Bioinspired engineering study of Plantae vasculues for self-healing composite structures

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This paper presents the first conceptual study into creating a Plantae-inspired vascular network within a fibre-reinforced polymer composite laminate, which provides an ongoing self-healing functionality without incurring a mass penalty. Through the application of a 'lost-wax' technique, orthogonal hollow vasculues, inspired by the 'ray cell' structures found in ring porous hardwoods, were successfully introduced within a carbon fibre-reinforced epoxy polymer composite laminate. The influence on fibre architecture and mechanical behaviour of single vasculues (located on the laminate centreline) when aligned parallel and transverse to the local host ply was characterized experimentally using a compression-after-impact test methodology. Ultrasonic C-scanning and high-resolution micro-CT X-ray was undertaken to identify the influence of and interaction between the internal vasculature and impact damage. The results clearly show that damage morphology is influenced by vasculue orientation and that a 10 J low-velocity impact damage event is sufficient to breach the vasculature; a prerequisite for any subsequent self-healing function. The residual compressive strength after a 10 J impact was found to be dependent upon vasculue orientation. In general, residual compressive strength decreased to 70 per cent of undamaged strength when vasculature was aligned parallel to the local host ply and a value of 63 per cent when aligned transverse. This bioinspired engineering study has illustrated the potential that a vasculature concept has to offer in terms of providing a self-healing function with minimum mass penalty, without initiating premature failure within a composite structure.

Keywords: self-repair; vascular network; biomimetic; polymer composite; compression-after-impact

1. INTRODUCTION

In a materials engineering context, the concept of self-healing is applicable where manufacturing or operationally induced damage can be repaired by the materials already entrained within the structure, i.e. self-healing of engineering structures should be analogous to the healing process of living organisms whether from the Animalia or Plantae¹ biological kingdoms (Trask *et al.* 2007a). In recent years, research groups have developed discrete bioinspired concepts for autonomous delivery of a mobile fluid phase from either microcapsules (e.g. Kessler & White 2001; White *et al.* 2001) or hollow fibres (e.g. Pang & Bond 2005; Trask & Bond 2006; Trask *et al.* 2007b; Bond *et al.* 2008) to effect repair of bulk polymeric and advanced fibre-reinforced polymer

composite materials. This concept has taken a further biomimetic step with the introduction of integrated, pervasive vascular networks at the micro- and meso-scale (e.g. Theriault *et al.* 2003, 2005; Toohey *et al.* 2007; Williams *et al.* 2007), which have been demonstrated to provide a replenishable and repeated self-healing function.

In bulk polymeric materials, the inclusion of microcapsules (White *et al.* 2001), nanocapsules (Blaiszik *et al.* 2008) or vascular networks (Toohey *et al.* 2007) has been found to have negligible detrimental effect on the material's structure and mechanical performance, as the polymer is able to form around and easily accommodate any added self-healing entities. The situation for advanced fibre-reinforced polymer composite materials is more complex as they comprise at least two distinct phases: a reinforcement, typically a fibre (carbon, glass or aramid) of 10–30 µm in diameter oriented in a two-dimensional plane according to the anticipated loading environment; and a polymer matrix material (e.g. polyester, epoxy, or cyanate-ester) which fully envelopes the reinforcement. The inclusion of discrete self-healing entities, whether hollow glass fibres, microcapsules or a vascular network,

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¹In this work, Animalia and Plantae are defined from the scientific system of classification which divides all living things into groups (taxa). Plants are in the kingdom Plantae while animals are in the kingdom Animalia. Other kingdoms include Fungi and Protista (one-celled organisms including yeasts, bacteria and protozoans). The plant kingdom is divided into two taxa, bryophytes (including mosses and liverworts) and vascular plants (plants with a vascular system of xylem and phloem). It is the latter taxon which is of interest in this study.

Figure 1. (a) Ray cells in ash hardwood. Scale bar, 100 μm . (b) Scanning electron microscopy of the fracture surface in ash on the radial–longitudinal plane. Scale bar, 25 μm . (Reiterer *et al.* 2002.)

can easily disrupt the composite architecture (i.e. in-plane and out-of-plane fibre alignment) resulting in a detrimental effect on mechanical performance. Furthermore, poorly implemented vascular networks have been shown to potentially incur a significant mass penalty (values up to 25% have been reported by Williams *et al.* (2007)). To overcome, or at least minimize, the disruption to the host material by inclusion of a self-healing system, one obvious approach is to seek minimization of system dimensions, e.g. nanocapsules (Blaiszik *et al.* 2008). However, the application of nanocapsules restricts the available healing potential to tackle only very minor damage states, unless the volume loading is increased to such an extent that it again affects the inherent properties of the host material/structure.

