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Structural Properties of Self-Healing Microvascular Fibre Composites

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ABSTRACT

This paper presents a finite element analysis and experimental study into the effect of microvascular fibres on the mechanical properties of self-healing carbon-epoxy composite materials. The major aim of this study is to quantify the beneficial and detrimental effects of microvascular fibres on the elastic modulus, strength and interlaminar fracture toughness properties of self-healing composites. Finite element modelling and experimentation showed that microvascular fibre networks reduce the tensile and compressive strengths but increase the mode I interlaminar fracture toughness by blunting and/or deflecting the crack tip. The localised ply waviness induces inter-ply splitting cracking under tensile loading and ply kinking under compression loading which lowers the strength properties; the larger the fibre diameter the greater the reductions in strength and stiffness.

Keywords: *Self-healing, microvascular fibres, mechanical properties, FE modelling*

INTRODUCTION

Fibre-polymer composite structures are prone to delamination cracking caused by impact, through-thickness loads, edge stresses, environmental degradation and other damaging events. A solution to delamination damage is the autonomic repair process of self-healing using microvascular (hollow) fibres for resin transport and storage. Microvascular networks using thin, hollow brittle fibres embedded in composite materials mimic the bleeding mechanism in biological systems. When a hollow fibre is fractured the self-healing fluid is released into the damaged region where it cures and heals the material. Microvascular fibres are typically 50 to 500 microns in diameter and are placed at the interface between the ply layers where delamination damage is most likely to occur. Damaged materials containing microvascular glass fibres show good self-healing behavior and recovery of mechanical properties [e.g. 1-6].

There is concern, however, that microvascular fibres may adversely affect the mechanical properties because of stress concentration effects and removal of load-bearing material to accommodate the fibres. However, only a limited amount of information is available on the

effects of the size, volume fraction, orientation and distribution of microvascular fibres on the mechanical properties of composites [3,7-9]. This paper presents a computational and experimental research study into the effect of microvascular fibres used for self-healing on the mechanical properties of carbon-epoxy composite. Specially, the effect of increasing fibre diameter and fibre orientation on the elastic modulus, strength and mode I interlaminar fracture properties was determined. The information presented in this paper can be used in the design of vascular self-healing systems that have minimal impact of the mechanical properties of composite materials.

MICROVASCULAR FIBRE COMPOSITES

Carbon-epoxy composite specimens were made containing thin glass tubes to assess the influence of microvascular fibres on the tension, compression and interlaminar fracture properties. The composite was made using unidirectional T300 carbon fibre prepreg tape (HexPly 914C) with a $[0/90]_{16s}$ ply pattern. Hollow glass fibres were placed between the two mid-thickness plies during lay-up with a constant pitch spacing of 5 mm, as shown in figure 1. The fibres had an external diameter of 170, 320 and 680 microns, and their wall thickness was 0.6-1.5 microns. Hollow fibres were aligned in the lengthwise (0°) or transverse (90°) directions of the composite (figure 1). The fibres were not filled with liquid healing agent during mechanical testing of the specimens. The composites were consolidated and cured in an autoclave at an overpressure of 690 kPa and temperature of 180^oC for two hours. Control specimens without microvascular fibres were manufactured and cured under identical conditions. The final thickness of the cured composite was 4 ± 0.1 mm.
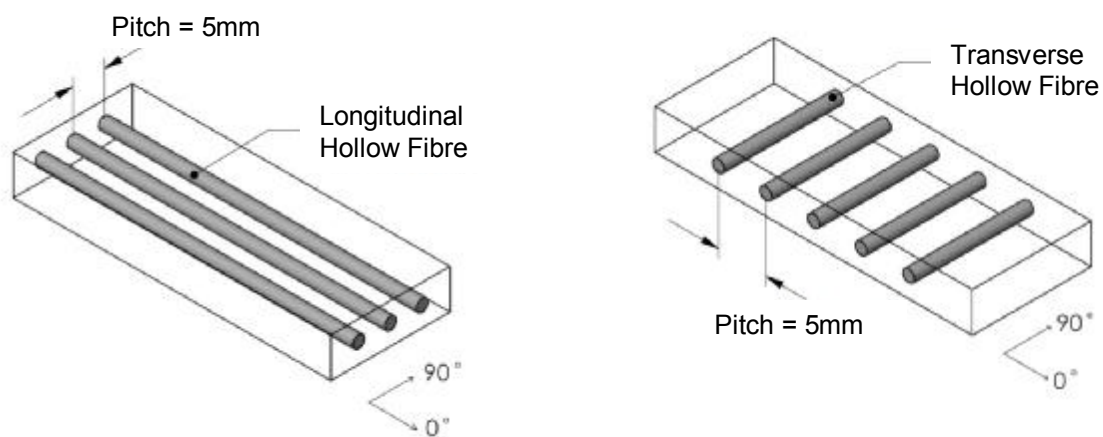

Figure 1: Schematic of the arrangement of microvascular fibres in the (a) longitudinal and (b) transverse directions along the mid-plane of the composite. The composite was loaded in tension or compression in the 0° direction.

