Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Special Issue 5, 2025
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

# Mechanical Characteristic Analysis of Five-Layer Carbon-Carbon Composite Material

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**_Abstract_**

*The current study investigates the fabrication and mechanical strength of five-layer carbon-carbon composite. The strong five-layer carbon-carbon composite material with high strength and modulus is made of a raw material called precursors. The polyacrylonitrile (PAN) method is used in the fabrication of carbon fiber. The characteristics of the resulting carbon material depend on the composition and structure of the precursor. A sheet of 50 x 40 cm five-layer carbon-carbon composite material has been made out of this PAN method. Tests like flexural, tensile, compression, and impact were performed on the fabricated samples to evaluate the mechanical strength of the carbon-carbon composite material. A total of 14 samples were made according to ASTM standards. The material withstood a maximum tensile strength of 492.12 MPa and a flexural strength of 578.13 MPa. The maximum impact energy is recorded as 6.1 joules. Graphs are plotted between the load and deflection to illustrate the mechanical behaviour of the composite material. The material exhibited linearity throughout the test among all the samples. The process involves the creation of two-ply plain weave laminates using T300-1k carbon fiber combined with Hexcel HexPly 913 epoxy resin, resulting in a fiber volume fraction of 0.62. The examination of different idealized tow cross-sectional shapes and weave profiles, including a beam model, a solid material model with a comparable cross section of rectangular shape, and two models with sinusoidal tow profiles.*

**Keywords:** Polyacrylonitrile, Precursor, Carbon-Carbon Composite, Flexural, Tensile, Impact

## INTRODUCTION

The greater number of fiber layers in the laminates led to a rise in the tensile strength, with the maximum strength of 576.079 N/mm² achieved with 10 layers. Increasing the loading rate from 2 mm/min to 5 mm/min during tensile testing resulted in an elevated deformation rate of the samples. The carbon fiber composites developed in this study can be used to fabricate prosthetic feet, which can help in the rehabilitation of lower-limb amputees. The development of carbon-fiber laminates consisting of 2, 6, and 10 layers through the hand layup technique. The laminates were subjected to tensile testing utilizing the UTM in accordance with the ASTM D3039 standard, with a loading rate of 5 mm/min during the testing process [1]. In case of PALF composites with polyester matrix adding 30 wt.% of silane-treated PALF (30 mm length) to a general-purpose polyester matrix resulted in a tensile strength of 73.5 MPa, an ultimate strain of 4.3%, a flexural strength of 85.6 MPa, and an impact strength of 24.2 kJ/m² [13]. Pure basalt/epoxy laminate presented 21% higher tensile strength than the pure Kevlar/epoxy laminate because of the higher density of basalt fiber. The hybrid laminate incorporating additional layers of

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Received Date: March 07, 2025
Accepted Date: July 14, 2025
Published Date: July 24, 2025

**Citation:** Ganesan S, Jayavelu S, Sravanth Chandaka. Mechanical Characteristic Analysis of Five-Layer Carbon-Carbon Composite Material. Journal of Polymer & Composites. 2025; 13(Special Issue 5): S405–S417p.

lower-density Kevlar fiber (S4) exhibited reduced tensile strength in comparison to the other hybrid configurations. The hybrid laminate with extra layers of lower-density Kevlar fiber (S4) displayed low tensile strength compared to the other hybrid configurations. Developing two pure and six hybrid materials utilising basalt/Kevlar/epoxy composite layers through a hand layup technique, incorporating 300 gsm Kevlar and basalt fibre mats as reinforcements. Using epoxy resin (LY556) and hardener (HY951) as the matrix material, mixed in a 10:1 weight ratio. Controlling the fiber volume fraction by using a 1.5:1 weight ratio of reinforcements to matrix and by placing seven layers of reinforcement fiber in the laminates, with care taken to orient the fiber [2] Neumeister et al. evaluated a homogenized Kirchhoff plate model to predict the constitutive relationship of plain weave laminates made of two-ply layers in the form of a 6x6 ABD stiffness matrix. He determined that a solid model incorporating a fourth root sine wave profile yielded the most accurate predictions of mechanical properties in contrast with two other cross-section and weave profile models. The comparative positioning of the plies (in-phase vs. out-of-phase) can significantly influence the bending stiffness and direct axial strength of the laminate alongside a comparison of the findings with predictions from several tow models. The study is restricted to a total of two-ply laminates alone, necessitating further research into the impacts of three or more plies. This paper suggests that classical lamination theory may be questionable for laminates with less than three plies, implying potential limitations in the current study's focus on two-ply laminates [3]. The tensile strength increases with decreasing crystallite interlayer spacing (d002) and degree of structural disorder (ID/IG) and with increasing crystallite thickness (Lc) of the carbon fiber material. The distribution of the tensile strength, as identified by the Weibull modulus, rises with decreasing micropore radius. The Griffith theory tends to overestimate the tensile strength of the six carbon fibres, and a more precise formula has been introduced according to the experimental data available. The measurement of carbon fiber diameter is done using a laser scanning microscope, and its density is measured by using a density gradient tube. Tensile testing of carbon fiber monofilaments using the UTM according to the ASTM-D3379 standard. The characterization of carbon fiber cross-section morphology using scanning electron microscopy. Analysis of carbon fiber microcrystalline structure and micropore radius using small-angle X-ray scattering and X-ray diffraction by the estimation of carbon fiber graphitization [4]. A quantification of tensile strength and strain throughout the thickness of the carbon fibre 2D woven reinforced polymer composites exhibit low performance initially, but this significantly improves with increased loading rates, demonstrating a linearly elastic behavior prior to failure. Failure primarily occurred at the junction of the carbon fibre weave and the polymer matrix. An experiment involving dynamic loading at 97 MPa/m.s revealed an unusual two-peak stress-strain curve and a unique fracture surface when compared to other loading conditions. Quasi-static tensile testing was conducted using material testing equipment at a steady crosshead velocity of 2 mm/min. In addition, dynamic tensile testing was carried out with a split Hopkinson tensile bar apparatus, which included a gas gun, striker, incident bar and gearbox bar. The scanning electron microscope study of the cracked surfaces of specimens from both quasi-static and dynamic tensile testing. The numerical simulations were limited by the use of inaccurate material parameters and the simplification of the carbon weave as an isotropic material. Further research into the fracture mechanics of this composite material is needed to validate their interpretation of the different breakage modes. The method of determining tensile strength from the dynamic testing data has limitations, as a minute error in the break time can lead to a large dissimilarity in the estimated tensile strength [5]. The bulk modulus and compression strength rise linearly with increasing fiber volume fraction (V-f) within a certain range. For composites with the same (V-f), the five-layered MBWK fabric-reinforced composites had the maximum bulk modulus, while the fabric fabricated by connecting three layers had the minimum. Both the reinforcement structure and composites reinforced with MBWK fabric showed a considerable change in compression strength as a function of fiber volume fraction. The fabrication of MBWK fabrics using carbon fiber and polyester yarns and the fabrication of 3-layer, 4-layer, and 5-layer MBWK fabric reinforced composites using resin transfer molding (RTM). Compression testing of the MBWK composites made of fabric-reinforced materials using a universal testing machine and strain gauges. This study focused on key interventions involving three distinct types of MBWK-reinforced composites, specifically three-layered, four-layered, and five-layered composites. Additionally, the testing of these composites was conducted at various carbon fibre volume fractions (V-f). They are limited to only three types of MBWK fabric-reinforced composites; more research is needed on four-layer and five-layer connected composites. The correlation between compression strength and fibre volume fraction exhibits linearity solely within the investigated range. The influence of various fibre stacking sequences on compression properties remains inadequately investigated [6]. The lighter fiber network sandwich specimens with less resin have significantly higher damping and lower vibratory levels compared to the heavier specimens. Through the difficulty of the fabrication process, Sehar et al. [7] was able to relatively successfully reproduce large fiber network sandwich specimens. Fabrication of sandwich specimens with a carbon fiber network core and unidirectional carbon fiber prepreg skins. Compression testing to scale the elastic modulus of the specimens and three-point bending testing to scale the strength of the shear modulus of the core. The vibration testing is done to measure the natural frequencies and damping ratios of the specimens. The fabrication process is still being developed and not standardized, resulting in some variability between specimens. The resin distribution is difficult to control, leading to inhomogeneous specimens. Future work should explore using glass fiber instead of carbon fiber to improve the structural strength.

