IMPROVING THE DAMAGE TOLERANCE OF CFRP USING A BIOMIMETIC CROSSED-LAMELLAR MICROSTRUCTURE

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Abstract

The damage tolerance of composites can be enhanced by bio-inspired microstructural designs. The crossed-lamellar microstructure is the toughest microstructure found in molluscs, despite consisting almost entirely of brittle ceramic. In this work, we investigate microstructures for CFRPs inspired by the crossed-lamellar microstructure in order to improve the damage diffusion capability of the former. This includes exploring two different prototyping procedures with different interface properties. The results indicate that the investigated configurations have the potential to significantly increase the damage dissipation capability of CFRP. The microstructures diffuse damage in a stable manner while preserving their structural integrity up to large curvatures under bending load. We demonstrate that composites with crossed-lamellar microstructures have very attractive properties in terms of damage diffusion.

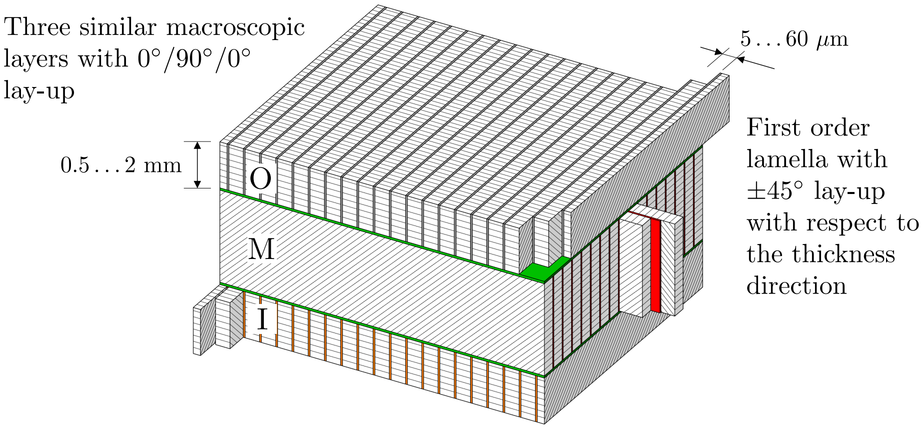
1. Introduction

Although being lightweight and strong, Carbon Fibre Reinforced Polymers (CFRPs) are brittle and have relatively low damage tolerance, which limits their use. However, it has recently been demonstrated that the damage diffusion capability of CFRP can be improved by careful microstructural design [1]. Natural composites, such as molluscs and bone, provide an excellent source of inspiration for such microarchitectures, as they often have a microstructure that makes the composite significantly stronger or more damage tolerant than its brittle and relatively weak main constituents [2].

The crossed-lamellar microstructures are the most prevalent and toughest microstructures found in molluscs [3, 4], with much research focusing on the *Strombus gigas* shell (Figure 1(a)) [4–6]. The shell consists 99.9 w% of ceramic aragonite but, due to its microstructure, it is up to 20,000 times tougher than pure aragonite [4]. The microstructure (schematically illustrated in Figure 1(b)) comprises three macroscopic layers (marked I, M and O) with 0°/90°/0° orientation and, within each macroscopic layer, the lamellae are oriented ±45° with respect to the thickness of the shell. Upon bending, the shell dissipates energy through various strategies including parallel cracking on the tension side, crack deflection and frictional sliding, and pull-out of the lamellae in the middle layer [4, 7].

In this work, we explored families of advanced CFRP composites broadly inspired by the crossed-lamellar microstructure. This entailed investigating different manufacturing methods and interface properties. The configurations were tested in an SEM environment, and the results indicate that CFRP with a crossed-lamellar microarchitecture has the potential to significantly increase the damage diffusion capability of CFRP.

(a)



(b)

Figure 1. (a) The Strombus gigas shell [8] and (b) a schematic of its microstructure (not to scale).

2. Crossed-lamellar CFRP

2.1. Prototyping

Two prototyping routes for the crossed lamellar CFRP were investigated, with a geometry chosen based on a parametric study using a unit cell FE model. The microstructures were prototyped using IM7/8552 carbon/epoxy prepreg with a 1:2:1 ratio of the macroscopic layer heights.

The first route was based on cutting strips of uncured prepreg, rotating and arranging them to the desired microstructure, and co-curing the microstructure to the final configuration. In this procedure, thermoplastic PES was used between the macroscopic layers. Specimens manufactured via this route are called co-cured specimens.

