the carbon or glass z-binders, once a crack is formed it cannot be easily repaired. The damaged material must usually be repaired by patching over the damaged region (although the crack remains) or by scarf repair (replacing the defective material with similar or dissimilar composites) [12]; with both repair methods being labour intensive and slow.

A novel approach is to repair the damage *in-situ* within the 3D fibre composite by modifying the fabric and/or the polymer matrix phase.

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When damage occurs, the healing process can be self-activated or activated using external stimuli (e.g. heat) to repair the 3D composite and restore the mechanical properties. Two self-healing methods have been reported in the literature for 3D woven composites. One method involves creating a microvascular network by weaving sacrificial z-binder fibres into the 3D textile fabric [13,14]. The sacrificial z-binders, which are made of solid organic material, are removed by heat-treating the 3D woven composite which causes depolymerisation and volatilisation, leaving an open channel, interconnected vasculature network that can be used for multiple functions, including thermal control, damage detection as well as self-healing via the storage and release of liquid resin and catalyst into open cracks [13]. The second approach is to use a shape memory polymer (containing small thermoplastic particles) as the matrix phase of the 3D woven composite [15]. Nji and Li [16] showed that the shape memory properties of the polymer can seal (close) cracks and the thermoplastic additive can heal the cracks at the molecular scale.

Another self-repair method is the addition of a thermoplastic agent to the material, although this has not yet been evaluated for 3D woven composites. Various thermoplastic agents have been evaluated for the *in-situ* repair of 2D woven laminates, including poly(ε-caprolactone) [17], nylon [18], ethylene-vinyl acetate [19,20], and poly[ethylene-co-methacrylic acid] (EMAA) [21–23] which has been the most extensively studied. The addition of a relatively low volume content of EMAA (typically under 10%) in the form of interleaves, small particles or stitches can heal delaminations in carbon-epoxy laminates [21–31]. Not only does the EMAA heal cracks, but it has the added benefits of remaining dormant in the composite until thermally activated for healing, and it can be effective for multiple healing operations rather than being single-use.

These recent research findings suggest that it is feasible to create 3D fibre composites which combine high delamination resistance with *in-situ* healing properties by hybridising thermoplastic z-binders with carbon or glass z-binders. This study presents an experimental and modelling study into a novel 3D fibre composite containing a hybrid combination of z-binders made of carbon fibre for high interlaminar fracture toughness and EMAA filaments for *in-situ* self-healing. The mode I interlaminar fracture toughness properties of this 3D hybrid composite material both before and after healing are compared to 3D fibre composites containing z-binders solely made of carbon fibre or EMAA. A finite element model is developed to calculate the interlaminar fracture toughness of these 3D fibre composite before and after healing, and its numerical predictions are compared against the experimental results. The model is then applied to characterise the effect of varying ratios of z-binders made of carbon or EMAA on the interlaminar fracture toughness and healing efficiency of 3D hybrid composites.

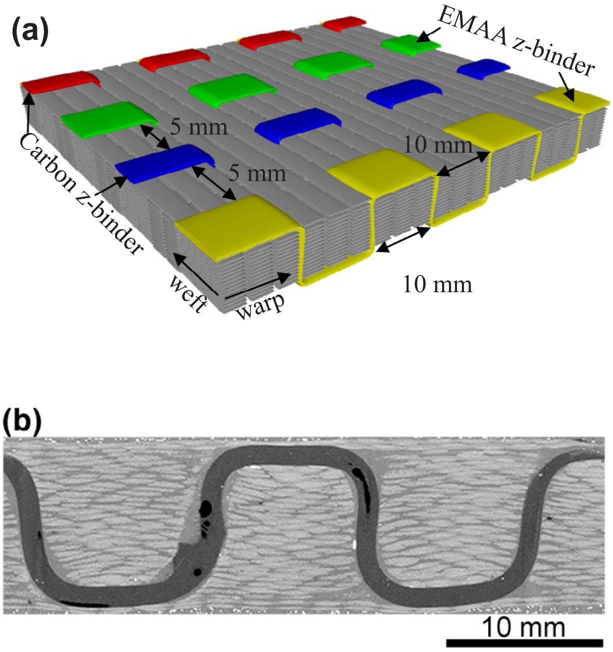

Fig. 1. (a). CAD image of the 3D fabric showing the hybrid z-binder architecture. (b) Cross-sectional X-ray computed tomography image showing the architecture of a z-binder. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Composite material and experimental methodology

2.1. Composite materials and manufacturing process

The composite materials used in this study were fabricated using a 198 gsm plain woven T300 carbon fabric (AC220127 supplied by Colan Ltd.). This fabric was woven using carbon tows of 198 tex (3K) roving containing filaments with a nominal diameter of 7 µm. The fibre preforms consisted of 36 plies of the carbon fabric that were manually woven in an orthogonal pattern using one or two types of z-binder materials: carbon fibre tows and EMAA (poly[ethylene-co-(methacrylic acid)]) filaments. The carbon z-binder tow was 800 tex (12 K) roving (Tenax® HTS40) with a nominal diameter of ~0.75 mm. The carbon fibres within the z-binder have a Young's modulus of 240 GPa and average tensile strength of 4.4 GPa, as reported by the supplier [32]. The EMAA z-binder was produced from fused pellets of Nucrel® (Dupont Packing and Industrial Polymer), which is an ethylene acid copolymer containing 19% by weight of methacrylic acid randomly distributed along the EMAA polymer chain. The EMAA z-binder was rectangular in cross-section (1.0 × 2.0 mm) with a tensile modulus and ultimate strength of 3 GPa and 16 MPa, respectively [26].

The orthogonal through-thickness insertion of the carbon tows and EMAA filaments was performed on 32 plies of carbon fabric along the warp direction in straight, parallel rows, as shown in Fig. 1a. Two additional plies of the carbon fabric were placed on the top and bottom surfaces of the 3D reinforced fabrics to prevent leakage of EMAA during high temperature curing and healing. Three types of 3D fibre composite were made containing z-binders made of (i) carbon only, (ii) EMAA only and (iii) combination of carbon and EMAA. Irrespective of the type of z-binders, the spacing between them both along and between the rows was 10 mm and 5 mm, respectively. The density (i.e. number of z-binders per unit area) and the pattern (orthogonal) for the three types of 3D woven composite was similar. However, as can be seen in Table 1, the areal contents (i.e. percentage surface area occupied by z-binders) for the 3D fibre composites were different due to the difference in the cross-section area of the carbon tows and the EMAA filaments. The areal contents for the z-binders in 3D fibre composites were 0.7 vol% for carbon and 3.2 vol% for EMAA, respectively. The hybrid 3D woven composite contained a 50-50 weave density of the carbon and EMAA z-binders (i.e. 0.35 vol% carbon and 1.6 vol% EMAA). The carbon tow used as the z-binder was of higher tex in comparison to the tows of the plain woven fabric. The higher tex carbon z-binder was used to maintain its areal content in the preforms at approximately one-fifth (0.7%) the z-binder areal content of EMAA (3.2%) while maintaining similar density for both the z-binder materials.

A 2D woven laminate without any z-binder, but with the same number of carbon fibre plies, was used as the control material to bench-

Table 1
Properties of the z-binder weave architecture in the 3D fibre composites.

Z-binder material	Z-binder density (binders/cm^2)	Z-binder areal content (%)
EMAA	1.6	3.2
Carbon	1.6	0.7
EMAA, carbon	0.8, 0.8	1.6, 0.35