The microstructure of the composite was changed by the microvascular fibres, and this can alter the mechanical properties. Major changes were increased ply waviness around the fibres and resin-rich zones next to the fibres, as shown in figure 2. Ply waviness is caused by the prepreg plies being forced to bend around the microvascular fibres. The ply waviness angle is greatest along the flanks of the distorted region, and this angle increases with microvascular fibre diameter. Waviness to the load-bearing plies (which are in the 0° direction) is dependent on the

fibre orientation. When microvascular fibres are aligned in the transverse direction it is the load-bearing (0°) plies that experience increased waviness. The plies in the transverse direction (90°) remain straight and are not distorted because they are aligned with the microvascular fibre axis. Conversely, when microvascular fibres are in the longitudinal direction it is the 90° plies that are distorted while the 0° plies remain straight. Resin-rich regions formed at both sides of the microvascular fibres. Displacement of the prepreg plies around the fibres during lay-up caused small void regions to develop, which then filled with resin during the curing process. The length of the resin-rich zone increased with the microvascular fibre diameter.
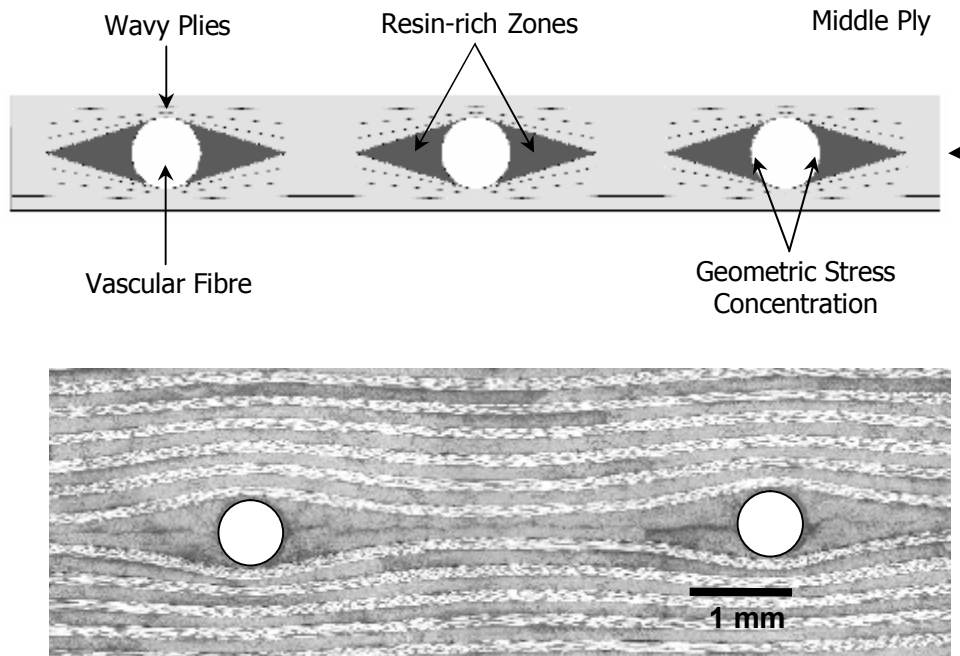

Figure 2: Schematic and photograph of the composite containing microvascular fibres. White circles have been placed over the fibres in the photograph to more clearly indicate their location.

EXPERIMENTAL METHODOLOGY

The tensile modulus and strength of the composites was determined using rectangular-shaped specimens with a gauge length of 190 mm and width of 25 mm. A constant loading rate of 2 mm/min was applied to the specimens in the 0° fibre direction using a 100 kN MTS machine. The compression modulus and strength was measured using the NASA short block test method. The compression specimens were 40 mm wide and had an unsupported gauge length of 25 mm. The compression load was applied in the 0° fibre direction using a 250 kN MTS machine at an end-shortening rate of 0.5 mm/min. Five samples were tested for each type of specimen - control composite material and composite containing 170, 320 or 680 micron diameter hollow fibres - in tension and compression.