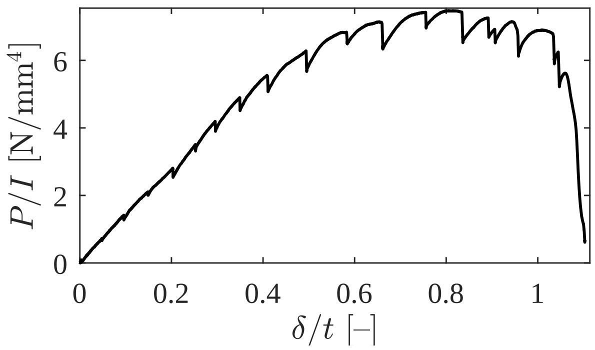
The second route was based on curing a thick laminate, cutting it into thin sections, and rotating and bonding them to achieve the desired microstructure. In this procedure, the layers were bonded together using ScotchWeld 9323 toughened epoxy adhesive. Specimens manufactured via this route are called bonded specimens.

2.2. Mechanical testing

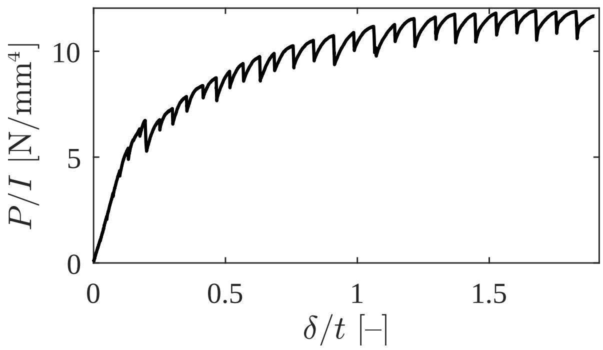
The specimens were tested in a three-point bending (3PB) configuration in an SEM environment. Before damage occurred, the tests were paused at regular load intervals to take SEM images. At a later stage, when the damage was growing, the tests were paused at regular displacement intervals, or when other interesting features were observed.

The test results are summarised in Figure 2. The normalised load vs displacement curves of the co-cured and the bonded specimens, respectively, are given in Figures 2(a) and 2(b). The load drops in the curves are caused by specimen relaxation while the tests were paused to take SEM images. The maximum displacement of the tester was reached before the final failure of the bonded specimen. Figures 2(c) and 2(d) show the specimens near the end of the test, and Figures 2(e) and 2(f) show SEM images of their fracture surfaces obtained when the specimens were manually broken in half after the tests.

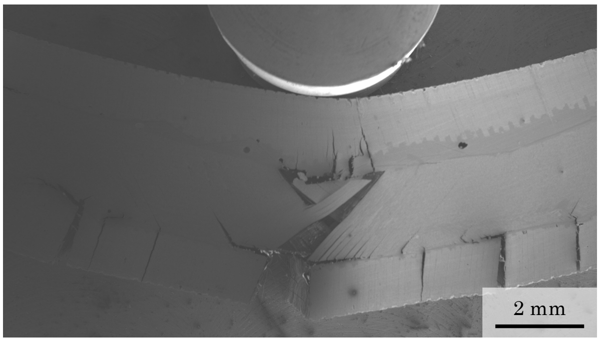
The crossed-lamellar CFRP dissipates energy in a stable manner up to large curvatures, leading to large



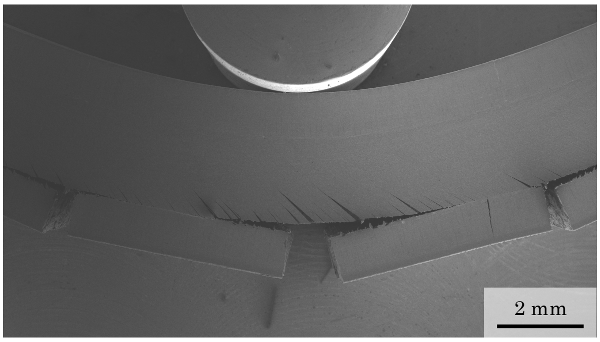
(a) Normalised load vs displacement curve of the co-cured specimen. The load drops are caused by specimen relaxation.



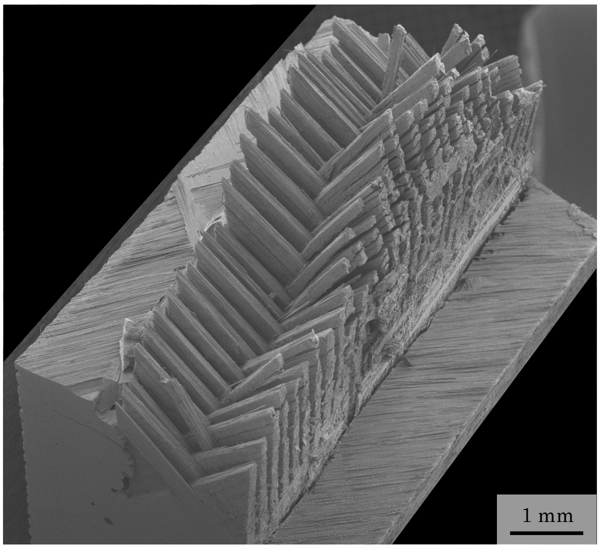
(b) Normalised load vs displacement curve of the bonded specimen. The load drops are caused by specimen relaxation.



