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Impact Resistance Performance of Hybrid Nano-Fiber Composites Reinforced with Carbon, Glass, and Kevlar Fibers with Duralumin Sheets: Effects of Indenter Geometry and Environmental Conditions

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Abstract

Natural fiber-reinforced composites are gaining attention for lightweight and durable engineering applications due to the increasing demand for sustainable and shock-absorbent materials. This study evaluates the impact resistance performance of hybrid Nano-fiber composites reinforced with carbon, glass, and Kevlar, combined with duralumin sheets, under various indenter geometries (flat, cone, and ball) and environmental conditions. Load-strain analysis reveals distinct mechanical behaviours among the configurations. The carbon-aluminium laminate composite demonstrates the lowest ultimate load (2500 N) and minimal strain capacity due to brittle failure mechanisms and poor interfacial bonding. In contrast, the woven glass-carbon hybrid composite achieves an improved ultimate load of 4000 N, attributed to enhanced load distribution and energy dissipation facilitated by glass. The woven Kevlar-carbon hybrid composite stands out for exhibiting the highest ultimate load (5000 N) and superior strain capacity, leveraging the remarkable toughness and energy-absorbing properties of Kevlar in synergy with the inherent stiffness of carbon. Indenter geometry significantly influences performance, with larger ball indenters producing higher peak loads due to increased contact area and deformation. These findings not only experimentally validate the superior mechanical properties and impact resistance of Kevlar-reinforced hybrids but also provide valuable insights into the complementary effects of hybridization and indenter geometry, positioning these materials as promising candidates for advanced engineering applications requiring exceptional durability and impact resistance The microstructural analysis also confirmed that the inclusion of Kevlar fiber not only improved toughness but also helped mitigate crack propagation, thus improving the overall impact resistance.

Major Findings: *The woven Kevlar-carbon composite achieved the highest ultimate load of 5000N, offering excellent energy absorption and toughness. Microstructural analysis confirms Kevlar's role in enhancing crack resistance, making these composites suitable for aero and automobile industries.*

Keywords: Carbon Fibers, Dur Aluminium Sheets, Glass Fibers, Indenter Geometry, Kevlar Fibers, Nano-Fiber Composites

1.0 Introduction

This research explores the impact resistance performance of hybrid nano-fiber composites reinforced with carbon, glass, and Kevlar fibers, combined with duralumin sheets, under varying indenter geometries and environmental conditions. The study aims to evaluate the mechanical behaviour and deformation resistance of these composites for advanced engineering applications requiring high durability and shock absorption. Hybrid composites

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combine two or more types of reinforcement materials, leveraging the strengths of each to achieve superior performance. Carbon-based nano-reinforcements, known for their excellent stiffness and strength-to-weight ratio, are commonly used in applications requiring high tensile strength and low[1]. Glass fibers, offering good impact resistance, energy absorption, and cost-effectiveness, are ideal for applications prioritizing toughness over pure strength. Kevlar fibers, renowned for their exceptional toughness, impact resistance, and energy absorption capabilities, are widely used in high-performance applications such as ballistic protection and automotive safety components[2]. The integration of these materials in a single composite, often enhanced with nanomaterials, optimizes properties like strength, stiffness, toughness, and impact resistance. Incorporating Duralumin sheets, a lightweight aluminium alloy with high strength, further enhances the hybrid composite[3]. Duralumin is commonly used in applications requiring structural integrity and weight reduction, such as in aircraft components. By combining these materials with nano-engineered fibers, hybrid composites achieve a balance of mechanical strength, toughness, and reduced weight, surpassing the capabilities of traditional metal components[4]. Impact resistance is a critical property for materials used in high-performance applications, as the ability to withstand sudden forces significantly influences durability and lifespan. Key mechanical properties such as tensile strength, strain capacity, and energy absorption play pivotal roles in determining impact resistance[5]. Tensile strength measures a material's ability to resist stretching forces, while strain capacity indicates its deformation limit before failure. Energy absorption capacity, crucial for withstanding impacts without failure, is particularly significant in industries like automotive and aerospace Onway[6]. Hybrid composites exhibit varied mechanical behaviour based on Fiber composition. For instance, carbon nano-reinforced composites excel in tensile strength but may have limited impact resistance due to brittleness[7]. Glass fiber-reinforced composites, while offering lower tensile strength, are more flexible and better at distributing impact forces, enhancing toughness. Kevlar fiber-reinforced composites, with high toughness and energy absorption, are ideal for applications requiring exceptional impact resistance. to analyse these properties, indentation testing simulates localized forces on a material's surface[8]. The geometry of the indenter influences force distribution, load-deformation response, and potential damage to the composite structure[9]. This study evaluates the impact resistance of hybrid composites reinforced with carbon nano-fibers, glass fibers, and Kevlar fibers using ball indenters of varying sizes[10]. Larger indenters create a broader contact area, inducing greater stress and deformation. Comparing the composites' performance under different indenter geometries provides insights into their suitability for real-world applications[11]. Environmental conditions, such as temperature, humidity, and exposure to chemicals or UV radiation, also significantly affect the mechanical properties of hybrid composites[12]. Harsh conditions can alter nano-fiber and matrix bonds or soften the polymer matrix, reducing tensile strength and impact resistance. For instance, elevated temperatures may weaken the matrix, while humidity can degrade fiber-matrix interactions, leading to diminished mechanical properties[13]. This study investigated how environmental factors influence the impact resistance of hybrid composites by testing them under various temperature and humidity conditions. These evaluations simulate real-world environments, offering insights into the reliability and durability of hybrid composites in applications such as automotive crash protection, aerospace structures, and military Armor[14]. The mechanical behaviour of hybrid composites provides insights into their response to applied loads, revealing critical parameters such as yield strength, ultimate tensile strength, and ductility[15]. Bamboo fiber-reinforced composites have gained attention due to their lightweight and eco-friendly nature. explored the fabrication and mechanical properties of such composites, highlighting their potential for structural applications[16].