A comparison should be done of the properties of these fiber network sandwich materials to more traditional sandwich materials with honeycomb or foam cores and the entangled sandwich beams, and the predicted natural frequencies to the experimental results to verify the measured core properties [7].

Composites with an angle-ply layup of (0°, 235°, 0°, 135°, 0°) displayed the uppermost tensile, flexural, and impact strength. The composites holding 60 wt% carbon fiber had superior mechanical properties compared to those with 40% wt fiber. Although 5-ply composites had marginally better mechanical characteristics than 3-ply composites, the difference was negligible. Unidirectional carbon fiber and epoxy resin were used to fabricate composite laminates. Composites with 3-ply and 5-ply were produced using a hand lay-up and vacuum bagging process, followed by curing in an autoclave. Mechanical properties like tensile, flexural, and impact were tested according to ASTM standards. The fracture surface of the composites have been investigated by SEM analysis. The manufacturing process is sensitive, and any issues with the vacuum bagging could introduce defects or variability in the samples. Increasing the number of plies may introduce more defects like voids and porosity, which could limit the mechanical properties, though the inequalities were not highly significant in this study. The angle-ply layup of 90°, 45°, and 90° resulted in weaker fiber-matrix adhesion, which could limit the mechanical properties [8]. In otherwise identical circumstances, the tensile strength of these composites is influenced by factors beyond just the fibre volume percentage. The process of weaving can improve the fabric's longitudinal strength and fibre efficiency, even though it may introduce new fibre defects and waviness, leading to increased fibre stresses. Fabrication of composite panels using the ACC-4 processing technique, with T-300 graphite fiber and a phenolic-derived carbon matrix. Testing of six different fiber architectures, including unidirectional, biaxial, and woven composites with varying fiber volume fractions. The mechanical testing of the composites using tensile, Iosipescu shear, and short three-point bending tests. The use of custom specimen designs to account for size limitations and low shear/transverse strength. Strain measurement using strain gauges and displacement measurements to capture localized deformation. The findings may not generalize to other composite systems and architectures beyond the tests. Insufficient data regarding in-situ fibre strength statistics and localized variations in shear strength for the composites under examination. The intricate nature of the issue presents challenges in creating straightforward predictive models [9].

## METHODOLOGY

### Carbon Fiber Fabrication

Materials developed from carbon fiber, whiskers, or polyacrylonitrile fiber, when exposed to optimal heating conditions, exhibit remarkable strength and durability. The carbonization level exceeds 90%, and the fibers exhibit a diameter ranging from 7 to 8 microns. Fibers measuring approximately 510 μm in diameter serve as the fundamental components of carbon fibre. At their core, these structures are made up of carbon atoms. To produce this whisker or high-tensile fiber, the correct temperature is utilized for polyacrylonitrile, rayon fiber, or petroleum residue. These fibers generally have a diameter of 7-8 microns and are composed of 90% carbon. Carbon fiber is composed of atoms that are crystallized and interconnected. The long axis of the fiber is aligned with the crystals. The orientation leads to an optimized strength-to-volume ratio of the fiber. A sequence of thousands of carbon fibers constitutes the essence of carbon fibre itself. This material can be utilized independently or integrated into carbon fibre textiles. The structure of five-layered carbon fiber is illustrated in Figure 1. The 0° orientation provides maximum tensile and compressive strength along that axis and 90° orientation gives strength perpendicular to the loading direction, but is usually weaker due to the matrix carrying the load. The detailed properties of the five-layer carbon fiber material are mentioned in Table 1. The value of the coefficient of linear thermal expansion of carbon fiber is always less than zero. Unlike other composite materials, the axes of the molecules of the carbon fiber are oriented in a preferred direction rather than a random arrangement. Specimens for the tests are taken out from the fabricated sheet according to ASTM standards. ASTM FD638/ASTM D790/ASTM D256/ASTM C109 codes are used to cut the specimens. Figure 2 represents the specimens with ASTM codes.

