International Conference on Recent Progresses in Science, Engineering and Technology (ICRPSET-2024), December 07-08, 2024

Journal of Science and Engineering Papers
Volume: 02, Issue: 02 (July), 2025, page: 131-134
Journal homepage: www.jsciengpap.com
https://doi.org/10.62275/josep.24.1000001

ISSN: 3006-3191 (online)

Mechanical performance analysis of carbon fiber reinforced polymer composites: Influence of fiber orientation and polymer matrix

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ARTICLE INFO

Received: 30th September, 2024
Revised: 6th November, 2024
Accepted: 12th November, 2024

Keywords:
carbon fiber reinforced polymer composites,
fiber orientation,
polymer matrix,
FEA,
ANSYS

ABSTRACT

Carbon fibre-reinforced polymer composites (CFRPCs) have drawn considerable interest, highlighting their exceptional mechanical properties, including high strength-to-weight ratio, corrosion resistance, and fatigue performance. Carbon fibers serve as the primary load-bearing element, while polymer matrices such as PVC, polyester, and epoxy distribute loads and protect the fibers. The optimization of the mechanical performance of these CFRPCs is highly essential to ensure their suitable application in the automotive industry. Therefore, the study focuses on improving safety through the evaluation of tensile properties and energy absorption capabilities across different configurations. The study introduced three CFRP composites—CF-PVC, CF-Epoxy, and CF-Polyester—at various fiber orientations, such as 0,15, 30, 45, 60, and 75 degrees. The effect of different fiber orientations on the Tensile stress-strain behaviour was investigated. The study indicates that the effect of fiber orientation was quite similar for all the proposed CFRPCs. The tensile stress is relatively higher at 0° arrangement, while the tensile stress decreases along with the elevation of the angle of fiber orientation. The exhibited tensile stress was quite low regarding the lower angle. The study also shed light on the energy density of CFRPCs and the influence of orientation angle. It is shown that at lower fibre orientations, especially 0° and 15°, the composites demonstrate higher energy density and greater elastic deformation before failure. Beyond 15°, a significant drop in energy density and non-linearity is observed across all composites. It should be noted that CF-Epoxy outcompetes the other composite regarding both tensile stress and energy density behaviour.

1. Introduction

The Carbon fiber reinforced polymer composites (CFRPCs) have garnered considerable attention in recent years owing to its exceptional mechanical qualities, including a high strength-to weight ratio, corrosion resistance, and outstanding fatigue performance. These materials comprise carbon fibers (CF) embedded within a polymer matrix, which imparts distinctive properties to the composite [1]. CF serves as the primary loadbearing element, whereas the polymer matrix facilitates load distribution and safeguards the fibers against environmental degradation. The application of CFRPCs is especially significant in sectors where minimizing weight while maintaining structural integrity is essential, including aircraft, automotive, and sports equipment manufacture. CF is distinguished by its exceptional tensile strength and rigidity, coupled with its lightweight nature, rendering it a crucial material for high-performance applications. It is predominantly utilized in the aerospace, automotive, and civil engineering industries to manufacture components that are both lightweight and resilient. The capacity to integrate carbon fiber with various polymers, including polyvinyl chloride (PVC), polyester, and epoxy, enables engineers to customize

Table 1. Properties of matrix material

Material	Density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio	Bulk Modulus (GPa)	Shear Modulus
PVC	60	0.07	0.3	0.058	0.0269
Resin Epoxy	1160	3.78	0.35	4.2	1.4
Resin Polyester	1200	3	0.316	2.717	1.1398

Table 2. Properties of reinforcement (carbon fiber)

Property	Magnitude	Unit
Density	1800	kg/m^3
Young's Modulus X direction	230	GPa
Young's Modulus Y direction	23	GPa
Young's Modulus Z direction	23	GPa
Poisson's Ratio XY	0.2	
Poisson's Ratio YZ	0.4	
Poisson's Ratio XZ	0.2	
Shear Modulus XY	9	GPa
Shear Modulus YZ	8.2143	GPa

the mechanical characteristics of CFRPCs for particular purposes [2- 4]. Polymer matrices, including PVC, polyester, and epoxy, are essential in influencing the mechanical and thermal properties of composites. PVC is frequently utilized in vehicle interiors for its flexibility and cost-effectiveness, whilst polyester is preferred for its chemical resistance, and epoxy is distinguished for its exceptional adhesive qualities and strength in high-stress applications. When these polymers are combined with carbon fibers, CFRPCs demonstrate enhanced strength, stiffness, and endurance, rendering them exceptionally appropriate for the automotive sector, where minimizing vehicle weight immediately enhances fuel efficiency and reduces emissions [5, 6].