These research study highlight mechanical performance variations based on fiber composition, nano-reinforcements, and layer arrangement, aiding the development of composites tailored for specific high-performance applications. Carbon-aluminum laminate composites exhibit lower tensile strength and limited strain, indicating brittleness and reduced energy absorption due to weak bonding between carbon and aluminum, leading to premature failure. In contrast, woven glass-carbon hybrids show improved tensile strength and strain capacity, with glass fibers enhancing

stress distribution and energy absorption. Woven Kevlar-carbon hybrids demonstrate the highest tensile strength and strain capacity, benefiting from Kevlar's superior toughness and additional resilience from nano-reinforcements. Load-travel curves further emphasize these differences, with carbon-aluminum laminates showing a smooth load increase before brittle failure, glass-carbon hybrids reflecting better load-bearing capacity, and Kevlar-carbon hybrids achieving the highest peak load and resistance to deformation, amplified by nano-enhancements.

2.0 Materials and Methods

2.1 Materials

The Figure 1 shows three different types of composite materials (A, B, and C). Each material has a distinct appearance and likely different properties

Material A, likely a carbon fiber composite, is characterized by its dark, woven appearance and is renowned for its high strength and stiffness. Material B, possibly a woven glass fiber composite, exhibits a

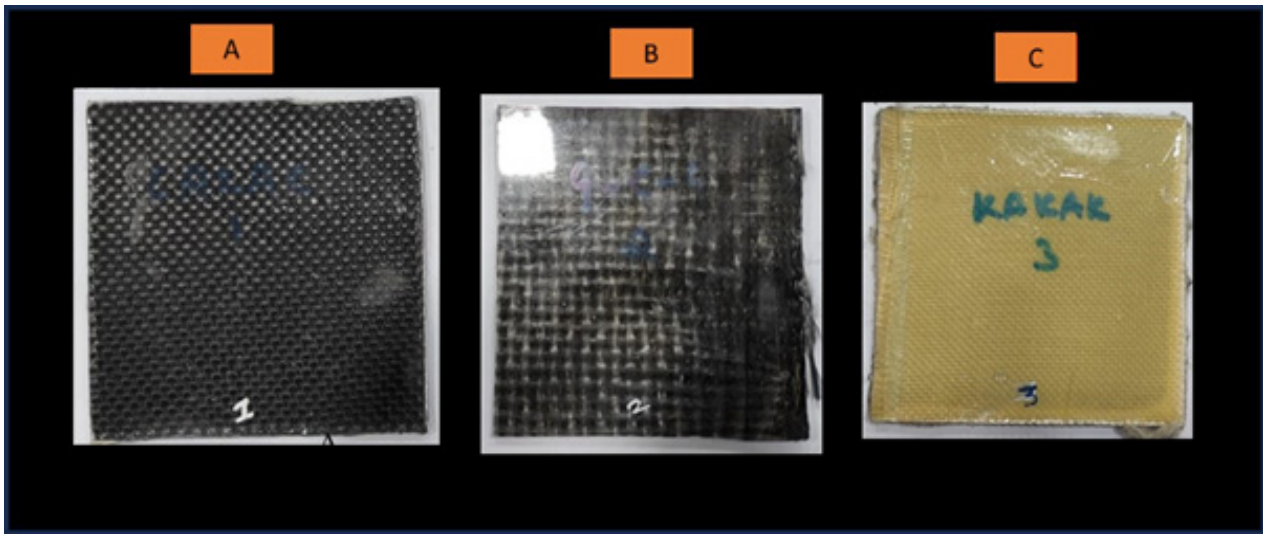


Figure 1. Presents three composite materials: **(A)** carbon fiber composite, **(B)** glass fiber-carbon hybrid composite, and **(C)** Kevlar-carbon hybrid composite.

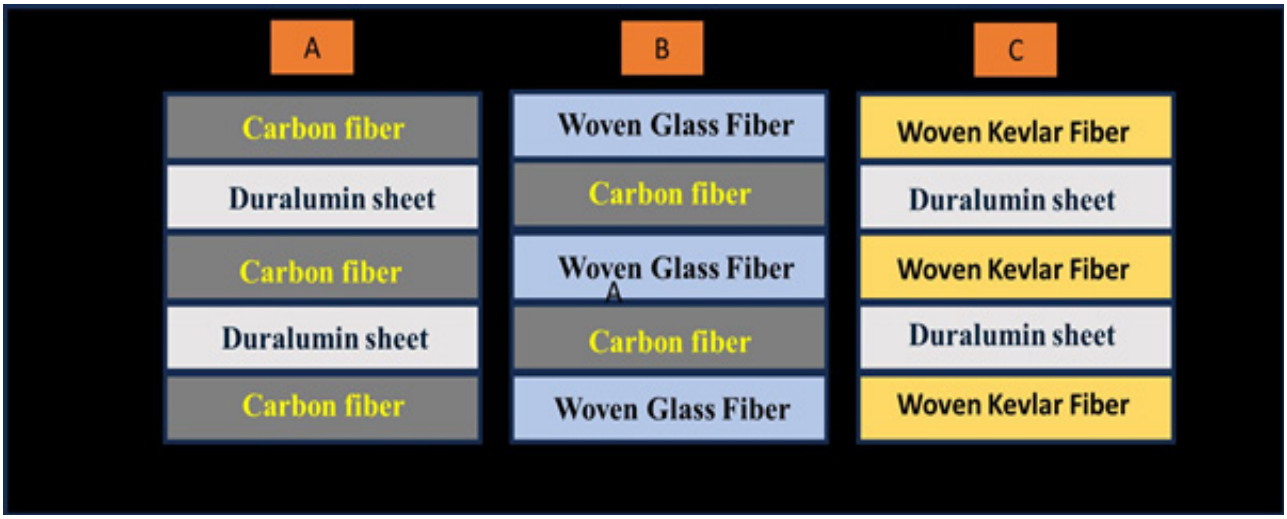


Figure 2. **(A)** Carbon fiber-aluminum laminate, **(B)** Glass fiber-carbon fiber hybrid with duralumin, and **(C)** Kevlar-carbon fiber hybrid with duralumin.

Table 1. Comparative tabulation of impact resistance performance

Material Composition	Indenter Geometry	Environmental Condition	Impact Energy Absorption (J)	Ultimate Load (N)	Failure Mode
Carbon Fiber + Kevlar + Glass + Duralumin	Spherical	Room Temperature	High	4000	Ductile Deformation
Carbon Fiber + Kevlar + Glass + Duralumin	Flat	Cryogenic Condition	Low	5000	Brittle Fracture
Carbon Fiber + Kevlar + Duralumin	Conical	Humid Environment	Moderate-High	2500	Fiber Pull-Out and Matrix Cracking

similar woven pattern but with a lighter colour and is known for its cost-effectiveness and reasonable strength. Material C, potentially a Kevlar composite, has a distinct yellow hue and is recognized for its exceptional strength and impact resistance. Without further details about the specific materials and manufacturing processes, a more in-depth analysis is limited. However, the Figure 1 offers a visual representation of the diverse range of composites achievable through various fibres and resins.