**Table 1.** Physical properties of carbon fiber.

| | |
|---|---|
| **Density (g/cm^3)** | 1.7-1.9 |
| **Tensile Strength (GPa)** | 2-7 |
| **Tensile Modulus (GPa)** | 200-700 GPa |
| **Elongation** | 0.5-2 % |
| **Thermal Conductivity (W/m.K)** | 8-12 |
| **Electrical Resistivity (Ωm)** | 10-15×10^-6. |

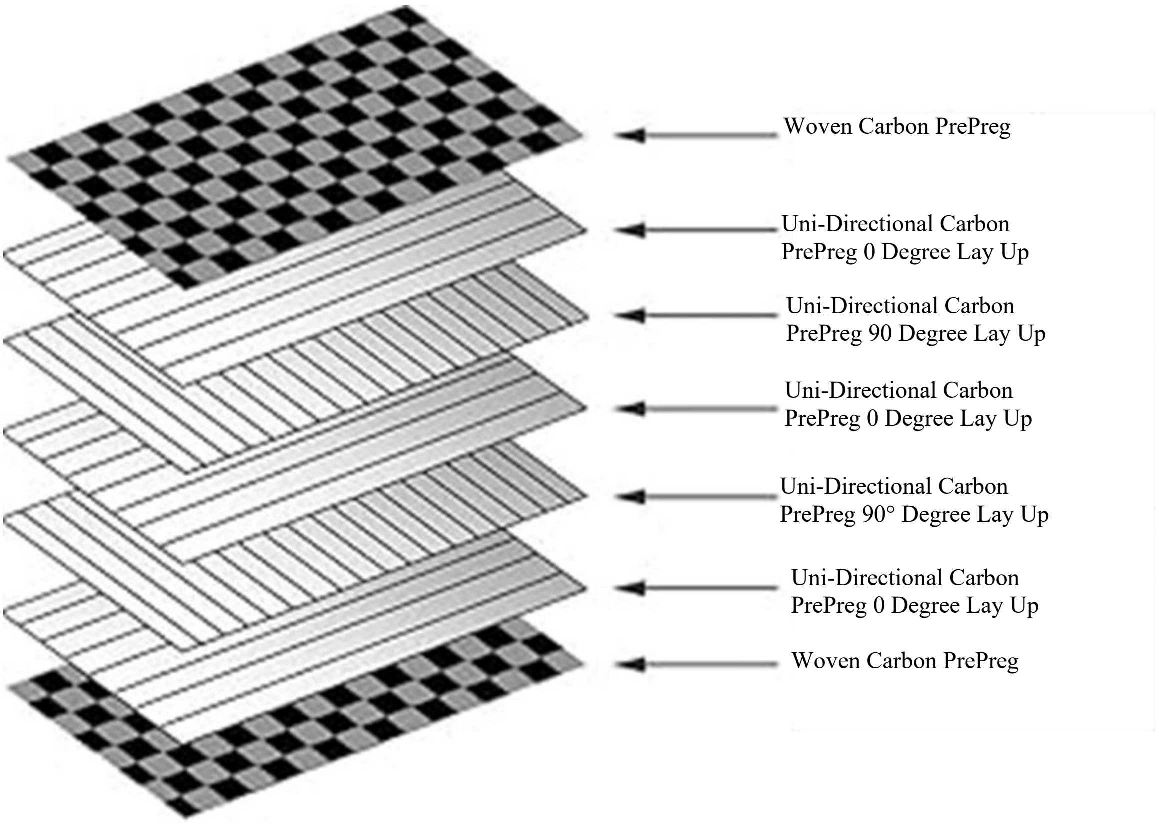

**Figure 1.** Structure of Five-layered Woven carbon-carbon composite.

### Mechanical Testing

The tensile, flexural, and compression tests are carried out in a universal testing machine as shown in Figure 3. The specimen is held firmly at the two ends, and tensile load is applied. The maximum loading capacity of the UTM is 5 tons. The crosshead speed accuracy is 0.01mm. The maximum gear rotation speed of the machine is 300 mm/min. The UTM is integrated with the software in which the desired loading conditions and other settings are set according to the requirements. The impact test is carried out by the XJJU-5.5 impact testing machine with a maximum impact energy of 14 joules. Gradual loading conditions are given from 0.1 to 14 joules. The impact testing machine is depicted in Figure 4. The impact speed of the machine is 3.5 m/s. ISO179, ISO180, and GB/T1043 standards are used.

