Composites Part B 264 (2023) 110930

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Bio-inspired interleaved hybrids: Novel solutions for improving the high-velocity impact response of carbon fibre-reinforced polymers (CFRP)

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ARTICLE INFO

Handling Editor: Prof. Ole Thomsen

Keywords:
Bio-inspired
Hybrid interleaved layup
Carbon-fibre-reinforced polymer (CFRP)
High-velocity impact (HVI)
Zylon fibre (PBO)

ABSTRACT

We propose a novel design methodology consisting of bio-inspired (BI) and interleaved layups to develop hybrid carbon fibre-reinforced polymer (CFRP) composite structures for improved high-velocity impact (HVI) performance. Firstly, we apply a BI helicoidal design method consisting of various pitch angles (considering both thick- and thin-ply CFRP) to develop BI monolithic CFRP laminates. Secondly, we apply the interleaving design method to develop BI hybrid CFRP-based laminates interleaved with blocks of BI Zylon fibre-reinforced polymers through the thickness. We evaluate their response and compare it with traditional quasi-isotropic (QI) hybrid bulk layups. In addition to hybridising with Zylon, we apply titanium (Ti) foils to both the monolithic and hybrid CFRP-based laminates to investigate and compare their response. For all our hybrids, we kept the ratio of the hybridising material(s) to be less than 50% to ensure suitable in-plane mechanical properties and aimed at a target areal weight of 0.95 g/cm^2. We also manufactured QI thick- and thin-ply monolithic CFRP laminates as baselines. We tested all laminates at 170 and 210 m/s and studied their response and failure modes. Our results show that the average energy dissipation of the QI monolithic thin-ply baseline improved by up to 22% by changing the layup from QI to BI, and by about 118% by changing the baseline QI layup to BI hybrid interleaved. Post-mortem analysis reveals that there are additional failure mechanisms activated in the BI hybrid interleaved layup with respect to the baseline.

1. Introduction

The aerospace industry has seen an ever-growing increase in the application of carbon fibre-reinforced polymer (CFRP) composite structures in its various sectors and products. Although CFRP composite structures provide excellent strength- and stiffness-to-weight ratios, they are brittle, which can question their applications and suitability in areas where there is a possibility of out-of-lane loadings, such as low-velocity impact (LVI) and high-velocity impact (HVI) [1–4]. For instance, in an aircraft, some areas can be subject to severe out-of-plane loadings, namely: the leading edge of the wing or the inlet of the engine in the event of a bird(s) strike; or the casing of the engine in the event of a fan blade-off, all representatives of HVI events. However, to keep CFRPs as the base of the structure due to specific design requirements in the aerospace industry and to alleviate their brittle performance at the same time, various approaches have been adopted in the literature to improve the damage tolerance in CFRP-based composite structures.

One of the common approaches for improving the HVI performance of CFRP composite structures is hybridising them with high strain-to-failure materials, such as glass [5,6], basalt [7], aramid [8], ultra-high molecular weight polyethylene (UHMWPE) fibres [9,10] and titanium [11,12] sheets. Although hybridising CFRP composite structures with high strain-to-failure materials usually results in improved response, hybridising can either result in increasing the weight of the composite structures or reducing the in-plane mechanical properties substantially. Thus, based on the design requirements for specific industrial applications, weight and mechanical properties considerations should be taken into account for developing hybrid CFRP-based structures. In this regard, Kazemi et al. [13] developed zone-based CFRP composite concepts. They kept around 80% of the mass of their composite structures as CFRPs (to maintain suitable in-plane mechanical properties) and used hybridising materials for the remaining 20%, and kept a similar areal weight. They revealed that a hybrid CFRP/Zylon laminate concept outperformed the rest of the developed concepts under HVI with an

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https://doi.org/10.1016/j.compositesb.2023.110930
Received 31 May 2023; Received in revised form 28 July 2023; Accepted 2 August 2023
Available online 4 August 2023

improvement in energy dissipation by about 80%.

A second approach to enhance the out-of-plane performance and damage resistance of CFRP composite structures is to apply bio-inspired (BI) helicoidal layup in the structure. In this regard, Mencatelli and Pinho [14] mimicked the helicoidal architecture of the mantis shrimp's dactyl club periodic region and applied it to thin-ply CFRPs consisting of various pitch angles through the thickness of the layup to evaluate the response under LVI. They obtained enhanced damage tolerance through a significant diffused sub-critical damage accumulation before the peak load. Other researchers [15,16] also found similar findings when they applied BI layup in CFRP-based composite structures.

The third approach to enhance the damage resistance and energy dissipation of CFRP-based composites structure is to apply interleaved layer(s) or block(s) of hybridising materials through the thickness, either in an organised or a dispersed way [17]. Interleaving can result in having more delamination zone(s), and thus, lead to enhanced energy dissipation and damage resistance. In this regard, Zhang et al. [18] investigated the LVI behaviour of CFRP composite structures interleaved with glass non-crimp fabrics. They showed that the hybrid layup plays an important role in the peak force, energy dissipation and failure modes. Other researchers [19–22] also studied the role of interleaved hybridising material(s) on the damage resistance of CFRP-based structures.

Potential synergies between the three approaches described above have never been investigated for LVI/HVI. In this study, we fill this gap and develop a new design methodology incorporating bio-inspired and hybrid interleaved layups to develop novel CFRP-based laminates, while keeping the areal weight similar and also maintaining suitable in-plane mechanical properties. We test all developed laminates above the ballistic limit of the QI monolithic baselines, study their response in terms of energy dissipation, and demonstrate their failure modes through post-mortem analysis.

2. Methodology

2.1. Laminates design

Three main failure zones can be defined for composite structures under HVI [13], see Fig. 1 (a):

- crushing and fragmentation at the impact face, zone 1;
- shear plugging from the impact face and possibly towards the back face (which is an unfavourable failure mode due to its limited energy dissipation), zone 2; and
- tensile failure and delamination at the back face (a favourable failure mechanism that can (greatly) enhance damage resistance and energy dissipation), zone 3.

To keep the areal weight constant and maintain suitable in-plane mechanical properties, we apply CFRPs for zones 1 and 2 (from the impact face towards the middle of the laminate, where crushing/fragmentation and possible shear plugging may occur). To improve the damage resistance and energy dissipation at the back face (in zone 3, where tensile failure and delamination occur), we apply Zylon fibre-reinforced polymers, known as PBO. Kazemi et al. [13] demonstrated that applying PBO at the back face significantly improves the response and damage resistance of CFRP-based composite structures under HVI.

Based on this, firstly, in study 1 provided below, we develop BI monolithic CFRP laminates and compare their response under HVI with that of traditional QI monolithic CFRP laminates. Then, in study 2, we hybridise the already developed BI CFRP with BI PBO in both the traditional bulk layup and interleaved layup. Then, in study 3, we hybridise BI monolithic CFRPs and BI hybrid CFRP/PBO with titanium (Ti) foils to further evaluate the response and compare the results.

2.1.1. Study 1: QI vs. BI CFRPs

In study 1, we explore the merit of BI CFRPs over baseline QI laminates, see Fig. 1 (b). For this, we developed and manufactured:

- QI [60/0/60] thick- and thin-ply CFRPs as baselines, see Fig. 2 (a,c);
- BI CFRP laminates, with helicoidal layups using pitch angles smaller than 5° for thin-ply and smaller than 30° for thick-ply CFRP, see Fig. 2 (b,d); and
- QI and BI thin-ply CFRRP/PBO hybrids (Fig. 2 (e,f)), to investigate the role of BI layup in a hybrid setting.

