OVERBRAIDING OF PULTRUDED RODS FOR HIERARCHICAL COMPOSITES

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ABSTRACT

Hierarchical advanced composites using pultruded rods as a component are under development. Unlike traditional ply based composites, using rods as a building block makes the composite intrinsically three dimensional, opening up a new design space. Rods, consisting of highly aligned carbon fibres in an epoxy matrix, are used to form larger structures with a second matrix. Inspired by nature, the hierarchical composites will incorporate structure at a range of different length scales intended to improve the performance of the composite under compression.

Overbraiding is considered a promising option at both the rod and structural member scales following results of earlier work which showed an improvement in compressive performance when a structural member is overwound, due to the radial compression from the overwind. This paper discusses manufacturing challenges in overbraiding small diameter (<1 mm) pultruded rods, including the achievable lay length and braid angle, using a circular maypole microbraider. A novel ‘fuzzy carbon’ overbraid concept is presented, with potential to improve shear support in the matrix region surrounding the rod.

1 INTRODUCTION

The Next Generation Fibre-Reinforced Composites (NextCOMP) programme [1] seeks to improve the compressive performance of composites using a bio-inspired, hierarchical, hybridized architecture. As shown for the example in Figure 1, such natural composites have a hierarchical structure, from the molecular level through fibrils and fibres to larger formations. Such composites contain features which control their behaviour under compression at a range of length scales.

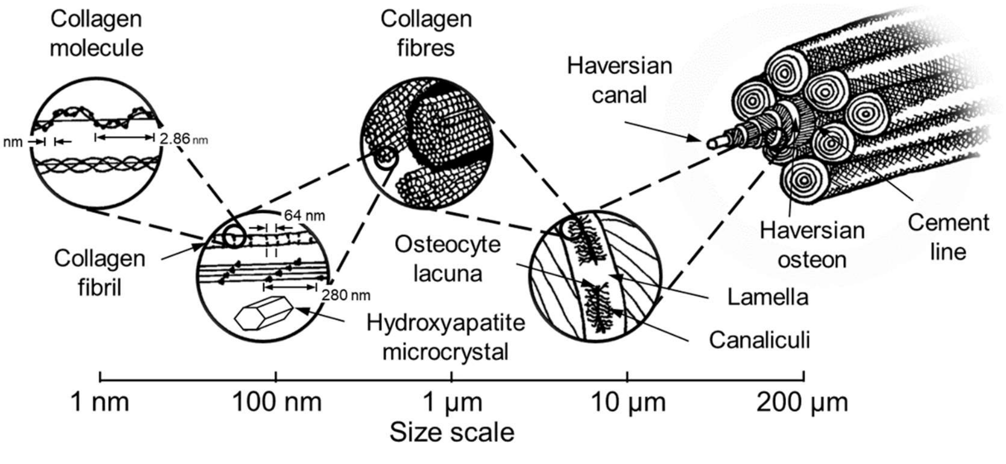

Figure 1. Illustration of the structure of human compact bone, a biological, hierarchical composite. Adapted from [2].

Manufacturing of hierarchical advanced composites is under development [3], using pultruded rods as a structural element. So, similarly to the natural composites, a hierarchical architecture of fibre+resin -> rod(+second resin) -> composite structural element -> larger composite assembly is produced. As the rods are surrounded by a second resin, this also allows the development of dual resin composites, which will not be discussed further here but is the subject of future work. These rod based composites represent a different approach to traditional ply based composites [4] and as such present new possibilities.

Pultruded rods, as shown under optical microscopy in Figure 2, are highly aligned unidirectional composites. Rods of diameter 0.7 mm to 0.8 mm have a radius of curvature of order 10 cm, varying depending on the constituent materials used. Such rods, when cured, are used as a component to build composite parts such as structural members (struts) [5], with an example shown in Figure 3.

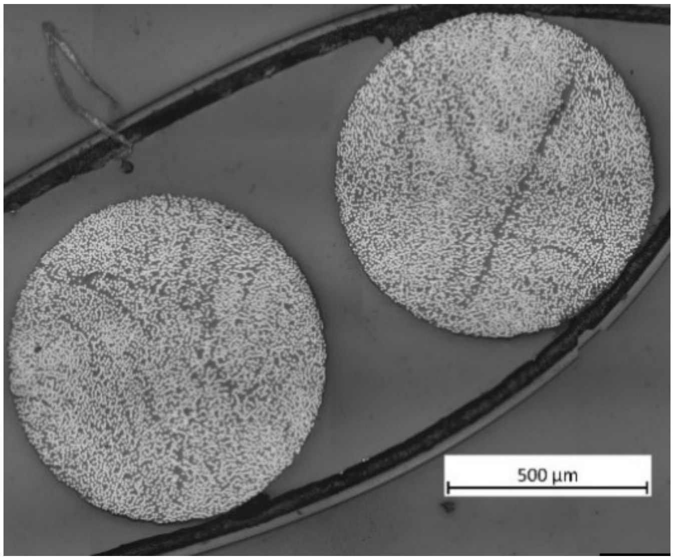

Figure 2. Cross section of two pultruded rods of 0.8 mm diameter [6] taken using Zeiss optical microscope with 20x lens.

