# Mechanical Behaviour of Fiber-Reinforced Polymer Composites Under Tensile Loading

**Sandeep Ahuja[1], Manisha Rawat[2], Rohit Bansal[3], Charu Negi[4], Vikas Pundir[5]**
**[1,2,3,4,5]Department of Mechanical Engineering, Doon Institute of Engineering & Technology, Rishikesh, Uttarakhand, India**

*Abstract*
***Fiber-Reinforced Polymer (FRP) composites have gained extensive attention in automotive, aerospace, marine, and structural industries due to their high strength-to-weight ratio, corrosion resistance, and design flexibility. Understanding their mechanical behavior under tensile loading is essential for predicting service performance and ensuring safe application in engineering structures. This study investigates the tensile behavior of FRP composites fabricated using different fiber reinforcements—including glass fiber, carbon fiber, and jute fiber—embedded in an epoxy matrix. Composite specimens were fabricated using the hand lay-up method followed by compression curing. Tensile tests were performed in accordance with ASTM D3039 to evaluate tensile strength, modulus of elasticity, elongation behavior, and failure characteristics. Experimental results revealed that carbon fiber composites exhibited the highest tensile strength and modulus due to superior fiber stiffness, whereas glass fiber composites demonstrated balanced strength and ductility. Jute fiber composites, though having lower strength, showed notable energy absorption and sustainable material characteristics. The study emphasizes the relationship between fiber type, interfacial bonding, fabrication quality, and tensile performance, providing valuable insights for selecting appropriate composite materials in load-bearing applications***.

***Keywords:*** *FRP Composites; Tensile Strength; Fiber Reinforcement; Epoxy Matrix; Mechanical Behaviour; Stress–Strain Characteristics*

## 1. Introduction

Fiber-Reinforced Polymer (FRP) composites have emerged as one of the most versatile classes of engineering materials due to their exceptional mechanical properties and design adaptability. Their ability to achieve high structural performance at significantly reduced weight makes them indispensable in industries such as aerospace, automotive, civil engineering, sporting equipment, and marine structures. FRP composites typically consist of high-strength fibers embedded within a polymer matrix, where the fibers primarily bear the applied loads while the matrix ensures load transfer, environmental protection, and structural integrity. The synergy between fiber and matrix results in materials with tailored mechanical behavior, allowing engineers to optimize performance based on specific application requirements.

Tensile loading is among the most critical mechanical conditions encountered by composite materials in practical applications. Components such as aircraft panels, automotive leaf springs, drive shafts, pressure vessels, and structural strengthening systems frequently operate under tensile-dominated stress conditions, making it essential to understand how composites respond to axial loads. The tensile behavior of a composite depends heavily on factors such as fiber type, orientation, volume fraction, matrix properties, fabrication quality, and the interfacial bonding between fiber and matrix. For example, carbon fibers offer high stiffness and low density, making them suitable for high-performance structures, while glass fibers provide a cost-effective alternative with balanced strength and flexibility. Natural fibers such as jute and sisal have also gained interest due to their low cost, biodegradability, and acceptable mechanical properties for medium-load applications.

Research in composite materials has shown that tensile performance is influenced not only by the intrinsic properties of the fiber and matrix, but also by fabrication techniques and processing parameters. Variations in curing temperature, resin distribution, fiber alignment, and void content can cause significant fluctuations in strength and elasticity. Therefore, experimental evaluation of tensile performance under controlled laboratory conditions is necessary to accurately assess the structural efficiency of composite specimens. Tensile testing offers quantitative data on behavior such as ultimate tensile strength, modulus of elasticity, elongation at break, and failure modes, all of which are essential for predicting long-term performance and ensuring reliability in service.

Despite extensive research, the comparative tensile behavior of composites fabricated using different fiber types under identical processing conditions remains an area of continued interest. The need for lightweight yet strong materials in modern engineering applications has further emphasized the importance of selecting suitable fiber reinforcements based on performance requirements. This study aims to provide a comprehensive experimental assessment of FRP composites reinforced with glass, carbon, and jute fibers, fabricated under similar conditions. By analyzing their stress–strain response, stiffness, ductility, and fracture patterns, the study offers insights that can support the design and development of composite components for structural and industrial applications.

