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Investigation the Effect of Low Velocity Impact on Mechanical Behavior of Composite Plates

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ABSTRACT

Composites are extensively used in aerospace, automotive, construction, and sports equipment, revolutionizing product design and engineering by offering tailored solutions for specific performance requirements. Damage in composites, especially due to low-velocity impacts from runway debris or tool drops, poses significant challenges, particularly in the aerospace sector where such impacts can be catastrophic. This study investigates the low-velocity impact (LVI) of Carbon/Kevlar hybrid composites, focusing on the influence of Kevlar in Carbon fiber laminates under different impact energies. Unlike previous research, this work examines the effects of an asymmetric stacking sequence of Carbon-Kevlar layers. Results show that with increased impact energy, variations in peak force, contact duration, and damage area are noted by altering the presence of Kevlar on top and bottom layers with carbon fibers. Kevlar-topped laminates exhibited a peak force reduction of 8.2% at 8J impact energy compared to carbon-topped laminates. Additionally, the contact duration for Kevlar-topped laminates was 21.4% shorter at 16J impact energy. Damage area studies revealed that Kevlar-topped laminates had 19% smaller damage areas on the top face and 28% smaller on the bottom face at 8J impact energy. These findings have significant implications for designing composite materials in high-performance applications, particularly in aerospace.

Keywords: Low Velocity Impact; Absorbed Energy; Hybrid Laminate; Damage Area;Contact Duration;.

1. Introduction

Composite materials represent an innovative class of materials, ingeniously created by integrating distinct constituent elements such as fibers and a matrix. This amalgamation endows composites with remarkable properties like enhanced corrosion resistance, improved stiffness, and an exceptional strength-to-weight ratio [1]. These superior characteristics have catapulted composites to the forefront of material science, leading to their widespread adoption in an array of over 40,000 end-use applications. Particularly notable is their utilization in industries such as automotive, aerospace, and construction [2,3]. The inherent lightweight nature of these composites plays a pivotal role in reducing carbon emissions, a crucial factor in today's environmentally conscious world. In aerospace applications, this reduction in weight directly translates to decreased fuel consumption, aligning with sustainability goals. Moreover, the ability to recycle these materials underscores their contribution to sustainable waste management practices [4]. The aerospace industry has been a prominent beneficiary of composite materials. These composites are extensively employed in critical aircraft components, including fuselages, wing and tail sections, engine parts, interior cabin elements, landing gears, and various structural components [5]. This wide-ranging application underscores the versatility and reliability of composite materials in high-performance environments. However, despite these numerous advantages, the use of composite materials is not without its challenges. A significant area of concern is their susceptibility to impact damage [6]. Impact damage in composites, particularly Barely Visible Impact Damage (BVID), poses a unique challenge. BVID, characterized by internal damage that is not easily detectable to the naked eye, can significantly compromise the structural integrity and residual properties of the composite material [7].

The phenomenon of Low Velocity Impact (LVI) on composite materials has been a subject of extensive study by researchers. These studies have utilized a combination of experimental and numerical approaches to gain a deeper understanding of the impact-induced damage on such materials [8]. In this realm, hybrid composites have emerged as a superior alternative to single-fiber composites. Offering a balance between cost-effectiveness and enhanced performance, hybrid composites have proven to be more adept at addressing the challenges posed by LVI [9]. These composites not only demonstrate improved mechanical properties but also exhibit greater strength and durability in response to impact-related events [10-14].

The success of composite materials heavily relies on the compatibility of the interface between different types of fibers and matrices. This compatibility is essential for creating strong bonds, and it becomes a challenging issue when the bond is weak [15]. Synthetic fibers such as Kevlar, Carbon, and glass fibers have shown promising results in terms of compatibility and performance in composite materials. Research, such as the study conducted by Kavin et al. [16], has highlighted the effectiveness of Kevlar-Carbon LVI composites. These composites exhibit higher stress at lower displacements, making them highly suitable for impact-critical applications in aircraft. Comparative studies, like the one examining Kevlar/Glass and Kevlar/Basalt composites, have revealed a significant improvement in impact resistance, with Kevlar/Basalt composites showing a 35% increase in resistance [17].