An alternative solution is the design and formation of a carefully designed, integrated self-healing vascular network system that takes much bioinspiration from the numerous proven approaches in the Animalia and Plantae biological kingdoms (Williams *et al.* 2007, 2008). These two groups of organisms offer distinct sources of inspiration for the development of self-healing networks within synthetic fibrous polymer composite materials. While both groups generally incorporate a capability to transport fluid around a structure using ‘vascular networks’, their configurations and detailed designs are divergent (with some notable exceptions, e.g. leaves).

McCulloh and colleagues (McCulloh *et al.* 2003, 2004; McCulloh & Sperry 2005) have published several papers which discuss possible reasons for these different approaches in nature and the applicability of Murray’s law (Murray 1926), which helps in the derivation of rules for network design. In Plantae organisms, the nutrient-carrying longitudinal cells which transport nutrients from the roots to canopy tend to run parallel to one another without intersecting. These are often referred to as segregated networks (Williams *et al.* 2008). The segregation concept effectively blurs the distinction between generations with vascular conduits running adjacent and parallel. This allows the different conduits to break away from each other at a junction, forming what is effectively a new generation, without a true junction in the fluid flow path (Williams *et al.* 2008). Conversely, Animalia tend to have pervasive branching vascular networks which carry fluids around the organism. Such networks are typically

hierarchical in design with larger supply channels (veins and arteries) breaking down into progressively smaller vesicles (capillaries) at various points around the animal’s body.

Nature provides a wealth of different vascular network design approaches as a source of inspiration. By considering their relative advantages and limitations from an engineering standpoint, new and novel networks, in essence hybrids, can be contemplated for advanced fibre polymer composites. For example, vascular networks in plants, referred to herein as segregated networks, offer an alternative evolutionary approach to the mammalian circulatory system, which consists of a dense network of capillaries, tailored to the demands of the local tissue (Gray 1918). In the segregated network, different conduits break away from each other at a junction, forming what is effectively a new generation, without a true junction in the fluid flow path (Williams *et al.* 2008), thus reducing the risk of catastrophic system failure through a breach (McCulloh *et al.* 2003, 2004).

In an aerospace application, where system mass is a critical design driver, Williams *et al.* (2008) postulated that a self-healing delivery system should seek mass minimization, while offering redundancy to the threat of blockages and leaks, i.e. the introduction of a segregated network would be an optimized solution.

In the present work, efforts are underway to introduce healing functionality within a composite laminate without incurring any (significant) additional mass while simultaneously not compromising the inherent mechanical performance of the material through the introduction of the functionality. Such an objective is already achieved in nature’s many hierarchical designs (e.g. the review by Fratzl & Weinkamer (2007) and Meyers *et al.* (2008)).

In this engineering study inspiration stems from hardwood morphology (figure 1). In hardwood morphologies the role of the ray cells is to transport nutrients across the diameter of the tree. In figure 1a,b, the longitudinal load-bearing fibres are seen to flow around the ray cells with minimal disruption. It is this characteristic that is desirable for composite laminates, i.e. the accommodation of an internal fluid transport system (e.g. for healing or thermal management) which does not degrade the impact resistance and energy-absorbing characteristics of the host material.

Figure 2. (a) Schematic of composite stacking sequence $[-45/90/45/0/-45/90/45/0/0/45/90/-45/0/45/90/-45]$ with embedded vasculures located at the centreline (dotted line) with the healing potential (a) parallel to the host plies and (b) normal to the host plies (open circle, 0° ply; open ellipse, 45° ply; open rectangular bar, 90° ply; filled circle, vasculure).

