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2010 Smart Mater. Struct. 19 085021

(http://iopscience.iop.org/0964-1726/19/8/085021)

Smart Mater. Struct. **19** (2010) 085021 (9pp) doi:10.1088/0964-1726/19/8/085021

The effect of self-healing hollow fibres on the mechanical properties of polymer composites

A Kousourakis and A P Mouritz[1]

School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, GPO Box 2476, Melbourne, Victoria, 3001, Australia

E-mail: adrian.mouritz@rmit.edu.au

Received 21 October 2009, in final form 28 April 2010
Published 15 July 2010
Online at stacks.iop.org/SMS/19/085021

Abstract
This paper presents an experimental study into the effect of self-healing hollow fibres on the mechanical properties and delamination resistance of carbon-epoxy composite panels and bonded joints. Hollow fibres made using thin-walled glass tubes are used in microvascular self-healing systems for the storage and transport of liquid reagents for autonomic repair of composite materials. This study shows that hollow fibres located along the mid-thickness plane of the composite material cause no change or a small loss (less than a few per cent) to the in-plane elastic modulus. The tension and compression strengths are not changed when hollow fibres are aligned parallel to the loading direction, but the strength properties are reduced when the fibres are normal to the load. The strength loss is caused by changes to the composite microstructure (e.g. increased ply waviness). The mode I delamination toughness increases with fibre diameter, with improvements up to ∼50%. The tensile (pull-off) strength of composite T-joints is not affected by hollow fibres at the bond-line. However, the fibres increase the failure strain and total work energy-to-failure of the joints up to 100% due to several bond-line toughening processes. The results can be used in the determination of the optimum size and orientation of hollow fibres for vascular self-healing systems in structural composite materials and joints.

1. Introduction

Fibre–polymer composite structures are prone to delamination cracking caused by impact, through-thickness loads, edge stresses, environmental degradation and other damaging events. Delamination cracks between the ply layers can severely reduce the structural properties of composite materials, such as reduced compression strength and fatigue life. Delamination damage within bonded composite joints can lower the pull-off strength and fatigue life. Various techniques have been developed to suppress the initiation and/or growth of delamination cracks in composite panels and bonded joints, including toughened resin systems, thermoplastic interleaving, and through-thickness reinforcement by three-dimensional weaving, stitching or pinning. While these techniques are effective at resisting delamination cracking, any damage growth must remain unrepaired until the component is taken out-of-service.

A solution to delamination damage is the autonomic repair process of self-healing, which is achieved by dispersing small vessels containing a low viscosity healing fluid and catalyst within the polymer matrix [1–3]. Self-healing basically works by the growing delamination rupturing the vessels and thereby releasing liquid healing agent into the crack. The healing agent is polymerized inside the crack by reacting with the catalyst, which is stored as a fluid in a separate vessel or as solid particles in the matrix. By the appropriate selection and dispersion of the healing agent and catalyst, it is possible to repair cracks and achieve good recovery to the mechanical properties of polymers, polymer coatings and polymer composites (e.g. [1–12]).

The original self-healing systems used small capsules to store the liquid healing agent. The capsules are typically 10–500 μm in size, which are dispersed in the polymer matrix

[1] Author to whom any correspondence should be addressed.

to volume contents between about 2% and 20% [2, 3]. There are several limitations in the use of capsules, such as the limited supply of self-healing fluid to repair large cracks and that they are single-use only. There is great interest in hollow fibres for resin transport and storage, which mimic the autonomic healing of living systems with a vascular network system of thin vessels. Microvascular networks using thin, hollow 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 crack where it cures and heals the material [2, 3, 13–27]. Toohey *et al* [7] demonstrated that vascular systems allow the continuous replenishment of healing fluids to the damaged region from an external supply. This replenishment is not possible with capsules and other closed storage vessels. In addition to self-healing, hollow fibres can have other functions in composite materials, such as cooling via the transport of cold fluids or sensing using florescent dyes [2, 18, 20, 24]. The hollow fibres are typically 40–200 μm in diameter, although smaller and larger sizes have been used, and fibres are placed at the interface between the ply layers where delamination cracking is most likely to occur. Damaged composites containing hollow glass fibres show good self-healing behaviour and recovery of mechanical properties [3, 21–23, 25–27].

Recent reviews of self-healing repair technology by Keller *et al* [2] and Wu *et al* [3] identified as a critical issue the effect of storage vessels on the mechanical properties of polymers and composites. A hollow fibre network may adversely affect the mechanical properties of the pre-damaged composite because of stress concentration effects and removal of load-bearing material to accommodate the fibres. However, only a small amount of information is available on the effects of the size, volume fraction, orientation and distribution of hollow fibres on the mechanical properties of polymer composites [22–24, 28, 29]. Trask *et al* [22, 24] measured a 16% reduction to the flexural strength of a fibre glass laminate containing 60 μm diameter hollow fibres. Williams *et al* [23] found that the same sized fibres caused a small loss in flexural strength to carbon-epoxy (under 10%), and concluded that hollow fibres do not appear to act as sites of structural weakness.

