The Eurasia Proceedings of Science, Technology,
Engineering and Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 2026

Volume 39, Pages 1-8

IConTech 2026: International Conference on Technology

Experimental Investigation on Tensile Property of Carbon Reinforced Composite Produced with Vacuum Bagging

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Abstract: In this study, carbon fiber reinforced epoxy composites (CFRP) were manufactured using the Vacuum Bagging Method (VBM). Twill woven carbon fibers with an areal weight of 245 g/m² were employed as the reinforcement material. The composite laminates were fabricated with a five-layer symmetric stacking sequence of $[0]_5$. Tensile tests were conducted in accordance with ASTM D3039 standards to evaluate mechanical properties, specifically tensile strength and elastic modulus. Furthermore, the fracture surfaces of the tested specimens were examined via fractographic analysis. The experimental results revealed that fiber orientation significantly influences the mechanical behavior of CFRP laminates. Specimens tested along the 0° fiber direction exhibited substantially higher tensile strength and modulus values compared to those tested at a 30° orientation. Fractographic analysis indicated that the 0° oriented samples showed predominantly brittle fracture characteristics, whereas specimens with a 30° orientation demonstrated more ductile behavior through shear-induced deformation. These findings underscore the critical role of fiber orientation in determining the mechanical performance and failure mechanisms of CFRP laminates.

Keywords: CFRP, Vacuum bagging, Tensile properties, Fractography, Fiber orientation

Introduction

Composite materials are new materials created by combining two or more materials with different physical or chemical properties, offering enhanced characteristics. These advanced composites are increasingly being used in industries such as aerospace, automotive, and oil and gas (Bhandary et al., 2012). The main reason composite materials are increasingly preferred in these industries is their lightweight structure and high rigidity properties, which make them suitable for demanding applications. Additionally, their superior properties, such as high impact resistance and the ability to maintain performance even at very high temperatures, offer significant advantages over traditional materials. Furthermore, composite materials are resistant to both corrosion and chemical effects (Cambell, 2010).

Composite materials are structures designed to achieve superior qualities that cannot be obtained individually by combining the unique properties of different types of materials. Such materials are typically formed by combining at least two different components, which come together without dissolving into one another during the process. One of the components is usually the reinforcing element that provides strength to the structure, while the other component is the matrix phase that surrounds and holds the reinforcement together (Cakır & Berberoglu, 2018).

In recent years, with developments in fiber technology, the use of technical fibers—particularly carbon fiber—with advantages such as lightness and corrosion resistance has become widespread in composite structures as reinforcement elements in various forms, with the aim of improving the weak points of brittle materials, reducing brittleness, and increasing strength. Carbon fiber-reinforced polymer composites offer high strength and stiffness in the plane of the layer, but their interlaminar mechanical performance is largely dependent on the properties of the matrix. Therefore, due to their high sensitivity to damage caused by impact and fatigue, and the difficulty or impossibility of repairing damage, there is a need for structural reinforcement (Cakır & Berberoğlu, 2018; Korkmaz et al., 2017). When used as a reinforcement material in composite structures, epoxy resin provides significant improvements in properties such as chemical resistance, hardness, toughness, and abrasion resistance. However, it is also known that epoxy resins increase the brittleness of the structure (Srinivas Bhagyashekar, 2021). Composite materials tend to accumulate damage within their structure, and this damage may not always be visible to the naked eye or appear in a macroscopic form. In the structure, various types of damage can develop, such as fiber breakage, interlaminar delamination, cracking in opposing layers, and microcracks within the matrix. Therefore, the application of mechanical tests such as tensile tests and the determination of the composite material's durability properties are critical requirements.

It is widely accepted that the stress relaxation behavior of fiber-reinforced composite panels is directly related to the amount and distribution of fiber contents (Ozen, 2017). The mechanical and physical properties of polymer-based hybrid composites are fundamental characteristics that determine the overall performance of these materials. In order to predict the tensile behavior of these composites, some semi-empirical mathematical expressions have been developed. The Rule of Mixtures (ROM) models, which have a relatively simple structure, can estimate the tensile properties of composites within upper and lower limits and provide results that are comparable to experimental data. These models have been developed over time and enriched in various ways, forming a fundamental structure in the numerical analysis of hybrid composites (Pant &Palsule, 2024). Such computational models enable a more accurate and detailed characterization of composite materials by revealing the decisive effect of fiber length distribution on tensile properties (Aziz et al.,2013).

