

## **FIBRE REINFORCED POLYMERS WITH EMBEDDED MICROVASCULAR NETWORKS - BIOINSPIRED IN BOTH DESIGN AND FUNCTION**

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### **ABSTRACT**

The continuing quest for lighter, agile, fuel efficient aircraft has led to the increased utilisation of fibre reinforced polymer (FRP) composite materials. The driving force for this trend is the superior specific strength and stiffness offered by FRP's, along with significantly reduced density, in comparison to their metallic counterparts. However, the planar nature of the fibre reinforcement and inherent brittleness of the thermoset matrices result in poor out-of-plane properties and subsequently poor resistance to impact events. Unlike metallic materials, FRP's do not have the ductility required to absorb high levels of impact energy and dissipate this energy through elastic deformation and damage formation mechanisms. The resultant damage, which can readily occur in-service or even during manufacture, causes significant reductions in mechanical performance whilst leaving little visual evidence of the impact event; a situation termed *barely visible impact damage* (BVID). To address this shortfall, the current philosophy is to adopt conservative designs, leading to overweight structures that do not utilise the full potential of FRP systems. High maintenance costs also ensue from a continued need for non-destructive testing (NDT) and subsequent expensive and complicated repairs to damaged composite structures. However, if the damage were autonomously healed by entities embedded within the composite component, then conservative designs could be avoided (a structural scenario commonly found in the natural world), leading to lighter more fuel efficient transport.

Nature has evolved sophisticated hierarchical structures using modest component materials that exhibit outstanding performance and multifunctionality. One of these incredible functions is the ability to autonomously self-heal in response to damage. This function may be conferred upon a synthetic composite structure via the embedment of a vasculature that is capable of delivering functional agents from an external reservoir to regions of internal damage. Minimising disruption to the host laminate, in terms of fibre architecture, is considered key to the successful implementation of such a technology.

Embedded bioinspired vasculatures were successfully incorporated into an FRP laminate via a two step process using solder wire preforms (Sn60:40Pb alloy). Firstly, the solder wire was either laid between plies (fabrication route A) or nested in pre-cut recesses within the plies (fabrication route B) during the stacking sequence. The solder was then removed post-cure under the application of heat and vacuum in a 'lost-wax' type process. Microscopic characterisation showed that the fabrication route adopted was critical in determining the level of disruption to the host microstructure, which in-turn dictated the interactions with low velocity impact events and propagating Mode I & II cracks. Based on the experimental results and observations, it is clear that fabrication route B offers the greatest potential for vasculature-damage interactions, a pre-requisite for efficient self-healing. Compression After Impact (CAI) mechanical testing results showed that vasculature orientation, diameter and location in the ply stack all need to be carefully considered to ensure the integrity of the fibre architecture and, therefore, that the laminate mechanical properties are maintained. Four vasculature configurations were selected for self-healing evaluation, all of which satisfied the requirements of vasculature-damage connectivity and minimum 'cost' of mechanical performance whilst offering the following comparisons: the effect of diameter, 0.25 versus 0.5mm; the effect of location in the ply stack, central versus asymmetric location and; the effect of fabrication route, method A versus method B.

A compression after impact (CAI) test protocol was followed, with specimens of each vasculature configuration tested in the undamaged, damaged (post 10J impact), and healed states. Syringes fitted with suitable gauge hypodermic needles were used to manually inject a self-healing resin into the vasculature located within the damaged region only. The selected resin consisted of 100pph Diglycidyl Ether of Bisphenol-A (DGEBA) (Epon 828, Polysciences, Inc.), 25pph Ethyl Phenylacetate (EPA) (Aldrich Chemistry) and 12pph Diethylenetriamine (DETA) (Sigma-Aldrich). The EPA was required to reduce the fluid to a workable viscosity. The specimens were left at room temperature for a minimum of 7 days to cure, based on the manufacturer's recommendations. The results (Fig. 1) show excellent recovery of post impact compression strength  $\geq 97\%$  (undamaged versus healed values) in all cases, proving that vasculatures can provide a means for efficient fluid delivery to impact damage in structural composite materials. The recovery of compression strength in every specimen tested is proof of vasculature-damage connectivity, allowing the epoxy healing agent to infuse the delaminations and microcracking formed during the impact event.

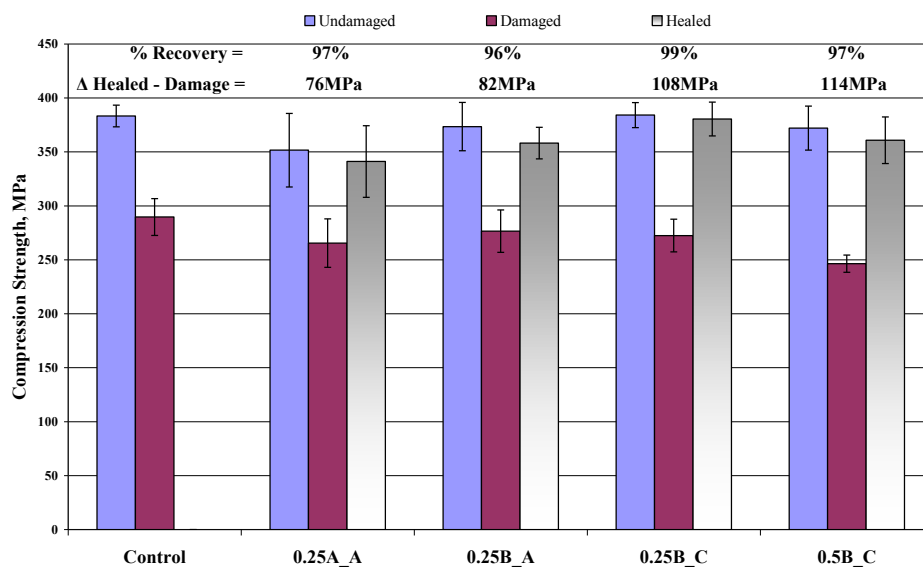


Figure 1: Compression strength recovery. Note: 0.25/0.5 represents vasculature diameter, first letter represents fabrication route A or B and third letter represents stack location, Asymmetric or Central.

Resin bleed out through backface tensile cracks, along with C-scan imaging of specimens (post-impact and post-heal) provide further evidence of good vasculature damage-connectivity (Fig. 2).

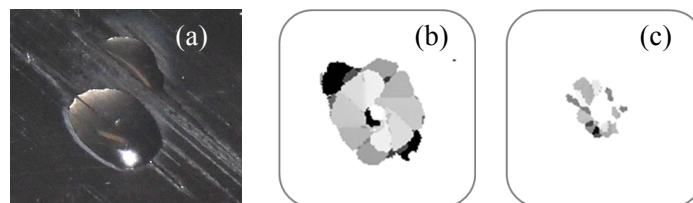


Figure 2: (a) backface resin bleed out, (b) C-scan of impact damage and (c) same impact zone post resin infusion.

The findings to date, along with the microvascular principles of minimum work flow, are currently being utilised for the design and fabrication of more elaborate branched networks.