This paper presents an experimental research study into the effect of hollow fibres used for self-healing on the mechanical properties of carbon-epoxy laminates and bonded joints. Hollow glass fibres were placed along the mid-thickness ply interface in composite materials and along the bond-line in composite joints. The effect of increasing fibre diameter (up to 680 μm) on the delamination toughness, tension, compression and fatigue properties of composite materials was determined. The influence of fibre diameter on the mechanical properties of T-joints was also investigated. Improvements and reductions to the mechanical properties of the materials and joints are related to changes to the composite microstructure and stress concentration effects caused by the hollow fibres. The information presented in this paper can be used in the design of vascular self-healing systems that have minimal impact on the mechanical properties of composite materials and joints.

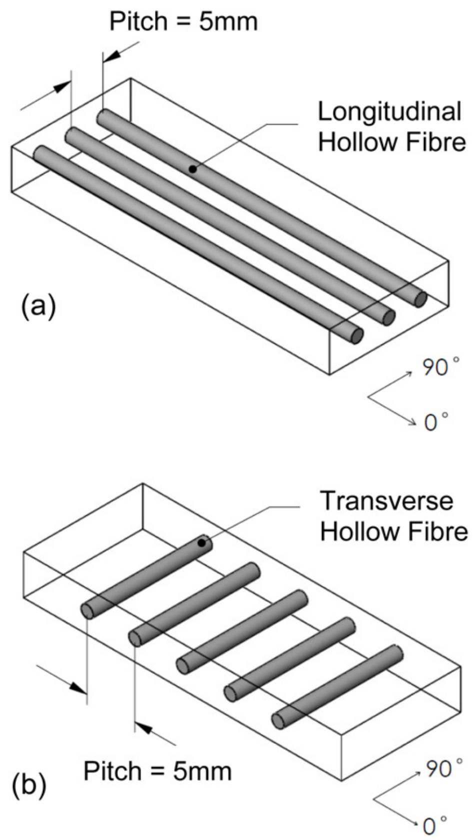

Figure 1. Schematic of the arrangement of hollow fibres in the (a) longitudinal and (b) transverse directions along the mid-plane of the composite. The composite was loaded in tension or compression in the 0° direction.

2. Materials and experimental details

2.1. Composite specimens

2.1.1. Manufacture of composites containing hollow fibres. Carbon-epoxy composite specimens were made containing thin glass tubes to assess the influence of hollow fibres on the delamination toughness and the in-plane tension, compression and fatigue properties. The composite was made using unidirectional prepreg tape (HexPly 914C) with a $[0/90]_{16s}$ ply pattern. The prepreg contains T300 carbon fibres. Hollow glass fibres were placed between the two mid-thickness plies during lay-up, as shown in figure 1. The fibre surface was coated with polyimide that promoted bonding with the epoxy matrix to the composite. The hollow fibres had an external diameter of 170, 320, 430 and 680 μm, and their wall thickness was 0.6–1.5 μm.

Hollow fibres were spaced at 5 mm intervals in the lengthwise (0°) or transverse (90°) directions of the composite (figure 1). The hollow fibres extended the entire length or width of the specimen. The fibres were not filled with liquid healing agent during testing and evaluation of the specimens. It is important to note, however, that hollow fibres and fibres filled with self-healing fluid have virtually identical mechanical properties because of the negligible stiffness and strength of the liquid.

The composites were consolidated and cured in an autoclave at an overpressure of 690 kPa and temperature of 180 °C for 2 h. The hollow fibres were not damaged by crushing during consolidation. Control specimens without fibres were manufactured and cured under identical conditions. The final thickness of the cured composite was 4 ± 0.1 mm. The average fibre volume content of the cured composite specimens was 60%. The fraction of the load-bearing area of the specimens occupied by the longitudinal hollow fibres with diameters of 170, 320, 430 and 680 μm was 0.1%, 0.4%, 0.7% and 1.8%, respectively. The load-bearing area occupied by the hollow fibres aligned in the transverse direction was significantly higher, with the 170, 320, 430 and 680 μm diameter fibres occupying about 4.3%, 8%, 10.8% and 17%, respectively.

2.1.2. Tension testing. The tension modulus and strength of the carbon-epoxy laminate with and without hollow fibres was measured in the 0° fibre direction according to ASTM D3039 specifications [30]. The tensile coupon specimens had a gauge length of 190 mm, width of 25 mm and nominal thickness of 4 mm. A constant loading rate of 2 mm min^{-1} was applied to the specimen in the 0° fibre direction using a 100 kN MTS machine. Five samples were tested for each type of specimen: control material and composite containing 170, 320, 430 or 680 μm diameter glass fibres. Tensile specimens with hollow fibres in the longitudinal or transverse directions were tested.