2.1.2. Study 2: bulk vs. interleaved design

In study 2, we explore the merit of hybrid interleaved over hybrid bulk laminates, see Fig. 1 (c). Based on the thickness of CFRPs (either thick- or thin-ply) and PBO, we applied various pitch angles to develop BI hybrid bulk and interleaved laminates. We should emphasise that all developed laminates in study 2 have BI layups. We developed and

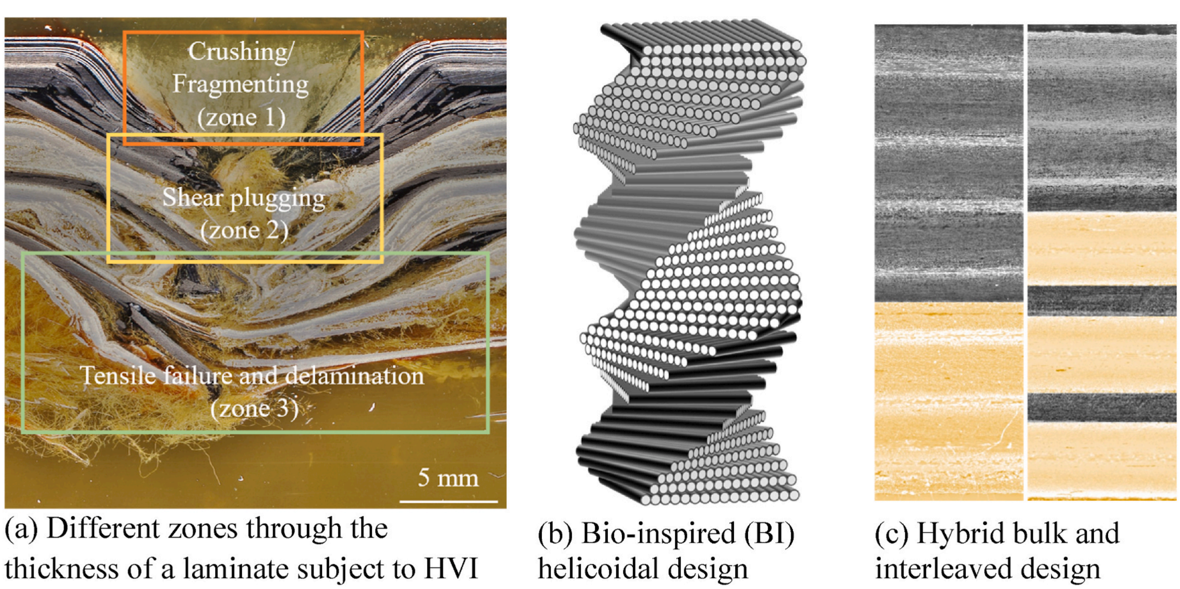


Fig. 1. (a) Different zones through the thickness of a CFRP-based laminate subject to HVI, and the methodology consisting of (b) bio-inspired and (c) hybrid bulk/interleaved designs.

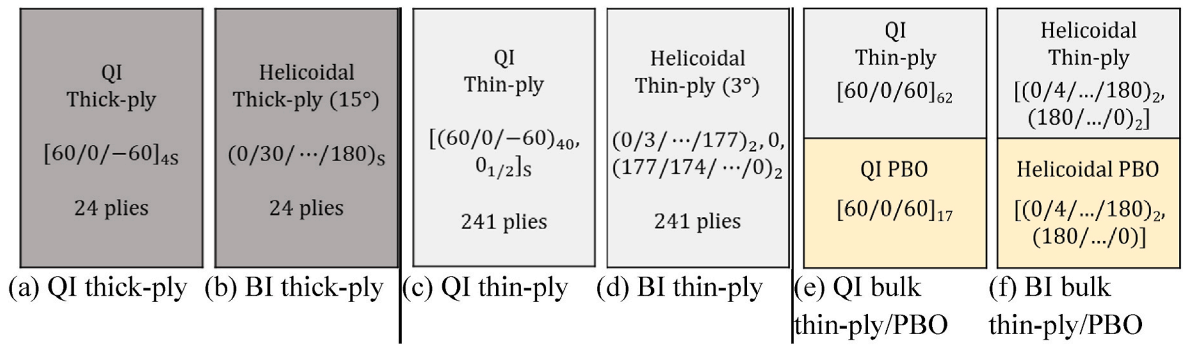


Fig. 2. Schematics of the layups of QI and BI laminates developed in study 1.

manufactured:

- BI hybrid bulk thick- and thin-ply CFRP/PBO, see Fig. 3 (a,c); and
- BI hybrid interleaved thick- and thin-ply CFRP/PBO, see Fig. 3 (b,d).

2.1.3. Study 3: the role of titanium on the response

To investigate the role of titanium (Ti) foils on the response of BI monolithic thick- and thin-ply laminates, as well as on the response of the hybrid interleaved CFRP/PBO laminates, we implemented Ti foils in the aforementioned layups. In study 3, we developed 4 types of BI laminates (Fig. 4): Ti/thick-ply/Ti, Ti/thick-ply/PBO, Ti/thin-ply/Ti and Ti/thin-ply/PBO. All developed laminates in study 3 have BI layups.

2.2. Materials selection

To develop monolithic CFRP laminates, we used two types of CFRP prepregs, thick- and thin-ply. Thick-ply CFRPs are an uni-directional (UD) aerospace-grade carbon-epoxy system with an areal weight of 280 gsm and a thickness of 0.25 mm. Thin-ply CFRPs are ultra-thin UD Skyflex USN20A prepregs with an areal weight of 20 gsm and a thickness of 0.05 mm. To develop hybrid CFRP/PBO laminates, we used ultra-thin UD PBO fibre-reinforced polymers (Zylon-HM545T prepregs consisting of a toughened epoxy system, ThinPreg™ (TP)513) with an areal weight of 25 gsm. In addition, to develop another type of hybrid laminate, we used titanium foils (ASTM B265 Grade 2) with a thickness of 0.5 mm, attached with 3M epoxy resin adhesive films together without any surface treatment. More information about the material properties can be found in Kazemi et al. [13].

2.3. Manufacturing and testing

We manufactured all laminates with an areal weight of about 0.95 g/cm^2 and with dimensions of 100 × 150 mm. Following materials suppliers' guidelines, we manufactured the thin-ply CFRPs in an autoclave

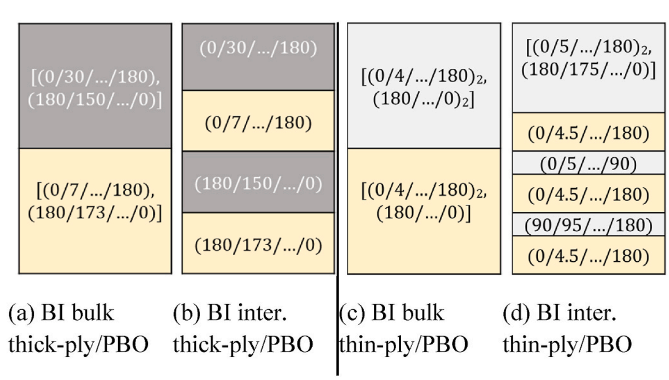


Fig. 3. Schematics of the layups of BI hybrid bulk and interleaved CFRP/PBO laminates developed in study 2.