Further research by Guo S et al. [18] delved into the impact of ply thickness on the damage resistance and compressive strength after impact of Kevlar laminates. Their findings indicated that reducing ply thickness can substantially enhance the material's resistance to damage. Additionally, the stacking sequence in Kevlar laminates was found to influence their resistance to impact damage and the extent of such damage [19]. However, this finding was not mirrored in carbon fiber laminates with thin-ply, which did not exhibit a significant increase in LVI resistance compared to conventional laminates [20]. Moreover, discrepancies in the thickness of the lamina within each laminate layer resulted in considerable variances in the impact response. It was observed that an increase in laminate thickness led to an escalation in the absorbed impact energy [21].

A noteworthy aspect of composite materials is the orthogonal fiber laminates' capability to provide better impact resistance compared to 2.5D woven fabrics [22]. In automotive applications, the hybrid effect of carbon-Kevlar laminates was studied, revealing an increase in specific impact strength [23]. A notable finding was that incorporating Kevlar in the top layer of hybrid Carbon-Kevlar composites resulted in a 55% increase in strength. However, the effects of a reverse stacking sequence in these composites remain largely unexplored due to the scarcity of research in this specific area. Some researchers have shown that hybrid composites always tend to provide better mechanical properties as compared to individual constituents [24]. Further in a study involving glass/jute epoxy, the hybrid nature of the laminate provides to provide better mechanical strength [25].

Addressing this gap, the current study focuses on an asymmetric stacking sequence of Carbon-Kevlar composites subjected to LVI. The investigation aims to analyze the damage sequence and provide comprehensive insights into the behavior of these composites under impact conditions with Kevlar on top and bottom and its influence in the damage area.

2. Materials and Methods

2.1. Fabrication

The fabrication of the composite laminate was meticulously carried out using the Vacuum Bagging Process, a method renowned for its accuracy and efficiency. In the fabrication process, a six-layer composite laminate was constructed, comprising three layers of Carbon and three layers of Kevlar in asymmetric sequence containing properties as given in Table 1.

Table 1 : Material properties of Kevlar and Carbon

Particulars	Kevlar	Carbon
Areal Weight (g/m^2)	160	160
Density (g/cm^3)	1.4	1.75
Tensile Strength (MPa)	3696	4855
Tensile Modulus (GPa)	105	240
Elongation %	2.7	1.8
Dry Fabric Thickness (mm)	0.24	0.17
Filament Diameter (µm)	8	7
Thermal Stability (°C)	450	400

To achieve the correct resin mix, a precise hardener-to-epoxy ratio of 1:10 (LY556 & HY951) was carefully measured and mixed. The process involved the use of 12 HP vacuum pumps, essential for forming the intended composite structure. The Vacuum Bagging Process, taking four hours, involved arranging the Carbon and Kevlar layers in a deliberate hybrid stacking pattern, represented as [C+K+C+K+C+K] as illustrated in Figure 1a. This specific arrangement aimed to thoroughly evaluate the laminate's resistance to damage on both its top and bottom surfaces, with each Carbon and Kevlar layer weighing 200 gsm. As part of ensuring quality, a bubble burster was used to remove excess resin and air bubbles, resulting in a uniform, flaw-free laminate as shown in Figure 1b [30]. After the vacuum bagging, the laminate was carefully transferred to a hot air oven for a detailed drying process at 60 degrees Celsius for four hours, enhancing its structural strength. Post-drying, the laminate was precisely cut according to ASTM Standard D7136/D7136M, producing pieces measuring 150mm by 100mm, each with a thickness of 2.15 ±0.2mm. To fine-tune the edges and meet specific criteria, the cut laminates underwent an additional drying period of 30 minutes at 40 degrees Celsius, following waterjet cutting.

