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Influence of Thermoplastic Matrix on the Mechanical Behavior of Hybrid Carbon–Kevlar Fiber Reinforced Composites for Aerospace Applications

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Abstract

The mechanical properties of two different thermoplastic matrices, polyethylene (PE) and thermoplastic polyurethane (TPU), containing hybrid carbon-Kevlar fiber-reinforced composites have been explored in order to determine useful material systems for aerospace structural components. Mechanical tests including tensile, flexure, low-velocity and high-velocity impact tests have been performed to assess the composite's behavior. Laminates were prepared through compression molding with plain and twill woven hybrid carbon-Kevlar fabrics and mechanical characterization was carried out as per ASTM standards. Mechanical tests including tensile, flexure, low-velocity and high-velocity impact tests have been performed to assess the composite's behavior. The mechanical performance comparison revealed that TPU-based composites, particularly the twill hybrid TPU, outperformed PE-based variants across most tests. In tensile tests, twill hybrid TPU laminates showed superior ultimate tensile strength of 63.54 MPa. Hybrid fiber reinforcement takes advantage of the high tensile strength of carbon fibers and Kevlar ductility with a balanced performance profile over matrix systems. In flexure test, the same composite achieved the highest flexural strength of 80.54 MPa. Both the low-velocity as well as high velocity impact test showcased that, twill hybrid TPU laminates withstood 3248 N and the residual velocity was reduced by 49% which signifies the high impact resistance and greater energy dissipation of TPU matrix. Overall, TPU-based composites exhibited superior impact resistance and energy absorption capability because of the inherent elasticity and toughness of the matrix, whereas PE-based composites showed relatively greater stiffness and weight efficiency. These results highlight the importance of matrix choice in optimizing composite properties for aerospace applications that require structural integrity as well as damage tolerance. The understanding derived from this study supports the knowledge-based design of lightweight, high-performance composite materials for future aerospace components.

Categories: Advanced Materials, Materials Engineering, Polymer Science and Engineering
Keywords: hybrid fibers, polyethylene, thermoplastic polyurethane, impact, aerospace structures, kevlar, carbon, advanced materials, polymers, mechanical characterization

Introduction

Polymer composites are next-generation materials formed by incorporating a polymer matrix and reinforcing fibers to attain enhanced mechanical, thermal, and chemical properties. As demand increases in aerospace, automobile, marine, and defense sectors, polymer composites offer light materials as substitutes for conventional metals and alloys [1,2]. Materials that balance light weight and excellent mechanical performance are continuously desired by the aerospace industry in a bid to enhance fuel economy, reduce emissions, and maintain structural integrity when exposed to adverse operating conditions. Within this respect, fiber-reinforced composites have become vital due to their high strength-to-weight ratios, resistance to corrosion and flexibility in terms of design [3]. With the ability to tailor mechanical performance for specific applications, hybrid composites, those strengthened with numerous varieties of fibers, have emerged as one of the most viable solutions to date. By combining multiple fiber types, such as carbon and Kevlar, engineers can engineer a combination of stiffness, strength, and impact resistance, all essential to aerospace structures [4].

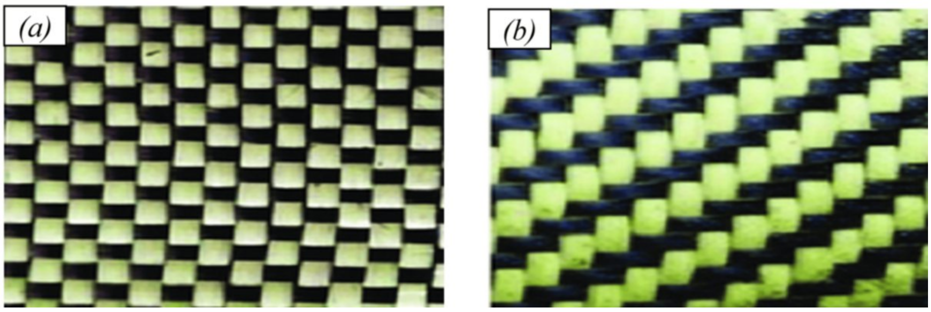

FIGURE 1: (a) Plain hybrid carbon-Kevlar fiber; (b) Twill hybrid carbon-Kevlar fiber