This study examines three distinct composite architectures, utilizing carbon fiber as the reinforcement material and PVC, polyester, and epoxy resin as the polymer matrix. The tensile properties and energy density of these composites are examined under various configurations. This study analyzes the mechanical performance of various materials to elucidate the best composite structure for automotive applications, where tensile strength and energy absorption are pivotal for performance and safety.

2. Materials and methods

2.1. Materials and geometry specification

The properties of the materials used in this work are listed in **Table 1** and **Table 2**. The materials are selected from the ANSYS in-built material library. As the work involves plastic materials that is why for preparation of the tensile test sample ASTM D638-10 Type V is followed, which is the standard tensile test specimen for plastic materials.

2.2. Methodology

In this work, a specimen is created, and a simulation is run to depict the results of a tensile test. For preparing the sample composite, Epoxy resin, Polyester, and PVC are used as the matrix material, respectively, and carbon fiber is selected as the reinforcement. At first, a surface geometry is created using SOLIDWORKS 13. Then, the geometry is imported to ANSYS Design Modeler 19.2, which is later transferred to ANSYS ACP Pre 19.2 to prepare the composite model. ANSYS ACP Pre 19.2 is used to create the laminates of the composite. A five-layered composite is prepared, each layer having a thickness of 0.64 mm. The stack-up sequence and the the dimensions of the tensile test sample as per ASTM D638-10 Type V standard is given in **Figure 1**. The reinforcement fibers are incorporated at different angles (0,15, 30, 45, 60, and 75 degrees), and a simulation is run to determine the results. Using ANSYS ACP Pre 19.2, carbon fiber-reinforced PVC, Polyester, and Epoxy composite samples are prepared. Then, the prepared geometries are given as input to the ANSYS Static Structural Analysis setup, and the Simulation is run to perform a tensile test to see the stress strain behavior of the material and, from there, visualize how energy density varies with stretch.

2.3. Meshing and boundary condition

After importing the composite model from ANSYS ACP pre to ANSYS Static Structural mesh is created in ANSYS Mechanical 19.2. For further Refinement of mesh quality, body sizing with 1 mm size and face meshing is applied. **Figure 2(a)** represents the meshed sample prepared in ANSYS. A total of 4422 nodes and 3300 elements are created. After that, boundary conditions are applied. One side of the sample is fixed, and a displacement at 100 mm/min rate is applied to the other side, as shown in **Figure 2(b)**. The simulation is run for 0.01 seconds, so the total displacement is 0.0167 mm.

