BIO-INSPIRED INTERLEAVED COMPOSITE STRUCTURES FOR HIGH-VELOCITY IMPACT APPLICATIONS

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Keywords: High-velocity impact; Bio-inspired layup; Interleaved, Hybrid CFRP composites

ABSTRACT

We propose a novel design for improving the high-velocity impact (HVI) performance of hybrid carbon fibre-reinforced polymer (CFRP) composite structures. Our novel design consists of a non-conventional bio-inspired hybrid interleaved layup that significantly enhances damage diffusion and energy dissipation in CFRP composite structures. In our design, we retain more than 50% mass of the structure as CFRP to keep in-plane mechanical properties substantial and also aim to maintain the areal weight (compared to the monolithic CFRP baseline). We applied this design methodology to develop laminate concepts made of thin- and thick-ply CFRPs, hybridised with aramid fibre-reinforced polymer (AFRP) for one of the concepts, and also titanium foils for another concept. We tested the laminate concepts under HVI from 150 to 300 m/s and investigated their response in terms of energy dissipation, ballistic limit and failure modes. The results demonstrate a strong increase in ballistic limit and specific energy dissipation for the developed laminate concepts. The bio-inspired monolithic thin- and thick-ply CFRP laminate concepts exhibit about 15% improvement in specific energy dissipation compared to their QI monolithic baselines. Implementing interleaved blocks of AFRP into the bio-inspired monolithic CFRP laminate concepts shows an improvement in specific energy dissipation by up to 54% for the thick-ply and by up to 135% for the thin-ply, compared to their monolithic QI baselines.

1 INTRODUCTION

Carbon fibre-reinforced polymer (CFRP) composite structures are susceptible to severe damage in extreme out-of-plane loading such as high-velocity impact (HVI). To alleviate this drawback, traditionally hybridising CFRP composite structures with various high strain-to-failure ratio materials has been reported as a successful approach in improving the response [1]. However, hybridising CFRP composite structures usually comes with the cost of sacrificing the in-plane mechanical properties and/or increasing the weight. As a result, design requirements such as retaining substantial in-plane mechanical properties and/or maintaining the weights of composite structures (in a specific range) should be taken into account when developing hybrid composite structures for industrial applications, such as the aircraft engine's casing performance under HVI in fan blade-off events.

Another approach to improve the out-of-plane response and thus the damage resistance of CFRP composite structures is to apply a non-conventional bio-inspired (helicoidal) layup in the design. Mencatelli and Pinho [2] mimicked and implemented the helicoidal architecture of the mantis shrimp's dactyl club periodic region by using thin-ply CFRPs with various pitch angles through the thickness of the layup. They found the performance of CFRP composite structures under low-velocity impact improves significantly by reducing the pitch angle in the layup.

Compared to traditional thick-ply, thin-ply CFRPs provide greater design possibilities and more stacking sequences. As a result, more interfaces and delamination zones can be created when applying thin-ply CFRPs to develop hybrid CFRP-based composite structures. Consequently, there is a possibility of further improving the HVI response of CFRP-based composite structures by implementing the combination of the aforementioned approaches but instead of hybridising the layup in a traditional bulk method, we apply interleaved blocks of hybridising materials through the thickness, which lets us create more interfaces and thus create more delamination zones.

Considering this, the main goal of this study is to apply a such combined methodology to develop novel laminate concepts made of thin- and thick-ply CFRPs that are hybridised with aramid fibre-reinforced polymers (ARFP) for one of the design concepts and also with titanium foils for another concept to possibly further improve the response in HVI while maintaining more than 50% weight of the structure as CFRP and keeping the areal weight constant for a meaningful comparison. Based on the ballistic limit response and failure modes analysis, we down-selected the best-performed design for an industrial demonstrator application.

2 METHODOLOGY

2.1 Concepts

We use and combine two approaches for designing thin-ply and thick-ply CFRP laminate concepts:

1. non-conventional bio-inspired (helicoidal) layups: to diffuse damage and maximise energy dissipation, Fig. 1 (left). We used pitch angles smaller than 5° for thin-ply CFRPs [3] and smaller than 30° for thick-ply CFRPs; and
2. interleaved blocks of the hybridising material: to create and control (more) delamination zones and further enhance energy dissipation, Fig. 1 (right).