Due to carbon fibers' high stiffness and tensile strength, they are often used in load-bearing parts [5]. On the other hand, Kevlar - an aramid fiber, offers high toughness and resistance to impact and abrasion. Blending these fibers in a hybrid form is able to overcome one another's deficiencies and develop composites that are damage-resistant and durable. Figure *1* shows the plain as well as twill woven hybrid fibers. To achieve structural stability, reduce stresses. and facilitate successful load transfer between the fibers, the matrix material plays an important role. Consequently, the fibers themselves do not control the effectiveness of such hybrids. There has been growing interest in thermoplastic matrices in recent years due to their inherent advantages over traditional thermoset resins, especially for aerospace applications. They can offer faster processing cycles, improved recyclability, and higher fracture toughness. Thermoplastics are also often repeatedly remelted and reshaped, which is beneficial for industrial versatility and greenness. Polyethylene (PE) and thermoplastic polyurethane (TPU) continue to be studied increasingly in aerospace-grade composite matrix materials due to their special mechanical and thermal behavior [6,7]. Impact-resistant aircraft structures can take advantages of TPU's superior flexibility, higher energy absorption, and better interfacial bond with fibers [8]. PE provides chemical resistance and light-weight properties but with poorer load transfer and lower ductility. Weight, flexibility, and ruggedness requirements of the application compound the decision between TPU and PE. Despite these advantages, the interaction between thermoplastic matrices and different fiber reinforcements, especially in hybrid arrangements, is still a complex issue that warrants intensive study.

A number of researchers have conducted extensive investigations into the mechanical performance of hybrid fiber composites to enhance their structural functionality. Rout et al. documented that the Glass-Carbon-Kevlar fiber configuration with carbon as the upper and mid-layer (CGKCKGC) attained a maximum flexural strength of 380.96 MPa due to the rigidity of carbon fibers [9]. Wu et al. examined the hybrid effects of carbon and aramid fibers during low-velocity impacts using finite element modeling and noted that the addition of aramid fibers as axial yarns extended the impact response duration and reduced failure severity [10]. Also, Tian et al. [11] noted the effect of stacking sequence on carbon-aramid laminates' low-velocity impact and post-impact bending behavior, and Da Silva et al. proved that quasistatic and ballistic energy absorption was better in plain-weave aramid/glass/epoxy composites, where hybrid laminates outperformed single-fiber systems in terms of higher ballistic limit velocities [12]. Sarkar et al. also supported this by concluding that the carbon-glass hybrids with stacking sequences and matrix-rich skin faces provided maximum ballistic performance [13]. On a larger scale, Al-Furjan et al. highlighted that fabricating parameters like matrix type, fiber orientation, and volume fraction play the most critical role in deciding tensile properties in applications related to aviation, military, and automotive industries [14]. Building on these findings, Li et al. investigated carbon, Kevlar, and UHMWPE hybrids and validated their improved bulletproof effectiveness, highlighting the utility of hybridization in designing composites for high-level structural and protective uses [15].

While a great deal of work has been conducted on fiber-reinforced composites, a majority of past work has been on standard thermoset matrices like epoxy and polyester. By contrast, work on thermoplastic matrices like polyethylene and TPU is relatively less studied, even though they have been shown to be advantageous in toughness, recyclability, and impact resistance. Similarly, although carbon and Kevlar fibers are each exhaustively explored as single reinforcements, scant attention is paid to the strategic combination thereof as hybrid configurations, such as using carbon in the warp and Kevlar in the weft, for instance. Moreover, not much is known about how various weave architectures and stacking sequences affect hybrid systems to optimize their mechanical performance, and hence there remains a considerable knowledge gap in this regard. Impact studies at high velocity using such thermoplastic hybrid composites are also limited, especially when both the strength and damage tolerance are of concern in aerospace-related applications. Bridging these gaps, this work is intended to examine systematically the mechanical behavior and impact resistance of carbon-Kevlar hybrid composites reinforced with TPU and polyethylene matrices with a view to presenting new information on their potential for advanced structural applications. The current work investigates one of the most critical materials engineering challenges: how the choice of different thermoplastic matrices, namely TPU and PE, controls the mechanical and impact performance of hybrid carbon-Kevlar composites. On a scientific level, an optimal balance between stiffness and toughness for aerospace structural elements subjected to complex loading conditions, including various static and dynamic impacts, should be achieved. Resolving this issue will contribute directly to the development of lightweight, damage-tolerant, and recyclable structural materials suited for aerospace applications such as rotor blades, fuselage panels, and protective components.