The effect of hollow fibres on the residual tension fatigue strength of the composite was measured using coupons with the same dimensions as the monotonic tensile samples. The fatigue samples were tested under repeated tension–tension loading with a sinusoidal load waveform. The stress was applied at an R ratio of 0.6 and frequency of 5 Hz for one million cycles. After fatigue testing, the residual strength of the composite was measured under tension loading to failure. A single specimen was tested for each tensile fatigue load condition.

2.1.3. Compression testing. The compression modulus and strength of the composite was measured using the NASA short block test method [31]. The specimens were 4 mm thick, 40 mm wide, and had an unsupported gauge length of 25 mm. The relatively high thickness-to-length ratio ensured global buckling of the specimen was suppressed. The compression load was applied in the 0° fibre direction using a 250 kN MTS machine at a constant end-shortening rate of 0.5 mm min^{-1}. Five samples of the control material and composites containing different sizes of hollow fibres were tested. Specimens were tested with the fibres in the longitudinal or transverse directions.

The compression fatigue strength of the composites was determined by subjecting short block specimens to cyclic compression–compression loading for one million cycles, and then measuring the residual strength. The compression load was applied using a sinusoidal waveform with an R ratio of 0.6 and loading frequency of 5 Hz. A single specimen was tested for each compression fatigue load condition.

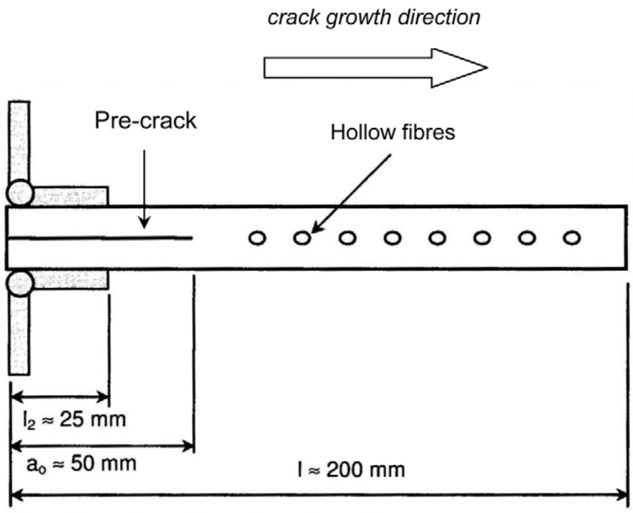

Figure 2. DCB specimen.

2.1.4. Delamination toughness testing. The double cantilever beam (DCB) test (ASTM D5528-01) was used to measure the effect of hollow fibres on the mode I interlaminar fracture toughness [32]. The DCB specimens were 200 mm long, 25 mm wide and 4 mm thick, as shown in figure 2. The crack opening force was applied at a rate of 2 mm min^{-1} via piano hinges bonded to either side of one end of the specimen. The delamination crack growth direction was normal to the direction of the hollow fibres, as indicated in figure 2. The mode I strain energy release rate (G_I) was calculated using modified beam theory:

$$G_I = \frac{3P\delta}{2ba} \quad (1)$$

where P is the applied load, δ is the load point displacement, b is the specimen width, and a is the delamination length. 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 hollow fibres orientated normal to the crack growth direction; specimens with fibres aligned parallel with the crack direction were not tested in this study.

2.2. Composite joint specimens

The effect of hollow fibres on the mechanical properties of T-joints was determined using specimens which are shown schematically in figure 3. The T-joints were made using unidirectional T300 carbon-epoxy prepreg tape (HexPly 914C) with a $[0/90]_{8s}$ ply pattern. Unidirectional carbon-epoxy was also used in the delta section at the stiffener base to avoid the formation of a resin-rich region. The joints were cured (without film adhesive between the stiffener and skin) in an autoclave at 180 °C and 690 kPa for 2 h.

Hollow fibres were located along the bond-line to the joint before curing, as indicated in figure 3. The fibres were evenly spaced 5 mm apart and were aligned across the width of the joint. The joint specimens were tested by applying a tension

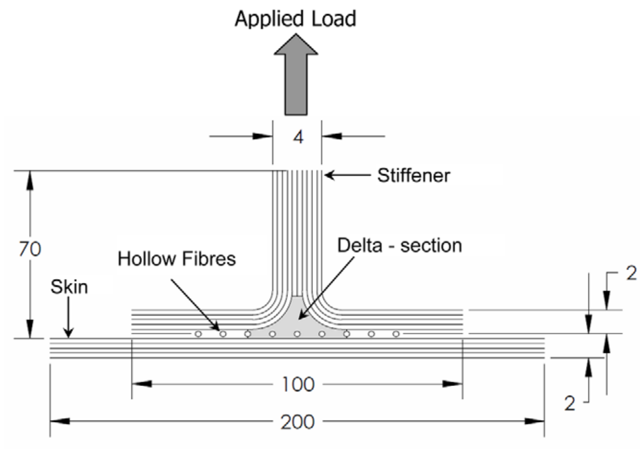

Figure 3. T-joint specimens. The dimensions are in millimetres.