For developing hybrid laminate concepts, we kept the mass ratio of hybridising material(s) to CFRP about 44% and we aimed to manufacture all laminates with a target areal weight of 0.95 g/cm^2 for a meaningful comparison.

2.2 Materials, Manufacturing and testing

We used unidirectional (UD) ultra-thin SkyFlex USN20A prepregs with the areal weight of 20 gsm and ultra-low thickness of 0.05 mm for developing thin-ply CFRP laminates. For thick-ply counterparts, we used aerospace-grade UD CFRP prepregs with the areal weight of 280 gsm and thickness of 0.25 mm. To develop hybridised laminate concepts, we used ultra-thin UD PBO aramid fibres (Zylon-HM545T/TP513) with the areal weight of 25 gsm for one of the concepts in addition to titanium (Ti) foils for another one.

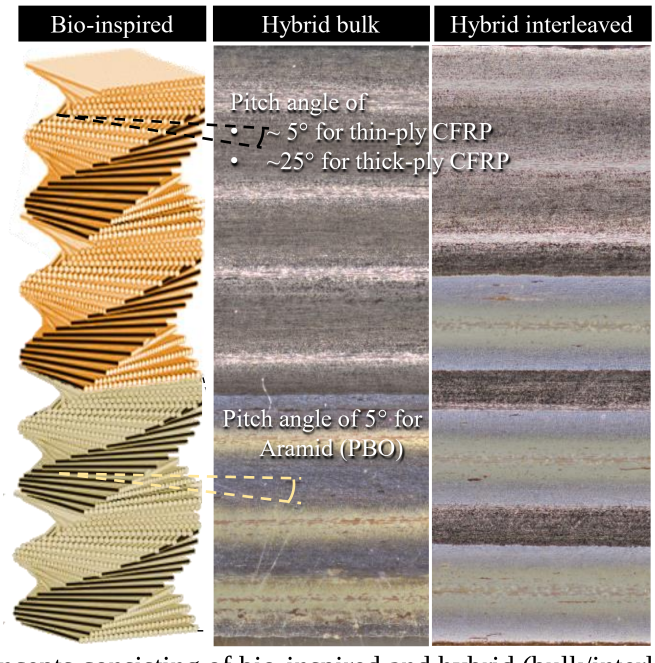


Fig. 1 Concepts consisting of bio-inspired and hybrid (bulk/interleaved) layup

We manufactured 4 types of 250×250 mm laminates made of both thin- and thick-ply CFRPs:

1. quasi-isotropic (QI) laminates as baselines;
2. bio-inspired CFRP laminate concepts;
3. bio-inspired hybrid interleaved CFRP/aramid laminate concepts; and
4. bio-inspired hybrid interleaved Ti/CFRP/aramid laminate concepts.

Selected cross-section examples of the novel bio-inspired hybrid thin-ply/aramid laminate concepts for the bulk and the interleaved designs are provided in Fig. 1. To perform HVI tests, we used a gas gun firing a steel ball with a diameter of 14 mm with a test rig having simply-supported boundary conditions [4]. For each design, we tested 6 specimens in the range of 150 m/s to 300 m/s. To track the impact event and calculate the impact and rebound/perforation velocities, we placed two high-speed Phantom cameras in the test setup.

3 RESULTS

Fig. 2 presents experimental results for the thick-ply family laminate concepts including: QI [60/0/-60] baseline, bio-inspired; bio-inspired hybrid interleaved CFRP/aramid; and bio-inspired hybrid interleaved Ti/CFRP/aramid. The residual velocity is plotted against impact velocity when penetration is achieved. We used the Lambert-Jonas equation [5] to fit the experimental data:

$$v_{\mathrm{res}} = \mathrm{A}\left(v_{\mathrm{ini}}^2 - v_{\mathrm{bal}}^2\right)^{1/2} \tag{1}$$

Where v_{res} is the residual velocity, v_{ini} is the (initial) impact velocity and v_{bal} is the ballistic limit. Fig. 2 demonstrates the improvement of ballistic limit in the developed thick-ply-based laminate concepts. By changing the layup from QI to bio-inspired, we observed a significant improvement in the ballistic limit from 147 m/s to 190 m/s. By implementing a bio-inspired hybrid interleaved design consisting of AFRP, the ballistic limit further increased to 212 m/s. However, by replacing AFRP (located at the back face) with titanium layers at the impact face in the layup, the ballistic limit did not increase further and we measured it about 197 m/s. A possible reason for the reduction of ballistic limit in the Ti/thick-ply/aramid laminate concepts might be due to the higher failure strain of aramid fibres compared to titanium foils.