One of the simplest and lowest-cost methods in composite part production is the hand lay-up technique. However, since sufficient compression pressure is not applied to the laminates in this method, the quality of the products obtained is generally low. The vacuum bagging technique was developed to overcome this problem. This method helps to reduce excess resin during the curing process and remove moisture, solvents, and volatile components. Although this method produces high-quality composite laminates with very low void content, it has some disadvantages, such as high cost, long curing time, and limitations on the size and geometry of the parts that can be produced (Norafizal, 2020). In VBO method, atmospheric pressure is applied to the laminate throughout the curing cycle to exert a homogeneous compression force. VBO offers advantages such as more balanced pressure distribution, high fiber volume ratio, and shorter setup time. However, despite these advantages, defects such as void formation and residual stress may occur depending on the production process (Francucci et al. 2018).In this study, carbon-reinforced composite material was produced using the vacuum bagging method within a stacking sequences of $[0]_5$, and then cut parallel to the fiber axis (0°), and at an angle to the fiber axis (30°). Tensile tests were then performed on these samples to examine their tensile strength/modulus properties, and their fracture surfaces were examined.

Materials and Methods

Properties of Composite Components

The reinforcement phase consisted of KCF3K TW245 twill-woven carbon fiber prepreg, impregnated with the OM13 epoxy resin system (KORDSA). The carbon fabric features an areal weight of 245 g/m², a nominal thickness of 0.2 mm, and a warp/weft density of 0.61 yarns/mm. The underlying fiber is Toray T300. The matrix system has a nominal resin content of 42% (www.kordsglobal.com). Table 1 shows the physical and mechanical properties of fiber and resin (Manufacturer Data)

Table 1. Physical and mechanical properties of fiber and resin (Manufacturer data)

Feature	Unit	Resin (OM13)	Fiber (T300)
Tensile Strength	MPa	70	3500
Elastic Modulus	GPa	2.5	230
Density	g/cm³	1.20	1.75

Production Stages

Composite laminates were fabricated using the Vacuum-Assisted Bag Molding (VBO) method. Five layers of 400 mm × 400 mm prepreg were stacked in a symmetric $[0^o]_5$ orientation. The layup and bagging sequence followed these steps:

1. Mold Preparation: Application of a release agent to the tool surface.
2. Stacking: Manual layup of the five TW245 prepreg layers.
3. Consolidation Materials: Placement of a perforated release film, breather fabric, and vacuum manifold (flow net).
4. Vacuum Bagging: Sealing the assembly with a vacuum bag and mastic sealant tape.
5. Curing: A dual-stage cycle was used: pre-curing at 90 °C for 30 minutes, followed by a full cure at 130 °C for 2 hours, as per the resin's technical data sheet.

Figure 1**.** VB technique and its application of vacuum.

Sample Preparation and Tensile Testing

Following ASTM D3039 standards, 10 specimens were extracted from the cured panels (250 mm x 25 mm x ~1 mm). Five specimens were cut at **0°** (longitudinal) and five at **30°** (off-axis). The mass data measured during production is presented in Table 2.

Table 2. Production mass data

Configuration	Surface Area (m2)	Dry Fiber (g)	Resin (g)	Total Prepreg (g)
1 Layer (Full)	1.00	245.0	115.0	360.0
5 Layers (Full)	0.80	196.0	92.0	288.0
5 Layers (1 Sample)	0.00625	7.65	3.59	11.25

Tensile tests were performed in accordance with ASTM D3039 standard. Tensile testing was conducted on a Besmak BMT-60E machine at a constant crosshead speed of 2 mm/min.

Results and Discussion

Tensile Behavior

Tensile test results of composite samples cut at different orientation angles to the fiber axis are shown in Table 3 and Figures 2, & 3, respectively. The tensile properties of the composite specimens, categorized by their orientation angles, are detailed in Table 3. Stress-strain profiles were generated for both the 0^o and 30^o configurations to evaluate the influence of fiber alignment on mechanical performance.

For the 0^o samples, the load is primarily sustained by the carbon fibers. The maximum tensile strength reached 302.64 MPa, with an average strength (sigma) of 287.26 MPa. The stress-strain behavior in this orientation is characterized by high linearity, reflecting the dominant influence of the high-modulus carbon fibers. For the elastic modulus, the average modulus was calculated at 23.93 GPa. In terms of strain, most samples exhibited failure at low strain levels (approx. 12.%–1.5%), confirming the brittle nature of the carbon/epoxy system when loaded longitudinally. One outlier reached a strain of 6%, which may be attributed to localized grip effects or minor fiber misalignment.