Reiterer *et al.* (2002) and Stanzl-Tschegg (2006) considered the role of ray cells and their influence on impact resistance and energy-absorbing characteristics in both oak (*Quercus robur*) and ash (*Fraxinus excelsior*) hardwoods. Figure 2 illustrates the fracture plane of a ring porous hardwood, ash (Reiterer *et al.* 2002). By investigating two generally similar wood structures with different ray cell characteristics, Reiterer *et al.* (2002) and Stanzl-Tschegg (2006) described the influence of these features on the tensile strength and fracture mechanics response in the radial reinforcement of the ring porous hardwood structure. Reiterer *et al.* (2002) concluded that the ray cells act as stiff pins preventing the layers of different stiffness (i.e. earlywood and latewood) from slipping past each other. Hepworth *et al.* (2002) considered the interaction of impact resistance and energy-absorbing characteristics of different hardwood vessel morphologies on the structural response to compressive loading, i.e. vessels in close proximity to one another initiated buckling failure at low loads. The problem of improving impact resistance and energy-absorbing characteristics of polymer composites is an area currently under extensive investigation. A number of methods to improve toughness, such as modified polymer matrices and z -direction reinforcement (e.g. stitching or pinning), are being considered. Unfortunately, these approaches do not fundamentally address the problem of crack arrest in a low strain-to-failure material system with two discrete phases, i.e. structural fibres and host matrix. In an effort to increase the work-of-fracture (i.e. toughness) of composite materials Gordon & Jeronimidis (1980) identified and mimicked the tensile failure mode observed in helically wound cellulose fibrillae in the cell wall of spruce (*Picea sitchensis*) and teak (*Tectona grandis*). The helically wound structure was found to offer significant toughening via the development of complex and energy-absorbing failure paths.

The concept of introducing vascular networks in bulk polymers and cellular foams for composite sandwich structure healing has been previously investigated (Toohey *et al.* 2007; Williams *et al.* 2007). By comparison, this paper describes the first investigation into the concept of forming and integrating a bioinspired segregated vascular healing functionality within a fibre-reinforced polymer composite laminate with minimal disruption and minimal mass penalty. The aim of this research is to form an integral vascular network in a host material during composite fabrication without

compromising the overall performance. This is an approach commonly observed in Plantae at the macroscopic level. For example, the hierarchical nature of the cell wall in spruce (*Picea sitchensis*; i.e. cellulose microfibrils embedded within a matrix of hemicelluloses and lignin) and the preferred tilt angle of the cellulose microfibrils yield a very tough and damage-tolerant material. Hepworth *et al.* (2002) observed that the drilling of small holes along the grain of spruce, which naturally lacks vessels, mimicked the effect of vessels and did not reduce the energy-absorbing capabilities of the structure, despite a reduction in the density. While the internal features in woods are distinct from fibre-reinforced polymer composite materials, the development of a synthetic material that mimics the vessel morphology of hardwoods is critical for minimum mass composite structures. Although direct biomimicry of the complex design of a hardwood is beyond current capabilities in advanced fibre-reinforced composite materials, it is the concept of integrating vasculatures within an engineering material without incurring additional mass, and understanding the consequences of these features on damage initiation, that is under consideration in this study.

2. RESEARCH METHODOLOGY

This study assesses the feasibility of introducing a bio-inspired vasculature into a fibre-reinforced polymer composite, based on the design principles observed in Plantae, i.e. a segregated network. Critically, the introduction of such features must result in minimal disruption to the surrounding structural fibre architecture and hence the mechanical properties. The design of a self-healing agent for transportation through such a network is beyond the scope of this project and will not be considered further in this study.

At various locations in a segregated, branched or grid network within a composite laminate, the vascular network will be misaligned with the local reinforcing fibres. The control of this misalignment is paramount in ensuring that the influence on the structural performance of resin pockets and fibre distortions is minimized.

To begin to understand the feasibility and consequences of incorporating such vasculatures, a series of experimental trials have been undertaken. The first concerns methods by which such features can be readily fabricated within a composite laminate. Once this was established, the research was directed to assess the

influence of such an embedded network when oriented parallel or perpendicular to the local structural reinforcing fibres, by quantifying the disruption on the impact and structural response of the host material. This approach ensured a fundamental understanding of vascular deployment within a laminated composite material.

3. FABRICATING A VASCULAR NETWORK IN A COMPOSITE LAMINATE

The initial phase of the study sought to develop a means by which a simple vascular network could be formed *in situ* within a typical laminated fibre-reinforced polymer composite. The material selected for this study was an aerospace grade carbon fibre-reinforced epoxy (Hexcel Composites IM7/8552) unidirectional preimpregnated tape with a nominal ply thickness of 0.127 mm, a nominal fibre volume of 57.7 per cent with very low matrix flow during processing (as specified by the manufacturer's data). The panel dimensions were 110 × 240 mm.

The laminate ply stacking sequence selected for this investigation (figure 2) was 16 plies arranged at ply angles of $[-45/90/45/0/-45/90/45/0/0/45/90/-45/0/45/90/-45]$ with the vasculcs residing between the 0° plies located on the centreline (bold). The vasculcs were spaced 10 mm apart. This laminate is representative of a typical 'damage-tolerant' stacking sequence employed in the aerospace industry.