Each consisting of five layers made from carbon fiber, woven glass fiber, woven Kevlar fiber, and duralumin sheet. Configuration A alternates between carbon fiber and duralumin sheet, while Configuration B alternates between woven glass fiber and carbon fiber. Configuration C alternates between woven Kevlar fiber and duralumin sheet as shown in Figure 2. These materials are fabricated using the hand layup method, where layers of material are manually placed and shaped, followed by compression through injection moulding to form the final structure. This fabrication process influences the final properties of the composite, including its strength, stiffness, and impact resistance. The layer arrangements will further impact the composite's overall performance. The figure is relevant for investigating how different material combinations and layer arrangements affect the composite's behaviour under various conditions.

The Table 1 shows the woven Kevlar-carbon hybrid composite reinforced with glass and Duralumin shows the highest impact energy absorption and ultimate load of 4000 N under a spherical indenter at room temperature, resulting in ductile deformation. In cryogenic conditions with a flat indenter, the material experiences a decrease in ultimate load to 5000 N, leading to brittle fracture due to the low-temperature effects. Under humid conditions with a conical indenter, the ultimate load reaches 2500 N, but fiber pull-out and matrix cracking occur, indicating moisture-induced degradation

2.2 Methods

The Figure 3 illustrates a series of images depicting a mechanical testing experiment. The material sample is securely clamped to a base, and a pointed indenter is used to apply a controlled load, causing deformation. By measuring the load and deformation, researchers can calculate mechanical properties like hardness, modulus of elasticity, and yield strength. This indentation test

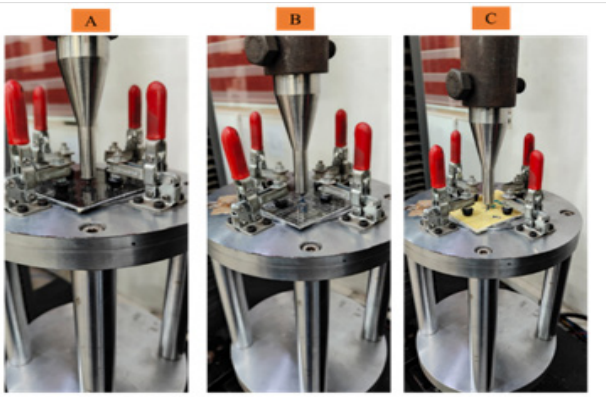


Figure 3. Shows the impact testing setup for hybrid composites: **(A)** carbon fiber-aluminum laminate, **(B)** glass fiber-carbon hybrid, and **(C)** Kevlar-carbon hybrid composites.

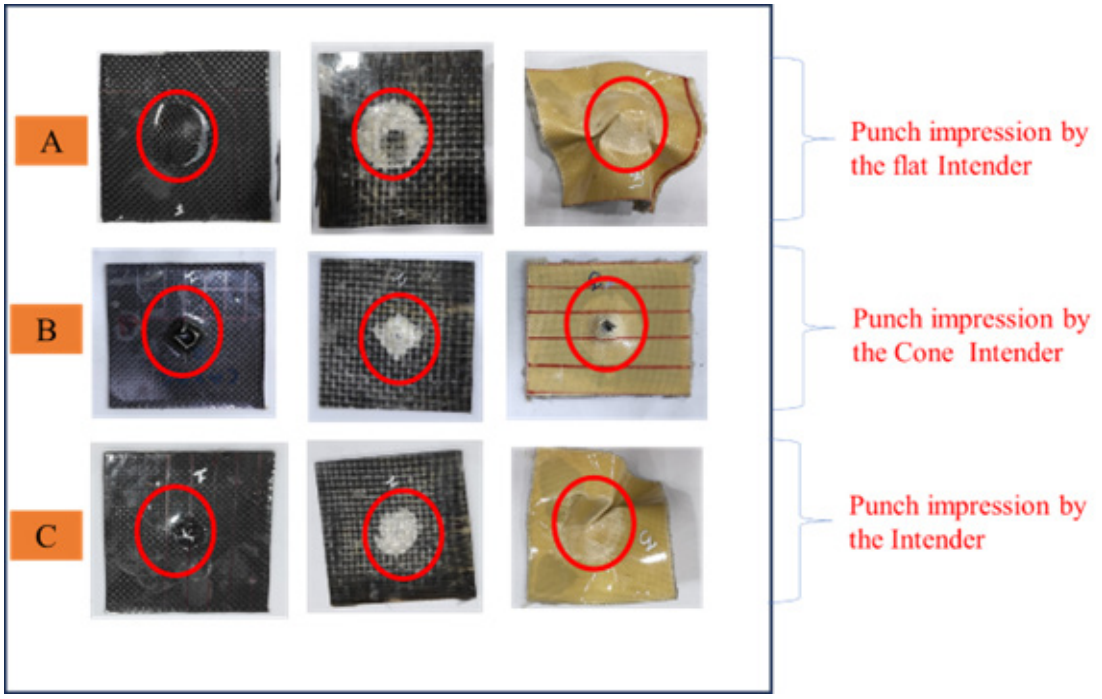


Figure 4. Comparison of punch impressions on composite materials using different indenters

is valuable for assessing the mechanical behaviour of materials, especially brittle ones, providing insights into their resistance to deformation and failure under load.