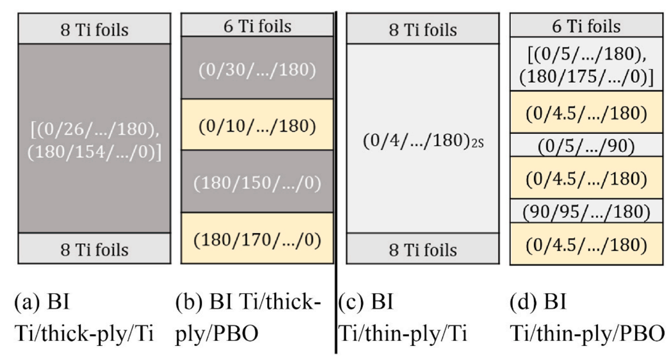


Fig. 4. Schematics of the layups of BI hybrid laminates with Ti foils developed in study 3.

at 125 °C and 5 bar. Information regarding the manufacturing of thick-ply laminates is not disclosed due to its commercially sensitive nature. We co-cured PBOs with thick- or thin-ply CFRPs depending on the laminate. Table 1 shows the precise layups and other properties of the laminates, followed by their manufactured cross-section images in Fig. 5. To perform HVI tests, we used a gas gun firing a spherical steel projectile with a diameter of 14 mm to the specimens mounted on a simply-support boundary conditions test rig. To track the HVI and calculate the impact and rebound/perforation velocities, we used two Vision Research Phantom V7.3 high-speed cameras in the test setup. We tested all developed laminates at 170 m/s (equivalent to 162 J) and 210 m/s (equivalent to 248 J), both above the ballistic limit of the QI monolithic thick-ply laminate (measured ∼150 m/s) and thin-ply laminate (measured ∼130 m/s).

3. Results

3.1. Study 1: QI vs. BI CFRPs

Fig. 6 (a) shows the energy dissipation of the developed laminates in study 1, namely QI and BI monolithic thick- and thin-ply CFRP laminates as well as QI and BI thin-ply/PBO laminates all impacted at 170 and 210 m/s. After measuring the energy dissipations of the developed laminates, if perforation occurred, we provide their average values in Fig. 6 (b), and if perforation did not occur, we provide the highest amount of energy dissipation for that developed laminate (which is for 210 m/s), Fig. 6 (b). Fig. 7 shows the post-mortem, consisting of impact face, back face and delamination area images of the developed laminates in study 1 impacted at 210 m/s. Fig. 8 presents the cross-sections of impacted developed BI monolithic thick- and thin-ply CFRP laminates and their QI baselines, followed by the fracture surface analysis of the developed BI monolithic thick-ply laminate impacted at 210 m/s provided in Fig. 9.

Table 1
Name, layups and properties of the developed laminates.

	Laminate name	Layup (pitch angle)	Thickness (mm)	Hybridising material(s) ratio	Areal weight (g/cm^2)
Thick-ply family	QI[a] thick-ply	$(60/0/\text{-}60)_{4S}$	6.4	0	0.94
	BI[b] thick-ply	$(0/30/ \ldots /180)_S$	7.1	0	1.12
	BI bulk thick-ply/PBO	$(0/26/ \ldots /180)_S$, $(0/5/ \ldots /180)_S$	8.0	0.46	1.17
	BI interleaved thick-ply/PBO	(0/30/ … /180), (0/7/ … /180), (180/150/ … /0), (180/173/ … /0)	6.8	0.43	1.02
	BI Ti/thick-ply/Ti	Ti_8, $(0, 26, \ldots, 180)_S$, Ti_8	5.1	0.38	1.01
	BI interleaved Ti/thick-ply/PBO	Ti_6, (0/30/ … /180), (0/10/ … /180), (180/150/ … /0), (180/170/ … /0)	6.5	0.43	1.05
Thin-ply family	QI thin-ply	$[(60/0/\text{-}60)_{40}, 0_{1/2}]_S$	5.5	0	0.84
	BI thin-ply	$(0/3/ \ldots /177)_2$, 0, $(177/ \ldots /0)_2$	5.1	0	0.77
	QI bulk thin-ply/PBO	$(60/0/\text{-}60)_{62}$, $(60/0/\text{-}60)_{17}$	5.4	0.42	0.80
	BI bulk thin-ply/PBO	$(0/4/ \ldots /180)_2$, $(180/176/ \ldots /0)_2$, $(0/4.5/ \ldots /180)_2$, $(180/175.5/ \ldots /0)$	8.0	0.42	1.12
	BI interleaved thin-ply/PBO	$(0/5/ \ldots /180)_2$, (180/175/ … /0), (0/4.5/ … /180), (0/ … /90), (0/ … /180), (90/ … /180), (0/ … /180)	7.2	0.44	1.02
	BI Ti/thin-ply/Ti	Ti_8, $(0/4/ \ldots /180)_{2S}$, Ti_8	4.9	0.38	0.82
	BI interleaved Ti/thin-ply/PBO	Ti_6, $(0/5/ \ldots /180)_S$, (0/4.5/ … /180), (0/ … /90), (0/ … /180), (90/ … /180), (0/ … /180)	7.0	0.58	1.06

[a] QI: quasi-isotropic
[b] BI: bio-inspired (Helicoidal).

3.2. Study 2: bulk vs. interleaved design

Fig. 10 (a) provides the values of energy dissipation of the BI hybrid bulk and interleaved CFRP/PBO laminates impacted at 170 and 210 m/s, and Fig. 10 (b) provides their average values compared to the BI monolithic CFRP laminates. Fig. 11 shows the post-mortem images of the developed BI hybrid laminates (in study 2), followed by their selected impacted cross-section images in Fig. 12.

3.3. Study 3: the role of titanium on the response

Fig. 13 provides results regarding the role of titanium on the response of developed BI monolithic and hybrid interleaved laminates (in study 3), followed by post-mortem images demonstrated in Fig. 14. Finally, Fig. 15 shows the cross-sections of the selected developed interleaved CFRP/PBO and Ti/CFRP/PBO laminates impacted at 170 and 210 m/s.

4. Discussion

4.1. Study 1: QI vs. BI CFRPs

As Fig. 6 shows, changing the layup from QI to BI enhanced the (average) energy dissipation for both monolithic thick- and thin-ply laminates by about 24% and 22%, respectively. To evaluate the role of BI layup on the response of hybrid laminates as well, we hybridised and tested the thin-ply CFRP with PBO fibres (thin-ply/PBO). Compared to QI thin-ply/PBO, BI thin-ply/PBO showed about 13% improvement in average energy dissipation. Moreover, QI thin-ply/PBO perforated at 170 and 210 m/s, while BI thin-ply/PBO rebounded the projectile at 170 m/s and sandwiched it at 210 m/s. As we did not observe perforation for BI thin-ply/PBO at either of the velocities, as mentioned in the result section, we did not provide the average value for energy dissipation, and thus, used maximum energy dissipation obtained at 210 m/s, Fig. 6 (b). BI thin-ply/PBO laminate showed about 97% improvement in energy dissipation compared to QI monolithic thin-ply baseline.

To explain the improved response of developed BI laminates compared to QI counterparts, we performed post-mortem analyses including micrography of the impact and back faces, as well as C-scan. As Fig. 7 (a,b) show, back face images of QI and BI monolithic thick-ply laminates do not present much difference in terms of failure pattern (except the way that the back face of QI thick-ply baseline failed in a straight line pattern, but the BI thick-ply laminate failed in a helicoidal pattern). Comparing the back face of QI and BI monolithic thin-ply laminates impacted at 210 m/s (in Fig. 7 (c,d)), we can observe that the QI monolithic thin-ply baseline failed mostly in shear, and we did not notice extended damage at the back face, while for the BI monolithic thin-ply laminate, the back face failed in tension and we observed helicoidal matrix/fibre failure, Fig. 7 (d). As Fig. 7 (e) shows, the back-face PBO fibres failed at 210 m/s, where perforation occurred for the QI thin-ply/PBO laminate; however, by changing the layup from QI to BI, the extent of delamination increased, resulting in more energy dissipation by the BI layup and thus resisting against perforation. In this developed (BI thin-ply/PBO) laminate, we did not notice any back-face PBO fibre failure, Fig. 7 (f).