The vasculcs were formed by a 'lost-wax' type process using low melting temperature (LMT) wire (0.25 mm diameter, Sn 60%, Pb 40%; Solder Chemistry, Landshut, Germany) positioned at key interfaces between plies to form parallel channels within the laminate stack before autoclave processing. The fibre stack was placed directly onto a metallic tool covered in non-porous release film. A second non-porous release film was placed over the top of the fibre stack and a 2 mm thick aluminium caul plate was placed on top to maintain the surface profile. The complete assembly was covered by breather cloth and vacuum film and sealed to the metallic tool using commercial sealing tape (Aerovac Systems Ltd, UK) and checked for vacuum continuity before being processed in the autoclave.

The LMT wire was aligned at 0°, 45° or 90° to the adjacent plies within the stack, as indicated in figure 3. The LMT wire was selected such that it would survive exposure to the manufacturer's recommended cure cycle for the composite system, 120°C for 1 h, followed by 180°C for 2 h, with a temperature ramp rate of 2°C min⁻¹ and a pressure of 700 kPa. The LMT was subsequently removed under the application of a post-cure heat cycle of 190°C for 2 hours while under vacuum. Once removed, an open channel or vasculc, as shown in figure 3, was formed. All channels were visually checked to ensure full evacuation had occurred before the specimen was accepted for subsequent mechanical testing.

Figure 3 illustrates the typical level of disruption resulting from the wire inclusion at three different ply interface locations. In the aligned case (figure 3a), the local reinforcing fibres and the vasculature embed very

well with only slight fibre waviness in the adjacent plies. However, as expected, when the LMT wire is misaligned with the surrounding fibres a resin-rich pocket is formed (figure 3b,c), a feature absent from ring porous hardwoods where the ray cells nest precisely among the longitudinal reinforcing 'fibres' (figure 1). The overall length of the resin pocket created depends upon the angular mismatch between the vasculc and the local reinforcing fibres, and the conformability of the fibres during processing. In these studies, the host ply angular deformation was recorded as 7.5° from a nominal horizontal through the centreline of the vasculature (as indicated in figure 3b) with a slight variation arising from the LMT wire and the 0° ply undergoing some deformation during exposure to 180°C and 700 kPa pressure.

As detailed above (§2), the aim of this investigation is to introduce a healing agent transport network without incurring a mass penalty, i.e. the host matrix material has been used to form the vasculc. This has clearly been successful; however, as figure 3b,c indicates, a resin-rich pocket has formed around each vasculc despite the epoxy matrix being a low-flow resin system (as specified by the manufacturer) and the manufacturing process being a closed loop system, i.e. no additional resin has been introduced into the laminate. To accommodate the formation of the localized resin-rich pocket, resin must be redistributed from the surrounding local area. This is evident in figure 3b,c where a localized increase in fibre volume fraction occurs above the vasculc (identified as region 'A' in figure 3b,c) and the formation of internal porosity (identified as region 'B' in figure 3b,c and corresponding magnified views) at the run-out of the resin-rich pocket. It is believed that these regions of porosity occur due to an uneven distribution of consolidation pressure from the adjacent caul plate during manufacture. In this study, specimens were produced with a 2 mm thick aluminium caul plate to ensure the inner and outer surfaces of the laminate remained parallel (a key feature for compression testing). However, the presence of a prominent wire vasculc preform within the stack influences the local fibre bed pressure. Effectively, this raises local pressure immediately above and below the wire preform and reduces local pressure towards the resin pocket run-out where there is a significant fibre misalignment. Furthermore, in this region the misaligned (curved) plies are able to support the autoclave pressure as in-plane fibre stresses, thereby reducing the load experienced in the through-thickness direction. In this scenario, the external global consolidation pressure is 700 kPa; however, it is possible that the localized pressure at the resin-rich tip is much lower, leading to inadequate consolidation in the local vicinity. The results in table 1, detailing the magnitude of the ply variation observed in figure 3c, support this hypothesis but to the authors' knowledge the analysis of pressure distributions inside a complex lay-up has never been attempted to validate such an experimental observation.

The data in table 1 have been determined by measuring the ply thickness using IMAGE-J software at set distances (indicated in figure 3b) from the vasculature edge.