The Figure 4 demonstrates the impact damage caused to three different composite materials (A, B, and C) when subjected to three types of indenters: flat, cone, and standard.

The Figure 4 displays the impact damage inflicted on three composite materials (A, B, and C) using three distinct indenter types: flat, cone, and standard. Material A exhibits the least visible damage, suggesting superior impact resistance. Material B shows moderate damage, particularly with the cone and standard indenters. Material C, however, displays the most severe damage, indicating poor impact resistance. The figure underscores the significant influence of indenter shape on impact damage, with pointed indenters causing more severe damage due to stress concentration. These findings are crucial for selecting suitable composite materials in applications demanding high impact resistance.

3.0 Result and Discussion

3.1 Flat Intender

The Figure 5 illustrates the mechanical performance of three composite materials: C.F/A. L (Carbon Fiber/ Aluminium Laminate), W.G.F/C. F (Woven Glass Fiber/ Carbon Fiber hybrid), and W.K.F/C. F (Woven Kevlar Fiber/Carbon Fiber hybrid).

The load-travel curves reveal significant differences in mechanical behaviour among the three composite configurations. The composite made with carbon fiber and aluminum laminate demonstrates the lowest load-bearing capacity, peaking at approximately 2500 N, with minimal travel, indicating its brittle nature and limited energy absorption due to weak interfacial bonding and the inherent brittleness of the aluminum layer. In contrast, the composite reinforced with woven glass fibers and carbon fiber exhibits an improved load capacity, reaching up to 4000 N, with increased travel, reflecting better energy absorption and load distribution facilitated by the inclusion of glass fibers. The composite reinforced with woven Kevlar fibers and carbon fiber shows the

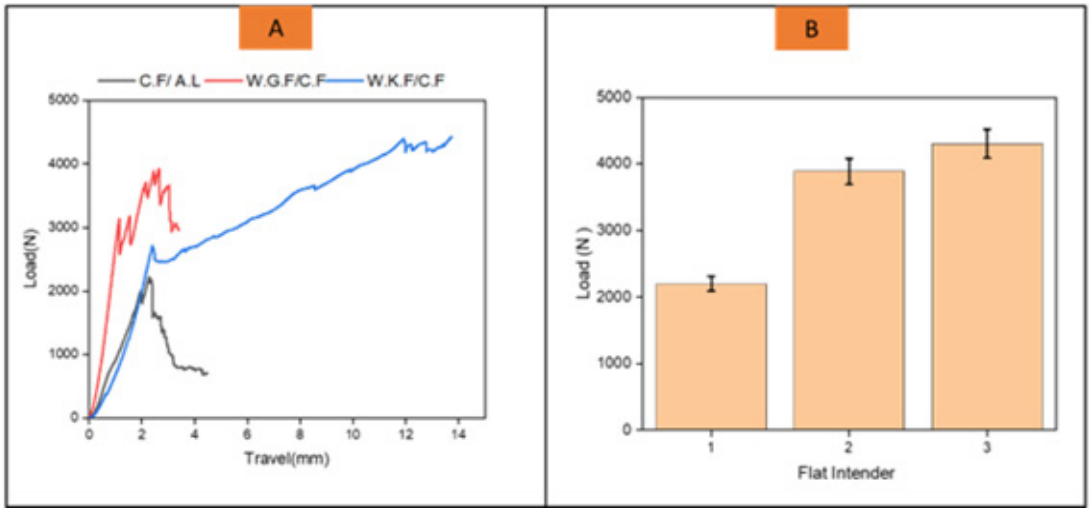


Figure 5. Comparison of load-travel curves and bar chart of peak load with error bar for different composite materials used by flat intender.