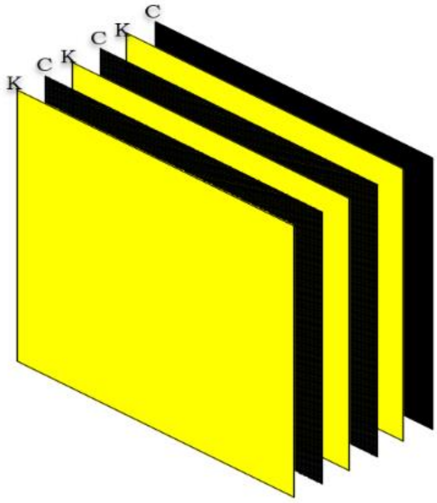


Fig. 1a. Stacking sequence of Kevlar and Glass fibers

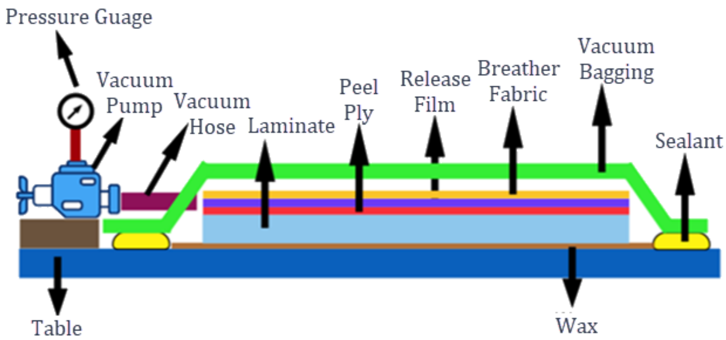


Fig. 1b. Fabrication using vacuum bagging process [30]

2.2. Drop Weight Impact Testing

Low-velocity Impact Testing is essential for evaluating materials' resilience and impact resistance under controlled conditions. This testing methodology establishes a maximum drop height of 1.5 meters, where the energy imparted onto the material ranges from a low of 8J to a high of 60J. The samples, now identified as A1 and A2, are composed of Carbon as the upper layer and Kevlar as the lower layer, differing in their exposure to specific impact energies and drop heights. Conversely, samples A3 and A4 invert this layering, featuring Kevlar on the upper side and Carbon on the underside, each subjected to distinct impact scenarios. The revised impact energies for these tests are set at 8J and 16J, corresponding to adjusted drop heights of 198mm and 397mm, respectively as shown in Table 2, these values were chosen which corresponds to adjusted heights of tool drops during the service maintenance in an aircraft.

An anti-rebound mechanism is integrated within the test setup to eliminate the possibility of secondary impacts. Each specimen, measuring 150mm x 100mm, is secured in place using toggle clamps in compliance with ASTM D7136 standards, ensuring a consistent and reliable testing environment. The velocity at the point of impact is determined using a pair of sensors designed to record both the initial and concluding velocities, crucial for the precision of the experiment. The testing apparatus is outfitted with a 4.1kg Total Unitary Projectile (TUP) weight, facilitating uniform and controlled impact forces across all tests. The force and time data of the impact are captured using a NI 6210 Data Acquisition Card from National Instruments, providing detailed temporal resolution. Additionally, a high accuracy 50kN impact load cell measures the peak force during each impact, offering essential data for subsequent analysis as shown in Figure 2.

Fig. 2. Low velocity impact testing machine

Analysis of the test results is conducted using MATLAB, which processes data to derive key metrics such as displacement, velocity, and the energy absorbed by the specimen. This analysis gives an in-depth understanding of how the material reacts to impacts. Each testing cycle is repeated four times for every sample, with the results averaged to reduce the effect of any experimental variances. Employing this meticulous testing process and data averaging technique, Low-velocity Impact Testing delivers valuable insights into the behavior of materials like Carbon and Kevlar under low-speed impacts.

2.3. Damage Assessment

deformations on the surface. To precisely quantify and analyze the damage area, advanced software tools came into play. ImageJ software, renowned for its image analysis capabilities, was utilized for this purpose. By processing high-resolution images of the impacted laminate, ImageJ enabled the accurate measurement of the damaged region, taking into account both the Carbon and Kevlar layers present at the top of the laminate or at the bottom area. This meticulous analysis helped in identifying the size and distribution of the damaged area on the top face. Moreover, by conducting a similar assessment on the bottom face of the laminate, a comprehensive understanding of the material's response to the impact event can be achieved, and the influence of Kevlar on Carbon was established.

3. Results

The Low Velocity Impact (LVI) test was conducted to analyse a laminate material, focusing on the carbon and Kevlar sides under impact energies of 8J and 16J. This experiment utilized a high-frequency data acquisition system at 50kHz, employing an optical sensor to measure the velocity of the impactor precisely upon contact with the laminate. To ensure data accuracy, a sensor monitored the effectiveness of an anti-rebound mechanism after the initial impact, eliminating secondary rebounds. The study involved testing five distinct samples to confirm the consistency and reliability of the findings. A load cell with a 50kN capacity was integral to the experiment, enabling precise measurements of the forces exerted during the impacts and providing valuable insights into the dynamics of LVI tests on laminates with carbon components.