Figure 3. Composite laminate with stacking sequence $[-45/90/45/0/-45/90/45/0//0/45/90/-45/0/45/90/-45]$ with LMT wire network aligned (a) parallel to the adjacent 0° plies, (b) 45° to the adjacent 0° plies and (c) 90° to the adjacent 0° plies. The individual ply stacking sequence is indicated in each image. The local regions containing intra-ply porosity ahead of the crack tip are shown for both the 45° and 90° vasculatures.

Table 1. Change in thickness of the resin-rich pocket and the variation of the local fibre volume fraction (Vf) within each ply for the 90° vasculature. Positional locations (top row) correspond to numbered positions indicated in figure 3c.

		positional location								
resin-rich pocket	(mm)	0	1	2	3	4	5	6	7	8
ply angle										
0	Vf (%)	71	73	68	68	68	64	61	67	65
45	Vf (%)	54	54	52	52	54	52	52	47	49
90	Vf (%)	57	54	51	46	43	45	44	48	49
-45	Vf (%)	57	57	63	60	58	56	56	53	52
0	Vf (%)	57	56	57	56	56	57	58	60	58
45	Vf (%)	57	56	54	57	57	55	52	51	55
90	Vf (%)	57	56	50	51	53	50	50	48	51
-45	Vf (%)	60	56	54	52	51	51	55	57	56

Table 2. Variation of the local fibre volume fraction (Vf) within each ply around the location of the 0° vasculc. Positional locations (top row) correspond to numbered positions indicated in figure 3a.

		positional location				
		0	1	2	3	4
0	Vf (%)	47	47	51	51	55
45	Vf (%)	72	65	59	59	59
90	Vf (%)	65	59	62	65	69
−45	Vf (%)	62	57	59	62	57
0	Vf (%)	62	62	57	59	57
45	Vf (%)	59	57	59	62	62
90	Vf (%)	72	69	69	72	71
−45	Vf (%)	65	62	59	59	55

The results in table 1, for the 90° vasculature, illustrate the change in thickness of the resin-rich pocket and the variation of the local fibre volume fraction within each ply, at a set distance from the centreline of the vasculature. The increments are defined as a function of vasculature diameter, e.g. eight vasculature diameters equate to a distance of 2 mm which is beyond the end of the apex of the resin-rich pocket. Although considerable care was taken to accurately measure the exact ply thickness, it is anticipated that a measuring error of approximately 10 µm may occur, resulting in a volume fraction error of 5 per cent. The authors would, therefore, recommend that the absolute values in tables 1 and 2 are indicative of the overall trends (in local fibre volume fraction) around the location of the vasculatures.

The rapid decrease in thickness of the resin-rich pocket is evident with increasing distance away from the vasculature. By comparison, the local fibre volume fraction within each ply varies according to its location within the stacking sequence and its proximity to a vasculc. The first ply (0°) exhibits the largest increase in fibre volume fraction (above the baseline value of 57%, as specified by the manufacturer) to accommodate the vasculc locally and to provide the resin required to form the resin-rich pocket over the 8× vasculc diameter length. This value is approaching the theoretical limit for idealized simple cubic fibre packing, i.e. fibre volume fraction of 78 per cent, suggesting that the overall toughness of these regions may be degraded because there is insufficient resin to transfer the load. The second ply (45°) exhibits a lesser increase in local fibre volume fraction around the vasculc. Conversely, the second and third plies exhibit a reduced local fibre volume fraction along the length of the resin-rich pocket before returning to more typical levels beyond the resin-rich apex.

When the vasculature is aligned with the host ply (figure 3a), the resin-rich pocket observed previously is not formed which effectively eliminates the formation of any internal porosity within the laminate. However, the fibres in the host ply still need to accommodate the LMT wire, which once again results in a local fibre volume fraction variation around the vasculc, point A in figure 3a. The corresponding variation

in ply thickness when the vasculc is aligned to the host ply is given in table 2.

The inclusion of the vasculc has a pronounced effect on the host 0° ply up to four (in-plane) vasculc diameters away from the point of insertion. However, the influence of the vasculc in the out-of-plane direction is more pronounced locally than observed for the 90° vasculc. In this configuration, every ply above the point of insertion, apart from the two host plies, is compressed to accommodate the vasculc. Outside this local region the ply thicknesses rapidly return to their nominal size, i.e. over four vasculc diameters.