For the 30° Off-Axis Samples, the 30° specimens showed a marked decrease in mechanical properties. In this orientation, the matrix must transfer load through shear, leading to lower strength and increased deformation. Tensile strength indicated that the average stress dropped to 118.29 MPa (a ~59% reduction compared to 0° sample). As for the ductility, the 30° oriented samples demonstrated significantly higher strain at maximum stress (averaging ~0.11), representing a more ductile failure mode as the epoxy matrix undergoes plastic deformation.

Table 3. Tensile test results

Sample Set	Max Stress σu (MPa)	Avg. Stress σm (MPa)	Avg. Modulus (GPa)	SD	CV (%)
0° Orientation	302.64	287.26	23.93	12.23	4.25
30° Orientation	122.88	118.29	8.91	2.83	2.39

Statistical Analysis

The Standard Deviation (SD) and Coefficient of Variation (CV) were calculated using the following relationships:

$$SD = \sqrt{(\sigma_u - \sigma_m)2/N - 1} \quad (1)$$

$$CV = \frac{SD}{\sigma_m} * 100 \quad (2)$$

The low CV values (4.25% for 0° sample and 2.39% for 30o sample) indicate high manufacturing consistency and repeatability of the Vacuum Bagging Method (VBM). This suggests that the vacuum pressure effectively minimized voids and ensured a uniform resin distribution across all samples.

This is consistent with the previous studies carried out on tensile behavior of the polymeric composites, 0° oriented samples exhibited better performance than those of other orientations in the literature (Harper et al., 2009; Şahin 2024; Cecen & Sarıkanat 2008; Ozsoy et al., 2015). Whereas, this is not always the case. For instances, some others studies conducted on mechanical behaviour of the composites indicated that 90° oriented laminates have been reported to be higher properties in the literature, specially basalt fiber-reinforced composites (Sahin & Selek, 2025; Abdua & Ibrahim, 2025; Kumar & Singh, 2021).

Figure 3 illustrates the stress-strain behavior for composite samples cut at a 30° orientation. The curves reveal a mechanical response fundamentally different from the 0° longitudinal samples. In transition from Linear to Non-Linear region, the specimens exhibit an initial linear-elastic region followed by a pronounced non-linear region prior to failure. This transition indicates the onset of matrix yielding and inter-fiber shear. The dominant failure mechanism in this orientation is matrix-shear. Because the fibers are not aligned with the loading axis, the epoxy resin must bear a significant portion of the stress, leading to the observed ductile behavior. The average tensile strength was recorded at 118.29 MPa while the average elastic modulus for this group was significantly lower than the 0° samples, calculated at 8.91 GPa. The strain at failure was considerably higher than the longitudinal samples, with some specimens reaching decimal strain values of 0.15–0.16 (15-16% elongation). It can be noted that the provided graph in Fig. 3 shows most samples exceeding (10%) strain. Finally, Table 4 illustrates the summary of orientation comparisons for both tested composite laminates.

Table 4. Summary of orientation comparison

Property	0° Orientation	30° Orientation
Average strength	287.26 MPa	118.29 MPa
Average modulus	23.93 GPa	8.91 GPa
Ductility	Brittle (Linear)	Ductile (Non-linear)
Dominant phase	Fiber-dominant	Matrix-shear dominant

The 30° specimens indicated ductility behaviour. Because these are cut from a $[30°]_5$ plate at an angle, the "30° specimens" will rely heavily on the inter-laminar shear of the OM13 resin, which has a much lower modulus (2.5 GPa) than the fiber. Based on the Table 1, the fiber-to-resin ratio is excellent.