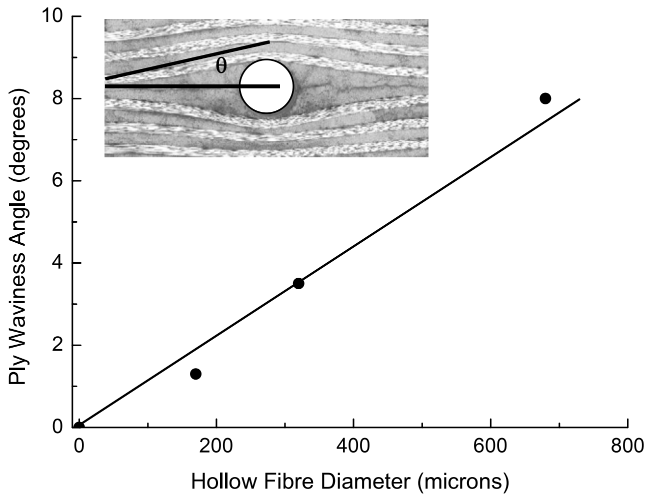

Figure 5. Effect of hollow fibre diameter on the ply waviness angle. A white circle has been placed over the hollow fibres in the photograph to more clearly indicate its location. The curve is a line-of-best fit.

(pull-off) load to the stiffener while the base panel was fixed. The load was applied in displacement control at an extension rate of 1 mm min^{-1} until complete separation of the stiffener from the base panel. Five T-joint samples were tested under identical conditions for each type of specimen.

3. Results and discussion

3.1. Microstructure of composites containing hollow fibres

The microstructure of the composite was changed by the hollow 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 4. Ply waviness is caused by the prepreg plies being forced to bend around the hollow fibres. The ply waviness angle (θ) is greatest along the flanks of the distorted region, and this angle increases with fibre diameter as shown in figure 5.

Waviness to the load-bearing plies (which are aligned in the 0° direction) is dependent on the fibre orientation. When hollow 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 fibre axis. Conversely, when hollow 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 hollow fibres, as shown in figure 4. 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 fibre diameter.

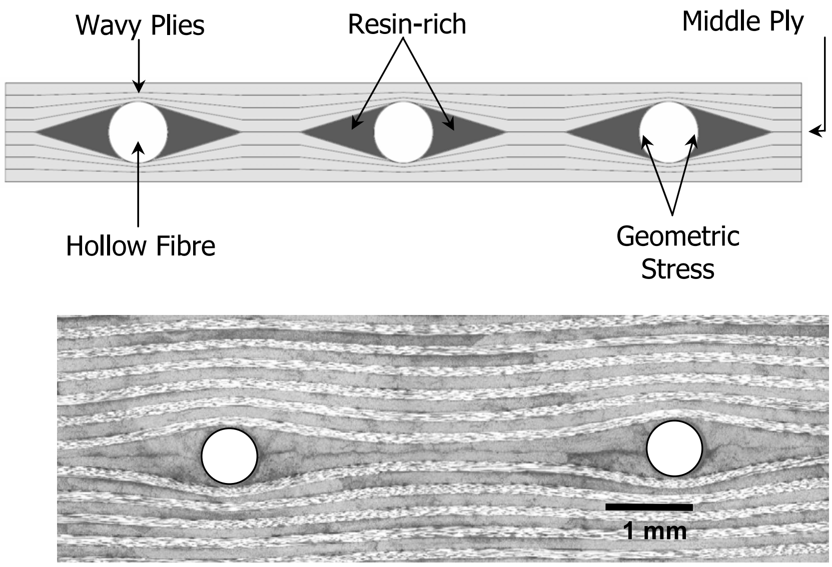

Figure 4. Schematic and photograph of the composite containing hollow fibres. White circles have been placed over the hollow fibres in the photograph to more clearly indicate their location.

