DESIGNING AND PROTOTYPING A MICROSTRUCTURE FOR CFRP INSPIRED BY THE STROMBUS GIGAS SHELL

Riikka Häsä[1] and Silvestre T. Pinho[2]

[1] Department of Aeronautics, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom, r.hasa15@imperial.ac.uk, http://tinyurl/pinholab
[2] Department of Aeronautics, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom, silvestre.pinho@imperial.ac.uk, http://tinyurl/pinholab

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ABSTRACT

Damage tolerance of composite materials can be improved significantly by nature-inspired microstructural design. Among the mollusc family, the Strombus gigas has the toughest shell although it consists almost entirely of brittle aragonite. The toughness of the shell arises from its microstructure. Despite its outstanding damage tolerance, few attempts have been made to exploit such microstructure in synthetic composites, and none using carbon fibre reinforced polymers (CFRP).

In this work, we design a Strombus gigas inspired microstructure for CFRP using a parametric FE model, develop a process to synthesise this microstructure in CFRP, and will test it in a SEM environment. The optical observations demonstrate that the designed microstructure was successfully obtained experimentally and with good accuracy, and that the microstructure holds the potential to successfully create diffuse damage.

1 INTRODUCTION

Despite its high strength-to-weight and stiffness-to-weight ratios, Carbon Fibre Reinforced Polymer (CFRP) is inherently brittle and exhibits relatively low damage tolerance, which has been identified as one of the major challenges for its use. Recent research has, however, revealed that its damage diffusion capability can significantly be improved by careful microstructural design [1].

Natural composites, such as bone, molluscs and wood, provide an excellent source of inspiration for new generations of CFRP microstructures due to their multiple toughening mechanisms. Extensive research on natural composites has shown that their damage tolerance can, to a great extent, be attributed to their hierarchical microstructure that leads to damage dissipation at multiple length scales, and through various strategies including crack deflection and damage diffusion [2].

Among the mollusc family, the Strombus gigas (Figure 1a) has the toughest shell despite consisting 99.9 w% of brittle aragonite, reaching toughness values that are up to three orders of magnitude higher than the toughness of pure aragonite [3]. The outstanding toughness of the shell arises from its hierarchical microstructure shown in Figure 1b, schematically illustrated in Figure 1c, known as a cross-lamellar structure. It comprises three macroscopic layers with 0°/90°/0° orientation (marked I, M and O) and, within each macroscopic layer, the lamellae have a ±45° architecture with respect to the thickness of the shell.

Under bending, the shell dissipates energy through multiple parallel cracking of the first order interfaces on the tension side (i.e., the inner layer I), crack deflection when the crack reaches the middle layer, and frictional sliding and pull-out of the lamellae in the middle layer [3, 4]. Despite its outstanding damage tolerance, few attempts have been made to exploit such microstructure in synthetic composites [5, 6, 7], and none using CFRP.

In this work, a CFRP composite with a Strombus gigas inspired microstructure is designed using FEA, prototyped, and tested in an SEM environment. The aim is to investigate the manufacturability and potential of this microstructure in CFRP for creating diffuse damage.