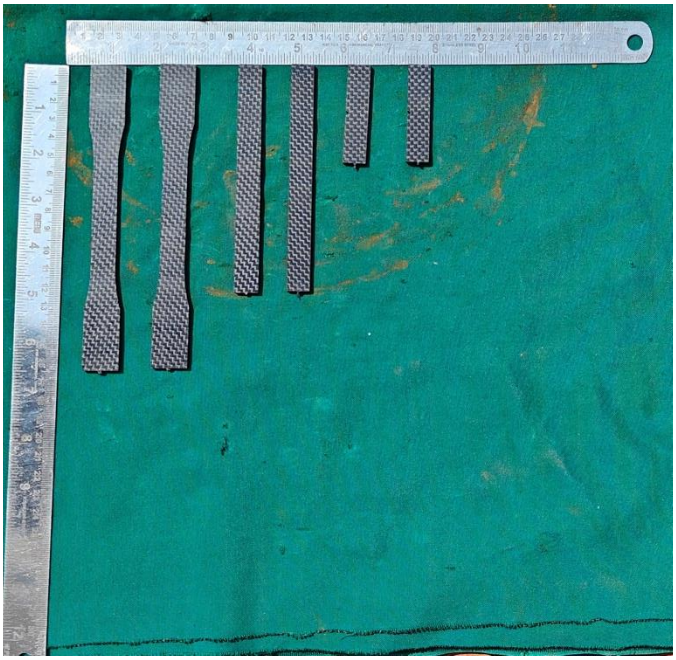

**Figure 2.** Fabricated Specimens.

**Figure 3.** Tensile Test in UTM

**Figure 4.** Impact Testing Machine

## RESULTS AND DISCUSSION

### Tensile Test

Tensile testing was performed on four specimens to determine the ultimate tensile strength of the five-layered carbon fiber composite material. The displacement is increasing linearly with the load, as shown in Figure 5. The maximum displacement of the individual sample is depicted in Figure 8 as a tensile property of the material. The maximum tensile load recorded was 19422.61 N with a displacement of 4.84 mm, while tensile strength values ranged from 421.69 MPa to 492.12 MPa. The highest tensile strength was exhibited by Specimen 2 with a value of 492.12 MPa. The results in Figure 7 demonstrate that even slight variations in specimen width significantly influence tensile performance. Specimen 4, having the smallest width, correspondingly showed the lowest strength value. The tensile strengths observed (~421–492 MPa) fall within expected ranges for carbon fiber epoxy composites, validating the material's integrity and manufacturing process used in this study. The orientation miss match in specimen 4 resulted in the development of interlaminar tensile stress. The five-ply CFF (carbon fiber fabric) has a tensile strength of 339.2–505 MPa; this tensile strength is limited to the percentage of polyimide/solvent ratio in the fabrication of carbon fiber [10]. Other composites, like basalt/Kevlar/epoxy composites, have lower tensile strength. The individual tensile strengths of the basalt and Kevlar laminates are 3.6 MPa and 4.8 MPa. Pure Kevlar/epoxy composite laminate of five layers has a tensile strength of 129.6 MPa; the laminate with BBKBKBB layers has higher density but lower tensile strength [7]. Tensile Strength of a single fiber intrinsic material reached 465.45 ± 51 MPa for a 40 mm gauge length [14]. Similarly, in case of pineapple fibers the tensile strength varies from 600 to 1300 MPa. However, lower diameter fibers may have a tensile strength not exceeding 170 MPa [15]. Palanisamy S et al., [16] obtained best tensile performance by introducing a small amount (10%) of short (6 mm) Phormium tenax fibers to P1 composite [16]. This also opens avenues for using this specific layup configuration in lightweight aerospace structural applications. The results clearly indicate that small variations in specimen geometry can have a substantial impact on the performance metrics. This highlights the importance of precision in cutting and machining composite samples, particularly at the prototype level or in custom manufacturing environments. The failed specimens are depicted in Figure 6.

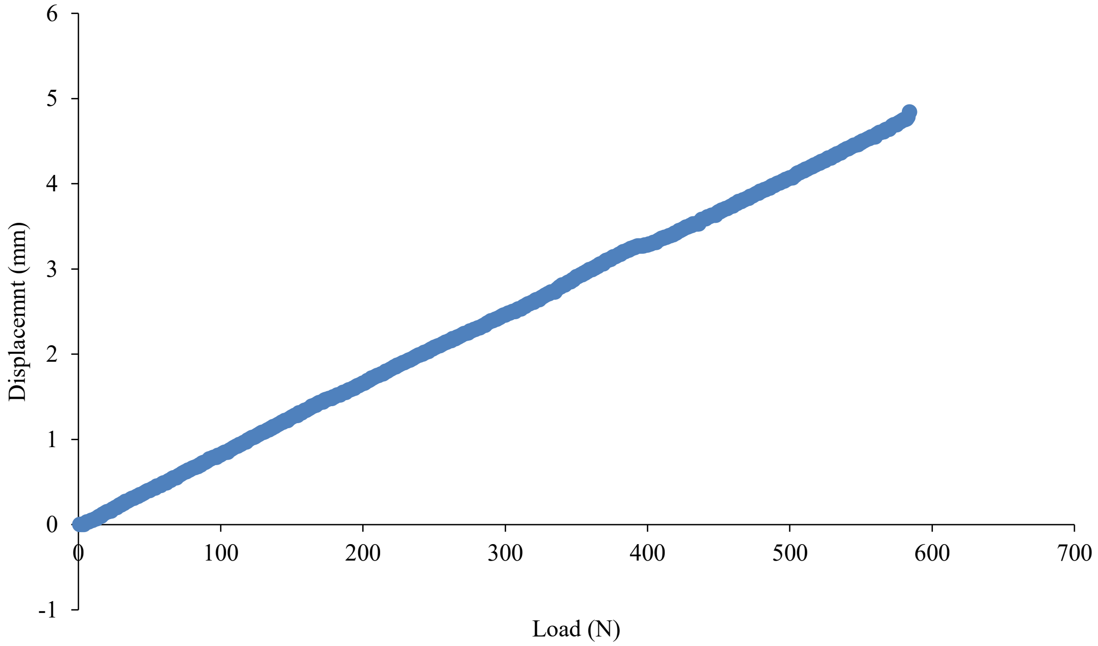

**Figure 5.** Load vs. Displacement of Sample 2.

**Figure 6.** Failed Specimen.

## Flexural Test

The flexural test results from Figure 9 show a consistent trend in load-bearing performance, which indicates good uniformity in lamination and curing of the carbon fiber composite. The individual flexural strength of the samples is depicted in Figure 10. No significant anomalies or premature failures were recorded, suggesting a stable fiber-resin interaction throughout the specimens. The overall flexural property from Figure 11 is a comparison of load and deflection. It was observed that specimens with a lower depth-to-span ratio exhibited greater deflection under similar loads, confirming classical beam theory behavior. In flexural samples, the structural rigidity increases with depth, aligning well with expected mechanics of composite beams. While microscopic failure inspection was not included, visible signs of brittle fracture and fiber pull-out were noticed post-tensile testing, especially in the lower-strength specimens.