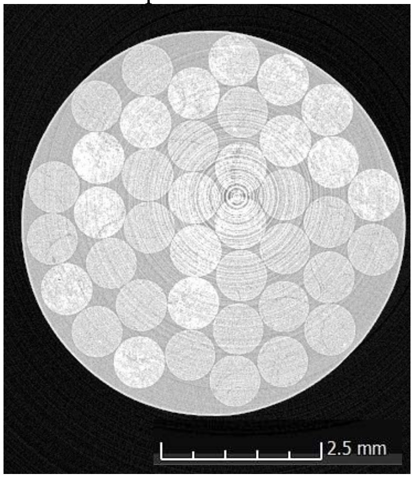

Figure 3. Slice from computerised tomography scan showing cured strut consisting of pultruded carbon-epoxy rods of 0.8 mm diameter and second epoxy resin [7] surrounding rods, manufactured by resin transfer moulding.

Adding overbraids to the pultruded rods is expected to improve the compressive performance, similar to the overwinding presented by Wisnom [8], whose model demonstrates radial compressive stress on a rod resulting from a Kevlar™ overwind. Potter et al. [9] demonstrated use of such a Kevlar™ overwind around a full strut to deliver improved ultimate compressive strength in compression after impact testing. Improvement was also seen in the un-impacted case. By overbraiding the individual rods, we apply this principle at a smaller length scale, in keeping with the NextCOMP hierarchical approach.

In addition, if a suitable braiding angle can be achieved it may be possible to obtain an auxetic effect through the braiding angle. Evans et al. [10] showed that a traditional laminate with reinforcement angles of approximately 60° can have a negative Poisson ratio, thus achieving a braiding angle of order 60° is a goal for this work.

The overbraids also represent a form of hybridization, allowing incorporation of different fibres within the same composite structure.