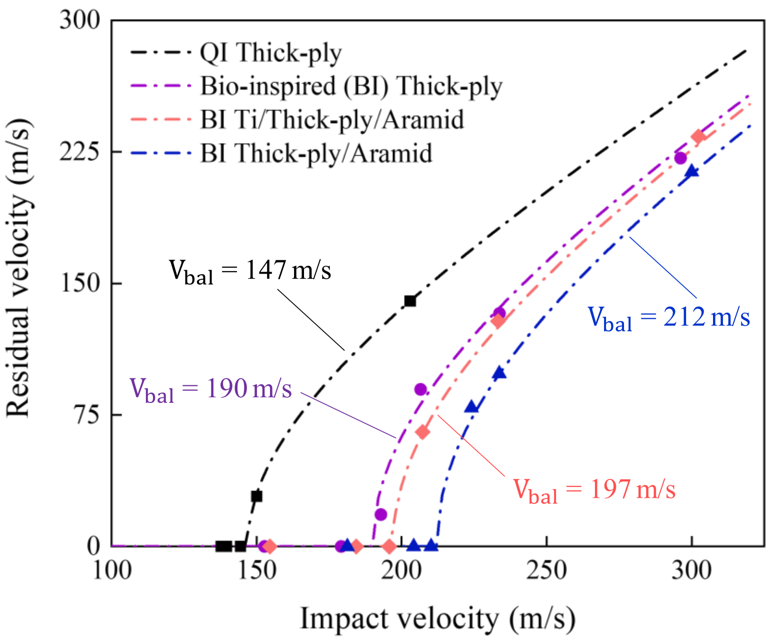


Fig. 2 Impact vs residual velocity response of thick-ply laminate concepts impacted from 150 to 300 m/s