4. DAMAGE INTERACTION WITH VASCULAR NETWORK

In an effort to determine the magnitude and extent of damage interaction with the vascular network, an Instron Dynatup drop weight tower was used to assess the two different laminate configurations, (i) single vasculature aligned with the host ply about the centreline and (ii) single vasculature aligned normal to the host ply about the centreline. The specimens were subjected to a series of 10 J low-velocity impacts before being assessed using non-destructive evaluation (NDE) ultrasonic C-scan or high-resolution (0.17 µm resolution) micro-CT X-ray inspection (SkyScan1172) before being tested under compressive loading.

NDE C-scans for the baseline material without any internal network, and vasculc spacing of 10 mm positioned parallel (0°) and normal (90°) to the host ply, which were all subject to a 10 J impact, are illustrated in figure 4. The black vertical and horizontal lines visible in the images are the ultrasonic reflection from the vasculature. As figure 4 clearly indicates, the internal channels have a pronounced effect on the damage formation, as it extends preferentially in the direction of the channels. The C-scan images in figure 4 were also used to determine whether the damage area differed for each configuration. The damage area calculated using IMAGE-J software indicated that 90° vasculcs appeared to trigger a 10 per cent increase in damage area compared with the 0° vasculcs. One possible reason for this difference could be attributed to the formation of laminate porosity in the vicinity of the resin-rich pocket (point B in figure 3c).

A micro-CT X-ray scanner was used to investigate the exact interaction between the impact damage and the two different vasculatures. Figure 5 illustrates the magnitude of the 10 J damage and the interaction with the 0° vasculature, while figure 6 illustrates the corresponding interaction with the 90° vasculature.

Figure 5 details six images of cross sections through a 10 J impact-damaged specimen and how it interacts with the vasculature. The impact site was on the upper surface in the middle of the image. Internal delaminations and linking transverse cracks are apparent within each of the images and fibre breakout on the back face is evident. Upon closer examination of the images it is also apparent that the internal damage impinges on the vasculature. However, at the laminate extremities this is not the case, suggesting

Figure 4. NDE of $[-45/90/45/0/-45/90/45/0//0/45/90/-45/0/45/90/-45]$: C-scan image showing the ultrasonic amplitude attenuation of a 10 J impact to (a) the baseline laminate (no network); (b) network spacing of 10 mm aligned normal (90°) to the host ply and (c) network parallel (0°) to the host ply at a nominal spacing of 10 mm. The presence of the vasculature is visible in each sample as vertical or horizontal shadow lines. Scale bar, 20 mm.

Figure 5. Micro-CT scan of $[-45/90/45/0/-45/90/45/0//0/45/90/-45/0/45/90/-45]$ with a vasculature spacing of 10 mm aligned parallel (0°) to host ply. Six slices through the thickness of the vasculature are illustrated. The presence of the vasculature is visible as the dark thick horizontal line, as indicated. The smaller and thinner dark lines are the associated damage (delaminations and matrix cracking) arising from the 10 J impact event.

additional vasculature would be required in these regions to ensure complete damage coverage.

The corresponding micro-CT scan for the normal vasculature is shown in figure 6. In this figure only two cross-sectional images of the damage event are included; the upper image is from the exact centre of the damage event, indicating direct interaction of the damage with the vasculature, while the lower image is taken at the outer edge of the impact site, which shows the absence of any interaction.

The ultrasonic C-scan inspection and the investigation using the high-resolution micro-CT X-ray scanner have shown that the formation of internal

impact damage interacts with embedded vasculcs and alters the global damage footprint. It has also shown that a single vasculc embedded at the centreline position is insufficient to interact with all internal delaminations and matrix cracking arising from a low-velocity drop weight impact event.

5. COMPRESSION STRENGTH AFTER IMPACT DAMAGE

To investigate the effect of relative alignment of the vasculcs and surrounding host plies and the consequences for the mechanical performance of the host laminate, a series of compression strength measurements were made following the low-velocity impact testing. A specimen of dimensions 89×55 mm was machined from the impacted panel ensuring that the impact event was located centrally. The compression testing was conducted on an Instron 1342 test machine using a 250 kN load cell. The sample was placed inside an anti-buckling fixture designed specifically for compression testing of composite laminates (in accordance with ASTM Standard 2007). The compressive loading was applied under displacement control at a rate of 0.4 mm min^{-1} until failure occurred. The results are reported according to laminate lay-up and vasculc alignment within the host plies.

The results from the compression tests, for the baseline material without any vasculcs and the 10 mm spaced vascular network aligned parallel and normal to the host plies (figure 2; $[-45/90/45/0/-45/90/45/0//0/45/90/-45/0/45/90/-45]$) are given in table 3. Each specimen configuration was tested as manufactured and after a 10 J impact at the centre point. A minimum of five specimens were tested for each configuration.