highest load capacity, close to 5000 N, and the greatest travel, highlighting the exceptional toughness and energy absorption properties of Kevlar. When combined with the stiffness of carbon fibers, this configuration achieves superior mechanical performance. Figure B, the bar graph, compares a specific property, such as maximum load or strain energy, across the three composite types. The values increase progressively from the carbon fiber-aluminum laminate to the woven glass fiber-carbon fiber hybrid, with the woven Kevlar-carbon fiber hybrid exhibiting the highest performance. Error bars represent variability or standard deviation in the measured properties, confirming the reliability and consistency of the results. These findings underscore the advantages of hybrid composites, particularly those reinforced with Kevlar, in achieving superior mechanical performance for advanced engineering applications. The performance progression from carbon-aluminum laminate to woven glass-carbon, and ultimately to woven Kevlar-carbon, is driven by the increasing ductility, toughness, and energy absorption capacity of the reinforcement materials. Hybridization with materials like Kevlar achieves a synergistic combination of properties, making these composites highly suitable for applications requiring both strength and durability.

3.2 Cone Intender

The Figure 6 compares the mechanical properties of three composite materials: carbon fiber-aluminum laminate, woven glass fiber-carbon fiber hybrid, and woven Kevlar fiber-carbon fiber hybrid.

The load-travel curves reveal significant differences in mechanical behaviour among the three composite configurations. The composite made with carbon and aluminum demonstrates the lowest load-bearing capacity, peaking at approximately 2500 N, with minimal travel, indicating its brittle nature and limited energy absorption due to weak interfacial bonding and the inherent brittleness of the aluminum layer. In contrast, the composite reinforced with woven glass and carbon exhibits an improved load capacity, reaching up to 4000 N, with increased travel, reflecting better energy absorption and load distribution facilitated by the inclusion of glass. The composite reinforced with woven Kevlar and carbon shows the highest load capacity, close to 5000 N, and the greatest travel, highlighting the exceptional toughness and energy absorption properties of Kevlar. When combined with the stiffness of carbon, this configuration achieves superior mechanical performance. Figure B, the bar graph, compares a specific property, such as maximum load or strain energy, across the three composite types. The values increase progressively from the carbon-aluminum laminate to the woven glass-carbon hybrid, with the woven Kevlar-carbon hybrid exhibiting the highest performance. Error bars represent variability or standard deviation in the measured properties, confirming the reliability and consistency of the results. These findings underscore

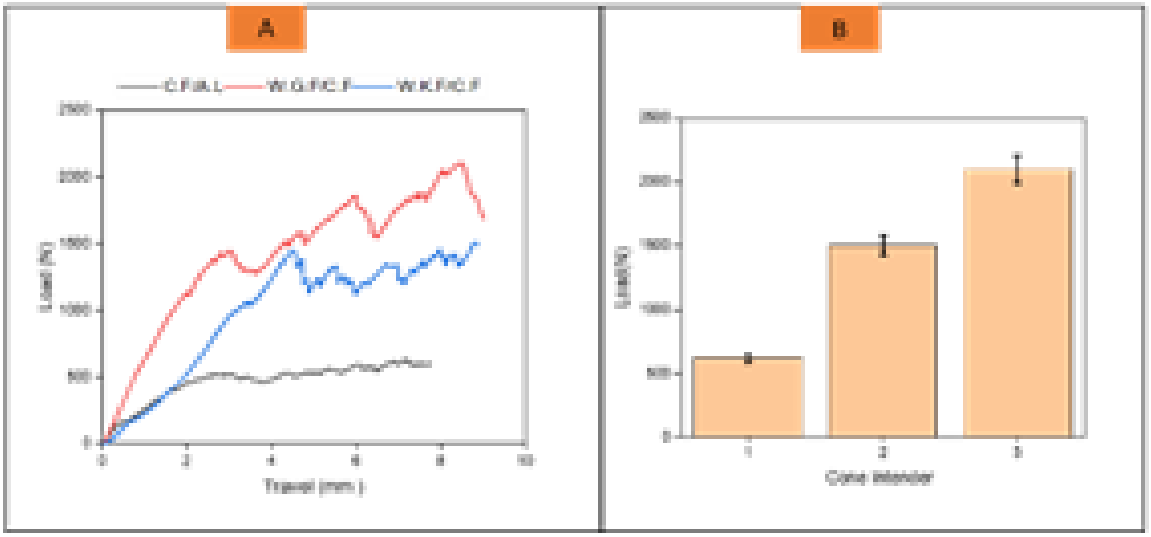


Figure 6. Comparison of load-travel curves and bar chart of peak load with error bar for different composite materials used by cone intender.

the advantages of hybrid composites, particularly those reinforced with Kevlar, in achieving superior mechanical performance for advanced engineering applications. The performance progression from carbon-aluminium laminate to woven glass-carbon, and ultimately to woven Kevlar-carbon, is driven by increasing toughness, energy absorption capacity, and interfacial bonding strength of the reinforcement materials. These properties make hybrid composites, especially those reinforced with Kevlar, highly effective for applications demanding a balance of strength, durability, and flexibility.