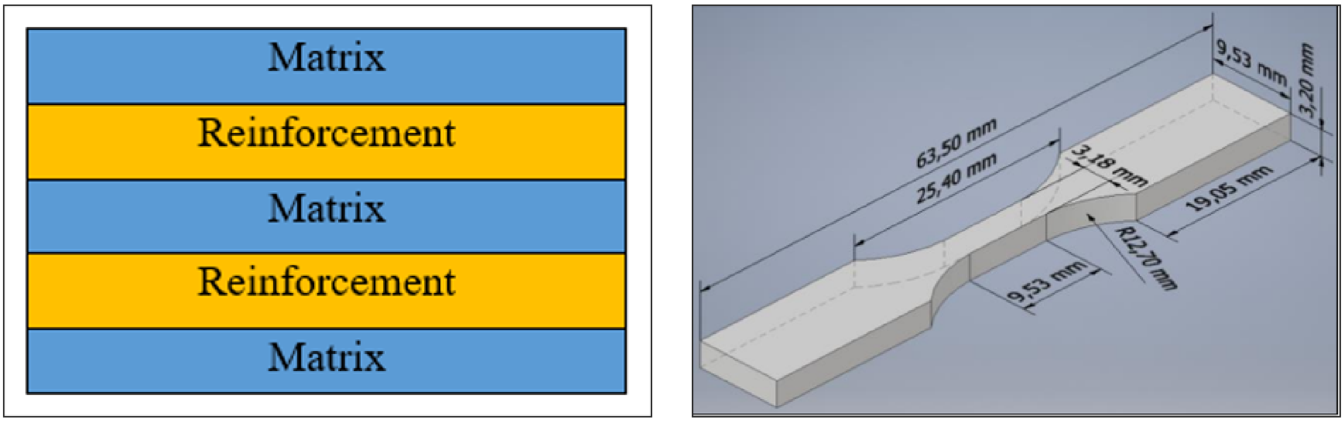


Figure 1. (a) Stack up sequence of the sample (b) standard specimens for mechanical testing.