2 METHODS AND MATERIALS

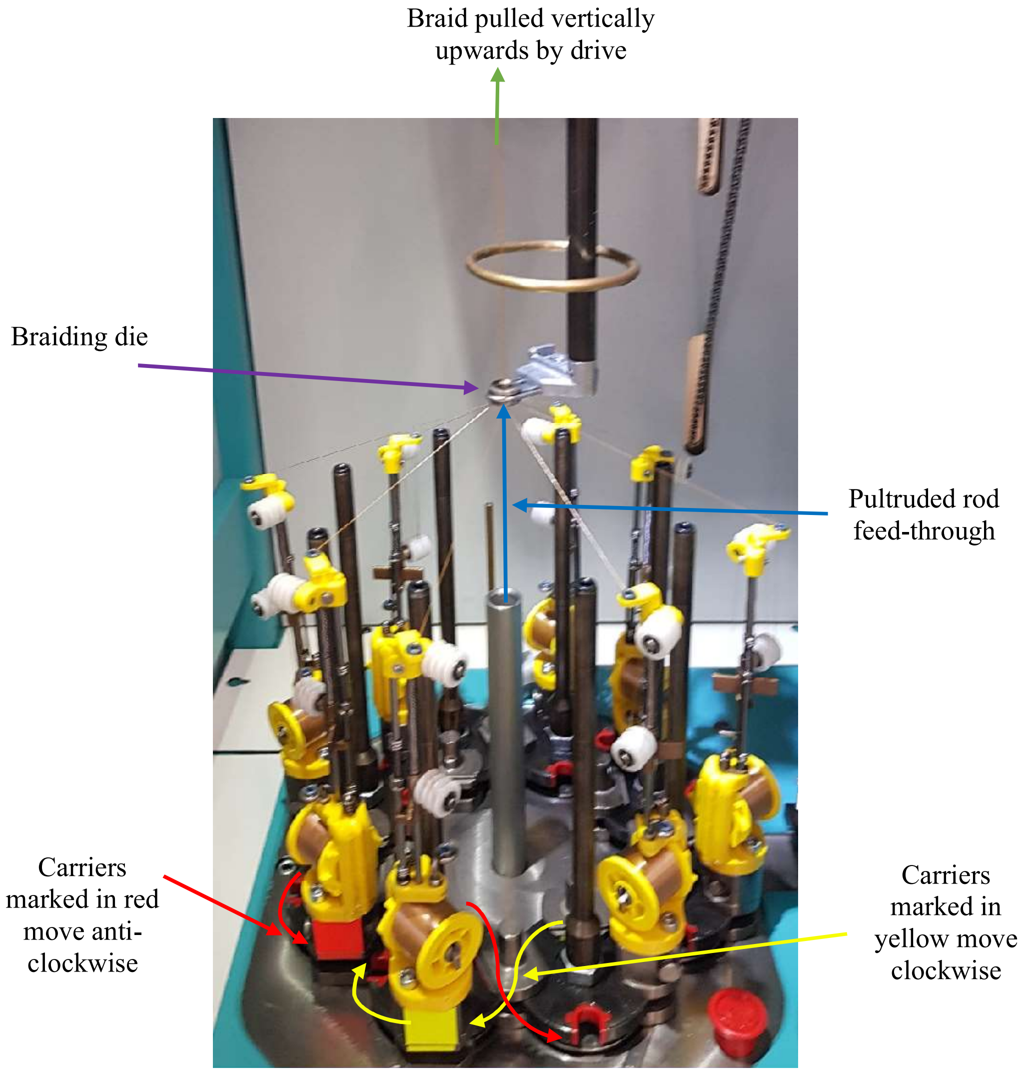

Figure 4: Herzog 1/16/80 circular maypole microbraider at half capacity, showing diamond interlace braiding setup with 8 yarn 273 dtex high modulus PBO.

The rods are overbraided using a Herzog 1/16/80 circular maypole microbraider. This microbraider can incorporate up to 16 yarns or tows, but is run at half capacity- 8 yarns or tows- allowing the braided material to fit around the diameter of the rod with minimal bunching at short lay lengths.

Commercially available carbon fibre-epoxy pultruded rods of 0.7 mm diameter consisting of Toray T700 carbon fibre and a bisphenol A epoxy resin [11] and of 0.8 mm diameter consisting of T300 carbon fibre and an epoxy resin [6], [12] were overbraided.

Overbraiding was carried out using 273dtex yarns of Toyobo high modulus Zylon™ poly(p-phenylene-2,6-benzobisoxazole) (PBO) fibre [13] and 1k tows of Toray T300 carbon fibre [14], each the smallest yarn/tow size readily available of the material in question.

Overbraiding was carried out for lay lengths from 8 mm to the minimum achievable. The lay length of a braid is the distance along the braid, or, in the picture in Figure 4, up the overbraided rod, required for a given tow to make a full revolution of 360°. The braid angle, between the rod and the tow, increases as lay length decreases. Lay length and braid angle are shown in Figure 5.

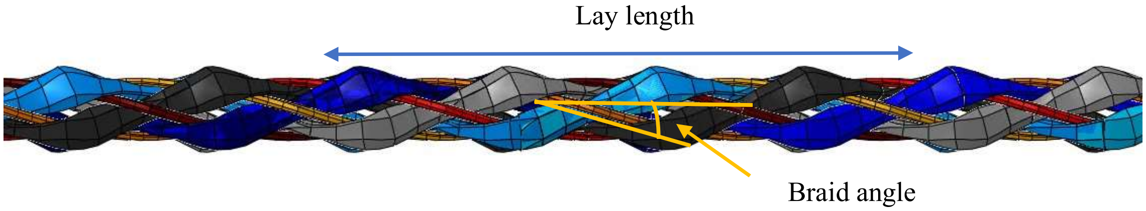

Figure 5. Illustration showing lay length and braid angle. Created following method of O'Keeffe et al [15]

The high modulus PBO has tensile modulus 270 GPa and elongation at break of 2.5 % [13] whereas the T300 carbon fibre has tensile modulus 230 GPa and strain at failure of 1. 5%, each according to the respective datasheets [14]. The PBO is expected to braid tightly around the rod and hence provide radial compression similar to that shown by overwinding by Wisnom [8] and Potter et al. [9]. The carbon, being more brittle, is expected to be more challenging to overbraid at shorter lay lengths, with fibre or tow breakage being a possibility as the tow bends around smaller angles to achieve the short lay length.

