

Influence of Fibre Architecture on Mechanical Performance and Failure Mechanisms of CF/LMPAEK Thermoplastic Composites under Flexural and Impact Loading

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ABSTRACT

Carbon fibre reinforced low-melt polyaryletherketone (CF/LMPAEK) composites have gained considerable attention for aerospace applications due to their high specific strength, weldability, recyclability, and damage tolerance. However, the relationship between fibre architecture, mechanical performance, and failure mechanisms remains insufficiently understood. This study investigates the effect of three laminate configurations, namely unidirectional (UD) [0/90]8s, woven [(0,90)]4s, and hybrid woven [(0,90)/(±45)]2s, on the flexural and impact behaviour of CF/LMPAEK composites. Flexural properties were evaluated using three-point bending according to EN 2562, while impact resistance was assessed using the unnotched Izod test following ASTM D256. Failure mechanisms were examined through optical microscopy and scanning electron microscopy (SEM). The woven [(0,90)]4s laminate demonstrated the highest flexural strength (903.55 MPa) and maximum load capacity (509.00 N), attributed to effective stress redistribution and enhanced fibre interlocking within the woven architecture. Meanwhile, the UD [0/90]8s laminate exhibited the highest flexural modulus (66.39 GPa) and impact strength (179.63 kJ/m²), resulting from efficient load transfer along the aligned fibre direction. The hybrid [(0,90)/(±45)]2s laminate achieved the highest flexural strain (0.0201), indicating improved deformation capability, with intermediate flexural strength (779.56 MPa) and impact strength (158.94 kJ/m²). Microscopic observations revealed delamination-dominated failure in the UD laminate, whereas woven and hybrid laminates exhibited fibre pull-out, matrix cracking, and localised compressive damage. SEM analysis further confirmed fibre fracture and fibre pull-out as the dominant impact-induced damage mechanisms.

Keywords: CF/LMPAEK thermoplastic composites; fibre architecture; flexural properties; impact behaviour; failure mechanisms

INTRODUCTION

The aerospace industry is progressively transitioning from traditional thermoset composites to high-performance thermoplastics, driven by the demand for rapid manufacturing, recyclability, and weight reduction (Lona et al. 2021; Sharif et al. 2024; Hamdan et al. 2026). Conventional thermoset composites, although widely utilised, exhibit inherent brittleness, long curing cycles, and limited reprocessability due to their crosslinked molecular structure (Günther et al. 2021; David Whisnant, 2022). In contrast, thermoplastic composites offer superior toughness, shorter processing cycles, and the ability to be reheated and reshaped without permanent chemical degradation, making them highly attractive for modern aerospace applications (Zuo et al. 2019; Sharif et al. 2024; Yuan et al. 2025).

Among high-performance thermoplastics, the polyaryletherketone (PAEK) family, including PEEK and PEKK, has gained considerable attention due to its excellent mechanical strength, thermal stability, and chemical resistance (Maloo et al. 2022; Sharif et al. 2024). However, their high melting temperatures present significant processing challenges, including increased energy consumption and manufacturing complexity. To address these limitations, Low Melt Polyaryletherketone (LMPAEK) has emerged as a strategic alternative, offering reduced melting temperature and improved processability while maintaining comparable mechanical and thermal performance (Kurtz, 2019; Wilkins & Strauss, 2023; Zhang et al. 2023). The lower melting temperature of LMPAEK enhances energy efficiency and facilitates fusion bonding techniques such as welding, eliminating the need for mechanical fasteners and contributing to significant weight reduction in aircraft structures (Choi et al. 2023; Pohl et al. 2024).

Despite these advantages, the structural performance of Carbon Fibre Reinforced Thermoplastic Composites (CFRTPs) is fundamentally governed by fibre architecture, including fibre orientation, stacking sequence, and textile configuration (Chowdhury & Summerscales, 2024; Iquilio et al. 2024). Unidirectional (UD) laminates are widely favoured for their superior stiffness and tensile strength along the fibre axis due to efficient load transfer through aligned fibres (Belliveau et al. 2023). However, their highly anisotropic nature makes them susceptible to transverse cracking, matrix-dominated failure, and interlaminar delamination, particularly under impact or multi-axial loading conditions (Rana & Figueiro 2016; Ropers 2017).

In contrast, woven fibre architectures provide improved damage tolerance and structural stability due to fibre interlacing, which promotes better stress redistribution

and resistance to crack propagation (Iquilio et al. 2024; Kushwaha & Meyer, 2025). Nevertheless, the presence of fibre crimp reduces effective stiffness, as fibres must first straighten before carrying the applied load, resulting in lower modulus compared to unidirectional laminates (Ropers, 2017).

To overcome these trade-offs, hybrid laminate configurations incorporating multiple fibre orientations, such as the integration of $0^\circ/90^\circ$ with $\pm 45^\circ$ plies, have been proposed as a promising approach to achieve a balance between stiffness, strength, and damage tolerance (GuruRaja et al. 2013; Nourmohammadi et al. 2025). The inclusion of $\pm 45^\circ$ layers enhances shear resistance, promotes stress redistribution, and improves energy absorption under complex loading conditions (Azam et al. 2022).

Although carbon fibre reinforced thermoplastic composites have attracted considerable attention for aerospace applications due to their superior mechanical performance, weldability, and recyclability, research on LMPAEK composites remains relatively limited compared with other members of the PAEK family, particularly PEEK and PEKK. Furthermore, the influence of fibre architecture on the mechanical behaviour and failure mechanisms of CF/LMPAEK laminates has not been comprehensively investigated. This limitation is significant because fibre orientation and stacking sequence directly affect load transfer efficiency, damage propagation, and structural integrity under service loading conditions, all of which are critical considerations in aerospace structural design.

Therefore, this study focuses on CF/LMPAEK laminates and aims to evaluate the effect of different fibre architectures, namely Unidirectional (UD) $[0/90]_8s$, Woven $[(0,90)]_4s$, and Hybrid $[(0,90)/(\pm 45)]_2s$, on their flexural and impact performance. By integrating mechanical characterisation with morphological failure analysis, the study seeks to establish a clear structure property relationship between laminate architecture and mechanical response. The findings are expected to provide a deeper understanding of the failure behaviour of CF/LMPAEK composites and to assess the feasibility of different laminate configurations for future lightweight and damage tolerant aerospace structures.