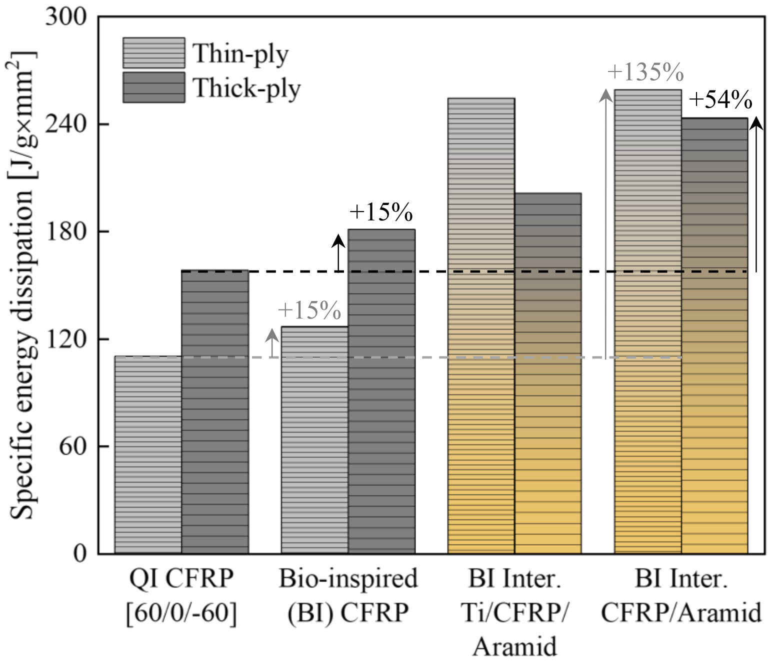


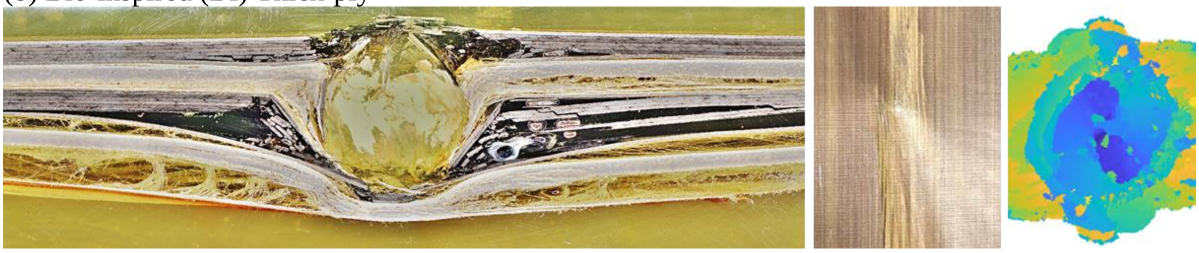
Fig. 3 Energy dissipation improvements of the developed thin- and thick-ply laminate concepts under HVI over their baselines

Fig. 3 demonstrates a strong increase in the specific energy dissipation of the developed laminate concepts over their baselines. Fig. 3 shows that bio-inspired monolithic CFRP laminate concepts exhibit about 15% improvement compared to their QI baselines (both for thin- and thick-ply). By implementing interleaved blocks of AFRP into the layup, specific energy dissipation increases by up to 54% for the thick-ply and up to 135% for the thin-ply laminate concepts compared to their QI baselines. Using titanium foils at the impact face instead of impact face CFRPs or back face AFRPs did not further improve the ballistic limit or the dissipated energy.

Fig. 4 depicts the changes in failure mechanisms of selected thick-ply laminate concepts including: QI baseline (Fig. 4 (a)), bio-inspired monolithic CFRPs (Fig. 4 (b)) and bio-inspired hybrid interleaved CFRP/aramid (Fig. 4 (c)) all impacted at 210 m/s. Fig. 4 (a) shows that the QI baseline failed in a brittle manner mainly under the shear plugging failure mechanism and it perforated. Back face and C-Scan images of monolithic thick-ply QI baseline show that the damage is confined around the impact region (with an exception of fibre spalling at the back face). This limited damage extent correlates with shear plugging that has been reported as a limited energy dissipation mechanism in the literature [6]. In addition, by looking at the cross-section of the impacted QI baseline specimen, we observed limited delamination between the CFRP plies away from the impact region, Fig. 4 (a). However, by changing the QI layup to bio-inspired, we observed additional and more complex failure mechanisms. The cross-section image reveals that the distal CFRPs failed in tension rather than pure shear, which is related to the helicoidal layup of the CFRPs along the thickness of the laminate concept, resulting in more energy dissipation. We also observed various failed fibres at different pitch angles by looking at the back face. The C-Scan image in Fig. 4 (b) of the bio-inspired monolithic CFRP laminate concept reveals: the helicoidal formation of matrix cracks from the impact face towards the back face; their migration from one ply to another; the initiation of delamination from the impact face; and its propagation towards the back face. Comparing the C-Scan images of impacted QI and BI monolithic CFRP clearly shows the difference in failure modes and energy dissipation mechanisms. Nonetheless, the bio-inspired thick-ply laminate concept also perforates at 210 m/s.

(a) QI Thick-ply baseline

(b) Bio-inspired (BI) Thick-ply



(c) BI Interleaved Thick-ply/Aramid

Fig. 4 Post-mortem images (including cross-section, back face and c-scan) of thick-ply laminate concepts impacted at 210 m/s

Fig. 4 (c) shows the post-mortem images of the developed bio-inspired hybrid interleaved design, which resisted perforation. Even at 210 m/s, the thick-ply/aramid laminate concept does not perforate, and the projectile gets sandwiched inside the laminate concept. By analysing the cross-section of the thick-ply/aramid, we detected extensive delamination in the last block of AFRP. Moreover, the laminate underwent high deformation at the back face due to the presence of high-strain-to-failure aramid fibres. In addition, having multiple interfaces between CFRP and AFRP blocks creates more potential delamination zones, which contributed further to higher energy dissipation of this laminate concept. The C-Scan image of the thick-ply/aramid laminate concept clearly shows the synergistic effect of bio-inspired layup and potential delamination zones, since the extent of delamination(s) and damage is the greatest in this laminate concept compared to others.