Materials And Methods

In this work, plain and twill types of hybrid carbon-Kevlar fabrics were used. Every fabric was acquired at 200 GSM [16]. Polyethylene and TPU in sheet form with a 1 mm thickness have been selected as the matrix material choices. TPU and PE matrices were selected because their properties are very different. TPU has elastomeric and highly deformable properties with great impact energy dissipation, whereas PE has semi-crystalline rigidity, higher modulus, but lower ductility. This contrasting response provides a very effective platform to understand how matrix chemistry and structure influence the fiber-matrix load transfer, crack propagation, and laminate durability. Many high-strength sheet parts that are useful for industrial and automotive applications are made using the commonly utilized compression molding method. Compression molding was used to fabricate the composites, using a 5-bar pressure and 90-minute temperature of 240°C for the TPU-based composites and 150°C for the polyethylene-based composites [17]. After 24 hours of curing, the composite laminate has been released from the mould. Even though the formal design-of-experiments optimization was not carried out, the parameters adopted were optimized by iterative trial-and-error optimization, as has been done in the preceding research where the compression moulding parameters were experimentally tuned for thermoplastic composites. The layup sequence so used here is M-H_{C-K}-M-H_{C-K}-M-H_{C-K}-M-H_{C-K}-M, where H_{C-K} is the hybrid carbon-Kevlar fiber and M is the matrix (either PE or TPU). The sequence was optimized to achieve the highest impact resistance by positioning the matrix layers on both outermost surfaces (skin layers). This arrangement enables the matrix to serve as a protective cushioning layer, enhancing energy dissipation as well as slowing surface crack growth during impact. Table *1* shows the layup sequence used to fabricate composites. The fabricated composites were cut using abrasive waterjet machining with 300 g/min of abrasive flow rate, 3 mm standoff distance and 300 MPa pressure in accordance with ASTM standards [18]. This machining method was chosen because it does not generate heat in the cutting zone. The developed methodology can be extended to other thermoplastic systems such as PPS or PEEK and to fiber combinations including glass or basalt, allowing for wider material optimization. Hence, this study provides both empirical benchmarks and mechanistic understanding of thermoplastic hybrid composites.

Woven pattern	Layup sequence used	Notation	Thickness (mm)	Sample number
Plain-woven Hybrid carbon - Kevlar(H_{C-K})	TPU- H_{C-K} -TPU- H_{C-K} -TPU- H_{C-K} -TPU- H_{C-K} -TPU	Plain Hyb. C-K-TPU	5.0	1
	PE-H_{C-K}-PE- H_{C-K} -PE- H_{C-K} -PE- H_{C-K} -PE	Plain Hyb. C-K-PE	5.0	2
Twill-woven Hybrid carbon - Kevlar(H_{C-K})	TPU- H_{C-K} -TPU- H_{C-K} -TPU- H_{C-K} -TPU- H_{C-K} -TPU	Twill Hyb. C-K-TPU	5.0	3
	PE-H_{C-K}-PE- H_{C-K} -PE- H_{C-K} -PE- H_{C-K} -PE	Twill Hyb. C-K-PE	5.0	4

TABLE 1: Composite laminate layup sequences with their notations

Water absorption test

Water absorption test was conducted according to ASTM-D 570. This was achieved through submerging 60 mm by 60 mm specimens for nearly 24 hours in distilled water. Before submerging, these specimens remained for about 24 hours in a desiccator, and a balance was utilized for finding the initial dry weight and weight at immersion.