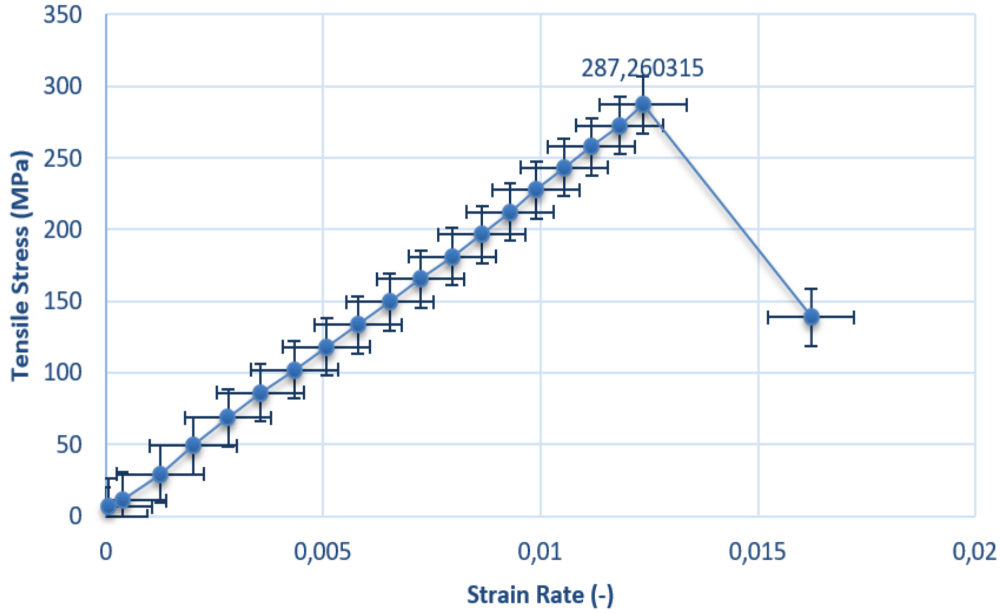


Figure 2. Stress-strain graphs of samples cut at 0° fiber direction

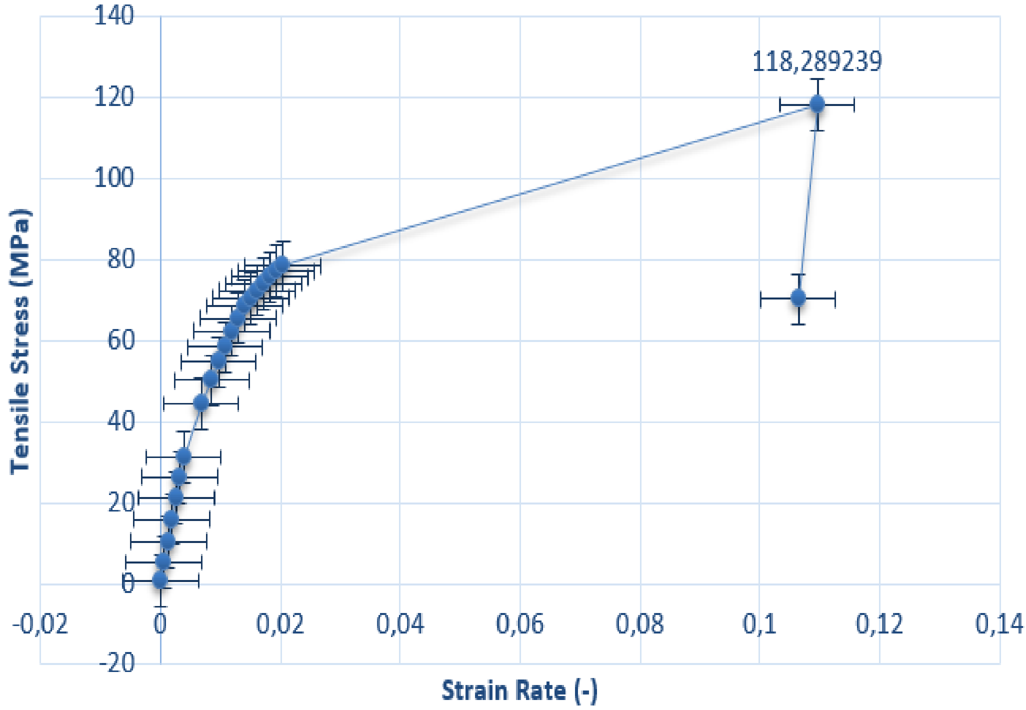
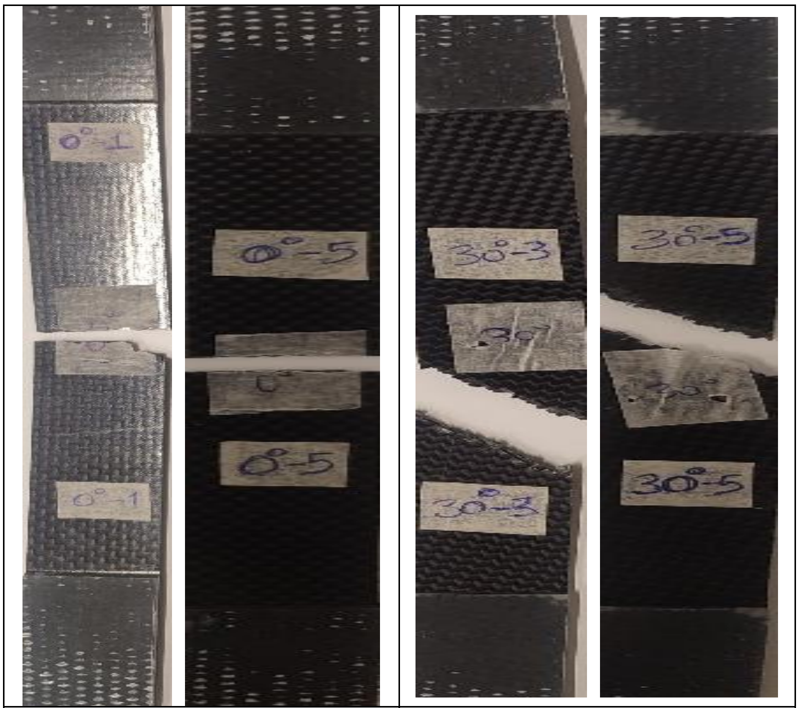


