LOW VELOCITY IMPACT AND COMPRESSION AFTER IMPACT OF THIN-PLY CFRP BOULIGAND STRUCTURES

Lorenzo Mencattelli, Silvestre T. Pinho

Department of Aeronautics, Imperial College London
South Kensington, SW7 2AZ, UK
Email: l.mencattelli@imperial.ac.uk
Email: silvestre.pinho@imperial.ac.uk
Web page: wwwf.imperial.ac.uk/aeronautics/research/pinholab/

Keywords: mantis shrimp, thin-ply Bouligand, LVI, CAI, helicoidal CFRP

Abstract
In this work, several bio-inspired thin-ply CFRP laminates mimicking the helicoidal architecture of the mantis shrimp's dactyl club periodic region have been modelled and tested under low velocity impact (LVI) and compression after impact (CAI), investigating the effect of the inter-ply angle (pitch angle) on the mechanical response and damage characterization of the biomimetic laminate. The use of thin-ply technology has allowed for the first time to explore the effect of very small inter-ply angles, down to 2.5°, better mimicking the microstructure of the dactyl club and achieving failure mechanisms akin those observed in the natural microstructure. Tests conducted for a wide range of pitch angles (2.5°, 5°, 10°, 20°, 45°) show that, by decreasing the pitch angle, is it possible to better mimic the failure mechanisms observed in the biological microstructure.

1. Introduction

Non-standard lamination sequences inspired by naturally-occurring impact-resistant microstructures, such as Bouligand [1] structures (Figure 1a), have been investigated in the literature for improving the resistance of standard CFRP laminates to out-of-plane loads. Bouligand-featured structures can be found for example in the mantis shrimp dactyl club (Figure 1b). The latter consists of a repetition of Bouligand units, stacked up along the thickness direction. Each Bouligand unit contains a helicoidal layup with very small inter-ply (pitch) angles (from 6° down to 1.6° [2]) for a total rotation of 180° inside each unit.

This particular architecture unveils an interesting failure mechanism under impact (Figure 1c): matrix cracks tend to grow in a double helicoidal pattern, parallel to the local fibre orientation, leaving fibres mostly undamaged, and with limited delaminations [2]. This allows biological Bouligand structures to withstand several impacts and yet retaining more of their undamaged mechanical properties.