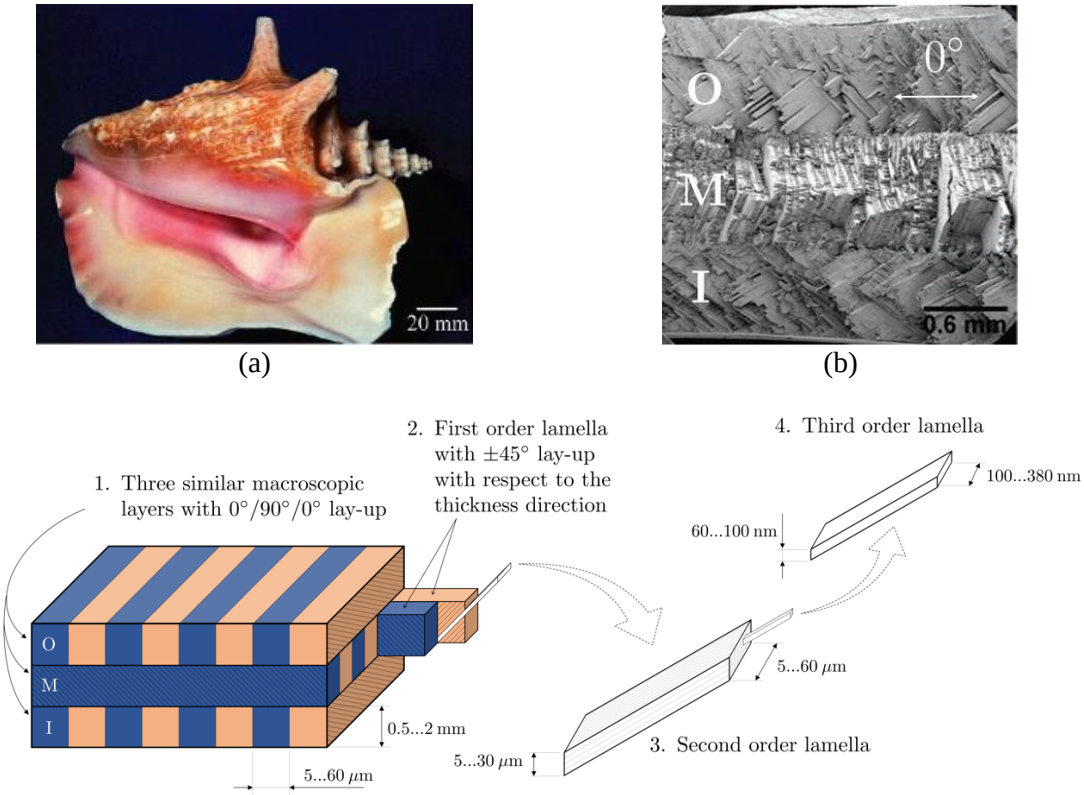


Figure 1: (a) Strombus gigas shell, from Su *et al*. [8], (b) its microstructure visible on the fracture surface of the shell (adapted from Su *et al*. [8]) and (c) a schematic drawing of the microstructure (not to scale).

2 MICROSTRUCTURAL DESIGN

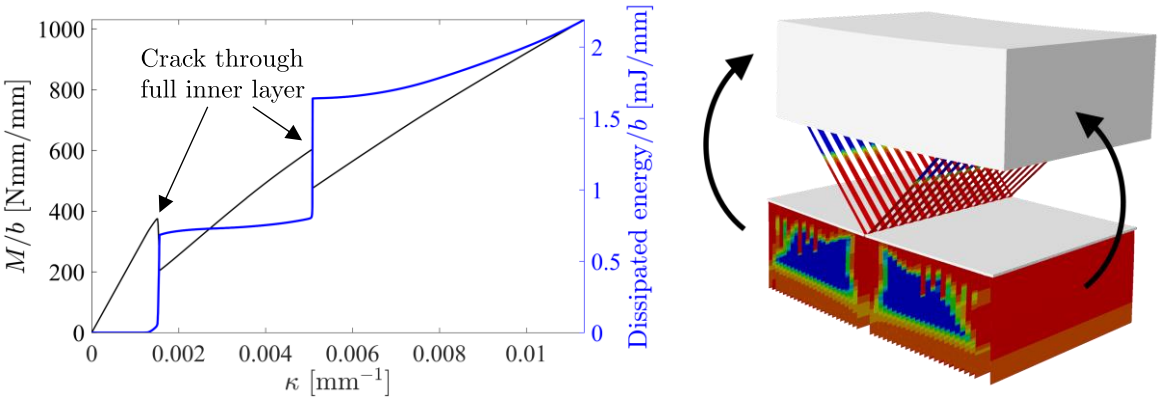
A key attribute for a CFRP mimicking the Strombus gigas shell is its ability to create diffuse damage in the inner layer, and eventually failure of the middle layer occurring under increasing load. We use a parametric FE modelling approach to investigate these attributes and to analyse the suitability of a Strombus gigas type microstructure in CFRP.