By comparing the C-scan of the QI and BI monolithic thick-ply laminates impacted at 210 m/s, provided in Fig. 7 (a,b), we observed that the extent of damage in the BI laminate is much larger than that of the QI baseline, which is due to the formation of helicoidal matrix cracks from the impact face towards the back face and their migration from one ply to another. The C-scan image of the QI monolithic thin-ply baseline also confirms that the damage extent is limited to around the impactor, Fig. 7 (c). However, as the BI monolithic thin-ply laminate failed mainly in tension and helicoidal matrix/fibre formed towards the back face, we observed a much larger delamination area, Fig. 7 (d). Nonetheless, both QI and BI monolithic thick-ply laminates perforated at 170 and 210 m/s.

The cross-section of the QI monolithic thin-ply baseline (Fig. 8 (b)) shows that the damage is mainly due to shear plugging and there is no indication of delamination in plies away from the impact region. However, by replacing the QI layup by BI, the back plies failed in tension rather than in shear, and delamination extended from the impact region to the area far from the impact region, Fig. 8 (d). The same scenario happened to the thick-ply counterparts, Fig. 8 (a,c).

The fracture surface of a BI monolithic thick-ply laminate impacted at 210 m/s, provided in Fig. 9, demonstrates: the helicoidal orientation of the thick-ply CFRP fibres, impacted (broken) CFRPs at the impact zone, the matrix cups, and thus the direction of crack propagation on the fracture surface. This confirms the helicoidal matrix cracks initiated at

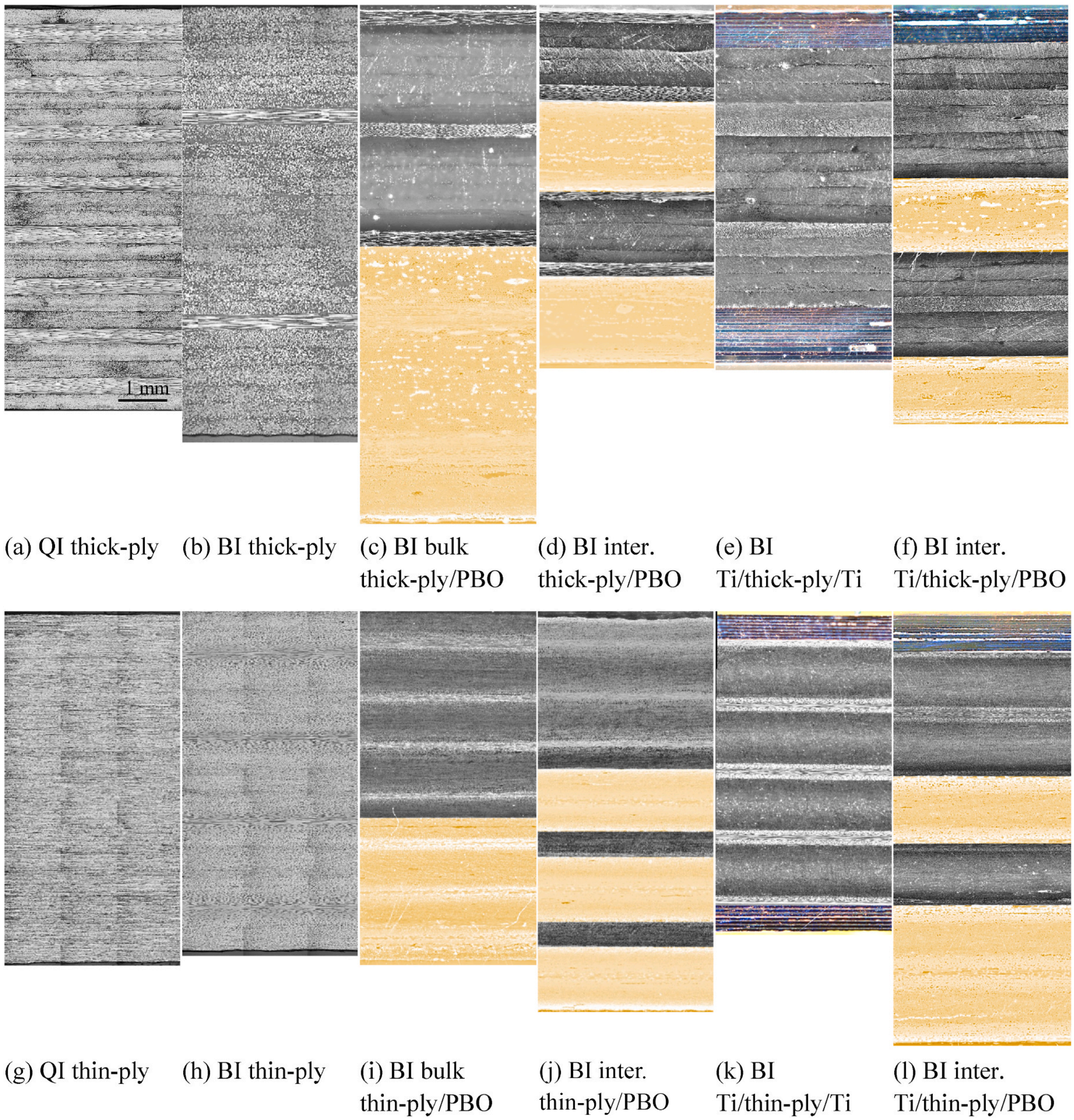


Fig. 5. Cross-sections of developed thick- and thin-ply laminates (scaled).

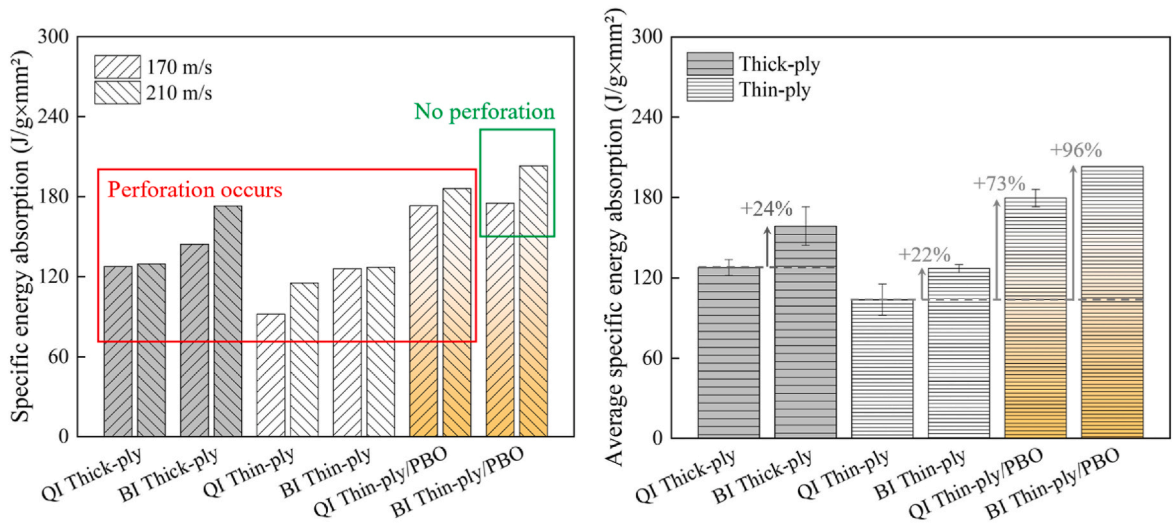
the impact region and propagated towards the edges of the specimen.