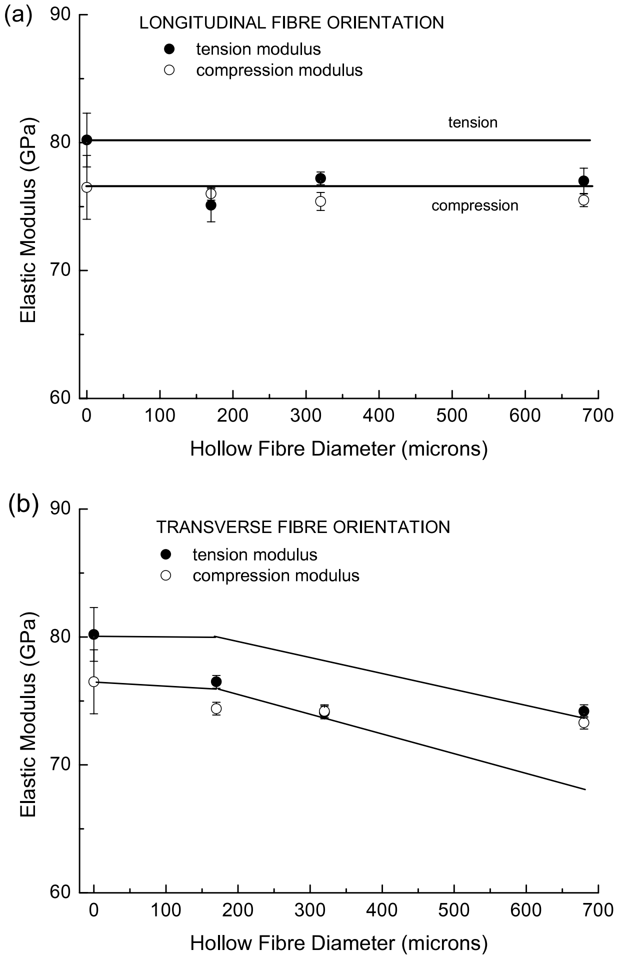

Figure 6. Effects of the diameter and orientation of the hollow fibres on the tension and compression modulus. The plots show the elastic modulus properties for fibres aligned in the (a) longitudinal and (b) transverse directions. The curves are calculated using rule-of-mixtures analysis for ply waviness and the error bars represent one standard deviation.

3.2. Elastic modulus and strength properties

Figure 6 shows the effects of the diameter and orientation of the hollow fibres on the in-plane tension and compression modulus of the carbon-epoxy. The fibres had little or no significant influence on the elastic properties. The average modulus values of the composites containing the hollow fibres are similar or slightly lower (up to 7%) compared to the control material, although the statistical variance in the measured properties suggests the change is within or just below the bounds of experimental scatter. Any reduction to the in-plane modulus can be attributed to the reduced load-bearing area due to the presence of the hollow fibres and ply waviness around the fibres. It is well known that the elastic modulus of composites decreases with increasing ply waviness (e.g. [33]). However, the ply waviness angle is shallow (between 1° and 8°) and is confined to a small volume of the entire specimen.

The effect of ply waviness on elastic modulus can be calculated by considering the volume fraction and angle (θ) of the load-bearing plies that are deflected by the hollow fibres using the rule-of-mixture equation:

$$E_{hf} \approx E_o V_{f(0°)} + E_{f(\theta)} V_{f(\theta)} \tag{2}$$

where $V_{f(0°)}$ and $V_{f(\theta)}$ are the volume fractions of the composite that contain load-bearing (0°) plies that have not or have been distorted by the hollow fibres, respectively. These volume fractions are based on the load-bearing area of the composite containing wavy fibres as measured from photomicrographs of the specimens. To simplify the analysis, it is assumed that all the fibres within the wavy volume of material are deflected to the same angle, θ. $E_{f(\theta)}$ is the modulus of the region of the composite containing load-bearing plies that have been deflected by the angle θ° by the hollow fibres, and is calculated using:

$$E_{f(\theta)} = \left[\frac{\cos^4\theta}{E_o} + \frac{\sin^4\theta}{E_o} + \left(\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_o}\right)\sin^2\theta\cos^2\theta\right]^{-1} \tag{3}$$

where G_{12} and ν_{12} are the in-plane shear modulus and Poisson's ratio, respectively. E_o is the in-plane elastic modulus of the composite without hollow fibres. When the hollow fibres are aligned in the longitudinal direction there is no distortion of the load-bearing plies (i.e. $\theta = 0°$), and therefore the effect of ply waviness on the elastic modulus can be ignored. However, the load-bearing plies are distorted when the fibres are in the transverse direction, and the measured ply waviness angles given in figure 5 were used to calculate the elastic modulus of the composite containing transverse fibres.

The calculated reduction to the tensile and compressive moduli with increasing hollow fibre diameter is plotted by the curves in figure 6. These curves were calculated by analysing the loss in elastic modulus caused by the wavy plies (equation (2)). There is no change in the elastic modulus when the hollow fibres are aligned in the longitudinal direction because there is no waviness in the load-bearing plies. The curves show a gradual reduction with increasing diameter of the transverse fibres due to the increasing angle and volume of wavy plies. The close agreement between the calculated and measured modulus values suggests that the ply waviness caused by the hollow fibres has only a small influence on the tension and compression modulus values for the composite.