Each macroscopic layer $i \in \{\mathrm{I}, \mathrm{M}, \mathrm{O}\}$ of the CFRP microstructure has a parametric height h_i, comprises prepreg (1st order lamellae) with a thickness t_i and at an angle $\pm\theta$ with respect to the thickness of the shell. Several options are considered for the macroscopic interfaces, including:

- epoxy matrix; and
- a thermoplastic polyethersulfone (PES) film with a parametric thickness t_{PES} (which increases the resistance to delamination and facilitates the accumulation of damage near that interface).

The mechanical response of the microstructure is studied using a parametric unit cell model loaded in pure bending. The model allows for multiple cracking of the first order interfaces in the inner layer and it is capable of simulating the delamination between the macroscopic layers, the debonding between the first order lamellae in the middle layer, and the splits along the 2nd order lamellae (i.e., along the fibres) in the middle layer. The unit cell exploits periodicity and symmetry so that its response can be generalised for the entire microstructure.

We now present typical results, for the case of Hexcel 8552 IM7 prepreg, macroscopic layers of height 2 mm, and a 50 μm thick PES interfaces between the macroscopic layers. Figure 2a shows the moment and the damage energy dissipation per unit depth as functions of applied curvature, κ.



(a) (b)

Figure 2: (a) Moment and damage energy dissipation per unit depth as functions of the applied curvature. (b) Damage in the FE model at the end of the simulation (the top macroscopic layer is shown in bulk, the middle layer shows damage along selected adjacent plies with ±45° orientation and the bottom layer shows the damage between the first order lamellae; the image shows the FE model tessellated in the depth direction for visualisation purposes).

The FE analysis shows that the damage initiates in a diffuse way simultaneously at all first order interfaces at the bottom of the inner layer. This can be attributed to the ±45° architecture that leads to damage initiation in mixed-mode as the adjacent plies try to rotate relative to each other. The effect of this diffuse damage can be seen as softening in the moment vs. curvature curve, and increase in energy dissipated at curvatures between 0.0012 mm^{-1} and 0.0015 mm^{-1}. Following the damage initiation, some discrete cracks form in the inner layer by initiating from the tension surface (seen as load drops in Figure 2a) and, upon further loading, they start forming at all inner layer interfaces, eventually some of them growing from the inner/middle macroscopic interface towards the bottom surface. Figure 2b shows the diffuse damage in the inner layer when damage propagation transitions to the middle layer.