METHODOLOGY

MATERIAL PREPARATION

The material employed in this study was Toray Cetex® TC1225, a high-performance carbon fibre reinforced thermoplastic composite based on a low-melt polyaryletherketone (LMPAEK) resin system. The

laminates were procured directly from the manufacturer in fully consolidated (pre-consolidated) plate form, with the fibre reinforcement and matrix already integrated under controlled industrial processing conditions. Consequently, laminate fabrication and consolidation were not included within the scope of the present research, as the study focused exclusively on the mechanical characterisation.

Three distinct laminate architectures were investigated, namely unidirectional (UD), woven, and hybrid woven configurations. The supplied laminates exhibited a uniform

fibre matrix distribution, providing a consistent baseline for evaluating the influence of processing parameters on the resulting mechanical and thermal performance.

The surface morphology of the laminates, as illustrated in Figure 1 and Figure 2, highlights the distinct fibre architectures and clearly differentiates the carbon fibre reinforcement from the LMPAEK matrix in each configuration. The detailed laminate architectures and material specifications are summarised in Table 1.

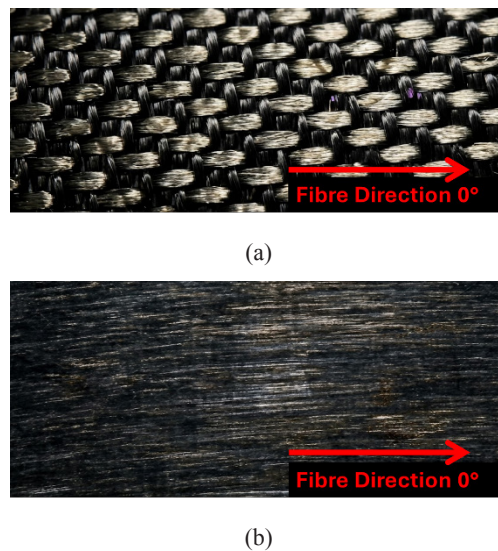


FIGURE 1. Surface view of CF/LMPAEK for (a) Woven [(0,90)/(±45)]2s, & Woven [(0,90)]4s, and (b) UD [0/90]8s, configurations.

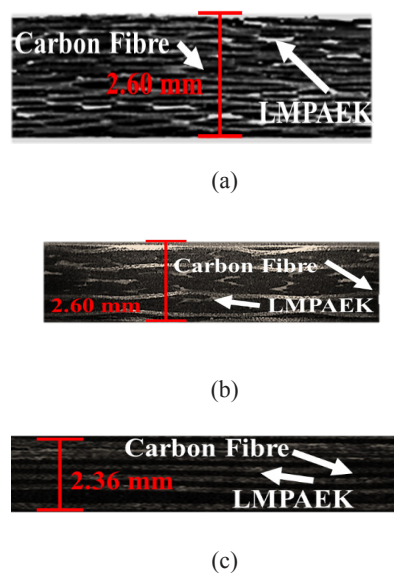


FIGURE 2. Lateral view of CF/LMPAEK laminates distinguishing reinforcement and matrix constituents for (a) Woven [(0,90)/(±45)]2s, (b) Woven [(0,90)]4s, and (c) UD [0/90]8s, configurations.

TABLE 1. Specification of CF/LMPAEK

Material	Configuration	Thickness (mm)	Resin Content by weight (%)	Density (g/cm ³)	In-plane shear modulus (GPa)
Unidirectional (UD) TC1225/T700 UD (16 Ply) LMPAEK	[0/90]8s	2.36±0.01	34.0	1.59	4.3
Woven TC1225/T300J 3K 5HS (8 Ply) LMPAEK	[(0,90)/(±45)]2s	2.60±0.01	42.0	1.53	3.8
Woven TC1225/T300J 3K 5HS (8 Ply) LMPAEK	[(0,90)]4s	2.60±0.01	42.0	1.53	3.8

Specimen preparation for each testing was carried out using a Flow Mach 2 waterjet cutting system, selected to eliminate heat-affected zones and prevent thermal degradation of the thermoplastic matrix, while preserving fibre integrity and interlaminar bonding. This approach is particularly critical for thermoplastic composites, where elevated temperatures may induce matrix softening or microstructural distortion. Subsequently, precision edge finishing was performed using a bench grinder to achieve strict dimensional tolerances and to minimise edge defects that could act as stress concentrators during mechanical testing.

MEASUREMENT METHOD

The flexural behaviour of the CF/LMPAEK laminates was characterised in accordance with EN 2562 using an Instron 5585 Universal Testing Machine fitted with a 150 kN load cell, as illustrated in Figure 3. Three-point bending tests were conducted with a support span of 80 mm and a crosshead displacement rate of 5 mm/min. Rectangular specimens measuring 100 mm × 10 mm (length × width) were prepared for testing. All experiments were performed under controlled laboratory conditions at a temperature of 24.3 °C and a relative humidity of 53%. For each laminate configuration, five specimens were tested to ensure the repeatability and statistical reliability of the measured flexural properties, including flexural strength, flexural strain, and flexural modulus.

The three-point bending configuration generates a non-uniform stress distribution through the laminate thickness, producing compressive stresses on the upper surface and tensile stresses on the lower surface. Consequently, the test provides a comprehensive evaluation of the structural response of composite laminates under bending loads while simultaneously assessing their resistance to damage initiation and propagation. This loading condition is particularly representative of service environments encountered in aerospace structures, where flexural loading may induce matrix cracking, fibre matrix interfacial debonding, interlaminar shear failure, and delamination. Therefore, the flexural test serves as an

effective approach for examining the influence of fibre architecture on the load-bearing capability and failure behaviour of CF/LMPAEK laminates.

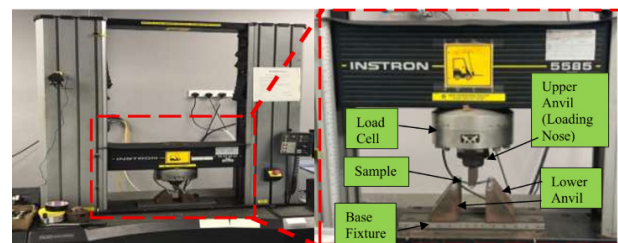


FIGURE 3. Flexural test setup

The impact performance of the laminates was evaluated using an unnotched Izod impact test in accordance with ASTM D256. Testing was conducted using an Eco Instrument Digital Pendulum Impact Tester, as shown in Figure 4. For each laminate configuration, five specimens with dimensions of 64 mm × 12.7 mm (length × width) were tested. All tests were performed under standard laboratory conditions at an ambient temperature of 24.4 °C and a relative humidity of 53%.