The effects of the diameter and orientation of the hollow fibres on the in-plane tension and compression strengths are shown in figure 7. The fibre orientation has a major influence on the strength properties. There is no significant change to the strength properties (within the bounds of experimental scatter) when the hollow fibres are parallel to the load direction. However, the strengths are reduced by 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 [33]. It is believed that the reduction to the tension strength of the composite containing transverse hollow fibres is primarily caused by ply waviness, which increases with fibre diameter (figure 5). The compression strength of composite materials also falls with increasing waviness of the load-bearing plies. The critical compression stress required to initiate microbuckling (kinking) failure decreases

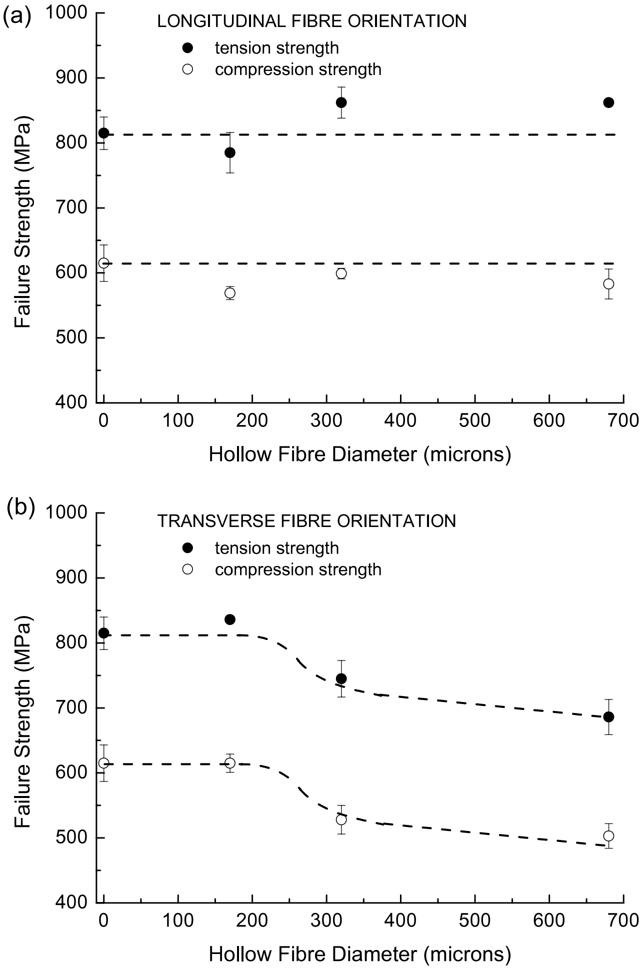

Figure 7. Effects of the diameter and orientation of the hollow fibres on the tension and compression strengths. The plots show the failure strengths for fibres aligned in the (a) longitudinal and (b) transverse directions. The curves are lines-of-best fit and the error bars represent one standard deviation.

with increasing ply waviness [33]. The increase in the waviness angle of the load-bearing plies is believed to reduce the compression strength with increasing diameter of the transverse hollow fibres. As mentioned, waviness of the load-bearing plies does not occur when the hollow fibres are aligned in the longitudinal direction. Therefore, the relatively constant tension and compression strengths of the composite with increasing size of the longitudinal fibres is the result of the load-bearing plies not being distorted.

The effect of cyclic stress loading on the residual fatigue strength of the carbon-epoxy containing transverse hollow fibres was determined. The composite was fatigued under repeated tension or compression loading for one million load cycles, and then the residual strength was measured. Fatigue tests were performed on the control material and the composite containing the smallest (170 μm) or largest (680 μm) fibres. (Fatigue tests were not performed on the composite containing the longitudinal fibres because the static strength properties did not change significantly.) Table 1 shows the effect of fibre diameter on the average strength properties before and after fatigue loading. The tension and compression strengths of

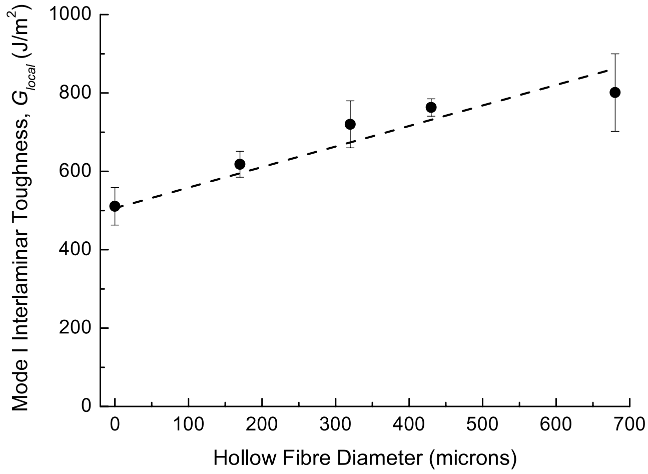

Figure 8. The effect of increasing hollow fibre diameter on the local mode I interlaminar fracture toughness of the carbon-epoxy. The fibres are aligned at 90° to the delamination crack growth direction, which is parallel with the 0° fibres. The error bars represent one standard deviation.

Table 1. Effect of transverse fibre diameter on the tension and compression fatigue strength of the carbon-epoxy.