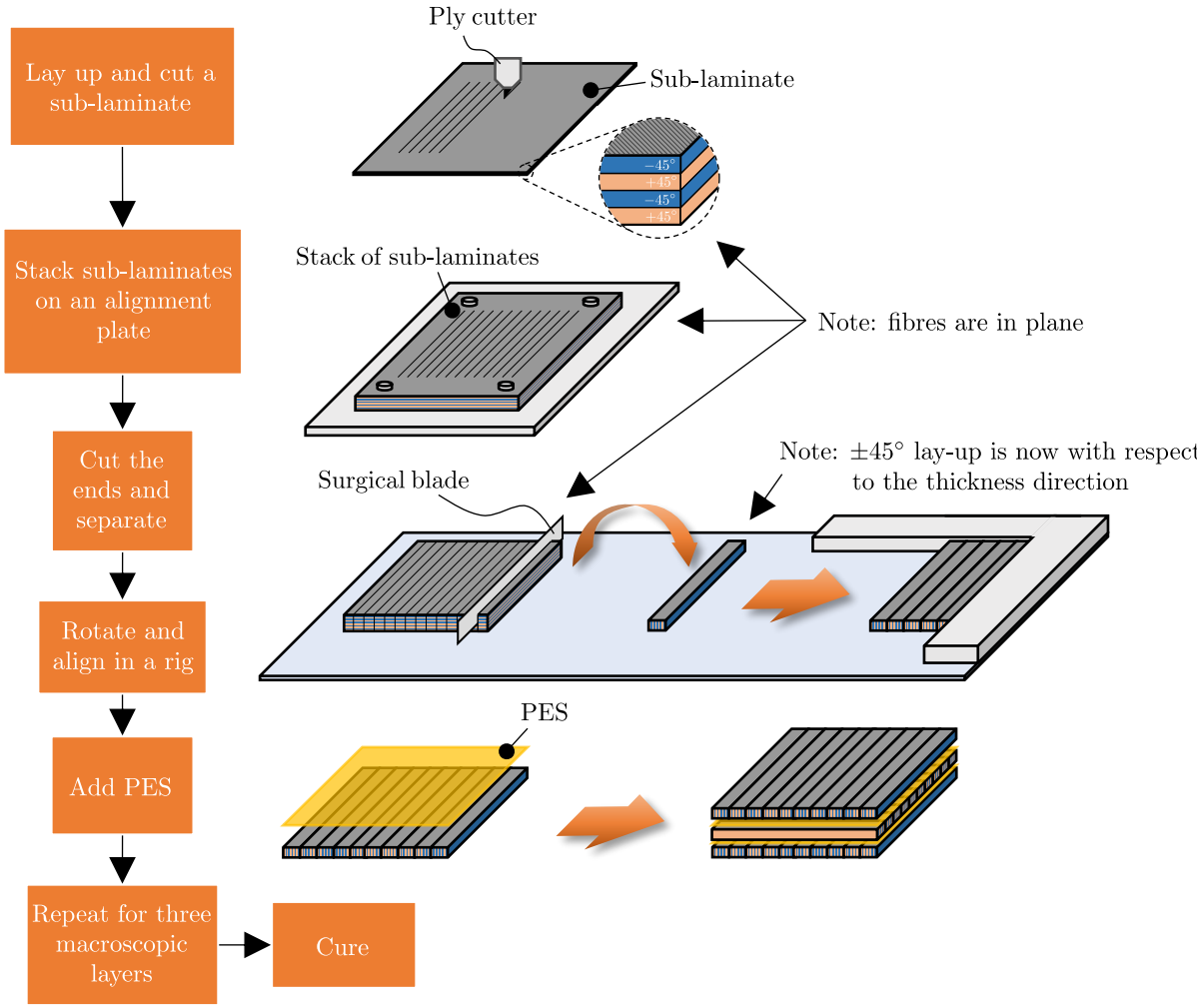
3 PROTOTYPING OF THE MICROSTRUCTURE

Based on the predictions of the FE analysis, the manufacturing feasibility, and the aim to achieve a high level of energy dissipation, the Strombus gigas inspired microstructure was prototyped using 8552 IM7 carbon/epoxy prepreg and the configuration described in the previous section.

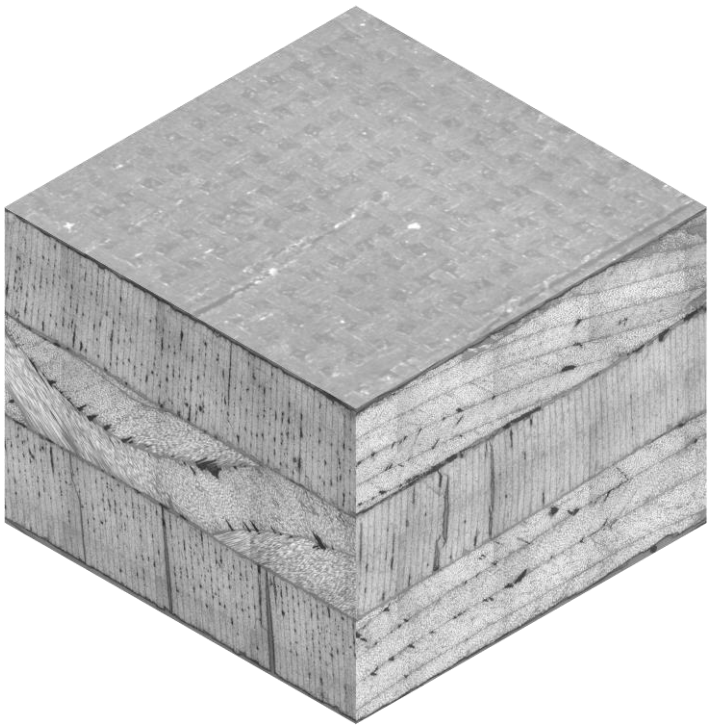
The manufacturing procedure is schematically illustrated in Figure 3a. Firstly, sub-laminates with ±45° architecture were sequentially laid up and cut into 2 mm wide partial strips using a ply cutter. In the same operation, alignment holes were also cut. The sub-laminates were then stacked using an alignment plate with pins matching the alignment holes to ensure accurate positioning of the partial cuts. Once a stack height of 5 mm was reached, the strips were separated along the cut lines with a surgical blade, rotated on their side and positioned using alignment tools. The operations were repeated for the three macroscopic layers, and the 50 μm PES film was added between the layers.