3.3 Ball Intender

Figure A presents load-travel curves for three different test conditions: C.F/A.C, W.G.F/C. F, and W.K.F/C.F. The curve for C.F/A.C

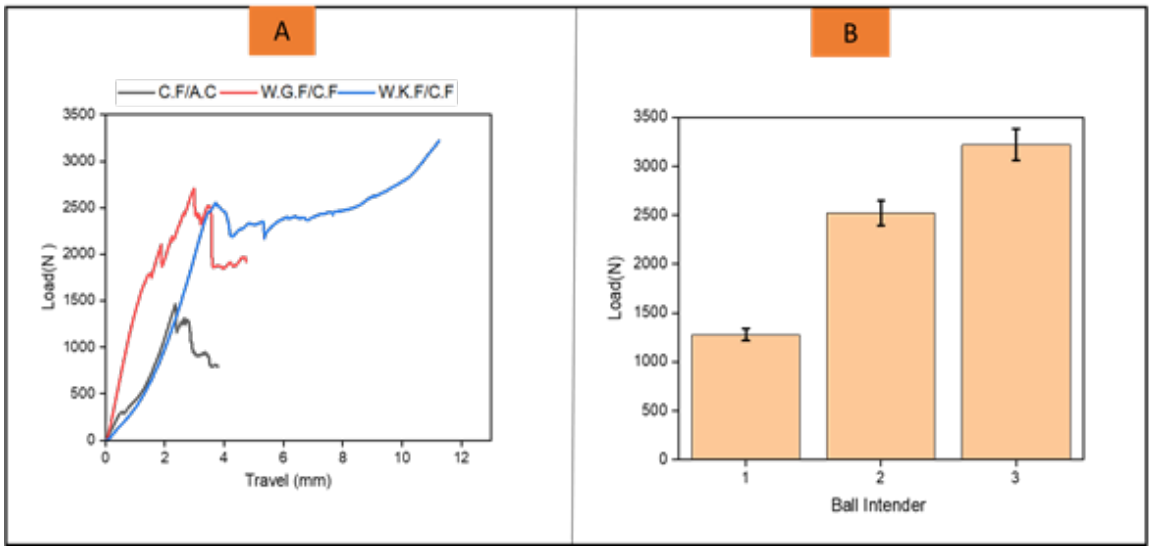


Figure 7. Comparison of load-travel curves and bar chart of peak load with error bar for different composite materials used by cone intender.

Figure 7A shows a relatively smooth and linear increase in load with travel, reaching a peak load of around 3500 N before experiencing a slight decrease. In comparison, the W.G.F/C. F curve follows a similar trend but exhibits a slightly higher peak load of approximately 3600 N. Meanwhile, the W.K.F/C. F curve demonstrates more pronounced initial stiffness, reaching a peak load of around 3700 N, followed by a more significant decrease. These differences in load-travel behaviour likely reflect variations in material properties and/or testing conditions, with the higher peak loads for W.G.F/C.F and W.K.F/C.F suggesting these materials offer greater resistance to deformation than C.F/A.C. The slight decrease in load after the peak for all curves might indicate material failure or limitations in the testing procedure. In Figure 7B, a bar chart displays the peak load values for three different ball indenters. Ball Indenter 1 produces a peak load of around 1200 N, Ball Indenter 2 results in a peak load of around 2500 N, and Ball Indenter 3 leads to a peak load of approximately 3200 N. The increasing peak load with ball indenter number suggests that larger indenters generate higher loads, as larger contact areas create increased stress and deformation.