https://doi.org/10.62275/josep.25.1000021

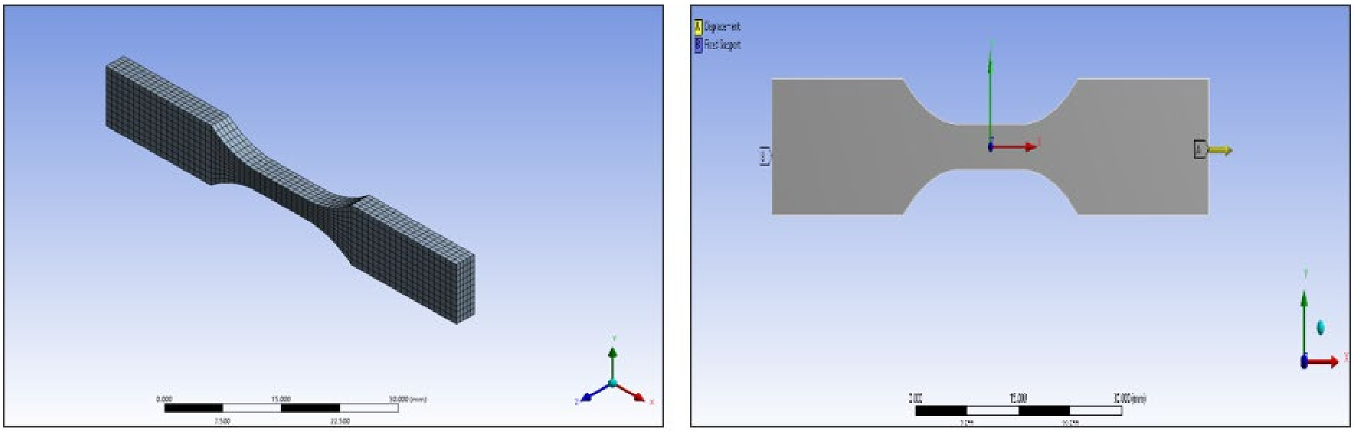


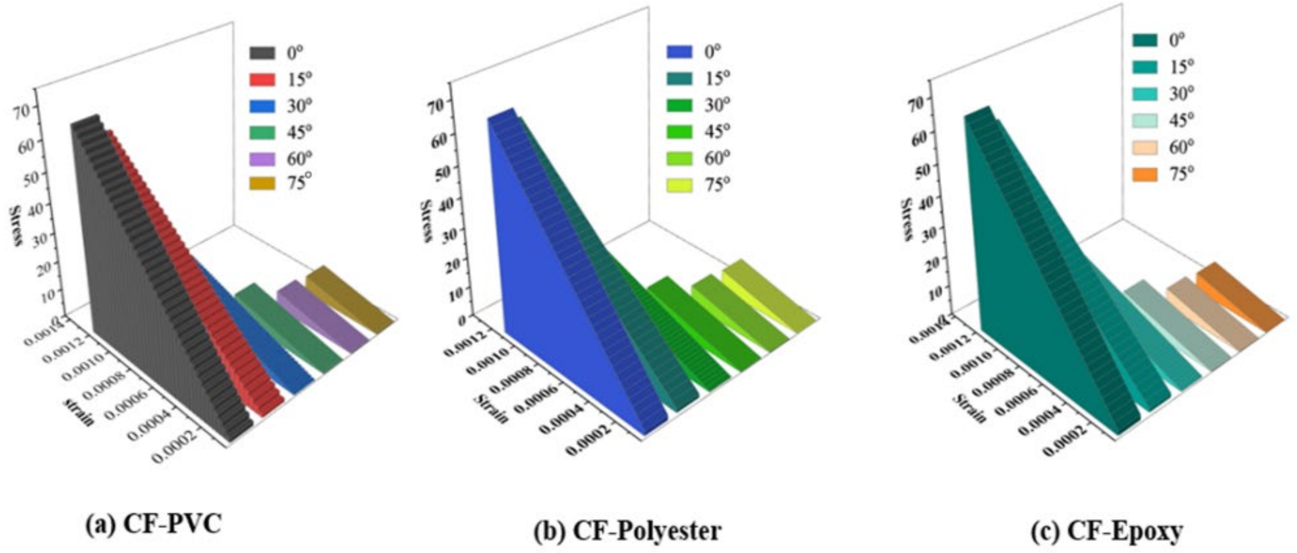
Figure 2. Representation of the (a) meshed sample (b) boundary condition.

Table 3. Maximum stress and minimum stress within angle

Sample	0°		15°		30°		45°		60°		75°	
	Max. Stress (MPa)	Max. Strain (mm)	Max. Stress (MPa)	Max. Strain (mm)	Max. Stress (MPa)	Max. Strain (mm)	Max. Stress (MPa)	Max. Strain (mm)	Max. Stress (MPa)	Max. Strain (mm)	Max. Stress (MPa)	Max. Strain (mm)
CF - PVC	68.5	0.00119	55.437	0.001435	15.868	0.00102	7.6065	0.000727	5.91	0.0006	5.95	0.00058
CF-Epoxy	69.04	0.0011	57.26	0.00135	17.951	0.00099	8.843	0.00071	6.864	0.00059	7.055	0.00058
CF-Polyester	68.895	0.0011	56.915	0.00137	17.565	0.00099	8.6061	0.00072	6.669	0.00059	6.792	0.0005

3. Result and discussion

Table 3 represents the tensile stress-strain behavior of three polymer composites- CF-PVC, CF-Epoxy, and CF-Polyester at different fiber orientations. All samples' total and directional deformation ranged from 0 mm to 0.0167 mm. The findings indicate that the tensile behavior of the three CFRPs is quite similar. At 0° fiber orientation, all the introduced composites exhibit higher tensile stress; however, the value is highest for CF-Epoxy (68.895 MPa). It is shown that the increase in angle results in a general stress reduction. CF-epoxy exhibits stress of 57.26 MPa and 17.951 MPa, respectively. The results demonstrated by the others are quite comparable. It should be noted that as the orientation angle exceeds 30°, a significant decrease in stress occurs. The lowest stress value is observed at 75° for all composites, whereas CF-Epoxy again displayed the highest stress at 7.055 MPa. However, the strain behavior remains consistent, with slight variation in all composites. **Figure 3** further validates the relation between fiber orientation and the tensile stress behavior of all three composites. Prior studies also suggested that the fiber orientation of polymer composites plays a vital role in their mechanical properties. Generally, the composites show superior performance when the fibers are oriented in one direction through proper load distribution along with the fiber direction. The study further focuses on unveiling the relationships between the energy density and the stretch and the effect of fiber orientation. It is discernible in **Figure 4**. The energy density profile of all three composites with respect to stretch are quite identical. It is shown at 0° and 15° fiber orientation; the energy density is significantly higher with an upward trend along with the stretch. In addition, the graphs address that the energy density with stretch has shown non-linearity, which means the composites experience significant elastic deformation before the failure.