Tensile test and Flexure test

Tensile and flexure tests were performed according to ASTM-D 638 and ASTM-D 790 standards, respectively. Tensile properties of composite materials in unreinforced and reinforced polymers under uniaxial stress are discussed in ASTM-D 638 [19]. Flexural properties of composites under three-point bending conditions are discussed in ASTM-D 790. The tests were performed using a Universal testing machine.

Low-velocity impact test

The test standard for performing this impact test is ASTM-D 5628 [20]. The main drawback of low-velocity impact is that it can damage composite materials internally and result in matrix damage, delamination, and breakage of fibers. Internal damage decreases the composite's load-bearing capacity. The size of the specimen was 89 × 89 mm, and the impactor load which hit it was 2 kg and 4 m/s was set as impactor's velocity. According to the kinetic energy equation, 16 J of energy hit the composite during testing.

High-velocity impact test

The test standard for performing this high-velocity impact test is ASTM-D 8101 [21]. A single-stage gas gun device is usually employed to accelerate the projectiles in a velocity range of 100-500 m/s for conducting high-velocity impact testing on polymer composites. . The mass of the bullet so used here is 12 g and it is conical shaped. The distance from the end of the barrel to the composite striking side is 3 m. Residual velocity provides the basis for estimating the ballistic limit, while projectile velocity is measured using high-speed cameras. Once specimens are clamped down, visual inspection and nondestructive tests such as X-ray CT or ultrasonic C-scan are employed to assess the impact. The tests detect delamination, matrix cracking, and breaking of fibers as significant modes of failure. For armor and aerospace, such data are critical in confirming analytical and numerical models.

Results And Discussion

Water absorption test results

The water absorption investigation was specifically restricted to a 24-hour immersion, in accordance with methods taken up in the past literature for analogous polymer composite systems. It was observed to be adequate in collecting the early diffusion dynamics and short-term water absorption trends, which are essential for the relative assessment between varying laminate configurations

The % water absorption can be calculated using the formula,

$$Water\ Absorption(\%) = \frac{W_1 - W_0}{W_0} \times 100$$

where, W_0 is the initial dry weight of the specimen (g) and W_1 is the weight of the specimen after immersion in water (g) and the data are tabulated in Table *2* and graph is represented in Figure *2*. The results of the water absorption test show that the resistance of hybrid fiber composites depends on the weave style and the type of matrix. Plain Hyb. C-K-TPU had the highest absorption (1.32%), which proves that TPU is relatively hydrophilic. Plain Hyb. C-K-PE, however, had the lowest absorption, proving PE's better hydrophobicity and stronger moisture barrier properties. Furthermore, the Twill Hyb. C-K-TPU took up higher amounts of moisture (1.13%) compared to its PE equivalent (0.89%), illustrating the matrix type's repeated effect in different weave patterns. The experiment further suggests that weave pattern has an important contribution, with plain structures taking up slightly more than twill, most likely due to tighter interlacing that forms voids. In general, the results emphasize the significance of the polymer matrix toward water resistance, with PE-based composites superior to TPU-based systems in stability toward moisture penetration [8].

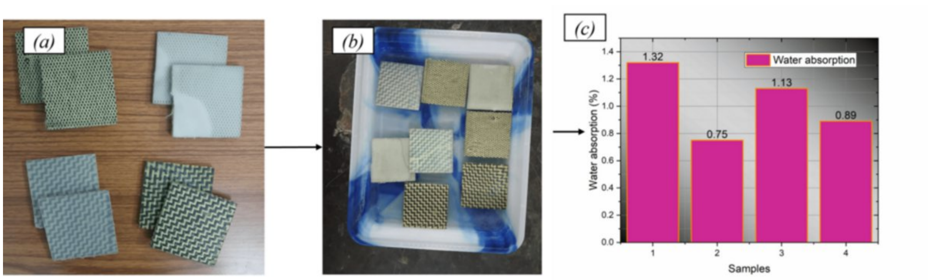

FIGURE 2: (a) Fabricated composite specimens, (b) specimens immersed in distilled water for absorption study, and (c) percentage of water absorption of different samples