4.2. *Study 2: bulk vs. interleaved design*

As Fig. 10 (a) shows, changing the hybrid layup from bulk to interleaved for BI thick-ply/PBO resulted in an improvement of about 22% in (average) energy dissipation. Compared to the BI monolithic thick-ply laminate, the average energy dissipation for the BI bulk and BI interleaved thick-ply/PBO laminates improved by about 26% and 78%, respectively, Fig. 10 (b). Compared to QI monolithic thick-ply baseline, the average energy dissipation for the BI bulk and BI interleaved thick-ply/PBO laminates improved by about 57% and 90%, respectively, Fig. 10 (b).

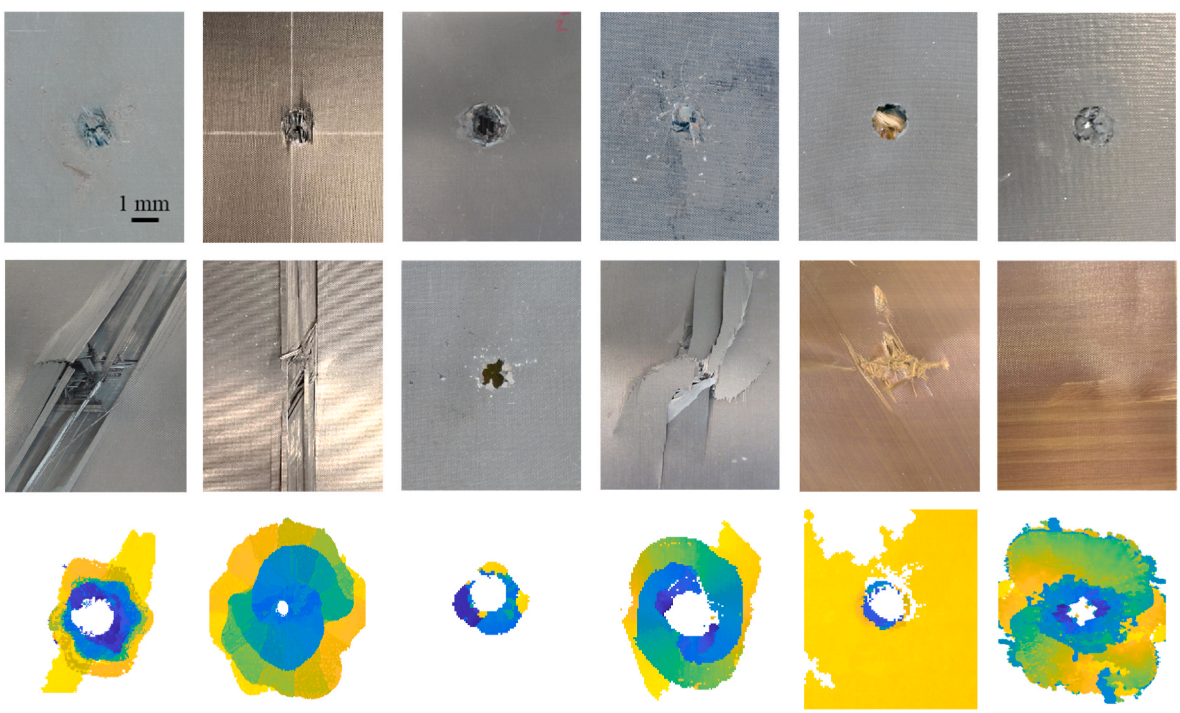
In a similar way for thick-ply laminates, changing the layup from bulk to interleaved for BI thin-ply/PBO resulted in an improvement of about 11% in average energy dissipation. Compared to BI monolithic thin-ply laminate, the average energy dissipation for the BI bulk and BI interleaved thin-ply/PBO laminates improved by about 60% and 78%, respectively, Fig. 10 (b). Compared to QI monolithic thin-ply baseline, the average energy dissipation for the BI bulk and BI interleaved thick-ply/PBO laminated improved by about 96% and 118%, respectively, Fig. 10 (b).

Post-mortem analysis of the BI hybrid bulk and interleaved CFRP/PBO laminates provided in Fig. 11 and Fig. 12 demonstrate that both hybrid bulk and interleaved layups (for either thick- or thin-ply laminates) resisted perforation. By analysing the selected impact face, back face, and cross sections of the hybrid bulk and interleaved laminates, provided in Fig. 11 and Fig. 12, we observed that the projectile rebounded at 170 m/s or sandwiched inside the laminates at 210 m/s. C-scan images in Fig. 11 demonstrate the increase of the size of the delamination when the layup changed from monolithic to hybrid bulk, and increased further when the layup changed from hybrid bulk to hybrid interleaved. By comparing the cross-sections of hybrid thick-ply/PBO laminates impacted at 170 and 210 m/s, provided in Fig. 12, we observed that the layup with the interleaved design showed extra failure mechanisms compared to the bulk design due to having more delamination zones (resulting in more energy dissipation). In addition, having a PBO block in the middle of the layup (in the interleaved design) let the



(a) Specific energy dissipation (b) Average specific energy dissipation

Fig. 6. Energy dissipation of developed BI laminates (in study 1) and their comparison to QI baselines.



(a) QI thick-ply (b) BI thick-ply (c) QI thin-ply (d) BI thin-ply (e) QI thin-ply/PBO (f) BI thin-ply/PBO

Fig. 7. Post-mortem (consisting of impact and back face as well as delamination) images of developed BI laminates (in study 1) impacted at 210 m/s and their comparison to QI baselines.

laminate undergo more deformation when impacted either at 170 or 210 m/s.

4.3. Study 3: the role of titanium on the response

Replacing some of the carbon fibres with titanium (Ti) foils at the impact and back faces of BI thick- or thin-ply laminates showed a marginal improvement in average energy dissipation (around 5%), Fig. 13. However, regarding hybrid interleaved CFRP/PBO layups, replacing some of the carbon fibre (at the impact face) with Ti foils or replacing some of the PBO fibres (at the back face) with impact-faced Ti foils did not contribute any further to the improvement of the response (compared to their corresponding interleaved hybrid CFRP/PBO counterparts). Nonetheless, the response of Ti/CFRP/PBO for either thick or thin-ply laminates outperformed the response of the corresponding QI and BI monolithic CFRP laminates or that of the Ti/CFRP/Ti counterparts.

Finally, by observing the post-mortem images of the developed Ti-

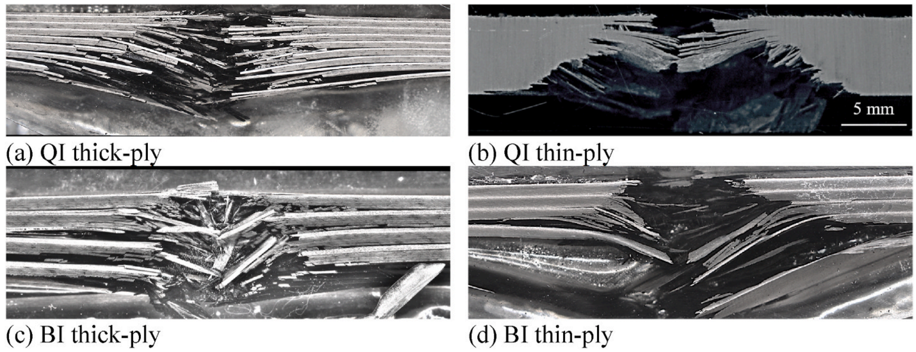


Fig. 8. Cross-section images of developed QI and BI monolithic thick-ply (a,c) and thin-ply (b,d) laminates impacted at 210 m/s.