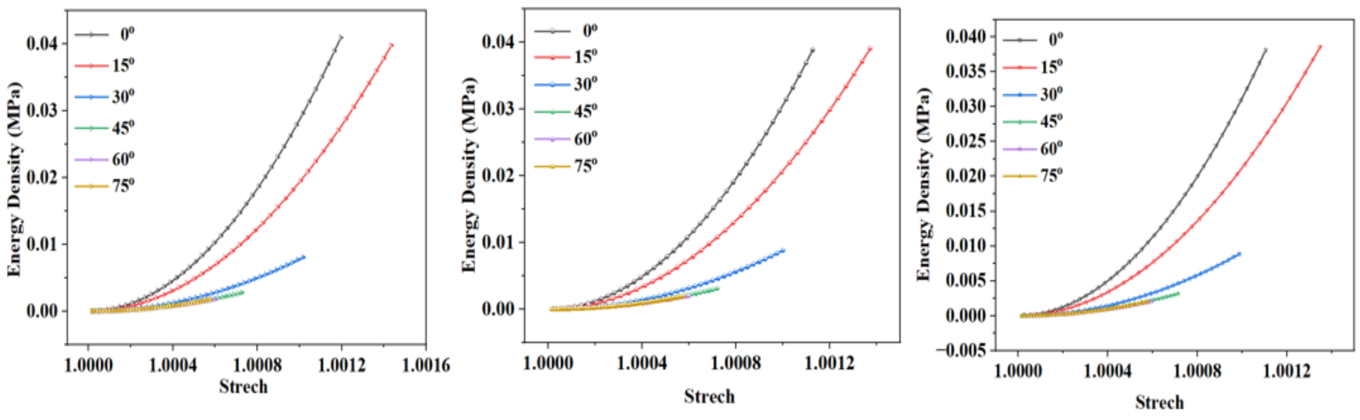


(a) CF-PVC

(b) CF-Polyester

(c) CF-Epoxy

Figure 3. Representation of tensile stress Vs. strain behavior along with the angle.



(a) CF-PVC (b) CF-Polyester (c) CF-Epoxy

Figure 4. Representation of energy density vs stretch along with the angle.

However, beyond 15° orientation, a considerable drop is observed in amount and non-linearity for all three composites.

4. Conclusion

The study on Carbon Fiber Reinforced Polymer Composites (CFRPCs) provides significant insights into the mechanical performance of composite materials tailored for automotive applications. The research highlights the influence of fiber orientation on tensile properties and energy density, examining three distinct composite architectures: carbon fiber reinforced with PVC, polyester, and epoxy. this research contributes valuable knowledge to composite materials by identifying optimal configurations for CFRPCs in automotive applications. The results demonstrated that the tensile strength of CFRPCs is highly dependent on fiber orientation, with optimal performance observed at 0° orientation for all composites. Notably, CF-epoxy exhibited superior tensile stress compared to its counterparts, emphasizing the importance of material selection in achieving desired mechanical characteristics. The findings align with existing literature that underscores the role of fiber orientation in enhancing load distribution and overall performance. Moreover, the relationship between energy density and stretch was explored, revealing that the composites maintain significant elastic deformation before failure, particularly at lower fiber orientations. This characteristic is crucial for applications where energy absorption is essential for safety and performance.

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Funding

The authors affirm that they did not receive any funding for this manuscript.

Acknowledgement

The authors extend our sincere gratitude to the Department of Mechanical Engineering, Rajshahi University of Engineering & Technology, Rajshahi- 6204, Bangladesh.

Ethical Approval

The submitted work is a unique contribution to the field, not published elsewhere in any form or language. Results are presented clearly, honestly, and without fabrication, falsification or inappropriate data manipulation.

Consent of Participate

No human subject or living organism/tissue is involved in this research.

Consent to Publish:

No consent to publish is to be shared.

Author Contributions

The concept for this work was developed with input from all authors. Ehasanul Islam Rafi and Hriday Kumar Gharamy carried out the modelling and simulation. Anik Molla and Hasan Muhommod Robin wrote the manuscript. All writers read and approved the final manuscript.