## 2. Literature Review

Fiber-Reinforced Polymer (FRP) composites have been extensively researched due to their superior mechanical properties, lightweight nature, and adaptability to a wide range of engineering applications. Studies by Agarwal and Broutman (2018) established the foundational understanding that the mechanical performance of composites depends strongly on fiber type, matrix selection, interfacial bonding, and fiber orientation. Carbon fiber–reinforced composites have been shown to possess exceptionally high tensile strength and stiffness, attributed to the inherent crystallinity and molecular alignment within carbon fibers. Glass fiber composites, according to studies by Hull and Clyne (2019), offer a balance between cost, strength, and impact resistance, making them suitable for automotive and marine applications. Natural fiber composites, including jute and sisal, have gained attention in recent years due to sustainability concerns. Researchers such as Mohanty et al. (2000) demonstrated that jute fiber composites provide moderate strength and good energy absorption, though their mechanical performance is inferior to that of synthetic fibers due to variability in fiber morphology and weaker interfacial adhesion with polymer matrices.

The tensile behavior of composites is strongly influenced by processing methods. Research conducted by Bledzki and Gassan (1999) and others highlights that manufacturing defects such as voids, non-uniform resin distribution, and fiber misalignment significantly reduce tensile strength and stiffness. The hand lay-up method, though widely practiced for its simplicity and low equipment cost, is known to introduce voids and uneven fiber wetting, thereby affecting composite uniformity. However, when combined with post-curing techniques such as compression molding, improved fiber wetting and reduced porosity can be achieved. Studies by Ahmad et al. (2016) found that tensile properties are greatly enhanced when void content is minimized and the fiber–matrix interface is optimized.

Another key area of composite research focuses on stress–strain characteristics and failure mechanisms under tensile loading. Carbon fiber composites typically exhibit brittle failure due to limited elongation, whereas glass fiber composites show more gradual failure with noticeable yielding regions. Jute fiber composites exhibit pronounced non-linear stress–strain behavior with significant elongation, as observed by Satyanarayana et al. (2007). The variability in tensile performance across different fiber types emphasizes the need for experimental comparison under uniform fabrication and testing conditions. The present study builds on these research trends by fabricating composite specimens using glass fiber, carbon fiber, and jute fiber under identical controlled conditions to evaluate and compare their tensile performance, modulus, and fracture characteristics.

## 3. Methodology / System Design (Detailed Paragraph)

The methodology adopted in this study consists of the fabrication of composite specimens using three different fiber reinforcements—glass fiber, carbon fiber, and jute fiber—followed by experimental evaluation under tensile loading in accordance with ASTM standards. The fabrication process began with the preparation of fiber mats, which were cut into uniform dimensions to ensure consistent fiber volume fraction across all samples. An epoxy resin system, consisting of epoxy and a hardener mixed in the manufacturer-recommended ratio, served as the polymer matrix due to its excellent mechanical stability and bonding characteristics. The hand lay-up technique was employed to fabricate the composite laminates, wherein fiber mats were placed layer-by-layer inside a mold and impregnated thoroughly with the epoxy mixture using rollers to ensure uniform wetting. To minimize voids and enhance fiber–matrix adhesion, the laminates were subsequently subjected to compression curing by placing them under a hydraulic press for several hours at controlled pressure. After curing, the composite panels were removed from the mold and machined into tensile test specimens following the ASTM D3039 standard, ensuring precise dimensions and smooth edges to avoid stress concentrations. Tensile tests were conducted using a universal testing machine (UTM) equipped with an extensometer to record elongation during loading. Each specimen was loaded gradually until failure, while stress–strain data, ultimate tensile strength, modulus of elasticity, and elongation at break were recorded. To ensure accuracy and repeatability, a minimum of three specimens from each fiber type were tested, and their average values were analyzed. Fracture surfaces were visually examined to identify dominant failure modes such as fiber breakage, matrix cracking, fiber pull-out, or delamination. This comprehensive methodology allowed for a detailed comparison of mechanical behavior among the three composite groups, facilitating an understanding of how fiber type influences tensile properties under identical fabrication and testing conditions.