The double cantilever beam (DCB) test (ASTM D5528-01) was used to measure the effect of microvascular fibres on the mode I interlaminar fracture toughness. Delamination fracture tests were performed on four to eight DCB samples for each of the different specimen types. Mode I interlaminar toughness tests were performed on specimens containing microvascular fibres orientated normal to the crack growth direction; specimens with fibres

aligned parallel with the crack direction were not tested in this study. Further details of the experimental methods are reported by Kousourakis et al. [8,9].

FINITE ELEMENT ANALYSIS

Numerical FE models of a representative volume element (RVE) of the control and microvascular fibre composites were developed using Abaqus to determine the tensile and compressive properties. The RVEs represented a quarter of a single microvascular fibre cross-section based on symmetry, as shown in figure 3. A ply-level meshing scheme was used for the RVEs with continuum shell elements for the ply layers and solid elements for the hollow glass fibre and resin-rich region. Cohesive elements were located at the interface between ply boundaries to model delamination cracking caused by in-plane loading. Zero-thickness cohesive element layers were embedded at every ply interface as well as between the resin-rich region and the adjacent ply.

For the RVE models of the self-healing composites the FE geometry was based on the actual microstructure by matching the microvascular fibre dimensions, ply waviness and resin-rich regions (as shown in figure 2). Ply waviness around the microvascular fibre was assumed to take the form of a cubic function and was proportional to the fibre height. The length of the resin-rich region was dictated by the ply misalignment angle. The ply waviness angle was assumed to reduce linearly in the through-thickness direction from a maximum around the microvascular to zero at the surface.

The Abaqus progressive damage model for fibre-reinforced composites was applied to the ply elements to analyse the in-plane ply failure modes. In this damage model, damage was categorised into four modes using the Hashin criteria. Once damage occurs within a ply its stiffness was gradually reduced to zero with increasing strain. Further information of the FE modelling is given by Nguyen and Orifici [10].
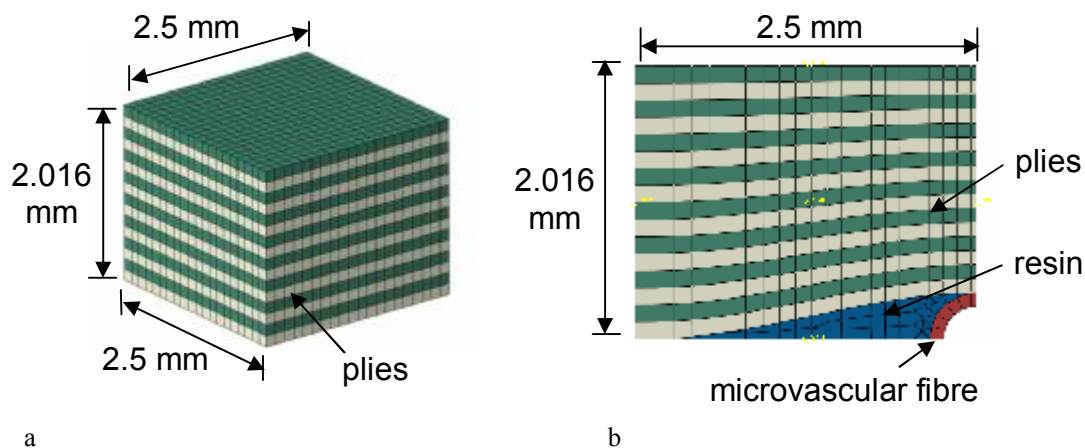

Figure 3: RVE definition. a) Control model. b) Model with microvascular fibre.