3 RESULTS

The minimum lay length achievable with the Herzog 1/16/80 circular maypole microbraider using these materials was 2 mm for the carbon and 1.5 mm for the PBO. Both may be seen in Figure 6. Below this lay length the braid point drops towards the carriers.

An 8 yarn 273 dtex high modulus PBO fibre overbraid confoms tightly to the rod geometry in all trials down to the minimum lay length. No fibre breakage is observed. The maximum braid angle achieved is approximately 60°, at minimum lay length. There is some slight bunching at this lay length leading to variation in the braid angle. As the narrowest available PBO yarn this is the limit of what is achievable with this equipment and these materials.

An 8 tow 1k T300 carbon fibre overbraid braids cleanly and without breakage at 8 mm lay length. At 4 mm lay length some fibre breakage is observed. At 2 mm lay length the overbraid is surrounded by protruding broken fibres as shown in Figure 6. Measurement of braid angle is not reliably feasible due to the protruding fibres.

A 0.8 mm diameter rod overbraided with 8 yarns of 273 dtex high modulus PBO at 1.5 mm lay length has final diameter of 1 mm, a 25 % increase. This is harder to measure for the carbon as the breakage results in a 'fuzzy' overbraid, making definition of the final diameter dependent on definition- whether or not the full extent of the broken fibres should be included.

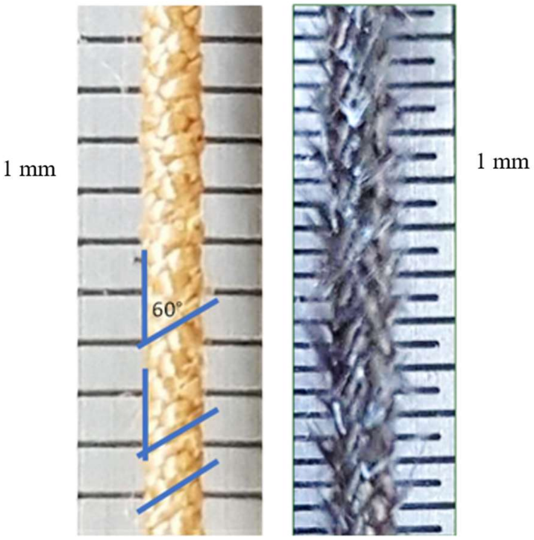

Figure 6. Rods of 0.8 mm diameter overbraided with 8 tows of 273 dtex Zylon™ at 1.5mm lay length with braid angle highlighted (left) and 8 tows of 1k T300 carbon at 2 mm lay length (right).

4 DISCUSSION AND NEXT STEPS

The rods used here are of smaller diameter (0.8 mm) than the 12.4 mm diameter struts overwound in that work, but the percentage increase in diameter due to the additional material, here 25 %, is approximately similar to that work, where 7 layers of overwind were 1.55 mm thick, so adding 3.1 mm to the strut. However, adding material to each rod within a strut will result in a reduction in the axial fibre volume fraction, as this may reduce the number of rods which can be packed into a strut of given size, such as that shown in Figure 3. It is therefore necessary to determine whether the advantage of the overbraid outweighs this reduction in the pultruded rod content, which will be addressed in the next stage of this work.

The PBO overbraid achieves a braid angle of approximately 60°, meeting the stated goal and opening up the possibility of auxetic behaviour.

It is unsurprising that the carbon shows fibre breakage when overbraided at comparatively short (2 mm) lay lengths. Carbon fibre is more brittle than PBO fibre. The resulting ‘fuzzy’ carbon overbraid is hypothesized to provide shear support in the matrix region between the rods in hierarchical composite structures. Finite element modelling suggests that such an increase in shear support will deliver improved compressive performance of the rods. This assertion will be tested in upcoming work. Multi-material overbraids, combining the benefits of PBO and carbon, are also to be tested as part of an ongoing study.

A truly hierarchical pultruded rod based composite system would include overbraiding at the strut level in addition to the rod level. Rods may also be made using the novel fibres and resins under development as part of NextCOMP, delivering structure at multiple length scales similar to our natural composite inspiration.

5 CONCLUSION

Overbraiding of < 1 mm diameter pultruded rods has been demonstrated using PBO and carbon fibres. The former conforms well to the rod geometry at lay lengths of 1.5 mm and up, with a 60° braid angle being achievable. The PBO is therefore suitable for providing radial compression of the rod.

The carbon overbraids smoothly at a lay length of 8 mm and can be overbraided down to a minimum lay length of 2 mm. This produces a 'fuzzy carbon' braid with broken fragments of carbon fibre protruding away from the rod, which is intended to provide shear support in the matrix surrounding the rod.

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