Load condition	Hollow fibre diameter (μm)	Static strength (MPa)	Residual fatigue strength (MPa)	Strength reduction (%)
Tension	0 (control)	790	671	15
	170	835	743	11
	680	681	531	22
Compression	0 (control)	641	513	20
	170	645	516	20
	680	551	413	25

the control composite decreased due to fatigue by an average of 15% and 20%, respectively. These reductions in fatigue strength are typical for a [0/90] carbon-epoxy composite subjected to one million load cycles [34]. The percentage reductions in fatigue strength of the composites containing hollow fibres are similar (within ±10%) to the control material. This reveals that the transverse hollow fibres do not reduce significantly the fatigue strength of the carbon-epoxy under cyclic tension or compression loading.

3.3. Mode I delamination toughness

The effect of increasing diameter of the hollow fibres on the mode I interlaminar fracture toughness of the carbon-epoxy composite is shown in figure 8. The delamination toughness values (G_{local}) for the hollow fibre composites are the apparent strain energy release rates corresponding to when the crack tip terminates at a hollow 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 8 shows that the delamination resistance increases with fibre diameter, despite significant scatter in the toughness data which is typical for carbon-epoxy. This reveals that hollow fibre systems can improve

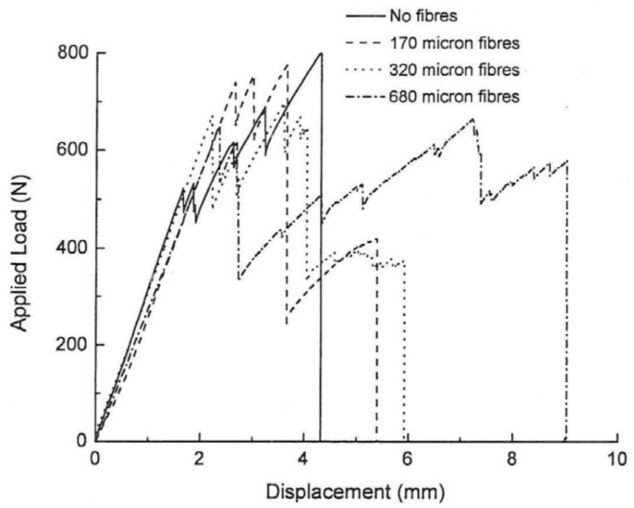

Figure 9. Effect of hollow fibre diameter on the tension load–displacement curves of the T-joints.

the delamination toughness of carbon-epoxy laminates when the fibres are aligned normal to the crack growth direction. The effect of hollow fibres on the delamination resistance of polymer composites has not been previously studied, however Brown *et al* [35] found the fracture toughness of epoxy (without fibres) is increased by self-healing capsules. The epoxy toughness was dependent on both the volume fraction and size of the capsules, and a maximum improvement of 127% was measured. Brown and colleagues attribute the toughening to a change in the fracture mode (from brittle type to hackle fracture) and sub-surface microcracking to the epoxy.

The fracture toughness of the hollow fibre composites is improved by different toughening processes to those determined by Brown *et al* [35] for neat epoxy resin containing microcapsules. The toughness of the carbon-epoxy composite was increased via pinning and deflection of the delamination crack by the hollow fibres and possibly by increased plastic yielding in the resin-thick region next to the fibres. It was observed during testing that when the crack front reached the hollow fibres it either breached the glass wall or was deflected around. When the fibre was breached the delamination was pinned and could not move unless the applied crack opening stress was increased significantly. This is because the geometric stress concentration factor of the open-hole fibre is much less than the stress concentration at the crack front. Therefore, when the delamination breaches the glass wall and enters the hollow fibre the stress acting on the crack tip is greatly reduced, thereby pinning the delamination and increasing the toughness. Crack deflection around some of the hollow fibres also increased the toughness. The mismatch in the elastic properties between the laminate and hollow fibre creates an asymmetric stress field surrounding the crack tip [36]. This asymmetry makes it harder for the crack to propagate around the fibre, thereby increasing the delamination toughness. The increased resin thickness in the polymer-rich region next to the fibres may also increase toughness. The size of the plastic zone ahead of the main delamination crack front increases with the thickness of the resin layer, and this

Table 2. Failure initiation load and maximum load capacity of the joints.

Joint type	Failure initiation load (N)	Maximum load (N)
No hollow fibres	600 ± 60	790 ± 70
170 μm hollow fibres	730 ± 30	760 ± 30
320 μm hollow fibres	660 ± 40	690 ± 40
680 μm hollow fibres	660 ± 70	750 ± 70

will increase the delamination toughness. Recent numerical analysis by Zhou *et al* [37] of the delamination toughness of the composite containing hollow fibres reveals that both crack deflection around the fibre or crack extension into the fibre is possible. Zhou *et al* [37] was able to accurately predict the increase in mode I delamination toughness of the composite caused by the hollow fibres. It appears that the strain energy release rate values for crack propagation around or through the hollow fibres are similar, and therefore both events occur. Obviously, self-healing requires the crack to rupture (and not by-pass) the hollow fibres, and therefore the self-healing system must be designed with a low strain energy release rate for hollow fibre fracture.