In the three non-impacted configurations, all the specimens failed by laminate end brooming towards the load introduction points. The inclusion of the 90° vasculc was observed to initiate failure at lower loads (approx. 10% below baseline). It is proposed that the fibre waviness and associated porosity occurring

Figure 6. CT micro-scan of $[-45/90/45/0/-45/90/45/0//0/45/90/-45/0/45/90/-45]$ with a vasculature spacing of 10 mm aligned normal (90°) to host ply. The presence of the vasculature is visible as the dark circle in the centre of the field of view. The smaller and thinner dark lines are the associated damage (delaminations and matrix cracking) arising from the 10 J impact event.

Table 3. CAI results for the $[-45/90/45/0/-45/90/45/0//0/45/90/-45/0/45/90/-45]$ laminate with a single vascular network parallel or normal to the host plies. Number of specimens indicated in brackets.

specimen designation	CAI _{average} (MPa)	s.d.	failure mode	normalized
laminate, no network, no impact (5)	437	23	end crushing	1.00
0° vasculature, no impact (5)	426	21	end crushing	0.98
90° vasculature, no impact (6)	386	24	end crushing	0.88
laminate, no network, 10 J impact (5)	307	6	central crushing	0.70
0° vasculature, 10 J impact (5)	318	11	central crushing	0.73
90° vasculature, 10 J impact (6)	270	36	central crushing	0.62

around the vasculature has degraded the laminate’s stability locally at the point of load introduction leading to a reduction in strength. Conversely, the aligned 0° vasculature was not observed to influence the (undamaged) failure mode because their inclusion within the host ply has not introduced any out-of-plane fibre misalignment in the critical load introduction region.

The influence of the impact damage on the compressive strength in all three laminate configurations is evident in table 3. In the impact-damaged specimens, the failure mode was governed by local buckling about the impact site before unstable growth of the internal delaminations leading to global failure of the specimen. Figure 7 illustrates the compressive failure modes for both the 0° and 90° after a 10 J impact, as observed by ultrasonic C-scan imaging and microscopy of the specimen edge. In these tests, the variation between the baseline laminate and the 0° vasculature is minimal, suggesting that the inclusion of these vasculatures has minimal effect. Conversely, in the case of the 90° vasculatures, the mean compressive strength was observed to be lower than both the baseline and the 0° vasculature laminate, as previously observed in the undamaged case. In these tests, it is postulated that the horizontal orientation of the vasculatures (and their associated local

porosity) combine under compressive loading to trigger the propagation of vertical delaminations along the centreline of the specimen, thus splitting the laminate into two sub-laminates before they buckle and fail catastrophically.

6. DISCUSSION

This is the first known study to show that a simple bioinspired vascular network can be integrated within an advanced fibre-reinforced polymer composite material, with negligible mass increase, i.e. no additional material is introduced to form the vasculature, and minimal detrimental effect on the local or global mechanical performance of the material. A single path vascular network was successfully integrated parallel and transverse to the local host plies along the centreline of a $[-45/90/45/0/-45/90/45/0//0/45/90/-45/0/45/90/-45]$ laminate. This work has considered the role these vasculatures have on the surrounding local structural reinforcement (figure 3), i.e. the formation of localized zones of increased fibre volume fraction when aligned with the host plies; the formation of resin-rich pockets; the creation of higher local fibre volume fraction; and internal porosity when oriented transverse to the host plies. The role of these ‘features’ in impact damage formation in the laminate was assessed using ultrasonic NDE and a CT micro-scanner. The former method indicated a propensity for the damage to follow the orientation of the embedded vasculature. However, the magnitude of the damage formation (figure 4) appeared to be suppressed when the vasculature was aligned transverse to the host plies, i.e. the resin-rich pocket offered some increase in damage tolerance potential when subjected to an impact event. However, the out-of-plane deformation of the host plies also influences the compressive buckling strength of the laminate, i.e. fibre deviation out-of-plane from the loading axis will tend to initiate the early onset of compressive buckling. Therefore, it appears from these results that the damage tolerance benefit of a resin-rich pocket is negated by the premature onset of buckling arising from the fibre misalignment with the plane of loading.