RESULTS AND DISCUSSION

Figure 4 shows the effect of the microvascular fibre diameter on the tension and compression modulus of the carbon-epoxy composite. The hollow fibres were aligned transverse to the loading direction. The data points show the experimental modulus values and the curves show the values calculated using FEA. Both the experimental and numerical results show a reduction with increasing diameter of the transverse fibres, and this was due to the increasing angle and volume of wavy plies. The FE model was capable of predicting the tensile and compressive moduli values to within an accuracy of less than 10%. When the microvascular fibres were aligned parallel to the load direction the tensile and compressive moduli were reduced less than that shown in figure 4, and this was because the load-bearing plies were not distorted. The agreement between the measured and calculated modulus values for composites containing longitudinal microvascular fibres was very good.
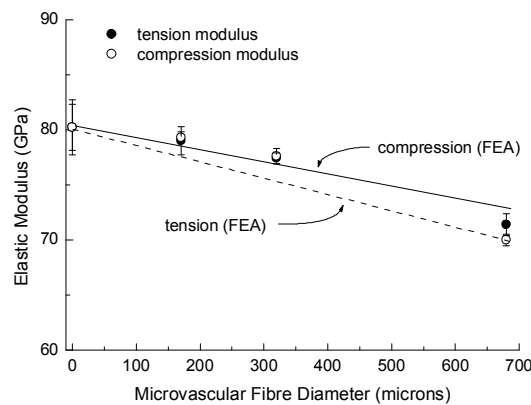

Figure 4: Effect of increasing microvascular fibre diameter on the tensile and compressive moduli of the composite when the fibres were aligned in the transverse direction. The data points and curves are the measured and calculated modulus values, respectively.

The effects of the diameter and orientation of the microvascular fibres on the tension and compression strengths are shown in figure 5. Both the experimental results (data points) and FEA (curves) show that the microvascular fibres have a major influence on the strength properties depending on their orientation. The strength properties were reduced by microvascular fibres aligned in the transverse direction. It is well known that the tension strength of composite materials decreases with increased waviness of the load-bearing plies. It is believed that the reduction to the tension strength of the composite containing transverse microvascular fibres was primarily caused by ply waviness, which increased with fibre diameter. The FE model predicted progressive tensile failure initiated by delamination cracking at the microvascular fibre which caused inter-ply splitting cracking. With increasing tensile strain this was followed by fibre fracture at the sides of the transverse microvascular fibres which then progressed in the through-thickness direction of the composite leading to final failure, as shown in figure 6. The compression strength also decreased with increasing diameter of transverse microvascular fibres due to increased waviness of the load-bearing plies. The critical compression stress required to initiate microbuckling (kinking) failure in composites decreases with increasing ply waviness. The increase in the waviness angle of the load-bearing plies is believed to cause the reduction to the compression strength with increasing diameter of the transverse microvascular fibres.

Figure 5 shows that there was a smaller reduction to the strength properties when the microvascular fibres were parallel to the load direction. As mentioned, waviness of the load-bearing plies does not occur when microvascular fibres are aligned parallel with the load direction. Therefore, the small reductions to the tension and compression strengths with increasing size of the longitudinal microvascular fibres was not the result of the load-bearing plies being distorted, but instead is attributed to the reduced load-bearing area caused by the space occupied by the hollow fibres.
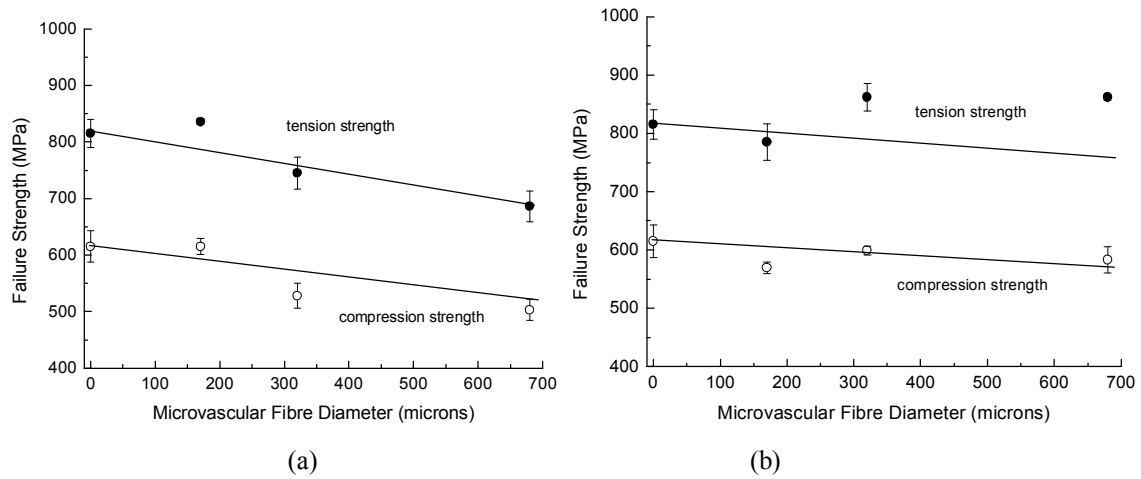

| (a) | (b) |

Figure 5: Effect of increasing microvascular fibre diameter on the tensile and compressive strengths of the composite when the fibres were aligned in the (a) transverse and (b) longitudinal directions. The data points and curves are the measured and calculated modulus values, respectively.

| (a) | (b) |

Figure 6: (a) FEA of fibre failures in the composite containing the 680 micron microvascular fibre aligned in the transverse direction. The colour coding shows the fibre fracture damage index. (b) Tensile failure of the same composite determined by experimental testing.