A lateral support was cast around the prototyped laminate to accommodate for unevenness of the edges of the laminate and to give it structural stability during the curing. The laminate was cured in an autoclave with the heating and cooling rates set to a low value (1 °C/min) to avoid thermal stresses, and to reduce the void content in the final laminate.

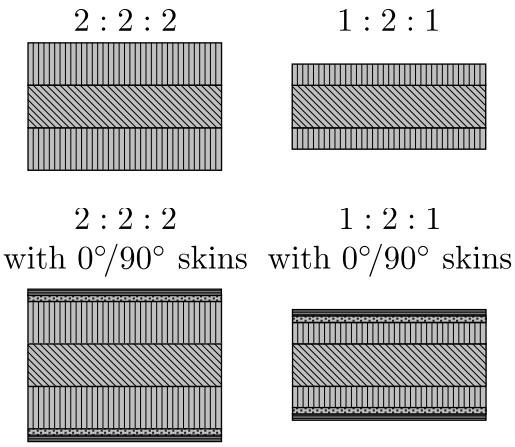
Figure 3b shows the microstructure of a cured laminate from an early iteration of the synthetising procedure. Different microstructure configurations, such as those shown in Figure 3c, were manufactured.


Lay up and cut a sub-laminate
Stack sub-laminates on an alignment plate
Cut the ends and separate
Rotate and align in a rig
Add PES
Repeat for three macroscopic layers
Cure
Ply cutter
Sub-laminate
−45°
+45°
−45°
+45°
Stack of sub-laminates
Note: fibres are in plane
Surgical blade
Note: ±45° lay-up is now with respect to the thickness direction
PES

(a)



(b)



(c)

Figure 3: (a) Procedure for synthetising the microstructure, (b) the actual microstructure after curing (from an early iteration) and (c) a schematic drawing of some possible microstructures.

4 MECHANICAL TESTING

Specimens with 65 mm in length and 10 mm in width are cut from the cured laminate. The specimens are tested in a three-point bending (3PB) configuration with a distance between the pins $\frac{L}{2} = 18$ mm. The 3PB tests are carried out in an SEM environment using a Deben Microstest Module with a 5 kN load cell. The specimens are loaded at a displacement rate 0.1 mm/min, and the loads and the displacements are recorded with an acquisition time of 200 ms. The displacements are read from the built-in extensometer and corrected to account for the stiffness of the testing rig. To capture the SEM images, the tests are interrupted at 50 N intervals and every time a sudden load drop is observed. The results of the tests will be shown during the conference.

5 CONCLUSIONS

This paper investigated the concept of synthetising a Strombus gigas type microstructure in CFRP. A Srombus gigas inspired CFRP laminate was designed, prototyped and will be tested with the aim of increasing the damage tolerance of the laminate. It can be concluded that:

- a parametric FE model predicts initiation of damage in a diffuse way in the inner layer. This diffuse damage initiates simultaneously at all 1st order interfaces in mixed-mode due to the ±45° lay-up in the inner layer;
- upon further loading, discrete cracks form in the inner layer, starting from the tension side, and correspond to successive load drops at progressively higher values of applied moment;
- subsequently, cracks start forming at all interfaces in the inner layer and grow from the inner/middle interface towards the bottom surface;
- finally, damage transitions to the middle layer;
- a manufacturing technique for synthetising a Strobus gigas inspired microstructure was successfully developed and the latter will be tested soon.

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