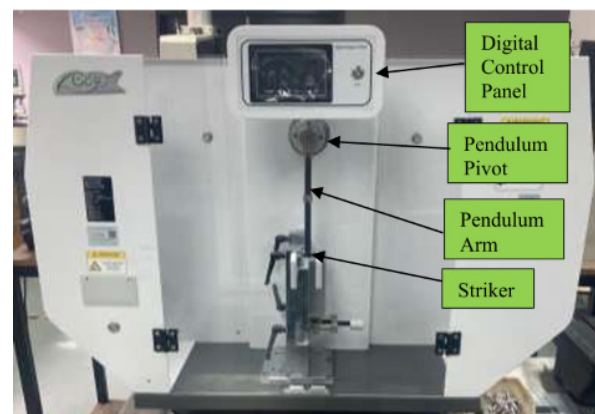


FIGURE 4. Impact test setup

The pendulum hammer operated at an impact energy of 22 J, with a velocity of 3.46 m/s and an initial release angle of 150°. The impact strength was determined by

normalising the absorbed fracture energy with respect to the specimen's cross-sectional area. This method provides a quantitative measure of the material's ability to dissipate impact energy through damage mechanisms such as matrix cracking, fibre breakage, and interlaminar delamination. Consequently, the Izod impact test is particularly effective in assessing the resistance of composite laminates to sudden loading and their susceptibility to catastrophic failure.

Following mechanical testing, the fracture surfaces of the specimens were subjected to morphological characterisation using a Dino-Lite Premier (AM4113ZT) optical digital microscope, as illustrated in Figure 5, and a Scanning Electron Microscope (SEM), as shown in Figure 6. SEM analysis was performed using a JEOL JSM-6010 Plus to investigate the fracture mechanisms and failure characteristics of the laminates in more detail. Prior to SEM examination, the specimens were sputter-coated with a thin layer of platinum to enhance surface conductivity and improve image quality.

High-resolution images were acquired to systematically characterise the dominant macroscopic and microscopic failure mechanisms, including fibre pull-out, interlaminar delamination, matrix cracking, and compressive kinking. This post-fracture examination provides critical insight into the underlying damage evolution and failure behaviour of the laminates, enabling correlation between microstructural features and the observed mechanical performance. Such analysis is essential for understanding load transfer efficiency, interfacial integrity, and the role of fibre architecture in governing failure initiation and propagation.



FIGURE 5. Dino-Lite Premier AM4113ZT optical microscope



FIGURE 6. SEM equipment-JEOL JSM-6010 Plus

RESULTS AND DISCUSSION

FLEXURAL PROPERTIES

The flexural behaviour of polymer composites is strongly influenced by fibre architecture, particularly fibre orientation, stacking sequence, and fibre-matrix interactions. According to Ogunleye et al. (2022), these parameters govern load transfer within the laminate and significantly affect damage initiation and propagation under bending conditions. Fibre architecture controls the distribution of stresses between reinforcement and matrix, while the stacking sequence determines the overall laminate stiffness and resistance to damage development under bending loads (Chowdhury & Summerscales 2024; Osti de Moraes et al. 2024).

During flexural testing, stress-strain curves were obtained for all individual specimens across each laminate configuration, as presented in Figure 5. The responses exhibited a characteristic three-stage flexural behaviour, consistent with the damage evolution mechanisms reported for fibre-reinforced composite laminates by (Jiang et al. 2020). As illustrated in Figure 5 (a–c), Stage I corresponds to the linear elastic region, where the laminate deforms elastically and the applied load is effectively transferred through the fibre-matrix network, resulting in a proportional increase in stress with strain. Stage II is associated with damage initiation and progressive damage evolution, characterised by the onset of matrix cracking, fibre-matrix interfacial debonding, and local delamination, which progressively reduce the laminate stiffness. As loading continues, these damage mechanisms accumulate and interact, leading to increased stress concentrations within the laminate. Stage III corresponds to the final failure stage, where extensive damage propagation results in a rapid loss of structural integrity and load-carrying capacity, ultimately leading to catastrophic laminate fracture. Although all laminate configurations exhibited this general three-stage response, differences in the extent and progression of damage were strongly influenced by fibre architecture, which governed the efficiency of load transfer and resistance to crack propagation (Hamdan et al. 2022; Zhao et al. 2024).

The average flexural properties obtained from these stress-strain responses, are summarised in Table 2, Figures 6 (a) and 6 (b). For clarity and comparison, the subsequent discussion focuses on these averaged results to evaluate the influence of fibre architecture on the flexural performance of the CF/LMPAEK laminates. Similar flexural responses have been reported for carbon fibre-reinforced thermoplastic composites subjected to bending loads, where progressive damage evolution precedes catastrophic failure (Zhao et al. 2024).

For Figure 6 (a), the UD $[0/90]_8s$ laminate exhibited the highest flexural modulus of 66.39 GPa, indicating superior resistance to bending deformation. This behaviour is consistent with classical laminate theory (CLT), which predicts maximum stiffness when fibres are aligned parallel to the loading direction. According to Ogunleye et al. (2022) under flexural loading, the continuous 0° carbon fibres effectively carry the majority of the applied load, resulting in efficient stress transfer and enhanced laminate stiffness. Consequently, the applied bending load is predominantly supported by the fibres, resulting in a higher effective modulus and improved resistance to elastic deformation (Osti de Moraes et al. 2024; Zhao et al. 2024). Furthermore, the absence of fibre crimp eliminates fibre straightening effects during loading, thereby increasing bending rigidity and structural stiffness (Stig & Hallström, 2019).

Despite exhibiting the highest stiffness, the UD laminate recorded a lower flexural strength (868.35 MPa) and maximum load (403.05 N) than the woven laminate as shown in Figure 6 (b). This behaviour can be attributed to the highly anisotropic nature of UD composites, where mechanical properties are concentrated primarily along the fibre direction. According to Mortell et al. (2016) during bending, tensile and compressive stresses develop simultaneously across the laminate thickness, generating transverse and interlaminar stresses that promote matrix cracking, fibre-matrix debonding, and delamination. Once initiated, these damage mechanisms can propagate rapidly through the laminate thickness, reducing its ability to sustain further loading (Choi et al. 2023; Osti de Moraes et al. 2024). Since load transfer between adjacent plies depends strongly on the integrity of the fibre-matrix interface, any localised interfacial failure can accelerate damage growth and ultimately reduce the flexural strength of the laminate.