Tensile test and Flexure test results

The tensile behavior of hybrid fiber composites obviously indicates the influence of the polymer matrix on load-bearing and failure characteristics. For each configuration, two specimens were tested, and the results corresponding to the superior performance are showcased here. The ultimate tensile strength data is tabulated in Table *2* and the respective graph is shown in Figure *3*. The highest stress and strain capacity was exhibited by twill hybrid with TPU laminates, which reflects TPU's high ductility and energy dissipation potential, the two attributes extremely desired in aerospace applications requiring impact tolerance. Moreover, plain hybrid with TPU laminates performed better than its PE counterpart, implying that TPU enhances load transmission and interfacial bonding of carbon and Kevlar fibers. The PE-based systems, however, exhibited lower elongation and strength, showing their poor ability to endure strain before fracturing. Although plain weaves favored enhanced stress distribution under reduced strain, twill geometries offered greater flexibility among the topologies.

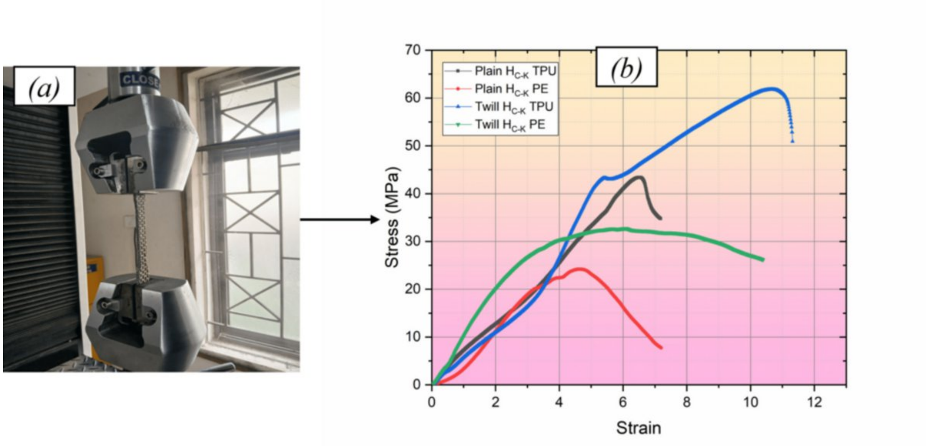

FIGURE 3: (a) Tensile testing of composite specimens and (b) stress–strain curves of plain and twill hybrid laminates

The flexural performance of hybrid fiber composites highlights the significance of the polymer matrix. The flexural strength data is tabulated in Table *2* and the respective graph is shown in Figure *4*. The TPU matrix, being ductile, enhances bending strength and energy absorption, as evidenced through the maximum flexural stress (81.34 MPa) exhibited by twill hybrid with TPU laminates. In contrast, plain hybrid with PE maintained the highest flexural modulus (2.97 GPa), reflecting that PE limits toughness while providing more stiffness. Twill hybrid with PE laminates exhibited the lowest values, reflecting the sensitivity of the matrix to weave architecture, while plain hybrid with TPU composites provided the best balance between strength and stiffness. The load-displacement curves also reveal that the PE-based systems fail earlier even with additional stiffness, while TPU-based systems can sustain higher loads and deformations. These observations indicate that PE enhances stiffness while TPU promotes toughness and impact resistance. Therefore, hybrid fiber composites are extremely versatile for aeronautical uses where stiffness and energy absorption are paramount due to this matrix-dependent compromise.

Sample number	Composite notation	Water absorption (%)	Ultimate tensile strength (MPa)	Flexural stress (MPa)	Flexural modulus (GPa)
1	Plain Hyb. C-K-TPU	1.32	45.68	58.06	2.24
2	Plain Hyb. C-K-PE	0.75	28.54	72.75	2.93
3	Twill Hyb. C-K-TPU	1.13	63.54	80.54	1.97
4	Twill Hyb. C-K-PE	0.89	34.59	54.67	1.21