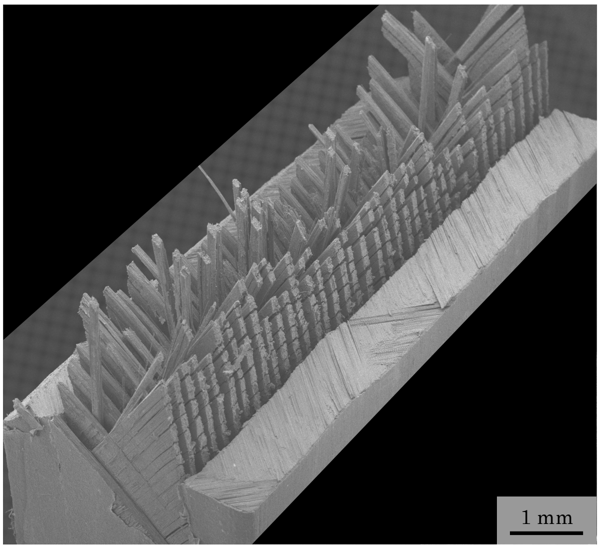
(c) The co-cured specimen near the end of the test



(d) The bonded specimen near the end of the test



(e) Fracture surface of the co-cured specimen



(f) Fracture surface of the bonded specimen

Figure 2. Results of the 3PB tests of the co-cured and bonded specimens.

debonded areas and regular arrays of splits along the fibre direction. The microstructure diffuses damage in the middle layer, while the damage on the tension side is localised around the cracks.

3. Conclusions

This paper investigated carbon/epoxy composites with microstructures inspired by the crossed-lamellar microstructure, aiming at enhancing the damage diffusion capability of these composites. It can be concluded that:

- crossed-lamellar CFRP specimens were prototyped successfully using two manufacturing routes;
- under bending load, these microstructures led to damage localisation on the tension side and damage diffusion in the middle layer;
- composites with a microstructure inspired by the crossed-lamellar microstructure have very attractive properties in terms of damage diffusion – they dissipate energy in a stable manner while preserving their structural integrity up to large curvatures.

Acknowledgements

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References

[1] G. Bullegas, S. T. Pinho, and S. Pimenta, "Engineering the translaminar fracture behaviour of thin-ply composites," *Composites Science and Technology*, vol. 131, pp. 110 – 122, 2016.

[2] P.-Y. Chen, J. McKittrick, and M. A. Meyers, "Biological materials: functional adaptations and bioinspired designs," *Progress in Materials Science*, vol. 57, no. 8, pp. 1492–1704, 2012.

[3] X. W. Li, H. M. Ji, G. P. Zhang, and D. L. Chen, "Mechanical properties of crossed-lamellar structures in biological shells: A review," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 74, pp. 54–71, 2017.

[4] L. T. Kuhn-Spearing, H. Kessler, E. Chateau, R. Ballarini, A. H. Heuer, and S. M. Spearing, "Fracture mechanisms of the Strombus gigas conch shell: implications for the design of brittle laminates," *Journal of Materials Science*, vol. 31, no. 24, pp. 6583–6594, 1996.

[5] X.-W. Su, D.-M. Zhang, and H. A. H., "Tissue regeneration in the shell of the giant queen conch, Strombus gigas," *Chemistry of Materials*, vol. 16, no. 4, pp. 581–593, 2004.

[6] L. Romana, P. Thomas, P. Bilas, J. L. Mansot, M. Merrifiels, B. Y., and D. Aldana Aranda, "Use of nanoindentation technique for a better understanding of the fracture toughness of Strombus gigas conch shell," *Materials Characterization*, vol. 76, pp. 55–68, 2013.

[7] M. A. Meyers, P. Y. Chen, A. Y.-M. Lin, and Y. Seki, "Biological materials: structure and mechanical properties," *Progress in Materials Science*, vol. 53, no. 1, pp. 1–206, 2008.

[8] H. Zell, "Eustrombus gigas," *https://upload.wikimedia.org/wikipedia/commons/9/9a/Eustrombus_gigas_01.jpg*, Accessed 13/12/2017.