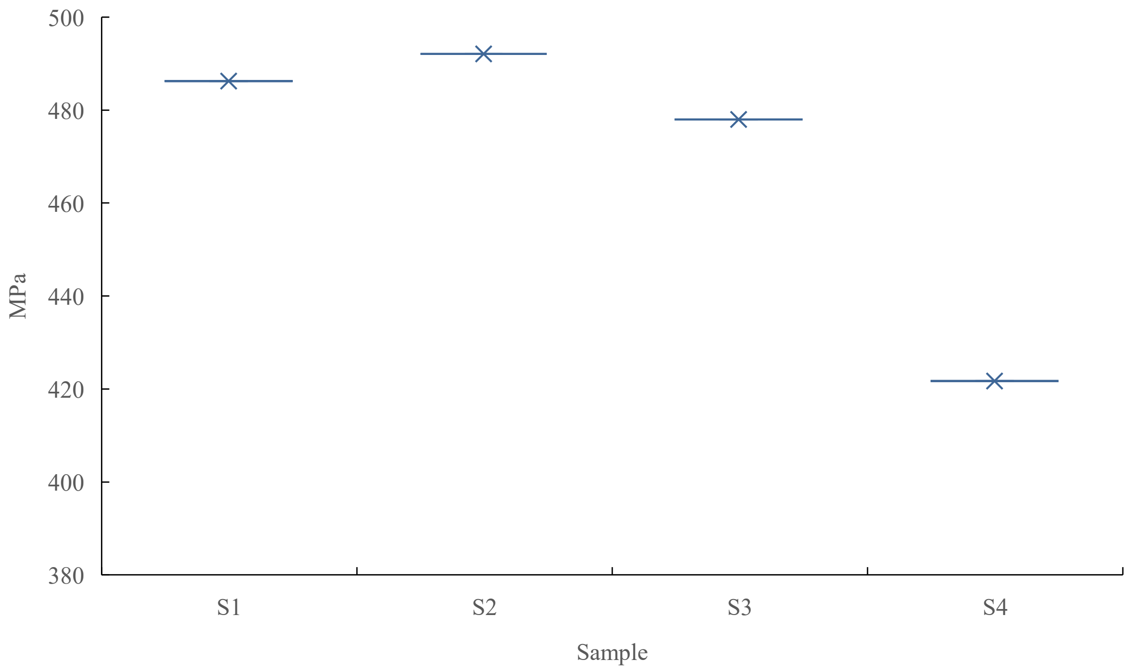

**Figure 7.** Tensile Strength of the Specimen.

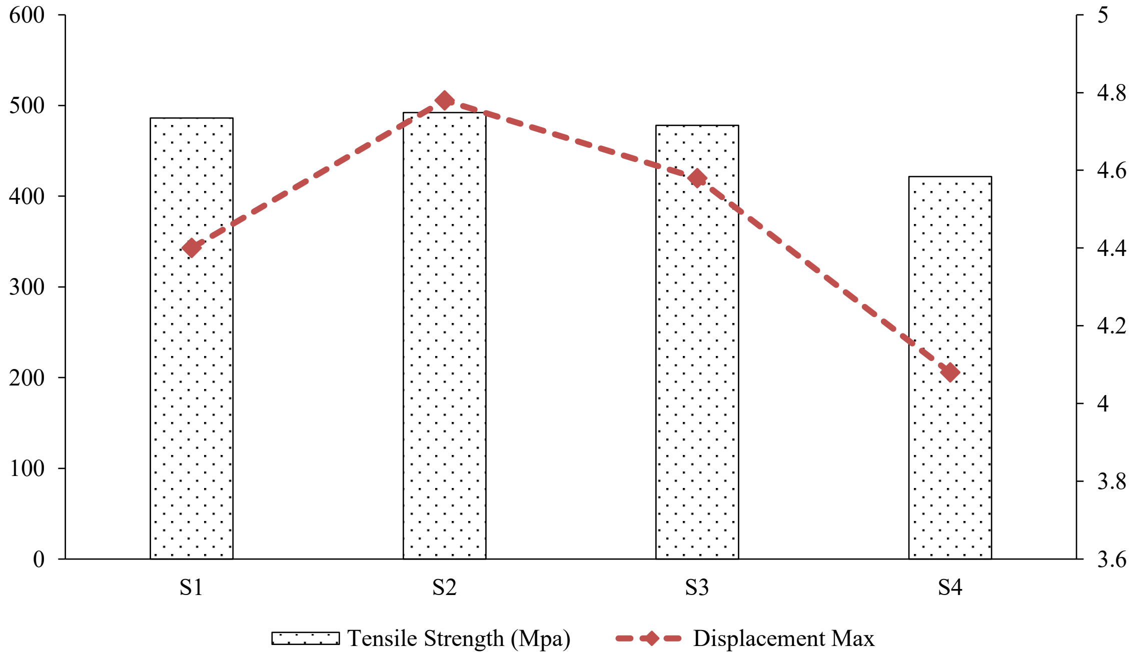

**Figure 8.** Tensile Property of the Specimen.

The incorporation of multiple layers of identical reinforcing fibers boosted stiffness, hence improving flexural strength. The composites made of basalt/Kevlar/epoxy fibers, among the combinations, the fabric with all the layers laminated with basalt exhibited a flexural strength of 110 MPa [7]. The flexural strength of five-layered carbon fiber material fabricated with PAN method 578.1 MPa is validated with the CFF with a 30% polyamide/solvent ratio, which has the flexural strength of 571.6 MPa [10]. This suggests a need for improved interlaminar bonding, possibly through alternate curing techniques or matrix modifications. Specimens with wider cross-sections demonstrated even stress distribution and higher strength, while narrower specimens revealed localized stress concentrations. This further confirms the importance of dimensional uniformity and fiber alignment in composite manufacturing. The failed pattern in all the specimens happened at the closed point. The load is increased gradually from 0 to 1200 N. It indicates the maximum load over the sample is 988.32 N. The failed specimens after the test are depicted in Figure 12.