TABLE 2: Data from water absorption, tensile, and flexure tests

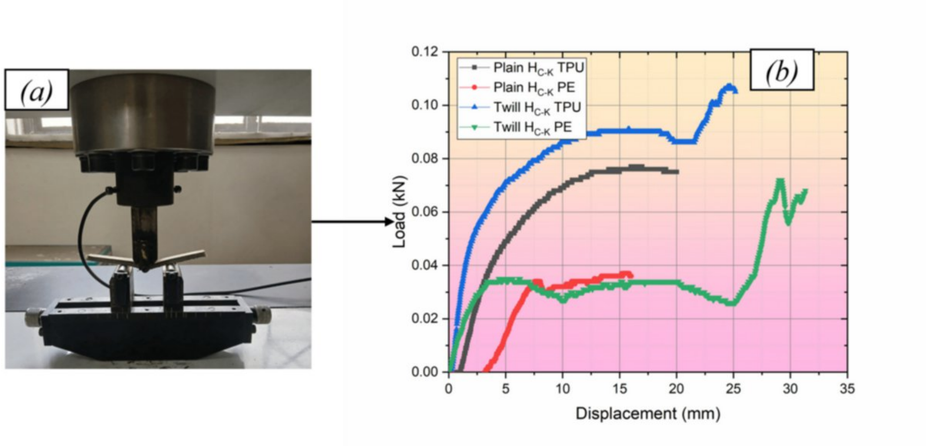

FIGURE 4: (a) Flexural testing of composite specimens and (b) load–displacement curves of plain and twill hybrid laminates

Low-velocity impact test results

Low-velocity impact response of those fabricated laminates indicates that TPU-based systems distinctly surpass their PE-based counterparts. The maximum load withstood by each laminate is depicted in Table 3. Their superior energy absorption and toughness were attested by the fact that plain and twill hybrid TPU composites could sustain higher peak loads and more deformation before failure. Through the retardation of catastrophic failure and effective dissipation of impact energy by way of plastic deformation, load-carrying capacity was enhanced by the ductile TPU matrix even after the maximum impact load. On the contrary, due to the brittleness of PE-based laminates, they failed at lower loads with reduced deformation, indicating poor energy dissipation. Twill hybrid fiber with TPU composites exhibited the highest impact resistance among the woven structures, plain hybrid fiber with TPU following closely behind. This indicates the way in which ductile TPU and interlacing patterns combine to enhance impact durability. These results demonstrate that for hybrid composites that are subjected to dynamic impact loading, TPU is a more reliable matrix. The post impacted specimens and their respective graph are displayed in Figure 5. The SEM micrographs from Figure 6 (a-d) show the morphology of failure of the plain-woven hybrid composite under low-velocity impact. The images show matrix cracking, fiber fracture, and localized fiber breakage, which together evidence the effective energy dissipation mechanism in the hybrid laminate. The combination of both carbon and Kevlar fibers improves synergistic load sharing capability, with stiff carbon fibers helping to resist impact and the ductile Kevlar fibers to resist sudden failure. The fracture patterns from observation ensure good interfacial adhesion and progressive damage absorption, which guarantees the hybrid layout resists impact loading under controlled failure instead of sudden delamination.

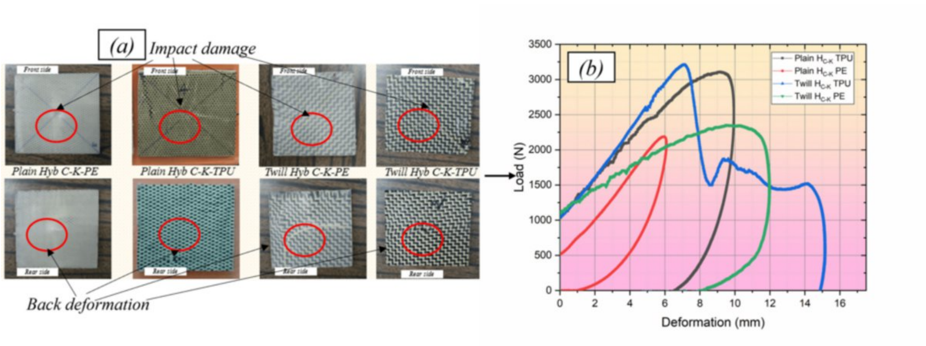

FIGURE 5: (a) Front and rear surfaces of impacted plain and twill hybrid laminates with TPU and PE matrices, and (b) load–deformation curves obtained from low-velocity impact testing