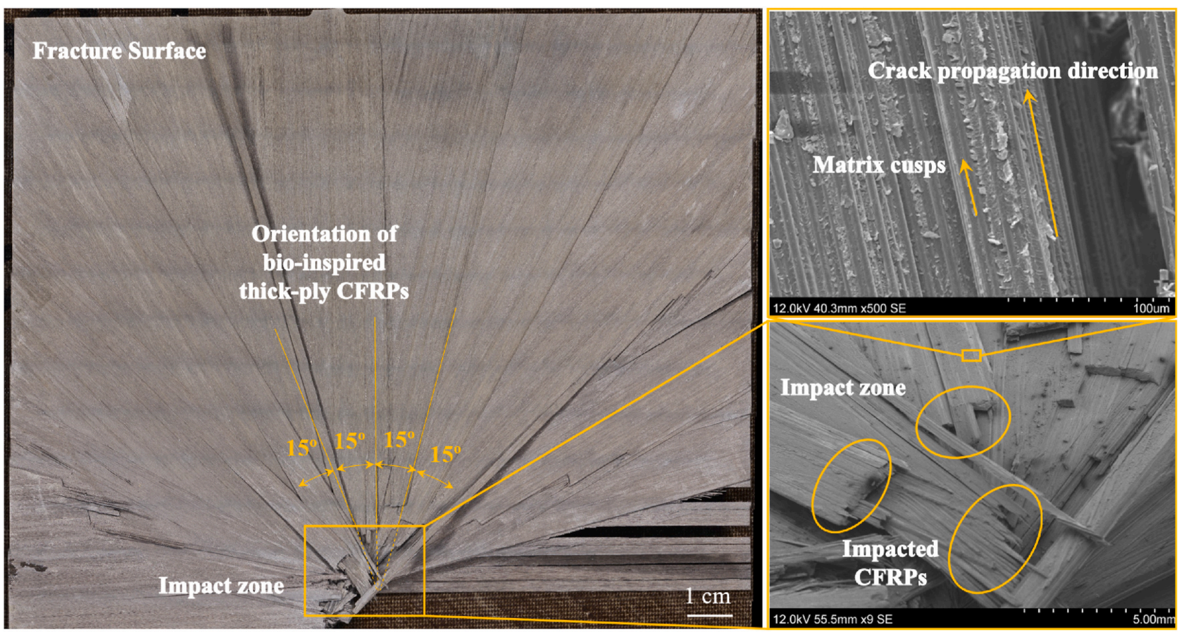


Fig. 9. Fracture surface of developed BI monolithic thick-ply laminate impacted at 210 m/s.

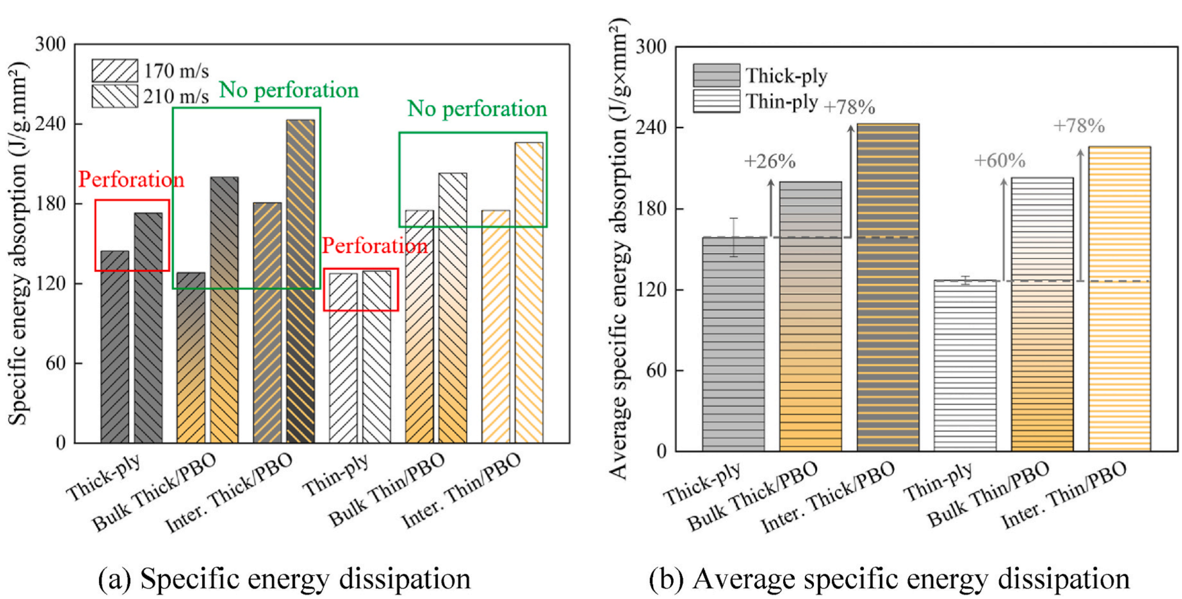


Fig. 10. Energy dissipation of developed bio-inspired bulk and interleaved hybrid laminates (in study 2) and their comparison to BI monolithic laminates.