3.1. Force vs Time

The force-time curve, as shown in Figure 3, serves as a foundational data set in a Low-Velocity Impact (LVI) test, from which all pertinent charts per ASTM D7136 standards are derived. This force vs time plot mirrors similar studies documented by prior researchers [26], offering insights into the dynamics of an impact event. When the impactor or tup, descends from a predetermined height, it strikes the composite panel, inducing a response that hinges on the panel's material properties, thickness, and structural layout. The experimental outcomes underscore a pronounced dependence on material composition, especially noticeable when comparing the peak forces in configurations where carbon is utilized as the top layer (A1 and A2) against those with Kevlar in the analogous position (A3 and A4). This discrepancy is primarily attributed to the intrinsic stiffness of carbon, which facilitates more efficient transmission of force upon impact [27].

This phenomenon is consistent across both configurations; an escalation in impact energy from 8 to 16 Joules significantly amplifies the peak force, a testament to the expectation that higher impact energies enhance force transmission as shown in Table 3.

Notably, this augmentation in peak force is more significant in specimens with carbon on the upper surface. In contrast, specimens with Kevlar on top exhibited a 2.64% diminution in peak force when subjected to the same increase in impact energy, highlighting Kevlar's superior impact mitigation capabilities.

Table 2 : Testing code and parameters

Sl No	Specimen Code	Material Presence (TOP)	Material Presence (BOTTOM)	Impact Energy (J)	Height of Fall (mm)	Velocity m/sec
1	A1	Carbon	Kevlar	8J	198	1.980
2	A2	Carbon	Kevlar	16J	397	2.801
3	A3	Kevlar	Carbon	8J	198	1.980
4	A4	Kevlar	Carbon	16J	397	2.801

This is further elucidated by examining the duration of contact across all samples, where it was observed that carbon composites exhibited a shorter contact duration relative to their Kevlar counterparts. Specifically, the contact duration decreased by 18.9% and 21.4% for impacts at 16 Joules for samples with carbon and Kevlar top layers, respectively, when compared to impacts at 8 Joules. This reduction in contact duration for Kevlar-topped specimens vividly illustrates Kevlar's exceptional stiffness and impact resistance, effectively shortening the impact event's duration during testing.

One notable point that is found in force time graph is the A2 and A4 were subjected to higher impact energies of 16J compared to 8J impact energy for A1 and A3. This increased energy resulted in a more significant force being impacted onto the laminate., causing sharp peak in the graph. The intrinsic stiffness of the carbon layer on the top in the A2 facilitates efficient force transmission upon impact, since carbon fibers are known for their high tensile modulus. And stiffness, which can result in a higher peak force when they are positioned to receive the impact directly. While Kevlar is generally less stiff than

carbon, its high tensile strength and energy absorption capacity allow it to mitigate the impact force to some extent. However, when combined with the high impact energy of 16J, it still results in a sharp peak due to the rapid deceleration of the impactor. This indicates that while Kevlar helps in reducing the overall damage area and contact duration, the initial impact force can still be high, contributing to the sharp peak.

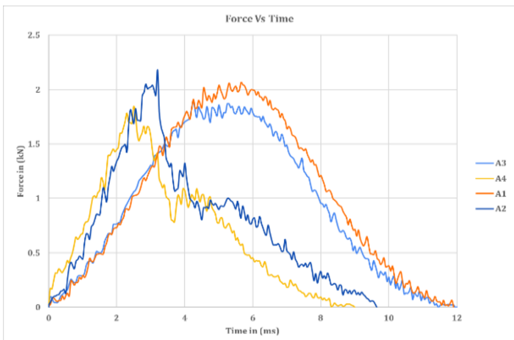


Fig. 3. Force vs Time plot

Table 3. Results of Drop Weight Impact Test Carbon and Kevlar Laminates

Specimen code	Material Top Face	Material Bottom Face	Impact Energy	Height of Fall (mm)	Peak Force (kN)	Absorbed Energy (J)	Contact Duration (ms)	Damage Area Top (mm2)	Damage Area Bottom (mm2)
A1	Carbon	Kevlar	8	198	2.065	7.82	11.9	114.61	123.69
A2	Carbon	Kevlar	16	397	2.180	14.50	9.65	191.26	224.45
A3	Kevlar	Carbon	8	198	1.895	7.84	11.45	92.81	88.70
A4	Kevlar	Carbon	16	397	1.845	13.19	9.00	141.72	173.63