Figure 3. Stress-strain graphs of samples cut at 30° fiber direction

Fracture Surfaces

The fracture surface images of the samples after the tensile test are shown in Figure 4 (a, b), respectively. Labels were affixed to each sample to prevent them from being mixed up. For example, the label 0° indicates that this sample was cut at 0° to the fiber direction. It can seen that flat-fracture surface was observed due to indicating a brittle behavior, three of the samples are fractured along the gauge length of the samples, but other fractured close to critical region. Figure 4 (b) exhibits the fracture surfaces of 30° oriented samples subjected to tensile testing. Fracture surface shows angle-ply surface because the efficiency of load transfer decreases as the angle deviates from the fiber direction. Fibers can be acted as the zig-zag movements to change their positions in the resin. In other words, resin also becomes dominant role, instead of carrying the load by fiber reinforcements, hence resulting in a lower tensile and modulus.



a) 0^{o} orientation	b) 30^{o} orientation

Figure 4. Fracture surfaces of two oriented samples after tensile testing

As a result, the experimental investigation confirms that the VBM produces high-quality CFRP laminates with low coefficient of variation. Fiber orientation is the primary determinant of both the magnitude of strength and the mode of failure. While 0° orientations provide maximum structural stiffness, 30° orientations allow for significantly higher energy absorption through matrix deformation. The limited load-carrying capacity of the fibers at 30° angle, the more dominant role of the matrix, and increased shear stresses have led to a decrease in modulus and strength values. Moreover, the stress-strain curves obtained show that the 0° specimens exhibit brittle fracture behavior due to presence of fiber, while the 30° specimens exhibit a more ductile deformation tendency.

Conclusions

In this study, the tensile properties of twill-woven carbon fiber/epoxy composites fabricated via the Vacuum Bagging Method (VBM) were experimentally investigated across two distinct orientations (0^{o} and 30^{o}). The following conclusions were drawn:

1. Experimental results confirm that fiber orientation exerts a decisive influence on the tensile performance and failure mechanisms of CFRP laminates.
2. The highest mechanical properties were achieved in the 0^{o} fiber direction, yielding an average tensile strength of 287.26 MPa and an elastic modulus of 23.93 GPa.
3. Off axis of 30^{o} orientation deviation from the primary fiber axis resulted in a significant reduction in mechanical integrity, with tensile strength falling to 118.29 MPa and the elastic modulus decreasing to 8.9 GPa.
4. Fractographic analysis have shown that 0° oriented specimens exhibit predominantly brittle fracture characteristics due to the load-carrying capacity of the fibers. However, in the 30° oriented specimens, the role of the matrix became more pronounced, leading to a more ductile deformation tendency in these specimens.
5. .It has been confirmed that the vacuum bagging method is an effective methodology for producing high-quality composite panels by ensuring a low void ratio and homogeneous resin distribution.
6. Experimental data has proven that precise control of fiber orientation and production parameters in composite designs is critical for the final mechanical strength. The effectiveness of the vacuum bagging method (VBM) in the production process has been confirmed by the low coefficient of variation (CV) values obtained.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

Funding

* During this study no funding is available.

Acknowledgements or Notes

* This article was presented as an oral presentation at the International Conference on Technology (www.icontechno.net) held in Budapest/Hungary on February 05-08, 2026.

* We would like to thank ACME Kompozit Ltd.for providing support in manufacturing the composites for their workshop in OSTIM Organize Sanayi.

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To cite this article:

Nugayoglu, E., Sahin, Y., & Kadioglu, F. (2026). Experimental investigation on tensile property of carbon reinforced composite produced with vacuum bagging. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 39,* 1-8.