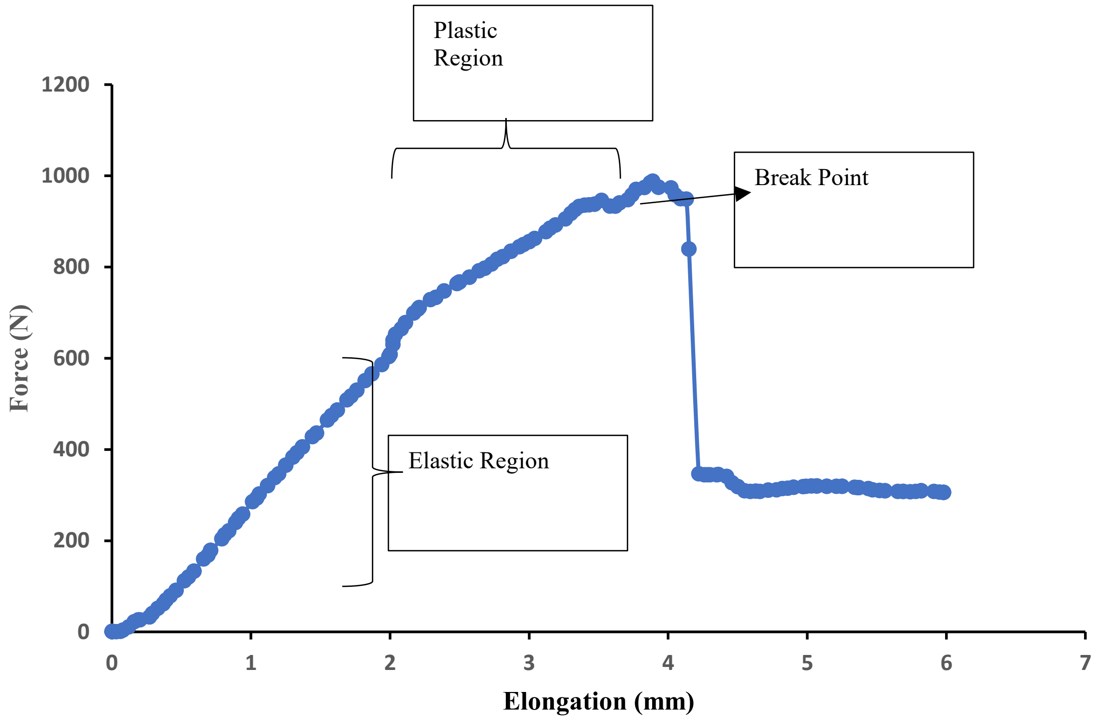

**Figure 9.** Load vs. Displacement of Sample-2.

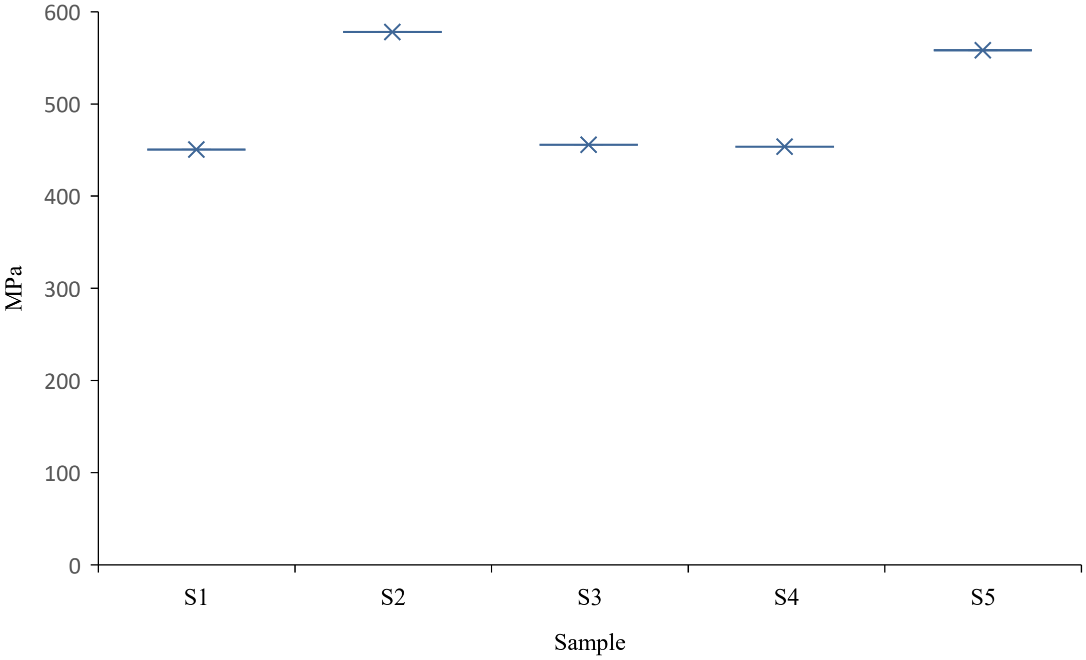

**Figure 10.** Flexural Strength of Samples

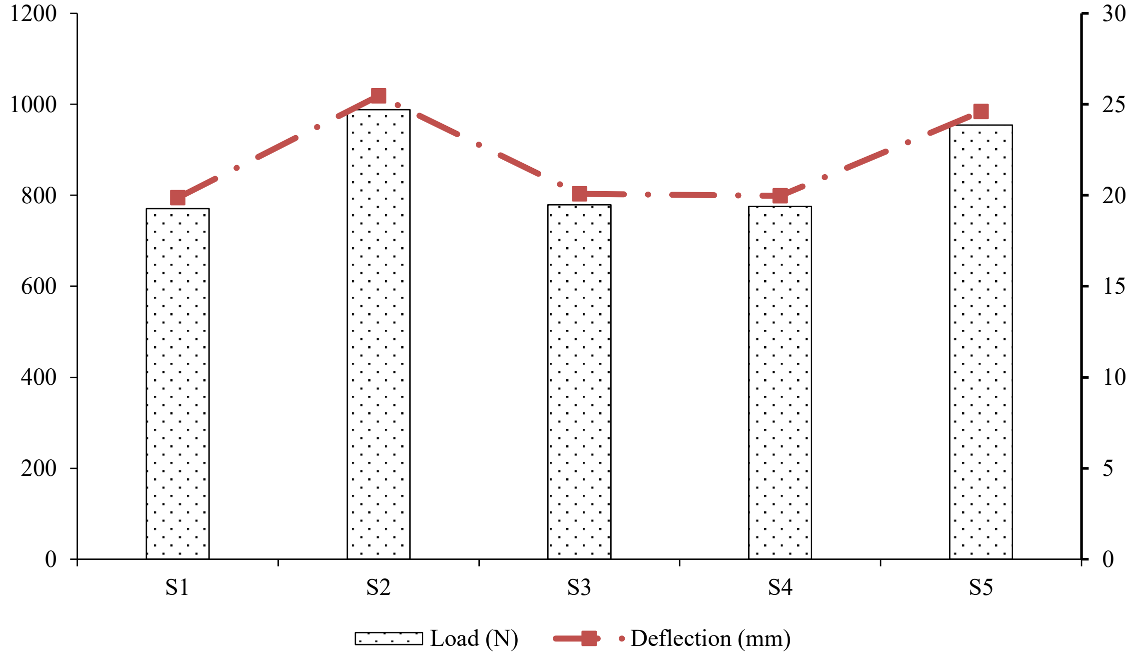

**Figure 11.** Flexural Property of Samples.

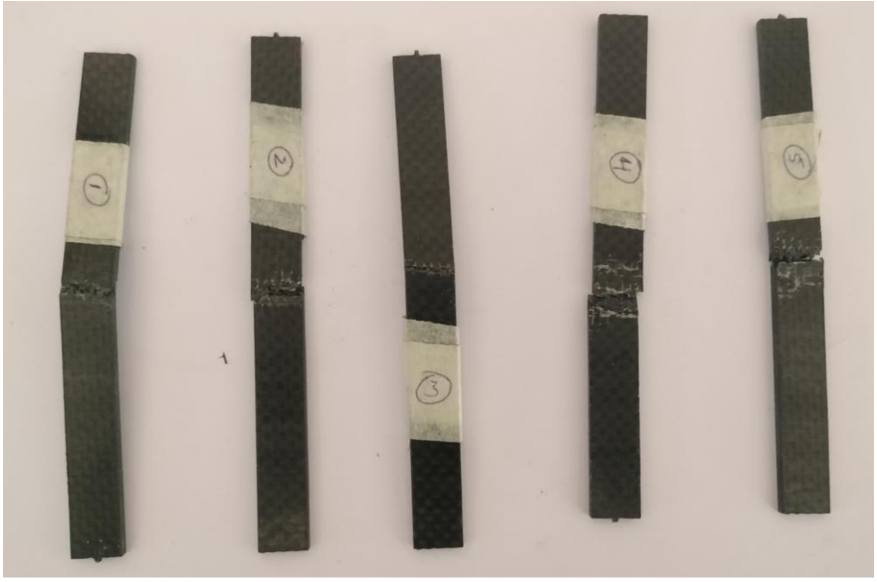

**Figure 12.** Failed Specimens in Flexural Test

## Compression Test

It was noted that unlike unidirectional layer carbon fiber, the five-layer carbon fiber material has the highest strength along the fiber direction but is weaker in the transverse direction. The compressive strength of the five-layer carbon fiber material lies in the range of 600-1200 MPa. Adding layers with angles of $0^0$, $45^0$ and $90^0$ increases the multidirectional strength by balancing the load. However, the resins provide a strong bond between layers and compressive strength to the carbon fiber material. The major drawback with resins is the micro-buckling under high compressive loads. Figure 13 depicts the linear compression strength of the material as being within the limit of 1134.16 MPa or N. The maximum displacement was 6.16 mm in the negative direction. The ultimate stress of the sample was recorded as 87.79 N/mm², and further increment in the load resulted in nonlinear behavior yet high compressive strength.

## Impact Test

The impact strength of the carbon fiber material depends upon the matrix strength, delamination, fiber breakage, and backside splintering. The impact properties of five-layer carbon fiber material is mentioned in Table 2. The material is tested under the ASTM D7136 drop-weight impact testing standard. The maximum impact energy is absorbed by S1 with 6.1 joules from Figure 14. The impact load creates the matrix cracking as a sign of initial failure. Lower impact strength at lower fiber loading levels was attributed to critical defects like voids and improper bonding [11]. The shear stresses developed cause layer separation. The fiber breakage occurs at high-energy impacts. However, the composites made of Kevlar fibers have lower tensile and flexural strength, but they offer greater impact strength due to lower density. The maximum impact energy absorbed is around 8.3 joules, while the composites with other laminates are around 6–8 joules [7]. In the case of hybrid laminates improvement with hybrid fiber mixing and alkali treatment, Alkali treated fibers ranged from 3.02 to 4.56 kJ/m² and Optimal natural fiber addition of 20 wt% AF yielded 4.56 kJ/m² impact strength [12].