3.2. Velocity vs Time

During an impact, the kinetic energy from the impactor is transferred to the material. The rate of deceleration is based on material stiffness and energy absorption properties. When the impactor bounces back it is designated by an increase in velocity in the opposite direction, however, when the material completely deforms it leads to penetration resulting in velocity moving to zero and not rebounding [28,29]. In the case of specimens A1 and A3, the velocity moved in the negative direction which gave a clear indication that the material resulted in a rebound scenario. This was due to the lower impact energy of 8J, wherein the material demonstrated a stiffer phenomenon and the impactor resulted in a rebound effect. However, for a 16J impact, there was no rebound scenario as the majority of the energy was absorbed and further restricted the movement of the impactor, which led to the complete failure of the specimen and resulted in a drastic reduction in velocity before tending to zero as shown in Figure 4. The velocity moved to zero at 6.6ms and 6.8ms in the case of carbon and Kevlar in the top face respectively for 8J, this gives a clear indication that the presence of Kevlar at the top face resists and takes more time to reach zero. For 16J it was noted that when carbon was in the top face, the time taken for the impactor to stop further movement was 1 m/sec as compared to Kevlar on top was 1.26 m/sec. This effect was due to the stiffness and rebound nature of Kevlar.

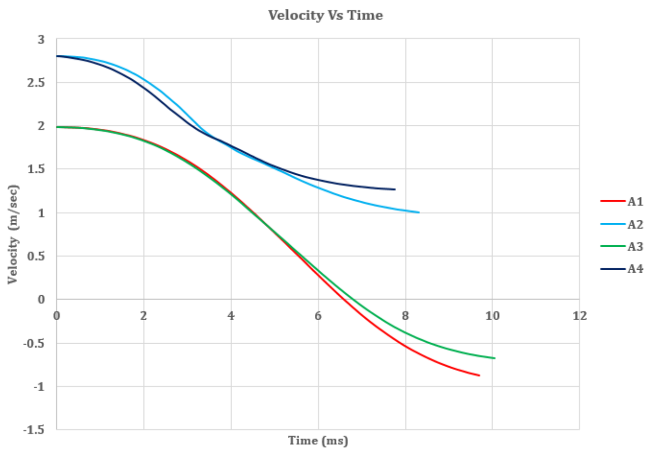


Fig. 4. Velocity vs Time plot for all samples

3.3. Damage Area Analysis

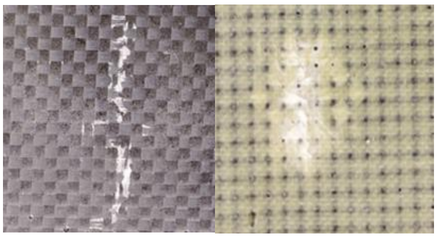
3.3.1. Image J Analysis

This investigation aimed to analyze the stiffness of composite laminates with varying material configurations when subjected to impact loading. The specimens, labeled A1, A2, A3, and A4, were composed of alternating layers of carbon and Kevlar, with A1 and A2 featuring carbon on the top face, while A3 and A4 had Kevlar on the top. The specimens were impacted with energies of 8 J and 16 J, corresponding to fall heights of 200 mm and 400 mm, respectively.

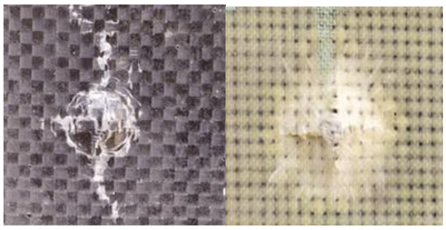
Using Image J software Specimens A1 carbon/Kevlar and A3 Kevlar/carbon, both subjected to an 8 J impact, showed distinct differences in damage area, with A1 exhibiting larger damage on both the top (114 mm^2) and bottom (123 mm^2) compared to A3 92 mm^2 top and 88 mm^2 bottom) refer to Figure 5. This suggests that the Kevlar top layer in A3 offered greater stiffness than the carbon top layer in A1, resulting in less damage.