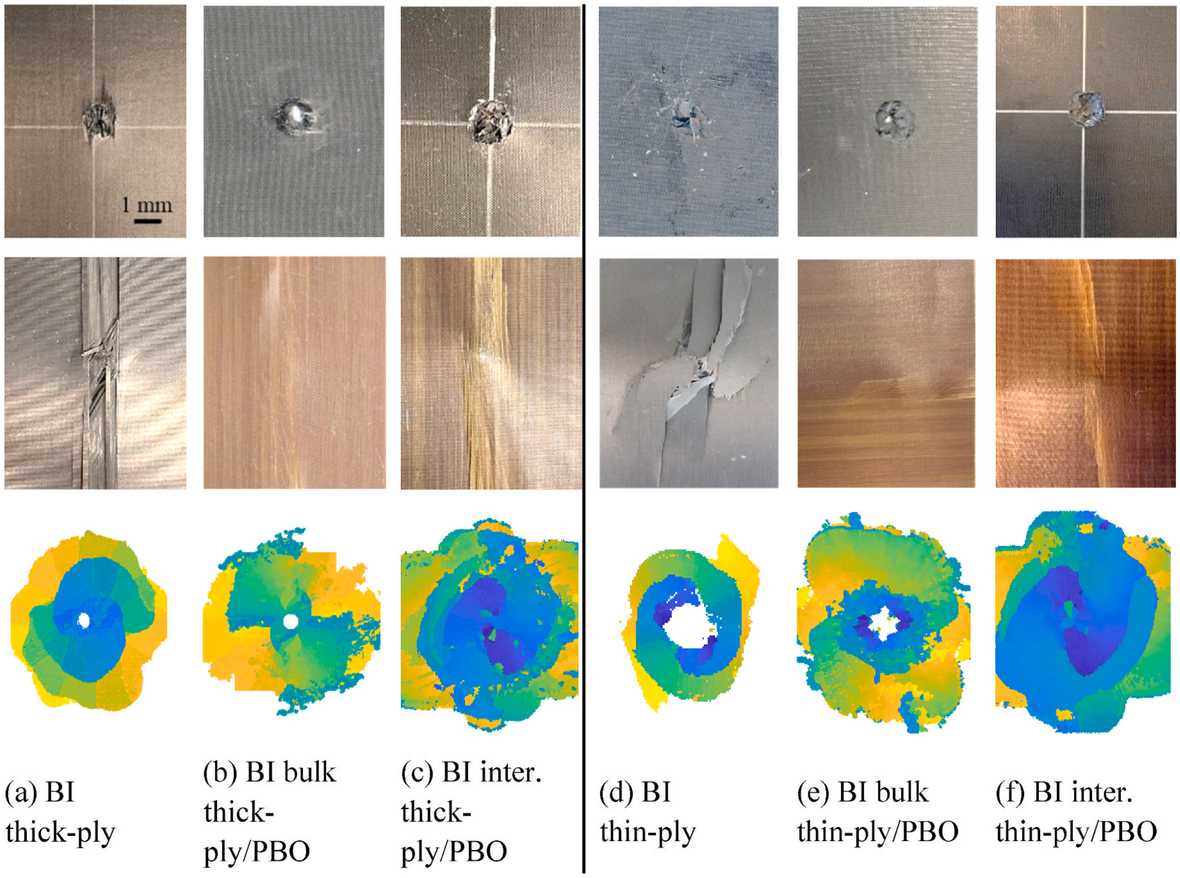


Fig. 11. Post-mortem (consisting of impact and back face as well as delamination) images of developed bio-inspired bulk and interleaved hybrid laminates (in study 2) impacted at 210 m/s and their comparison to BI monolithic laminates.

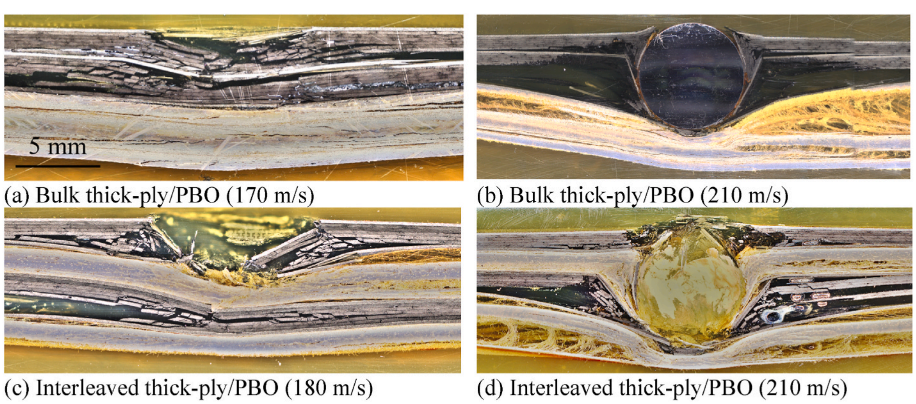


Fig. 12. Cross-sections of developed hybrid (a,b) bulk and (c,d) interleaved thick-ply/PBO laminates (in study 2) impacted at ~170 m/s and 210 m/s.

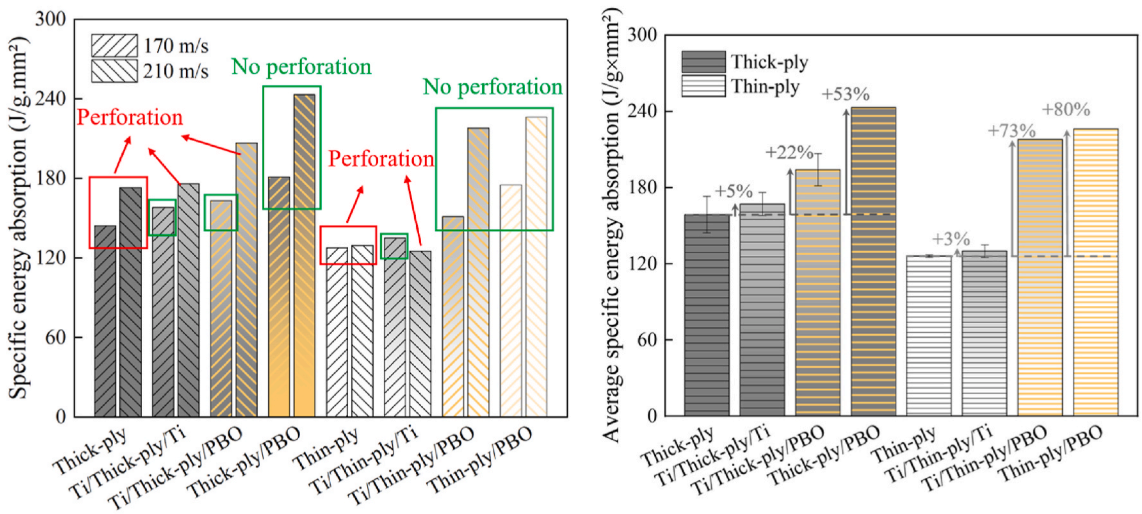
based laminates provided in Fig. 14, we find that both BI thick- and thin-ply Ti/CFRP/Ti laminates perforated at 210 m/s. An adhesive failure occurred between the Ti sheets and the composite laminate. By comparing the C-scan images of the Ti-based laminates, we notice that the extent of delamination is smallest for the Ti/CFRP/Ti laminates, which increased in size in the Ti/CFRP/PBO laminates, and finally, reached its largest size in the CFRP/PBO laminates, confirming energy dissipation values obtained in Fig. 13. The cross-sections of developed hybrid thin-ply laminates, i.e., thin-ply/PBO and Ti/thin-ply/PBO, demonstrate that the presence of Ti foils precluded the shear failure of the top block of CFRPs failing at 45°, Fig. 15. However, it appears that adding Ti layers to the impact face did not result in further damage mechanisms in the layups.

5. Conclusions

In this study, we designed and developed novel bio-inspired (BI) and hybrid interleaved CFRP-based laminates for improved HVI response. We tested the developed laminates at 170 and 210 m/s and characterised their response and failure modes.

Firstly, we applied various pitch angles based on the ply thickness of CFRPs to develop BI monolithic laminates and concluded the following:

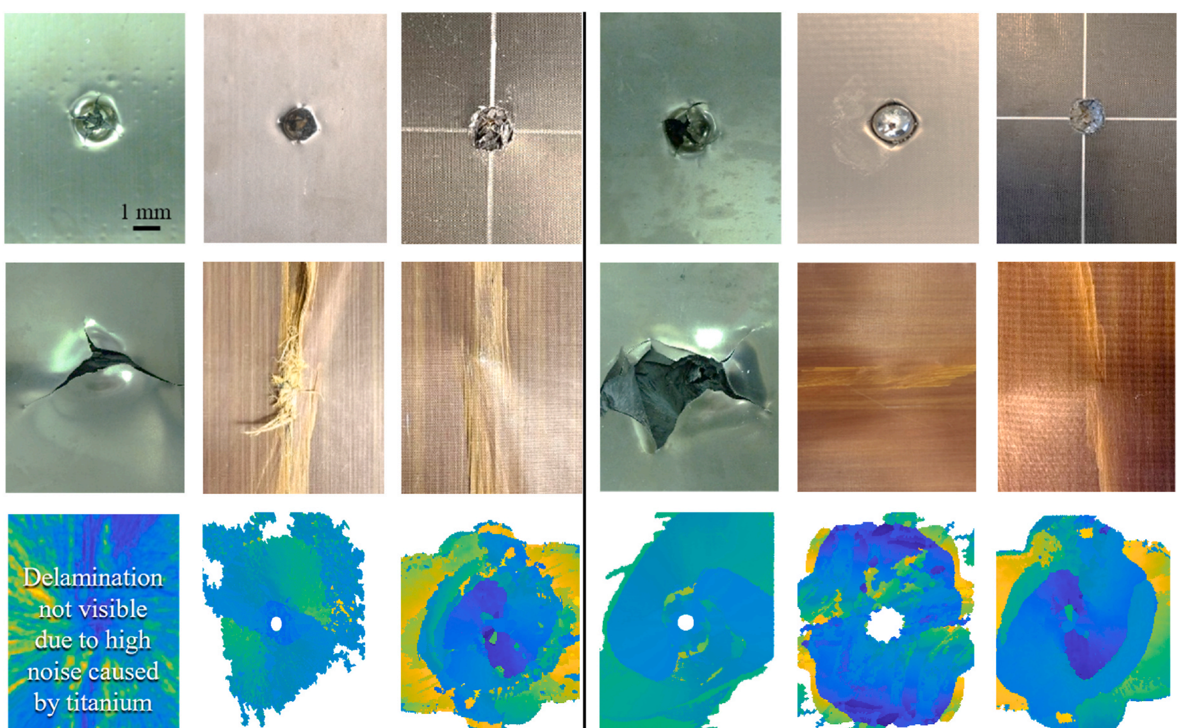
- replacing the QI layup of the monolithic CFRP baselines by BI resulted in an increase of about 24% (for the thick-ply) and about 22% (for the thin-ply laminates) in energy dissipation;



(a) Specific energy dissipation of developed BI laminates with Ti at the impact face

(b) Average specific energy dissipation of developed BI laminates with Ti

Fig. 13. Energy dissipation of developed BI laminates with Ti at the impact face (in study 3) and their comparison to BI monolithic laminates.



(a) BI Ti/thick-ply/Ti (b) BI Ti/thick-ply/PBO (c) BI thick-ply/PBO (d) BI Ti/thin-ply/Ti (e) BI Ti/thin-ply/PBO (f) BI thin-ply/PBO

Fig. 14. Post-mortem (consisting of impact and back face as well as delamination) images of developed BI laminates with Ti at the impact face (in study 3) impacted at 210 m/s and their comparison to CFRP/PBO laminates.

- hybridising the QI thin-ply baseline with PBO fibres (QI thin-ply/PBO) improved the energy dissipation by about 73%; changing the layup from QI to BI for this hybrid (thin-ply/PBO) further increased energy dissipation by about 13%; making it about 97% in total improvement compared to that of the QI thin-ply baseline; and
- the post-mortem C-scan of the QI thin-ply baseline showed that the failure mode is mainly shear plugging, and that delamination and matrix cracks are limited to the vicinity of the impact region; however, replacing the QI layup by BI increased the delamination size

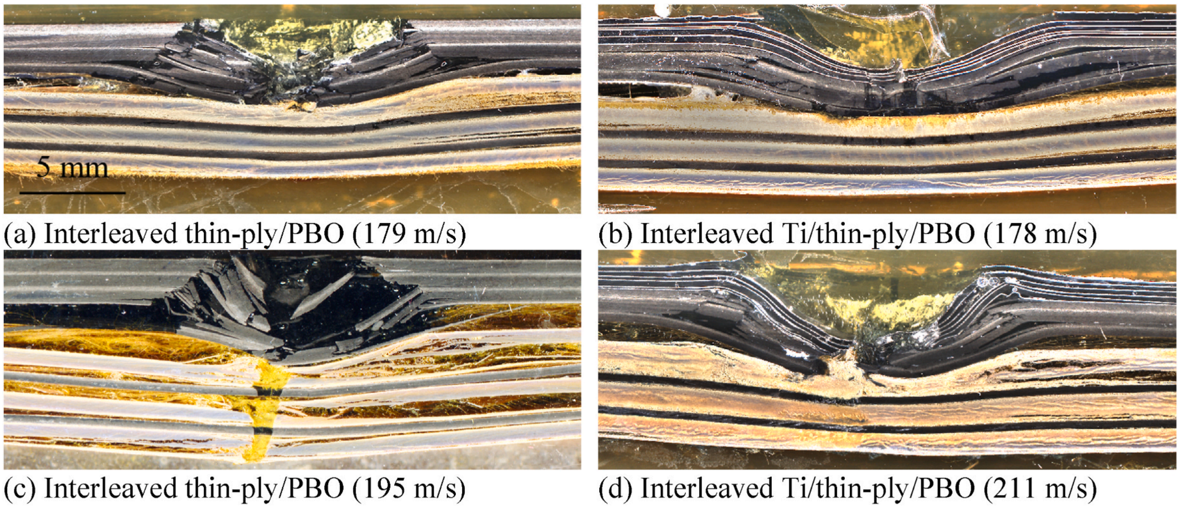


Fig. 15. Cross-sections of developed hybrid interleaved (a,c) thin-ply/PBO (in study 2) and (b,d) Ti/thin-ply/PBO laminates (in study 3) impacted at ~170 m/s and ~210 m/s.

and matrix cracks significantly, and the failure mode changed to tensile failure and delamination.

Following this, we hybridised the monolithic BI laminates with blocks of BI PBO fibres in both bulk and interleaved ways, and found that:

- replacing the bulk layup by interleaved layup in the BI hybrid thick-ply/PBO resulted in an improvement of about 22% in energy dissipation; we also observed a similar trend (maximum of about 11% improvement) in the BI thin-ply/PBO laminate;
- compared to BI monolithic laminate, the BI hybrid interleaved CFRP/PBO laminates improved energy dissipation by up to 78% for both thick- and thin-ply; and
- post-mortem analysis of impacted hybrid laminates revealed that, in contrast to monolithic CFRP laminates, both BI hybrid bulk and interleaved laminates resisted perforation; the analysis also showed that the layup with the interleaved design exhibited additional failure mechanisms, such as having more delamination zones, which resulted in more energy dissipation and damage resistance.

Finally, we applied titanium foils to both of the monolithic CFRP and also the hybrid CFRP/PBO laminates and concluded that:

- replacing some of the CFRPs in the developed BI monolithic laminates with titanium foils on the impact and back faces did not substantially improve the energy dissipation; we observed only a marginal improvement, around 5%, for both the thick- and thin-ply laminates; and
- by replacing either some of the carbon fibres at the impact face with Ti foils, or by replacing some of the back-faced PBO fibres with impact-faced Ti foils, we did not observe any further improvement in the response compared to that of the interleaved CFRP/PBO laminates; nonetheless, developed Ti/CFRP/PBO laminates improved the response of QI monolithic thick- and thin-ply CFRP laminates by about 52% and 110%, respectively.

Given our results and further taking into account manufacturing practicalities, the developed BI hybrid interleaved thick-ply/PBO laminate proved to be the best-performing one. This laminate shows great potential for application in an industrial-sized 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.

Credit authorship contribution statement

M.Erfan Kazemi: Conceptualisation, Methodology, Investigation, Formal analysis, Visualisation, Writing – original draft. Victor Médeau: Conceptualisation, Methodology, Investigation. Emile Greenhalgh: Resources, Supervision, Funding acquisition. Paul Robinson: Resources, Supervision, Funding acquisition. James Finlayson: Conceptualisation, Resources, Project administration. Silvestre T. Pinho: Conceptualisation, Methodology, Writing – review & editing, Supervision, Funding acquisition, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgements

The funding from Innovate UK under the UKRI FANDANGO project No. 113232 (https://gtr.ukri.org/projects?ref=113232) is gratefully acknowledged.

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