The effect of increasing diameter of the microvascular fibres on the mode I interlaminar fracture toughness of the carbon-epoxy composite is shown in figure 7. The delamination toughness values (G_{local}) for the self-healing composites are the apparent strain energy release rates corresponding to when the crack tip is arrested at a microvascular fibre, and do not represent the average toughness measured over a large crack length. However, the interlaminar fracture toughness of the control material represents the average G_{Ic} value measured over a long crack length (at least 120 mm). Figure 7 shows that the delamination toughness increased with microvascular fibre diameter. The toughness was increased via pinning and deflection of the delamination crack by the microvascular fibres. It was observed during DCB testing that when the

crack front reached a microvascular fibre it either breached the fibre wall or was deflected around the fibre. When the microvascular fibre was breached the delamination was pinned and could not move unless the crack opening displacement was increased significantly. This is because the geometric stress concentration factor of the open-hole microvascular fibre is much less than the stress concentration at the sharp crack front. Therefore, when the delamination breaches the glass wall and enters the microvascular fibre the stress acting on the crack tip is greatly reduced, thereby pinning the delamination and increasing the fracture toughness. Crack deflection around some of the microvascular fibres also increased the toughness.
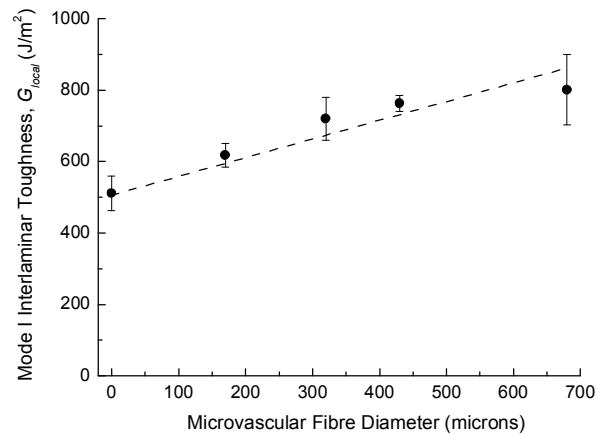

Figure 7: The effect of increasing microvascular fibre diameter on the local mode I interlaminar fracture toughness. The microvascular fibres are aligned normal to the delamination crack growth direction.

An FE model of the composite containing a 640 micron microvascular fibre was analysed using Abaqus to determine the stress concentration around the fibre and to model damage progression. To capture the fibre geometry around a microvascular fibre the cross-section of the material (figure 2) was digitised and the coordinates of composite plies were obtained and fitted with spline. Cohesive elements were placed along the composite mid-plane and along the composite-microvascular fibre interface to model the delamination crack progression. Further details of the FE modelling are provided by Zhou et al. [11]. The FE model revealed that by progressively increasing the applied load, the delamination crack advances through the resin-rich pocket and then around the fibre, as shown in figure 8.
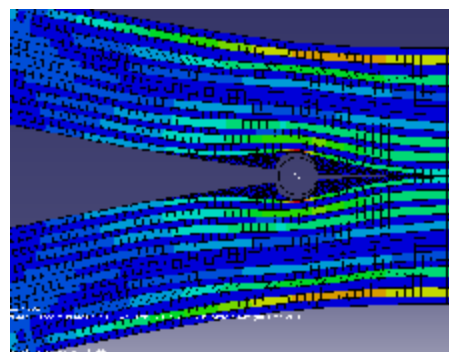

Figure 8: FEA showing the delamination crack passing around (and not through) the microvascular fibre.

The FE model does not predict fibre rupture, which was observed in the experimental DCB tests. However, it is believed that the crack can break or by-pass the microvascular fibres depending on their fracture strength. The tensile strength of glass fibres is highly variable, and it is speculated that lower strength fibres were breached by the delamination whereas higher strength fibres did not break and the crack was forced to propagate around. Obviously, for self-healing it is essential that the microvascular fibre is breached by the delamination to release the liquid resins.

ACKNOWLEDGEMENTS

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