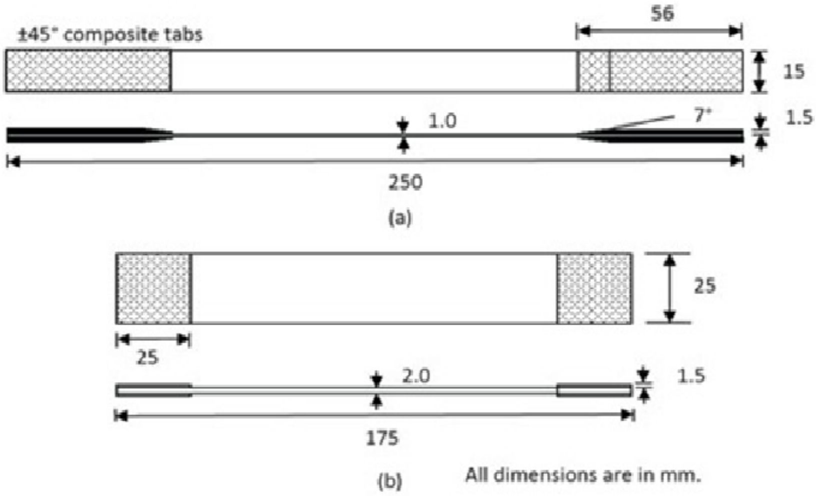


**Figure 1. Composite Specimen Fabrication and Tensile Testing Procedure**

**4. Results and Discussion**

The experimental investigation of FRP composite specimens reinforced with glass fiber, carbon fiber, and jute fiber revealed significant variations in mechanical behavior under tensile loading. The stress–strain curves obtained from the universal testing machine highlighted the distinct stiffness, ductility, and failure characteristics associated with each fiber type. Carbon fiber composites exhibited a linear stress–strain response up to failure, reflecting their inherently brittle nature and high modulus of elasticity. The average tensile strength recorded for carbon fiber composites was the highest among all samples, indicating superior load-carrying capacity attributable to the molecular alignment and high crystallinity of carbon fibers. The modulus of elasticity for carbon fiber composites also exceeded that of the other groups, confirming their suitability for applications requiring high stiffness and minimal deformation under tensile loads.

Glass fiber composites displayed moderate tensile strength and a combination of linear and slightly non-linear behavior before failure. Although their tensile strength was lower than carbon fiber composites, they showed greater elongation at break, making them less brittle. The glass fiber composites demonstrated a balanced combination of strength and ductility, which is consistent with their established use in automotive, marine, and consumer-product applications. The stress–strain curve indicated a distinct yielding region prior to fracture, suggesting that the matrix-fiber bonding allowed some degree of plastic deformation before rupture. The modulus of elasticity for glass fiber composites was lower than that of carbon fiber but significantly higher than that of jute fiber composites.

In contrast, jute fiber composites exhibited the lowest tensile strength and stiffness but showed the highest elongation among the tested specimens. The stress–strain response of jute composites featured a pronounced non-linear region, indicative of their ductile and energy-absorbing characteristics. This behavior can be attributed to the natural variability, hollow fiber structure, and lower stiffness of jute fibers, as well as their weaker interfacial bonding with the epoxy matrix. Despite their lower mechanical performance, jute composites offer advantages such as biodegradability, lower cost, and reduced environmental footprint, making them suitable for non-structural or semi-structural applications where moderate strength is acceptable.

Failure analysis of the fractured specimens provided further insights into the mechanical behaviors observed. Carbon fiber composites fractured suddenly with minimal warning, showing clean, brittle fracture surfaces characterized by fiber breakage and minimal matrix deformation. Glass fiber composites exhibited mixed-mode failure involving fiber pull-out, matrix cracking, and partial delamination, which contributed to their higher elongation and energy absorption prior to fracture. The jute fiber composites displayed extensive fiber pull-out, matrix tearing, and interfacial debonding, indicating that their lower mechanical strength was influenced by weaker bonding between the natural fibers and the epoxy resin. The presence of porosities and uneven fiber distribution in jute specimens, attributable to inherent limitations of the hand lay-up method, further reduced their tensile performance.

Overall, the results indicate that the mechanical performance of FRP composites under tensile loading is highly dependent on fiber type, stiffness, and fiber–matrix interfacial bonding. Carbon fiber composites offer the highest tensile strength and stiffness, making them ideal for high-performance structural applications. Glass fiber composites present a favorable balance of strength, cost, and ductility, while jute fiber composites provide environmentally sustainable alternatives for applications where lower loads and greater deformability are acceptable. The comparative analysis underscores the importance of selecting appropriate reinforcement fibers based on the mechanical requirements of specific engineering applications.