The woven $[(0,90)]_4s$ laminate demonstrated the highest maximum load (509.00 N) and flexural strength (903.55 MPa) as shown in Figure 6 (a). The superior strength can be attributed to the interlaced fibre architecture, which promotes multidirectional load transfer and improves stress redistribution throughout the laminate. The mechanical interlocking between warp and weft yarns enhances structural integrity, suppresses local stress concentrations, and delays crack initiation and propagation (Hamdan et al. 2026). Consequently, the woven architecture provides greater resistance to catastrophic failure and enables the laminate to sustain higher bending loads before fracture occurs (Mortell et al. 2016; Chowdhury & Summerscales, 2024). However, the woven laminate exhibited a lower flexural modulus (56.84 GPa) than the UD laminate. This reduction in stiffness is primarily associated with fibre crimp, where the inherent waviness

of woven fibres decreases the effective load-carrying efficiency. Prior to fully supporting the applied load, crimped fibres undergo straightening, resulting in lower bending rigidity and reduced stiffness compared with straight-fibre UD laminates (Kushwaha & Meyer, 2025; Zhao et al. 2024).

Meanwhile, the woven $[(0,90)/(\pm 45)]_2s$ laminate exhibited the lowest flexural strength (779.56 MPa) and flexural modulus (46.05 GPa), despite containing $0/90^\circ$ plies within its stacking sequence as shown in Figure 6 (a) and Figure 6 (b). This behaviour is primarily attributed to the incorporation of $\pm 45^\circ$ layers, which alter the load transfer mechanism during flexural loading. Under bending conditions, the highest tensile and compressive stresses are generated along the longitudinal axis of the specimen, making 0° fibres the most effective load-bearing reinforcement. In contrast, fibres oriented at $\pm 45^\circ$ are less efficient in carrying axial bending stresses and instead contribute predominantly through in-plane shear deformation (Serna Moreno & Horta Muñoz, 2022). As a result, a significant proportion of the applied load is transferred into matrix-dominated shear stresses rather than direct fibre loading, thereby reducing the laminate's effective bending stiffness and strength (Osti de Moraes et al. 2024; Zhao et al. 2024).

According to CLT, the transformed stiffness of off-axis plies is substantially lower than that of fibres aligned with the loading direction. Consequently, the inclusion of $\pm 45^\circ$ plies decreases the effective longitudinal stiffness and flexural rigidity of the laminate due to stiffness transformation effects. The contribution of these off-axis plies is therefore governed primarily by shear deformation rather than direct axial load transfer. According to Osti de Moraes et al. (2024) and Zhao et al. (2024) although the hybrid laminate contains $0/90^\circ$ reinforcement, its overall structural response becomes increasingly influenced by the lower stiffness characteristics of the $\pm 45^\circ$ layers, resulting in a reduction in the effective laminate modulus. This explains why the hybrid configuration recorded the lowest flexural modulus among all laminate architectures investigated.

The reduction in flexural strength observed in the hybrid laminate can also be linked to the presence of the $\pm 45^\circ$ layers. Unlike the woven $[(0,90)]_4s$ laminate, where most fibres are oriented along the principal load-carrying directions, the off-axis plies experience significant shear deformation and fibre rotation during bending. These mechanisms increase the likelihood of matrix cracking, interfacial debonding, and interlaminar stress development, promoting earlier damage initiation and premature failure. Nevertheless, the hybrid laminate exhibited the highest flexural strain (0.0201), compared with 0.0191 for the woven laminate and 0.0159 for the UD laminate as shown

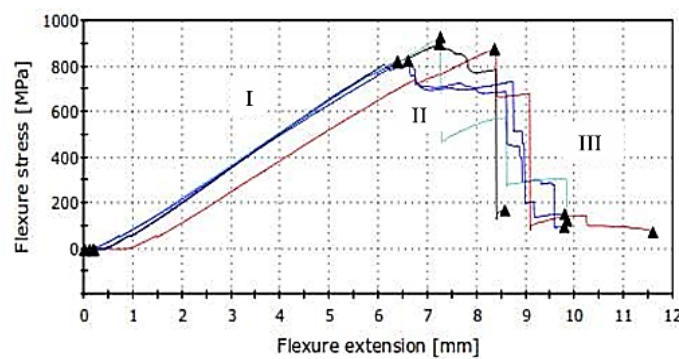
in Table 2. The increased strain capacity indicates enhanced deformation tolerance, as the $\pm 45^\circ$ plies facilitate stress redistribution and accommodate deformation through shear-dominated mechanisms before final failure occurs (Osti de Moraes et al. 2024).

Comparison with previously reported PAEK-family composites indicates that CF/PEEK and CF/PEKK laminates can achieve considerably higher flexural strengths (approximately 1861–1981 MPa) than the CF/LMPAEK laminates evaluated in the present study (779.56–903.55 MPa). This disparity is likely attributable to differences in fibre volume fraction, laminate architecture, interfacial quality, and processing conditions rather than solely to the intrinsic properties of the LMPAEK matrix, as the reported CF/PEEK and CF/PEKK (Balakumaran et al. 2024).

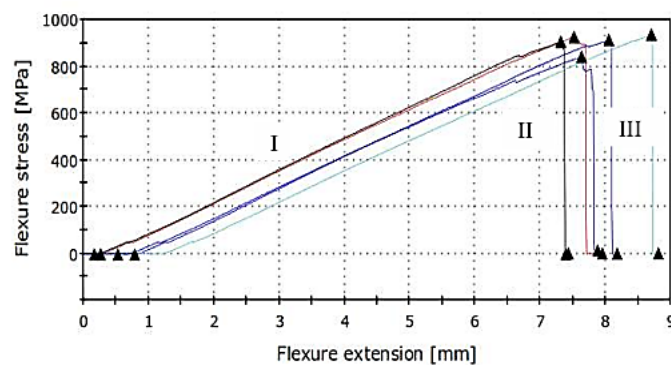
Overall, the results demonstrate that fibre architecture plays a crucial role in determining the flexural performance of CF/LMPAEK composites. The UD laminate provided the highest stiffness owing to the efficient alignment of fibres along the loading direction, whereas the woven laminate achieved the highest flexural strength and load-bearing capability through improved stress redistribution and mechanical interlocking. The hybrid laminate exhibited an intermediate structural response, combining the multidirectional load-transfer characteristics of woven layers with the deformation-tolerant behaviour of $\pm 45^\circ$ plies. Although the incorporation of off-axis fibres reduced the flexural strength and stiffness, it enhanced strain accommodation and delayed catastrophic failure through shear-mediated energy dissipation mechanisms (Chowdhury & Summerscales, 2024).