3.4. Composite T-joints

Figure 9 shows the effect of hollow fibre diameter on the tension (pull-off) load–displacement curve for the composite T-joint. The curves are representative of the different types of specimens, and show multiple spikes which indicate load drops due to the initiation and spread of damage. The load drops were caused by the start–stop propagation of delamination cracks along the bond-line between the stiffener and skin panel. The initial load drop to the curve is the point of failure initiation in the joint, and table 2 shows that this value is not affected significantly by the presence of hollow fibres. Table 2 shows the maximum load capacity of the joints is also not changed (within the bounds of scatter) by the fibres.

While the failure load of the joints was not affected by the fibres, the ultimate failure displacement value, which is the point when the load capacity of the joint drops to zero because the stiffener completely detaches from the skin panel, and the total work energy of the joint, which is the area under the load–displacement curve, both increase with the diameter of the hollow fibre. Figure 10 shows the effect of fibre diameter on the percentage increases to the failure strain and the work energy-to-failure of the joint. The failure strain was determined as the percentage of the measured failure displacement of the joint with hollow fibres compared to the failure displacement of the control joint. The work energy-to-failure defines the amount of elastic and plastic energy to rupture and completely debond the joint, and is measured from the area under the tension load–displacement curve. The normalized work energy values plotted in figure 10 show the value for the joint containing hollow fibres divided by the value for the control joint.

The improvement to the failure strain and the work energy-to-failure is due to the hollow fibres resisting the growth of bond-line cracks between the stiffener and skin panel. Under tension loading, joints with and without hollow fibres failed by

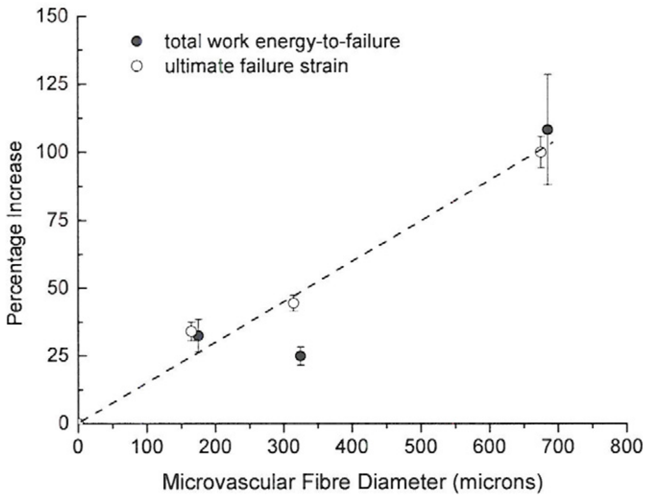

Figure 10. Effect of hollow fibre diameter on the percentage increase to the failure strain and total work energy-of-failure. The curve is a trend line and the error bars represent one standard deviation.

delamination cracking along the bond-line. In the absence of fibres, the bond-line crack propagated rapidly until the stiffener and skin panel were completely separated. In the presence of fibres, however, the delamination toughness of the bond-line is increased (figure 8). The fibres have a pinning effect which arrests mode I delamination crack propagation along the bond-line. The increased thickness of the bond-line near the fibres is also expected to increase the joint toughness by allowing greater plastic yielding ahead of the crack front. The bond-line cracks were observed to grow in start–stop steps as they propagated unstably between fibres and then stopped at the fibres due to pinning. The increased bond-line toughness due to crack pinning and plastic yielding is responsible for the percentage increases to the failure strain and work failure energy of the joints with increasing size of hollow fibres.

4. Conclusions

The future uses of microvascular self-healing systems in composite materials for certain applications, such as safety-critical aircraft structures, will be dependent on the hollow fibres having no adverse effect on the mechanical properties or any small reductions in properties being considered in the structural design. Hollow fibres cause local changes to the microstructure—ply waviness and resin-rich zones—which can affect the mechanical properties and damage tolerance of composites. This study has shown that the tension and compression properties of carbon-epoxy are not changed significantly when hollow fibres are aligned parallel to the load-bearing plies. However, the static strength properties are reduced at relatively large fibre sizes (above ∼200 μm) when aligned normal to the load-bearing plies. The normal fibres cause increased waviness in the load-bearing plies, which lowers the failure strength. Hollow fibres can increase the damage tolerance of composite materials and T-joints. The mode I interlaminar fracture toughness increases with fibre diameter due to pinning and deflection of the delamination crack and increased plastic yielding ahead of the crack tip in the resin-rich regions next to the fibres. The failure strain and work energy-to-failure of T-joints increases with fibre diameter due to these delamination toughening processes, without affecting significantly the joint strength.

Acknowledgments

The authors thank the Cooperative Research Centre for Advanced Composite Structures (CRC-ACS) and RMIT University for the facilities and technical resources used for this study. A Kousourakis thanks the CRC-ACS for a research scholarship. Discussions with Professor C H Wang are appreciated.

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