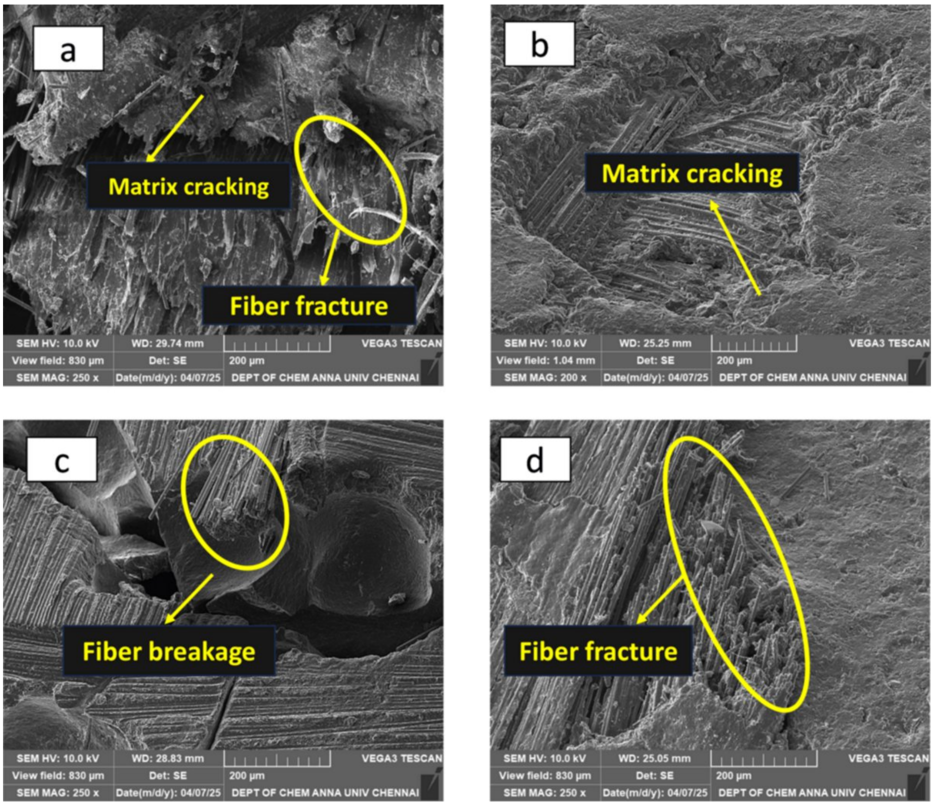

FIGURE 6: SEM micrographs of plain-woven hybrid composites after impact: (a and b) show the onset region on the impacted face, while (c and d) depict the side surface of the impacted region

SEM, Scanning Electron Microscopy

High-velocity impact test results

Ballistic limit velocity is the minimum bullet speed required to fully penetrate the composite target in high-speed impact studies can be calculated using the equation, $EV_{50} = \sqrt{V_s^2 - V_r^2}$

where Vs and Vr are the incident velocities and residual velocities, respectively. The energy absorbed by the composite due to impact is given by the difference between the incident and residual kinetic energies of the projectile.

$$E_K = \frac{1}{2} m_0 \left(v_i^2 - v_k^2 \right)$$

where, m_0 is the projectile's mass, v_i is the impact velocity of the projectile, and v_k is the projectile's residual velocity.

Sample number	Maximum impact load withstood in low-velocity impact test (N)	Impact velocity (m/s)	Residual velocity (m/s)	Energy absorbed by the composite (J)	Ballistic limit velocity (m/s)
1	3127	235	135	277.50	190.35
2	2200	234	147	248.60	183.12
3	3248	235	120	306.19	202.48
4	2410	235	143	260.82	187.82