TABLE 2. Flexural properties of CF/LMPAEK composites

Configuration	Max Load (N)	Flexural Strength (MPa)	Flexural Modulus (MPa)	Flexural Strain
UD [0/90] _{8s} 16 ply	403.05±7.50	868.35±15.20	66386.62±1250.00	0.0159±0.0003
Woven [(0,90)] _{4s} 8 ply	509.00±7.20	903.55±12.50	56836.68±820.00	0.0191±0.0003
Woven [(0,90)/(±45)] _{2s} 8 ply	439.15±5.20	779.56±8.80	46046.16±550.00	0.0201±0.0002

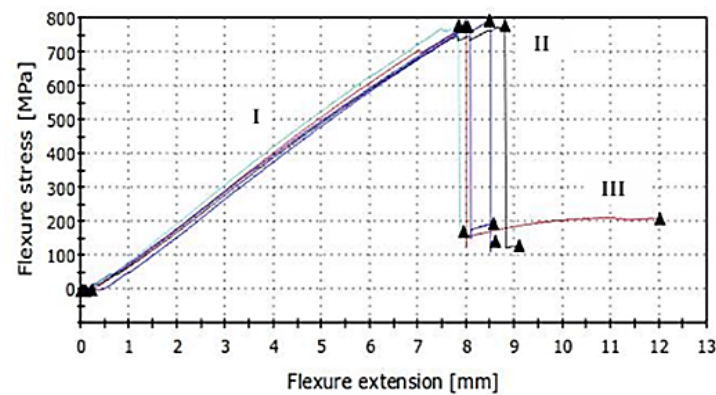


(a)



(b)

continue...



(c)

FIGURE 5. Stress versus Strain graph for flexural (a) UD [0/90]8s, (b) Woven [(0,90)]4s, and (c) Woven [(0,90)/(±45)]2s

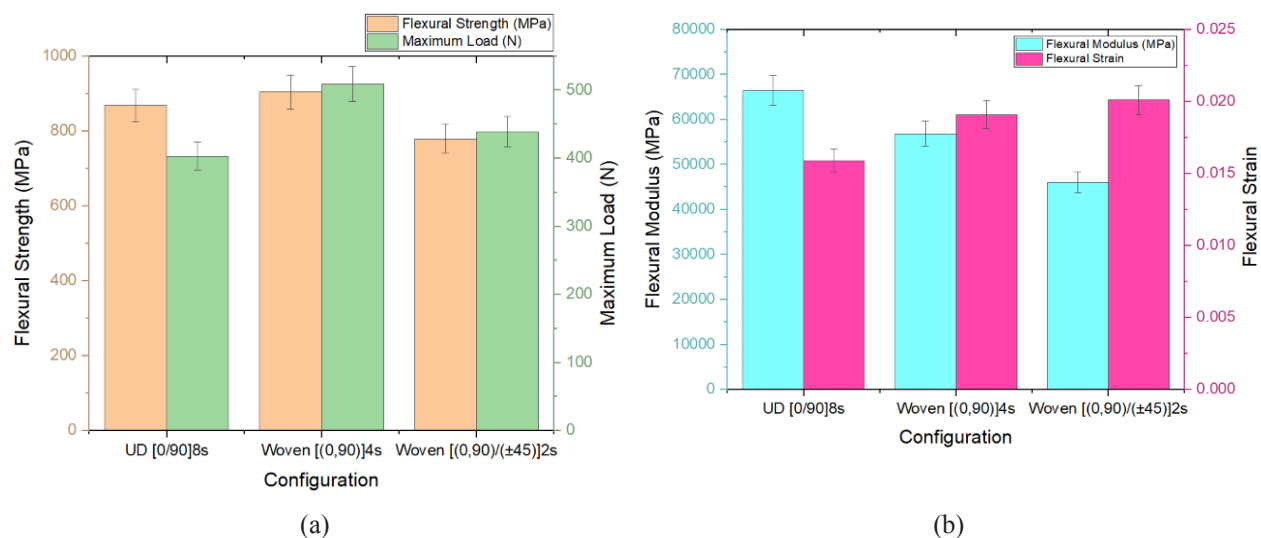


FIGURE 6. Comparison of (a) flexural strength and maximum load recorded; and (b) flexural modulus and flexural strain at different configurations

IMPACT PROPERTIES

The impact behaviour of CF/LMPAEK composites is primarily governed by energy absorption mechanisms, which are strongly influenced by fibre architecture, damage evolution, and interlinear properties. Under impact loading, the ability of a laminate to dissipate energy depends on the activation of multiple damage mechanisms, including matrix cracking, fibre-matrix debonding, delamination, and fibre fracture (Hamdan et al. 2026). The extent and interaction of these mechanisms are highly dependent on laminate architecture and significantly influence the overall impact resistance of fibre-reinforced thermoplastic composites (Osti de Moraes et al. 2024; Zhang et al. 2023).

The UD [0/90]8s laminate exhibited the highest impact strength (179.63 kJ/m²) and impact energy (5.384 J) as shown in Figure 7. This behaviour can be explained by the

delamination-dominated failure mechanism characteristic of unidirectional laminates. In UD composites, the relatively weak interlinear constraint between adjacent plies facilitates crack propagation along fibre-matrix interfaces and ply boundaries (Pascoe et al. 2019). Although delamination is generally considered a damage mechanism, it can substantially increase impact energy absorption because a significant amount of energy is dissipated through extensive crack growth, interfacial debonding, and damage propagation over a large area. According to fracture mechanics principles, the energy required for crack propagation increases with the extent of damage development and fracture surface generation (Dooren & Bisagni 2021; Zhang et al. 2023). The higher impact energy recorded for the UD laminate therefore indicates that the laminate was capable of absorbing a greater amount of kinetic energy before complete failure.

However, this mechanism also promotes catastrophic structural separation, as the absence of significant through-thickness reinforcement offers limited resistance to delamination growth and crack propagation through the laminate thickness (Lona et al. 2021; Liu et al. 2023).