3.4 Microstructural Studies

The microstructure analysis reveals several critical defects that significantly impact the mechanical properties of the composite materials. Porosity (Figure 8a), which arises from incomplete resin impregnation or trapped air, creates stress concentrators within the matrix, leading to a reduction in strength and toughness. Delamination (Figure 8b), caused by poor interfacial bonding between the layers or fibers, reduces the efficiency of load transfer and can result in premature failure under mechanical stress. Fiber pull-out or surface cracking (Figure 8c) indicates insufficient bonding between the fibers and the matrix, which, while contributing to some energy absorption, ultimately compromises the composite's mechanical strength. Finally, micro-cracks or contamination (Figure 8d) can propagate under stress, weakening the interfacial bonding and increasing the likelihood of failure. These defects highlight the importance of optimizing fabrication processes, including ensuring complete resin impregnation, improving interfacial adhesion between fibers and matrix, and reducing contamination. By addressing these issues, the mechanical performance

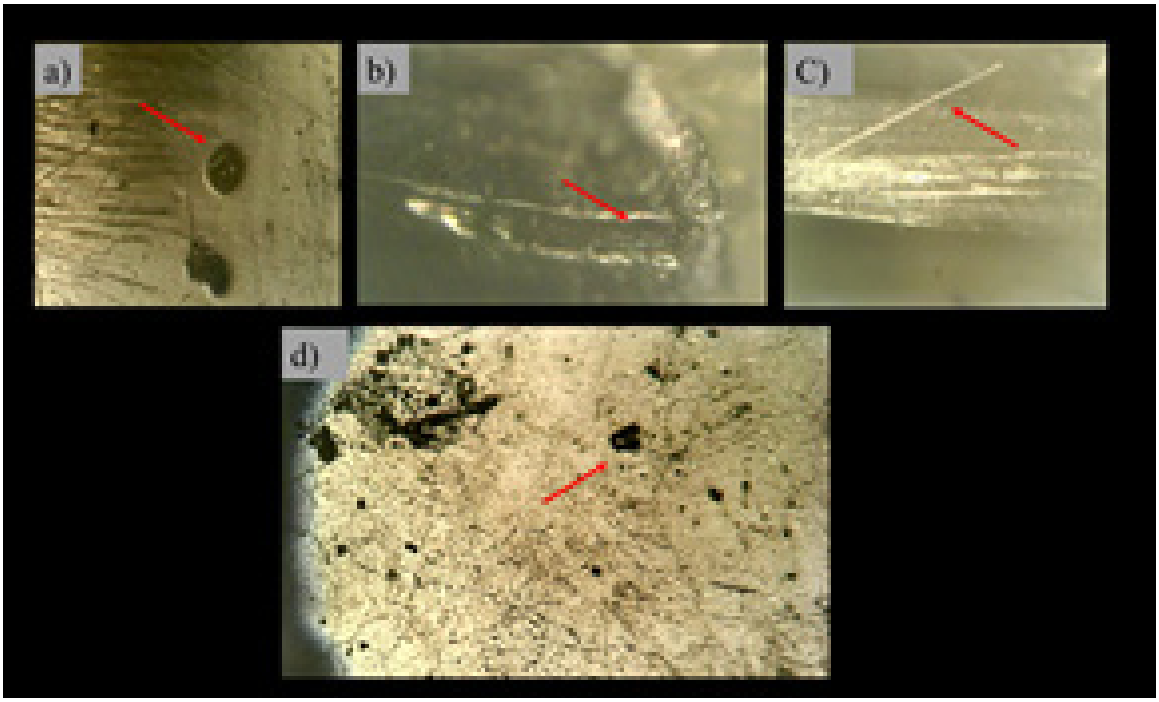


Figure 8. Microstructural defects in composite materials.

of composite materials can be significantly enhanced, leading to more reliable and durable materials for advanced engineering applications.

4.0 Conclusion

The performance of hybrid nano-fiber composites reinforced with carbon, glass, and Kevlar fibers, in combination with duralumin sheets, offers promising potential for high-performance engineering applications. The mechanical behaviour of these composites, including their impact resistance, tensile strength, strain capacity, and energy absorption, is significantly influenced by the fiber composition, layer arrangement, indenter geometry, and environmental conditions. This study provides valuable insights into how these factors affect the material's performance and highlights the superior mechanical properties of Kevlar-carbon hybrid composites. By understanding the impact resistance performance under varying conditions, this research contributes to the development of advanced composite materials that can withstand the demands of critical applications in industries such as aerospace, automotive, and military engineering.

5.0 Acknowledgments

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6.0 Authors Contribution

Rajesh Dhanabal, was instrumental in identifying the research topic and designing the study, as well as in drafting the manuscript and overseeing data collection. Dr. Vasudevan, was crucial in developing the questionnaires and conducting the data analysis. Together, they collaborated closely throughout the research process, Justin Raj Y is journal format enrichment of paper and grammatical corrections, ensuring then study was thorough and effectively communicated their findings. This partnership exemplifies their shared commitment to advancing knowledge in their field.

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