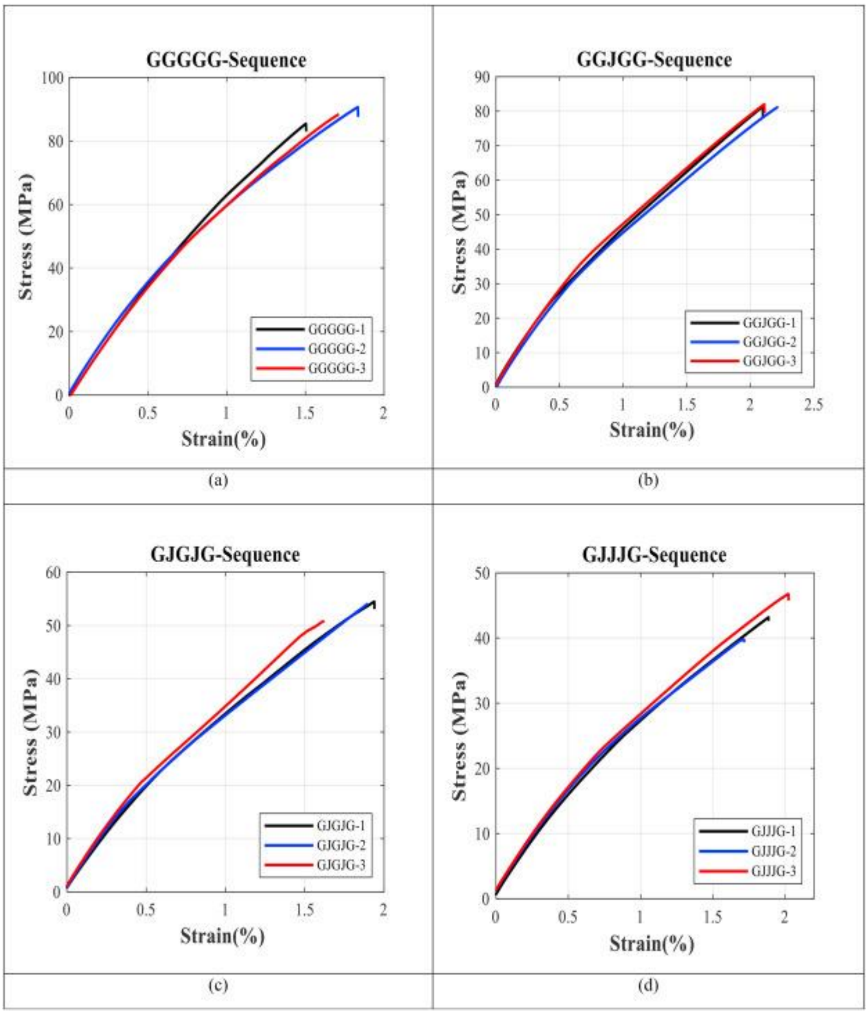


**Figure 2. Stress–Strain Curves for Carbon Fiber, Glass Fiber, and Jute Fiber Reinforced Polymer Composites Under Tensile Loading**

## 5. Conclusion

The experimental evaluation of fiber-reinforced polymer composites under tensile loading demonstrates that the mechanical behavior of FRP materials varies significantly with fiber type. Carbon fiber composites exhibited the highest tensile strength and modulus of elasticity, confirming their suitability for high-performance applications requiring superior stiffness and minimal deformation. Glass fiber composites provided a balanced mechanical response with moderate tensile strength and improved ductility, making them suitable for a wide range of structural and semi-structural uses. Jute fiber composites, while showing the lowest tensile strength, demonstrated the highest elongation and energy absorption capacity, supporting their use in low-load, eco-friendly applications where sustainability and cost-effectiveness are prioritized.

The differences in tensile behavior were further validated by the observed failure mechanisms: brittle fracture dominated in carbon fiber composites, mixed-mode failure in glass fiber composites, and interfacial debonding with extensive fiber pull-out in jute fiber composites. These findings highlight the crucial role of fiber–matrix bonding, fiber stiffness, and structural integrity in determining the tensile performance of FRP composites. The study emphasizes that appropriate selection of fiber reinforcement based on application-specific requirements can lead to optimized composite performance.

Future work may focus on improving natural fiber composites through chemical treatments, hybridization, and advanced processing techniques to enhance their mechanical properties and expand their engineering applications.

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