In contrast, the woven [(0,90)]_{4s} laminate exhibited the lowest impact strength (130.56 kJ/m²) and impact energy (4.311 J). The interlaced fibre architecture restricts crack propagation and suppresses long-range delamination by mechanically constraining damage growth within the laminate (Kim & Sham, 2000). Fibre crossover regions act as barriers to crack advancement, forcing propagating cracks to repeatedly change direction and thereby limiting the overall damage area. This interlocking mechanism improves damage containment and preserves structural integrity after impact loading (Chowdhury & Summerscales 2024; Kushwaha & Meyer 2025). However, because damage remains highly localised, the total amount of energy dissipated during fracture is reduced compared with the UD configuration. Consequently, the woven laminate absorbed less impact energy and exhibited lower impact strength despite maintaining better resistance to extensive structural separation (Han et al. 2024).

The hybrid woven [(0,90)/(±45)]_{2s} laminate demonstrated intermediate impact performance, with an impact strength of 158.94 kJ/m² and an impact energy of 5.248 J. The incorporation of ±45° plies introduce additional crack propagation paths and modifies the damage evolution mechanism during impact loading. Instead of propagating directly along a preferred fibre direction, cracks are repeatedly deflected and forced to interact with fibres oriented at different angles, producing a more tortuous crack path (Long et al. 2022). This mechanism promotes additional energy dissipation through matrix cracking, fibre-matrix debonding, crack branching, and localised shear deformation within the off-axis plies (Liu et al. 2023; Zhang et al. 2023). The relatively high impact energy obtained by the hybrid laminate indicates that the ±45° plies effectively enhanced damage tolerance and energy absorption while simultaneously limiting the extensive delamination observed in the UD laminate. As a result, the hybrid architecture provides a balance between structural integrity and impact resistance, producing impact performance that lies between those of the UD and conventional woven configurations (Kushwaha & Meyer, 2025).

Overall, the results demonstrate that fibre architecture strongly influences both impact strength and impact energy absorption in CF/LMPAEK composites. The UD laminate maximised energy absorption through extensive

delamination and interfacial damage propagation, whereas the woven laminate prioritised damage containment through fibre interlocking and crack-arrest mechanisms. The hybrid configuration combined the advantages of both architectures by promoting controlled crack deflection, shear-mediated deformation, and enhanced energy dissipation while maintaining improved structural integrity. Consequently, the hybrid laminate exhibited a more balanced impact response, offering a favourable compromise between impact resistance, damage tolerance, and structural stability (Chowdhury & Summerscales 2024; Zhang et al. 2023).

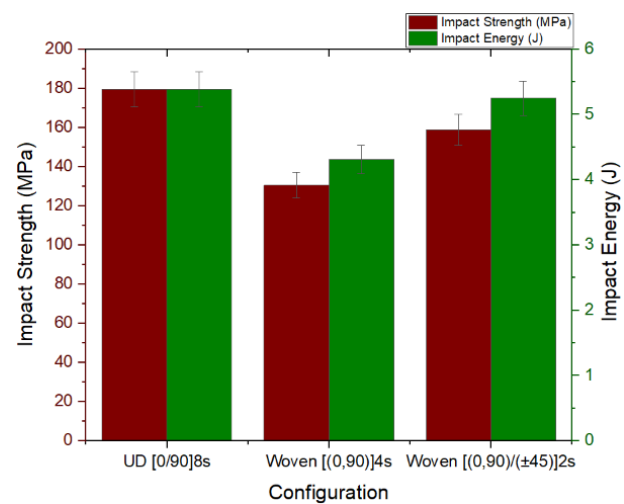


FIGURE 7. Comparison of impact strength and impact energy at different configurations

MORPHOLOGICAL ANALYSIS

Morphological analysis using optical microscopy provided valuable insights into the fracture behaviour of each laminate configuration, revealing distinct failure mechanisms governed by fibre architecture and laminate stacking sequence. The UD [0/90]_{8s} laminate exhibited failure dominated by extensive interlaminar delamination, characterised by pronounced separation between adjacent plies, as shown in Figure 8(a). In addition, compressive kinking was observed within the compressive region of the laminate. This behaviour is attributed to the relatively low through-thickness (Z-direction) strength of laminated composites, where the interlaminar region is primarily supported by the matrix rather than continuous fibre reinforcement. As a result, interlaminar stresses generated during flexural loading can readily initiate crack formation and delamination between adjacent plies (Choi et al. 2023;

Osti de Moraes et al. 2024).

Consequently, cracks can readily propagate along the interfaces between adjacent plies, resulting in large-scale delamination and structural separation. Although this failure mode appears severe, the extensive crack propagation and delamination process contribute significantly to energy dissipation by increasing the fracture surface area and promoting interfacial debonding (Jalalvand et al. 2016). This observation is consistent with the high impact energy and impact strength recorded for the UD laminate, indicating that a substantial amount of impact energy was consumed during damage propagation and crack growth (Lona et al. 2021).

In contrast, the woven [(0,90)]_{4s} laminate, shown in Figure 8(b), exhibited fracture behaviour dominated by fibre pull-out and localised compressive kinking. Most specimens experienced complete fracture following mechanical loading. The interlaced woven architecture effectively restricts crack propagation by forcing cracks to deviate around fibre bundles rather than propagating directly through the laminate (Kim & Sham, 2000). Fibre crossover regions act as natural barriers to crack advancement, promoting crack deflection and fibre bridging mechanisms that increase the energy required for damage propagation (Hamdan et al. 2026). Consequently, damage remains confined to localised regions, contributing to the higher flexural strength observed in the woven laminate. However, the restricted crack propagation limits the overall damage area and reduces the total amount of energy dissipated during fracture, thereby explaining the lower impact strength and impact energy compared with the UD configuration (Kushwaha & Meyer, 2025).

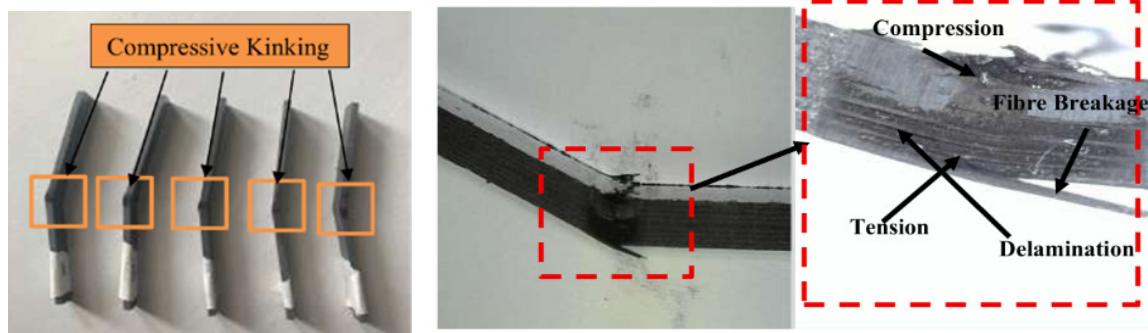
The most distinctive fracture behaviour was observed in the hybrid woven [(0,90)/(±45)]_{2s} laminate, where compressive kinking emerged as the dominant failure mechanism, as illustrated in Figure 8(c). All tested specimens exhibited pronounced kink-band formation, indicating that compressive instability governed the failure process. This mechanism occurs when fibres subjected to compressive loading undergo local buckling, resulting in fibre rotation and the formation of kink bands. The incorporation of ±45° plies promote in-plane shear deformation and forces cracks to propagate along a tortuous zigzag path rather than following a direct route. Furthermore, the off-axis plies facilitate shear-mediated stress transfer and promote progressive failure rather than abrupt fracture. This observation is consistent with studies reporting that