TABLE 3: Data from low-velocity and high-velocity impact tests

It was found that the matrix material and weaving pattern played an important role in determining the ballistic resistance of HC-K laminates in the high velocity impact test. The impact as well as residual velocities, their ballistic limit and energy absorbed by them are tabulated in Table 3. As compared to the plain hybrid fiber with PE matrix, which recorded a reduced ballistic limit velocity of 183.12 m/s and energy absorption of 248.60 J, the plain hybrid fiber with TPU matrix exhibited a ballistic limit velocity of 190.35 m/s with an absorbed energy of 277.50 J. The same trends followed twill hybrid laminates as well, in which the PE laminates registered 187.82 m/s and 260.82 J, whereas twill woven hybrid fiber with TPU registered the highest ballistic limit velocity of 202.48 m/s and highest energy absorption value of 306.19 J. Compared to the quite brittle PE matrix, our results clearly indicate that TPU, being a ductile matrix, significantly enhances energy absorption and projectile penetration resistance. Twill TPU laminates perform higher ballistic limit and absorption compared to plain TPU laminates, indicating improved stress distribution at high velocity impact [22]. Moreover, the woven structure influences the performance. Overall, the matrix plays a crucial role in governing the dissipation of impact energy, and TPU-based hybrids are superior in terms of ballistic protection when compared to PE-based hybrids. The post impacted specimens and their velocity graph is displayed in Figure 7.

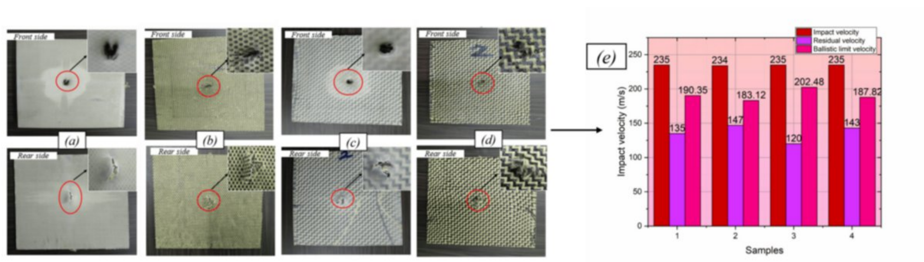

FIGURE 7: Front and rear surface damage morphology of (a) plain hybrid C–K–PE, (b) plain hybrid C–K–TPU, (c) twill hybrid C–K–PE, and (d) twill hybrid C–K–TPU laminates after ballistic impact, and (e) comparison of impact velocity, residual velocity, and ballistic limit velocity of the tested samples

Conclusions

The extensive investigation of PE- and TPU-matrix-reinforced hybrid carbon-Kevlar fiber composites reveals the prime importance of the matrix in governing multifunctional behavior. Water absorption studies showed that TPU laminates exhibited slightly higher uptake due to their polarity (1.32%), while PE-based laminates maintained lower absorption owing to their hydrophobic nature (0.75%). Despite this, TPU hybrids demonstrated superior mechanical performance, achieving a tensile strength of 63.54 MPa and a flexural strength of 80.54 MPa, attributed to the enhanced ductility and efficient stress transfer of the elastomeric matrix. Flexural tests further confirmed that TPU composites distributed loads uniformly and resisted crack propagation more effectively.

Low-velocity impact studies indicated that TPU laminates withstood a peak load of 3248 N, reflecting greater damage tolerance, while high-velocity impact tests showed a 49% reduction in residual velocity, signifying higher absorbed energy, ballistic limit, and specific energy absorption. By contrast, PE composites exhibited relatively lower mechanical and impact resistance but retained structural integrity under moisture exposure, making them suitable where water resistance is critical. Overall, TPU-based hybrid composites present a more favorable balance of strength, impact resistance, and energy absorption, rendering them highly promising for aeronautical and protective structural applications.

While the study has an experimental focus, future research should integrate finite element modeling to predict impact damage propagation and stress-wave interaction, strengthening the theoretical understanding of these mechanisms. From a sustainability perspective, both thermoplastic matrices support recyclability and reprocessing, which puts the study in line with global aerospace sustainability goals. The possibility of mechanical recycling and reforming of thermoplastic laminates further extends the life cycle benefits compared to thermosets.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Viswanaath Murugesan, Bhaskar GB, Madhan A

Acquisition, analysis, or interpretation of data: Viswanaath Murugesan, Bhaskar GB, Madhan A

Drafting of the manuscript: Viswanaath Murugesan, Madhan A

Critical review of the manuscript for important intellectual content: Viswanaath Murugesan, Bhaskar GB, Madhan A

Supervision: Bhaskar GB

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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