CONCLUSIONS

In this study, we proposed a novel design methodology to develop laminate concepts with improved damage resistance and energy dissipation for HVI applications. Our design concepts consist of a bio-inspired layup combined with interleaved blocks of the hybridising material(s). To develop bio-inspired CFRP laminate concepts, we used various pitch angles (depending on thin- and thick-ply CFRPs) to manufacture bio-inspired monolithic laminate concepts. Then, to hybridise, we used bio-inspired AFRP blocks and interleaved them through the thickness of the layup. For another design, we also added titanium foils to the impact face to evaluate and compare the response. Then, we tested the developed laminate concepts at various velocities to obtain the ballistic limit, analysed the response and compared the failure modes. Our study shows that:

1. changing the layup of the monolithic CFRP from QI to bio-inspired resulted in about a 15% improvement in energy dissipation and a 30% increase in the ballistic limit;
2. using a bio-inspired hybrid interleaved design resulted in about 135% increase in energy dissipation over the QI baseline and about 45% in the ballistic limit;

3. replacing CFRP (located at the impact face) or aramid fibres (located at the back face) with titanium foils (at the impact face) did not contribute further to the improvement of the response or the ballistic limit; and
4. post-mortem images provided new insights in the understanding of the failure mechanisms in our developed bio-inspired laminate concepts. Changing the layup from QI to bio-inspired hybrid interleaved resulted in the failure mechanisms changing from brittle shear plugging to tensile failure accompanied by matrix crack migration and more delaminations.

Considering the manufacturing aspects and practicalities of the novel laminate concepts developed in this study, the bio-inspired hybrid interleaved thick-ply/aramid concept proved the best-performing one. We will be using this laminate concept as a baseline to scale it up to develop and manufacture an industrial demonstrator to be tested in HVI at a specific angle to simulate the real condition of the performance of an aircraft engine's casing in the event of an engine fan blade-off in the aerospace industry.

ACKNOWLEDGEMENTS

The funding from Innovate UK under the UKRI FANDANGO project No. 113232 (https://gtr.ukri.org/projects?ref=113232) is gratefully acknowledged. We also thank Prof. Nik Petrinic, Dr Yanhong Chen and Dr Ziwen Xu at the University of Oxford for kindly carrying out the high-velocity impact tests.

REFERENCES

[1] Kazemi ME, Shanmugam L, Dadashi A, Shakouri M, Lu D, Du Z, et al. Investigating the roles of fiber, resin, and stacking sequence on the low-velocity impact response of novel hybrid thermoplastic composites. Composites Part B: Engineering. 2021;207:108554.
[2] Mencattelli L, Pinho ST. Realising bio-inspired impact damage-tolerant thin-ply CFRP Bouligand structures via promoting diffused sub-critical helicoidal damage. Composites Science and Technology. 2019;182:107684.
[3] Medeau V, Kazemi ME, Greenhalgh E, Pimenta S, Finlayson J, Pinho S. Helicoidal layups and interleaved hybrids: a novel design methodology for impact-resistant composite structures. 2022.
[4] Cui H, Thomson D, Eskandari S, Petrinic N. A critical study on impact damage simulation of IM7/8552 composite laminate plate. International Journal of Impact Engineering. 2019;127:100-9.
[5] Lambert JP, Jonas GH. Towards Standardization in Terminal Ballistics Testing: Velocity Representation. 1976.
[6] Alonso L, Martínez-Hergueta F, Garcia-Gonzalez D, Navarro C, García-Castillo SK, Teixeira-Dias F. A finite element approach to model high-velocity impact on thin woven GFRP plates. International Journal of Impact Engineering. 2020;142:103593.

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The Publisher:
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2 Composites, Structural Systems Design, Rolls-Royce, UK,
The Publication:
TWENTY-THIRD INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS (ICCM23)
Article Publication Reference: TBA

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