off-axis fibre orientations improve stress redistribution and increase the ability of composite laminates to accommodate deformation before final failure (Osti de Moraes et al. 2024; Nourmohammadi et al. 2025).

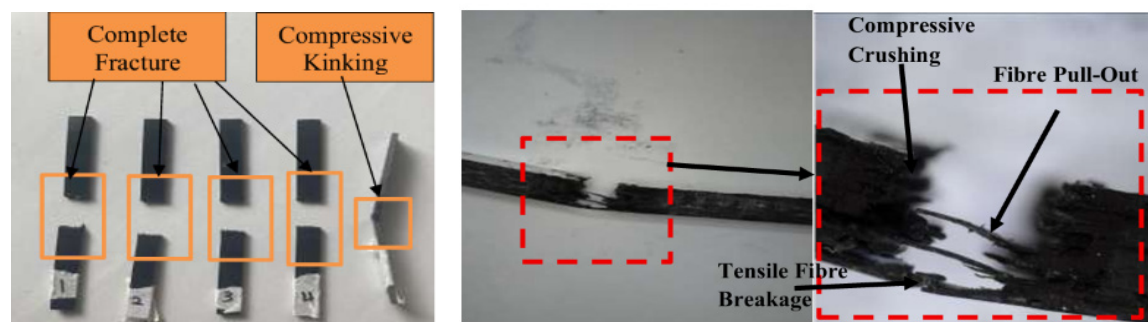
Moving to the impact-fractured specimens, morphological analysis using SEM revealed that all laminate configurations experienced complete fracture after impact loading, indicating that a substantial amount of impact energy was absorbed during failure. SEM examination showed the presence of fibre fracture and fibre pull-out across all laminate architectures, confirming that these were the dominant damage mechanisms activated during impact loading. Similar failure features have been widely reported in carbon fibre-reinforced thermoplastic composites subjected to impact loading, where energy dissipation occurs through a combination of fibre breakage, matrix cracking, interfacial debonding, and fibre extraction mechanisms (Hamdan et al. 2026).

As shown in Figure 9(a–c), fibre fracture indicates that the applied impact energy exceeded the load-bearing capacity of the carbon fibres, resulting in fibre breakage and ultimate structural failure. Meanwhile, fibre pull-out contributes to energy absorption through frictional resistance generated during fibre extraction from the surrounding matrix. The frictional sliding process requires additional energy and therefore increases the overall energy absorption capability of the laminate (Teklal et al. 2018). The coexistence of fibre fracture and fibre pull-out suggests that impact energy was dissipated through both fibre breakage and fibre extraction mechanisms, which collectively contributed to the measured impact performance of the laminates (Lona et al. 2021).

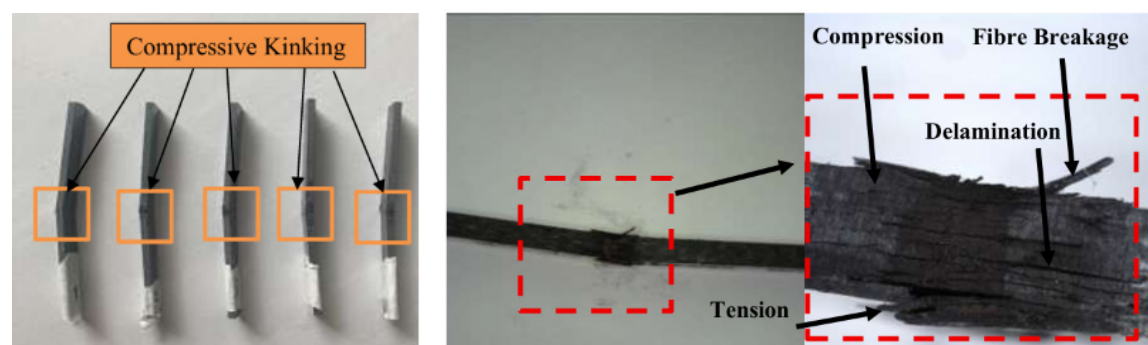
These observations are characteristic of impact-induced failure in carbon fibre-reinforced thermoplastic composites and provide direct morphological evidence supporting the impact performance obtained for the different laminate architectures. The extensive delamination observed in the UD laminate explains its superior impact energy absorption, whereas the crack-arrest capability of the woven architecture accounts for its lower impact energy but improved structural integrity. Meanwhile, the hybrid laminate exhibited an intermediate failure response, where crack deflection, shear deformation, and compressive kinking collectively contributed to a balance between energy dissipation and damage containment (Chowdhury & Summerscales 2024; Osti de Moraes et al. 2024).



(a)

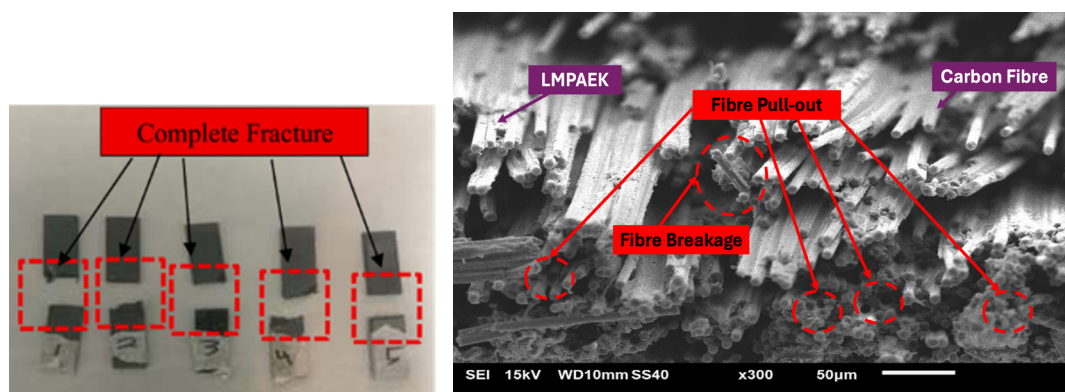


(b)



(c)

FIGURE 8. Fracture surface showing (a) UD [0/90]8s, (b) woven [(0,90)]4s, and (c) woven [(0,90)/(±45)]2s



(a)

continue...