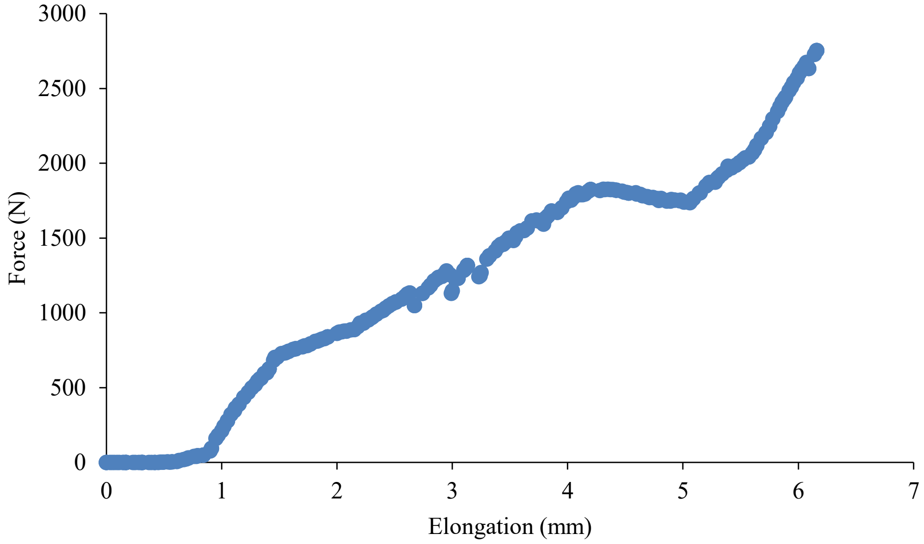

**Figure 13.** Compressive Strength of the Specimen

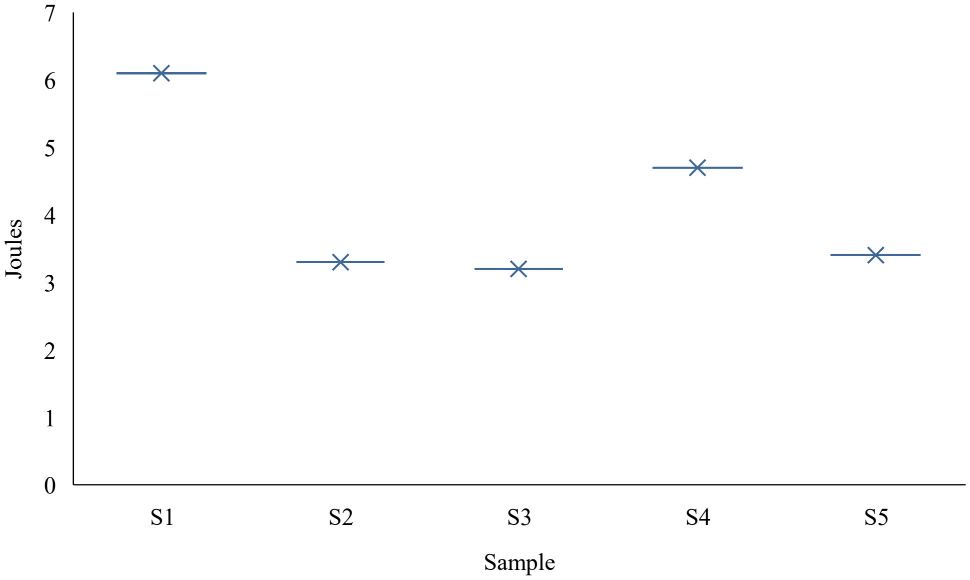

**Figure 14.** Impact Strength of the Samples.

**Table 2.** Impact Strength Performance of Five-Layer Carbon Fiber

| Layup Type | Energy Absorption (Joules) | Failure Mode |
|---|---|---|
| Unidirectional [0°] | 10–30 J | Brittle fracture, fiber splits |
| Cross-Ply [0°/90°] | 20–50 J | Delamination + matrix cracking |
| Quasi-Isotropic [0°/±45°/90°] | 40–80 J | Distributed damage, fiber pull-out |
| Hybrid (CF + Kevlar/Glass) | 60–120 J | Ductile deformation, fiber bridging |

## CONCLUSIONS

The mechanical testing of five-layer carbon-carbon composite, including flexural, tensile, impact, and compression tests, provides a comprehensive evaluation of its strength and modulus properties. The material exhibits high flexural strength and stiffness, indicating its ability to withstand bending forces with minimal deformation. The tensile strength and modulus demonstrate the composite's ability to resist stretching forces, showing high load-bearing capacity along the fiber direction. The impact resistance highlights the composite’s ability to absorb energy under sudden loading conditions. While carbon fiber generally has brittle characteristics, the multi-layer structure improves energy dissipation. The composite displays excellent compressive strength, making it suitable for applications requiring resistance to crushing or buckling forces. The following conclusions are made upon comparing the carbon-carbon material with other composites.

- The tensile strength of five-layered carbon-carbon fiber material is 3.8 times higher than that of pure Kevlar epoxy laminate material.
- The flexural strength of five-layered carbon-carbon fiber material is 5.2 times higher than that of seven-layered basalt epoxy laminate.
- The impact strength of five-layered carbon-carbon fiber material is 0.75 times lower than Kevlar/basalt laminate.

The five-layer carbon-carbon composite demonstrates exceptional mechanical capabilities, characterized by a high strength-to-weight ratio and stiffness. The findings validate its appropriateness for structural and high-performance applications in the field of aerospace like Thermal Protection Systems (TPS), Jet nozzles and throats and jet engine components like holders, afterburner linings, automotive, and racing sectors.

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