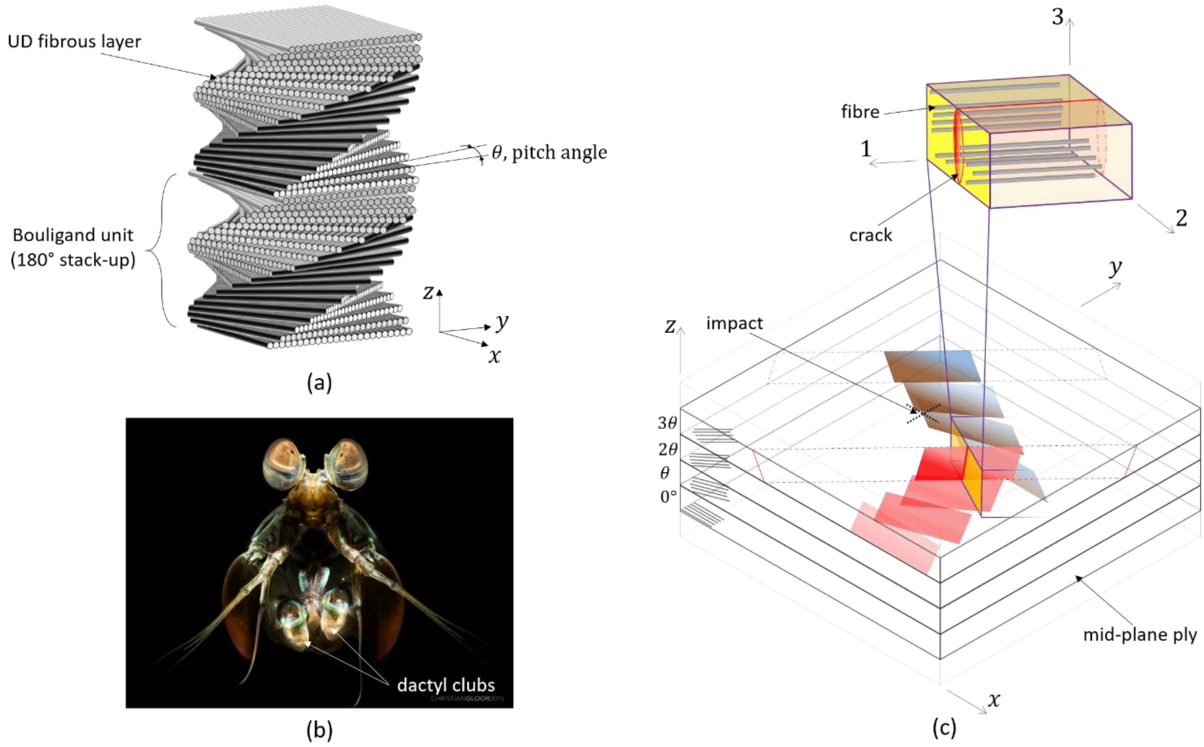

Figure 1. (a) Schematic of a Bouligand structure, i.e. a helicoidal arrangement of fibrous UD layers with constant pitch angle θ. (b) Photograph of the mantis shrimp (Christian Gloor, 2015). (c) Schematic of the double helicoidal crack typical of impacted Bouligand structures.

In this work, we aim at gaining a better understanding of how the pitch angle can promote the formation of crack paths similar to those observed in biological Bouligand arrangements and at how to mimic the same with CFRPs. To achieve these goals, we decided to use thin-ply composites, with ply thickness down to 0.02 mm (20 gsm). This allows us to explore, for the first time in the literature, small pitch angles and large numbers of repetitions in laminates with a reasonable overall thickness. By investigating a wide range of pitch angles (2.5°, 5°, 10°, 20°, 45°), we aim to establish any correlation between (i) pitch angle and (ii) response to low-velocity impact and corresponding residual compressive strength of biomimetic Bouligand CFRPs.

2. Experimental tests

2.1. LVI and CAI

Low Velocity Impact tests were conducted using a drop weight tower following the ASTMD7136 [9] standard. After being impacted, samples were scanned with ultrasonic C-scans to characterize the different types of damage, as shown in Figure 2.

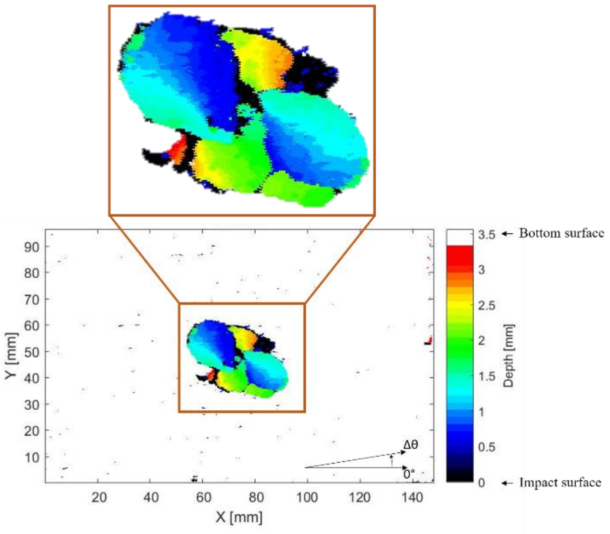

Figure 2. C-scan image of an impacted Bouligand thin-ply CFRP laminate with a pitch angle $\Delta\theta = 2.5°$.

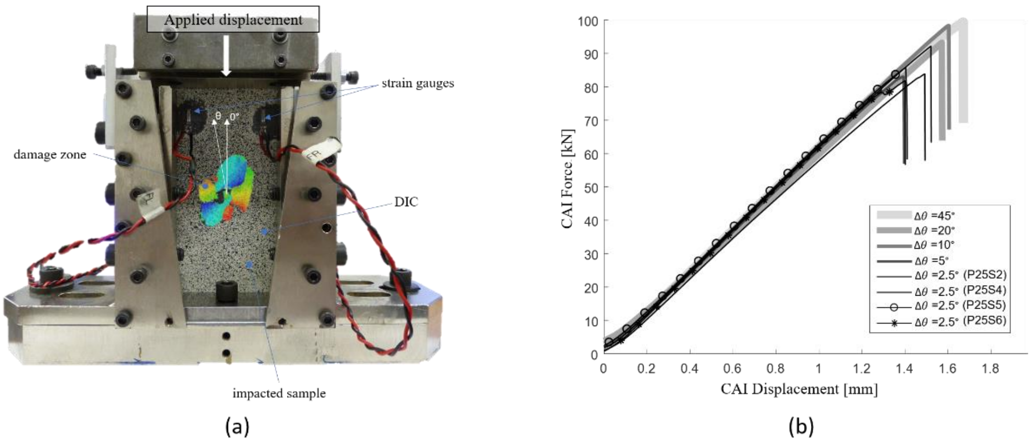

Figure 3. (a) CAI test fixture. (b) CAI force versus Displacement

Subsequently, the samples were compressed following the ASTMD7137 [10] standard. A photograph of the set-up and the results in terms of CAI force versus displacement for each sample are reported respectively in Figure 3a and Figure 3b.