While the results from the ultrasonic inspection illustrate the magnitude of the in-plane damage, the results from the CT micro-scanner indicate the nature of the

Figure 7. Compressive failure of a single vasculature network after 10 J impact: (a) C-scan image of failed 90° vasculature illustrating localized central buckling; (b) corresponding end view of the 90° vasculature specimen illustrating internal delaminations and cracks emanating from around the vasculature (scale bar, 2 mm); (c) C-scan image of failed 0° vasculature illustrating localized central buckling; (d) end view of the 0° vasculature specimen illustrating internal delaminations and cracking (scale bar, 2 mm). Note: compressive loading is in vertical plane.

interaction between the internal damage and the vasculature (figures 5 and 6). At these impact energy levels, the damage is observed to be concentrated below the vasculature (relative to point of impact) in both orientations with very limited damage evident above. This damage morphology is similar to the crack propagation observed by Hepworth *et al.* (2002) in the hardwood specimens at high-impact loads, i.e. cracking throughout the impact site. However, whether the collapse of the vascular cell walls would occur at lower energy levels, similar to the observation made by Hepworth *et al.* (2002) on beech and hickory, seems very unlikely due to the distinctively different morphologies and materials employed in this study.

Plain laminate specimens and those with vasculatures oriented parallel to the host plies exhibit the same failure mode and load under compressive loading. The observation that the failure mechanism is not changed by the presence of longitudinal galleries implies that they are not initiating a premature failure event. A similar observation was reported by Kousourakis *et al.* (2008) for the inclusion of sensor galleries manufactured

from hollow glass fibres with diameters ranging from 0.2 to 0.7 mm.

In the case of the vasculatures oriented transverse to the host plies, it is apparent that the control of fibre orientation and resin pockets around the vasculature is a critical consideration for such a concept. For example, in *Plantae* the 'reinforcing fibres' are aligned and oriented around open channels to ensure maximum load-carrying capability. Hepworth *et al.* (2002) identified the importance of the fibrous cells surrounding the internal vessels in hickory, beech and oak. When subjected to compression-after-impact loading the fibrous cells become greatly distorted before kink banding is initiated, leading to final failure through localized buckling. While the synthetic fibre morphology and engineered single path vasculures in these specimens is distinct from that observed in hardwoods, with their multiple vasculatures of varying geometries, it is interesting to note that final failure is still governed by the buckling strength of the reinforcing fibres and the breakdown in their local stability. Perhaps adopting, in an engineering sense, nature's hierarchical interfacial

concepts in the fibre-reinforced region surrounding each vasculc would ensure greater buckling strength in this critical region before failure.

The current composites manufacturing capability is able to tailor fibres in either a horizontal or vertical plane but not both simultaneously, as observed in natural composite structures. Ideally, such a capability would lead to the absence of the resin-rich pocket surrounding each vasculc. Providing that a three-dimensional architecture could be developed to ensure the attraction of a propagating crack front rather than deflecting it away, then biomimicry of vascular designs found in plant structures could be used to satisfy the minimum mass requirements of a healing agent vascular transportation network within a composite structure.

7. CONCLUDING REMARKS

This study has sought to explore the potential for and consequences of introducing bioinspired vasculatures for the transportation of a healing agent around a high-performance fibre-reinforced composite material. Assessing the influence of the vasculature on the host material during manufacture and under load is critical before this concept can be considered viable in an engineering context. The ability of the vasculcs to be accommodated within the composite laminate, via the application of a 'lost-wax' technique, has proved to be successful.

The influence of the vasculature on damage formation has also been investigated. The results indicate a direct interaction between the vasculc and the extent and propagation of damage. In the case of a vasculc oriented at 90° to the local fibres, the damage area is increased by 10 per cent compared with an aligned vasculc.

The results for the compressive strength pre- and post-impact damage indicate the composite laminate can accommodate a 0° vasculc (at 10 mm spacing) without any significant degradation in performance, compared with a plain baseline laminate. However, in the case of the 90° vasculc, a clear reduction in pre- and post-impact compressive strength (10 and 8% reduction; cf. plain baseline laminate, respectively) was observed. The introduction of periodic fibre waviness and regions of porosity, alongside the increase in the damage area across the width of the specimen due to the vasculature, are all contributory factors towards the compressive strength reduction.

The approach of using a removable network precursor to form an *in situ* integral vascular network within the matrix of a fibre-reinforced polymer composite has been shown to be effective. While considerable research remains in this nascent field, biomimicry of such integrated natural features whether for self-healing, thermal management or structural health-monitoring functionality appears to be a viable option for advanced fibre-reinforced polymer composites.

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