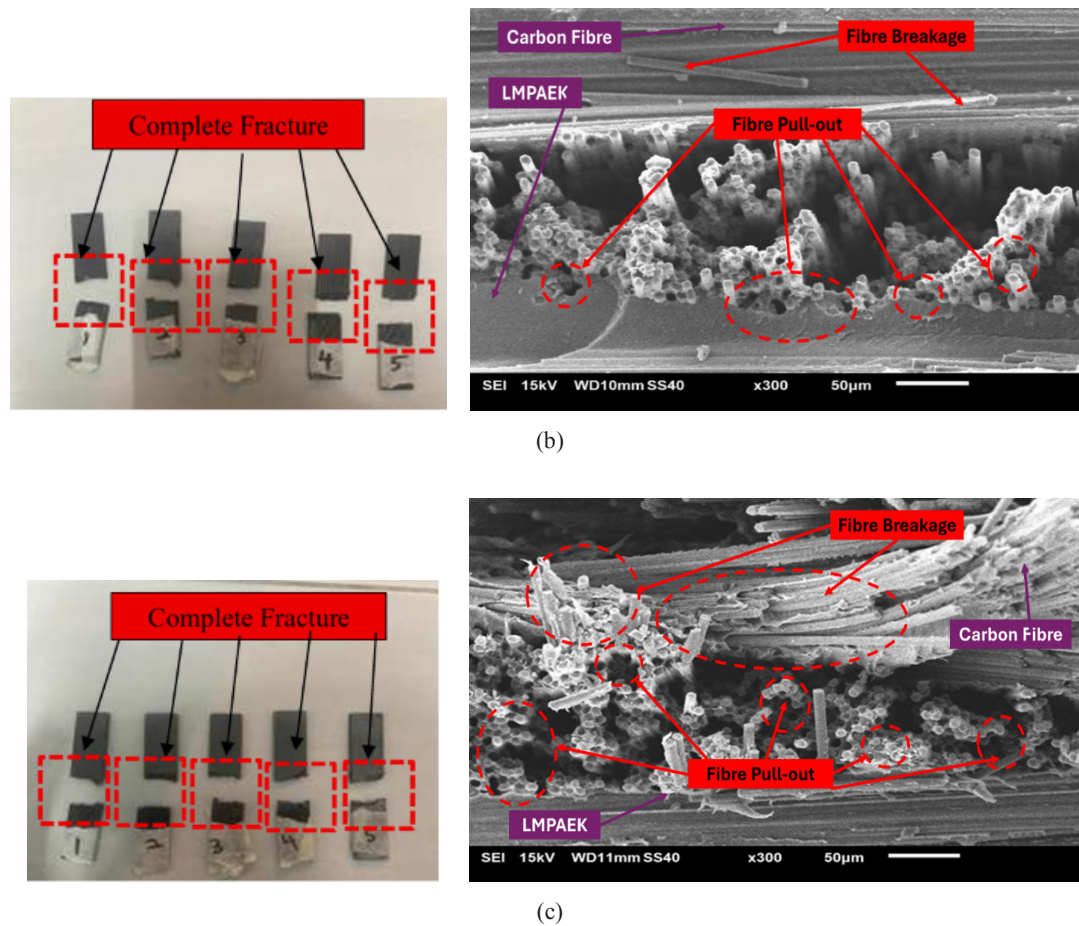


FIGURE 9. Morphological analysis under $\times 300$ for (a) UD $[0/90]_8s$, (b) Woven $[(0,90)]_4s$, and (c) hybrid woven $[(0,90)/(\pm 45)]_2s$

CONCLUSION

This study investigated the influence of fibre architecture on the flexural performance, impact resistance, and failure mechanisms of CF/LMPAEK composites for aerospace applications. The results confirmed that fibre orientation and stacking sequence significantly affect load transfer, damage evolution, and overall mechanical behaviour. The woven $[(0,90)]_4s$ laminate exhibited the highest load-bearing capacity and resistance to bending, recording the maximum load of 509.00 N and the highest flexural strength of 903.55 MPa. It also registered a flexural modulus of 56836.68 MPa, a flexural strain of 0.0191, an impact strength of 130.56 kJ/m², and an impact energy of 4.311 J due to efficient stress redistribution and delayed crack propagation. In contrast, the UD $[0/90]_8s$ laminate achieved the highest stiffness and total energy absorption, yielding a peak flexural modulus of (66.39 GPa), a top impact strength of 179.63 kJ/m², and the highest impact energy of 5.384 J. This configuration maintained a maximum load of 403.05 N, a flexural strength of 868.35 MPa, and a flexural strain of 0.0159, reflecting enhanced

toughness through extensive interlaminar delamination. The hybrid $[(0,90)/(\pm 45)]_2s$ laminate demonstrated intermediate strength and impact performance, recording a maximum load of 439.15 N, a flexural strength of 779.56 MPa, a flexural modulus of 46046.16 MPa, an impact strength of 158.94 kJ/m², and an impact energy of 5.248 J. However, it recorded the highest flexural strain of 0.0201, indicating significantly improved deformation tolerance and progressive failure behaviour. Morphological analysis established a clear relationship between fibre architecture and failure mode. The UD laminate exhibited extensive delamination, the woven laminate was characterised by fibre pull-out and localised compressive kinking, while the hybrid laminate showed pronounced kink-band formation. SEM observations further confirmed fibre fracture and fibre pull-out as the dominant impact-induced damage mechanisms. Overall, fibre architecture governs the balance between stiffness, strength, impact energy absorption, and damage tolerance in CF/LMPAEK composites. While the UD configuration is favourable for stiffness-dominated applications and the woven laminate provides superior load-bearing capability, the hybrid architecture offers the most balanced mechanical response. These findings

provide useful guidance for the design of lightweight and damage-tolerant thermoplastic composite structures for future aerospace applications.

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DECLARATION OF COMPETING INTEREST

None.

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