2.2. Analysis and Discussion

The analysis of C-scan images shows that reducing the pitch angle leads to a smooth helicoidal evolution of damage where delaminations are progressively spread through the thickness of the laminate in a 'stair-case' fashion, following the local fibre orientation. This characteristic pattern is more pronounced as the pitch angle is reduced. As shown in Figure 2, in the $\Delta\theta = 2.5°$ configuration, delaminations are very well aligned with a direction dictated by the local fibre orientation and evenly distributed through the thickness of the laminate. In addition, in terms of total projected delamination area, an overall decrease of about 29.5% is observed respective to the laminate with the largest pitch angle ($\Delta\theta = 45°$).

Concerning the CAI test results, it is very interesting to notice that the $\Delta\theta = 2.5°$ configuration, in which only 2.7% of plies are aligned with the loading direction (0°-plies), was able to retain a similar compressive strength to the $\Delta\theta = 45°$ configuration, in which 26% of the total number of plies are aligned with the loading direction.

3. Conclusions

Several bio-inspired Bouligand thin-ply CFRPs laminates with pitch angles ranging from $\Delta\theta = 2.5°$ up to $45°$ have been investigated. LVI and CAI test have been conducted to study the influence of pitch angle on damage morphology and mechanical response of the laminate. The main conclusions of the work are:

(i) reducing the pitch angle leads to better mimicking the failure mechanisms of natural occurring Bouligand structures. In particular, the $\Delta\theta = 2.5°$ configuration showed a helicoidal formation of damage with delaminations forming at several ply interfaces following the local fibre direction;

(ii) The $\Delta\theta = 2.5°$ configuration succeeded in obtaining the same CAI strength as the $\Delta\theta = 45°$ configuration, with only 2.7% of plies aligned in the loading direction (instead of 26% for the $\Delta\theta = 45°$ configuration).

Acknowledgments

The funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 722626 is gratefully acknowledged. fibremodproject.eu

References

[1] Y. Bouligand, "Twisted fibrous arrangements in biological materials and cholesteric mesophases," *Tissue Cell*, vol. 4, no. 2, pp. 192–217, 1972.

[2] J. C. Weaver *et al.*, "The stomatopod dactyl club: A formidable damage-tolerant biological hammer," *Science (80-.).*, vol. 336, no. 6086, pp. 1275–1280, 2012.

[3] F. Pinto, O. Iervolino, G. Scarselli, D. Ginzburg, and M. Meo, "Bioinspired twisted composites based on Bouligand structures," 2016, p. 97970E.

[4] L. Cheng, A. Thomas, J. L. Glancey, and A. M. Karlsson, "Mechanical behavior of bio-inspired laminated composites," *Compos. Part A Appl. Sci. Manuf.*, vol. 42, no. 2, pp. 211–220, 2011.

[5] J. S. Shang, N. H. H. Ngern, and V. B. C. Tan, "Crustacean-inspired helicoidal laminates," *Compos. Sci. Technol.*, vol. 128, pp. 222–232, 2016.

[6] T. Apichattrabrut and K. Ravi-Chandar, "Helicoidal composites," *Mech. Adv. Mater. Struct.*, vol. 13, no. 1, pp. 61–76, 2006.

[7] L. K. Grunenfelder *et al.*, "Bio-inspired impact-resistant composites," in *Acta Biomaterialia*, 2014, vol. 10, no. 9, pp. 3997–4008.

[8] D. Ginzburg, F. Pinto, O. Iervolino, and M. Meo, "Damage tolerance of bio-inspired helicoidal composites under low velocity impact," *Compos. Struct.*, vol. 161, pp. 187–203, 2017.

[9] ASTM D7136 / D7136M-15, Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event," in *ASTM Book of Standards Volume: 15.03*, 2015.

[10] ASTM D7137/D7137M-12, "Standard Test Method for Compressive Residual Strength Properties of Damaged Polymer Matrix Composite Plates," *ASTM Int.*, vol. i, pp. 1–17, 2012.