Similarly, specimens A2 and A4 were compared under a 16 J impact. A2, with the carbon top layer, showed greater damage areas (191 mm^2 top and 224 mm^2 bottom) than A4 (141 mm^2 top and 173 mm^2 bottom), which had a Kevlar top layer. The results from A4 imply that Kevlar, when used as the impact face, enhances the laminate's stiffness, mitigating the extent of damage.

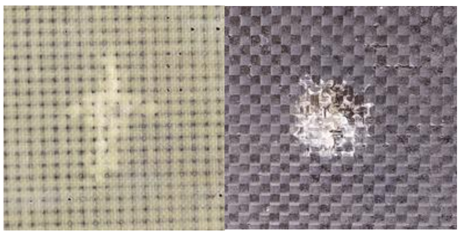
The data indicates that the stiffness of the laminate is greater when Kevlar is positioned as the top layer rather than carbon. This may be due to the intrinsic properties of Kevlar, which include high tensile strength and energy absorption capacity. Consequently, laminates with Kevlar as the outermost layer are less prone to damage and thus are stiffer under the given impact conditions. The damage mechanism of all the impact scenarios is shown in Figure 6.



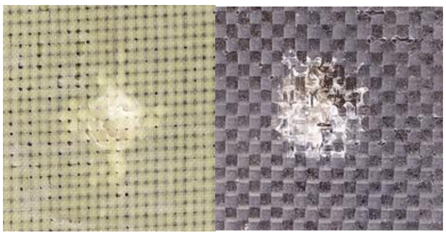
A1 Front A1 Back



A2 Front A2 Back



A3 Front A3 Back



A4 Front A4 Back

Fig. 6. Damage images of all specimen front and back sides.

Damage Mechanism of different impact is shown in table 4

Table 4 Damage Analysis due to impact

Type of Damage	A1	A2	A3	A4
Matrix Cracking	Yes	Yes	Yes	Yes
Delamination	Yes	Yes	Yes	Yes
Fiber Breakage	No	Yes	No	Yes

It is found the images clearly indicate that specimens with Kevlar as the top layer (A3 and A4) exhibit less front-side damage compared to those with carbon as the top layer (A1 and A2). This demonstrates Kevlar's superior ability to absorb and mitigate impact energy. The increase in impact energy from 8J to 16J results in more extensive damage across all specimens, but the relative effectiveness of Kevlar in reducing damage remains consistent. The presence of Kevlar, especially on the top layer, helps in better distribution and reduction of impact-induced damage, which is crucial for maintaining the structural integrity of the composite laminate.

4. Conclusions

The study investigated the influence of Kevlar in carbon fiber-reinforced composite laminate under low-velocity impact (LVI) conditions. The research revealed significant variations in peak force, contact duration, and damaged area of the composite laminates with varying impact energies and different configurations of Kevlar and carbon fiber layers.

Impact resistance enhancement: The presence of Kevlar in the composite laminate configuration significantly enhanced impact resistance, as evidenced by a reduction in peak force. For instance, specimens with Kevlar as the top layer showed a peak force of 1.895 kN at 8J impact energy, compared to 2.065 kN for specimens with carbon as the top layer.

Stiffness improvement: Kevlar-topped laminates exhibited superior stiffness and impact mitigation capabilities, reducing contact duration during impact events. Contact duration decreased by 18.9% and 21.4% for impacts at 16 Joules for samples with carbon and Kevlar top layers, respectively, compared to impacts at 8 Joules.

Damage area reduction: The presence of Kevlar in the top layer resulted in smaller damage areas on both the top and bottom faces of the laminate. At 8J impact energy, specimens with Kevlar as the top layer showed a damage area of 92.81 mm² on the top face and 88.70 mm² on the bottom face, compared to 114.61 mm² and 123.69 mm², respectively, for specimens with carbon as the top layer.

Hybrid composite effectiveness: The study highlighted the efficacy of hybrid composites combining Kevlar and carbon fibers in improving impact resistance. This was particularly evident in the asymmetric stacking sequence of carbon and Kevlar layers, which showed promising results in enhancing impact resistance and reducing damage.

The study introduces the approach of using an asymmetric stacking sequence of carbon and Kevlar layers, which has not been extensively explored in previous research related to LVI. Based on the findings, assessment of impact resistance under long term durability studies can be reviewed. Studies related to X ray computed tomography and DIC can be looked into to review the micro-level failure and vibration characteristics respectively. Further, hybridization with basalt can provide new opportunities in studies related to impact resistance.

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