Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Special Issue 4, 2025
DOI (Journal): 10.37591/JoPC

http://engineeringjournals.stmjournals.in/index.php/JoPC/index

Research JoPC

Effect of Hybridization on Tensile and Flexural Strengths of Carbon, Glass and Steel Fiber Composites: A Comparative Study

Purna Surendernath[1,*], Pothamsetty Kasi V. Rao[2], M.V. Satish Kumar[3]

Abstract

Fiber reinforced polymer composites are widely recognized for their high strength-to-weight ratio, excellent corrosion resistance, and design flexibility making them ideal for various engineering applications. Despite their numerous advantages, traditional composites possess significant limitations such as restricted mechanical performance under diverse loading conditions. To address this, hybrid fiber polymer composites are developed while enhancing material performance. In the present study, synthetic (carbon, glass) and metallic (steel) fiber reinforced composite materials are developed and tested for mechanical properties like tensile and flexural for the suitability in structural applications. These composites are further hybridized by integrating carbon, glass, and steel fibers within a polymer matrix, and their tensile and flexural strengths were compared to non-hybrid composites. Comparative analysis shows that hybridization leads to notable improvements in tensile and flexural properties, with specific fiber combinations showing a significant enhancement in the polymer composite's overall performance. However, the performance of the hybrid composites shows a mixed response, with certain fiber combinations yielding superior mechanical characteristics, while others offer moderate improvements. This study highlights the potential of hybrid fiber-reinforced polymer composites in optimizing structural materials, with an emphasis on the critical role of fiber- matrix interactions in enhancing mechanical properties.

Keywords: Composite, carbon, glass, steel, hybridization.

INTRODUCTION

Composite materials, where reinforcement fiber is the major constituent, combines two or more materials to achieve better properties compare to the individual [1]. High strength to weight ratio is the prominent feature of composite materials. These materials have better stiffness and low density too [2]. Composites generally includes matrix, reinforcement interphase region [3] as shown in figure1(a) and (b). The matrix phase and reinforcement phase together provide the superior functional characteristics of both the materials [4]. In composites, the reinforcing elements may be of different types. Generally, reinforcement is provided in the form of crystal filaments, particles or fibers whereas matrices are in the form of polymer or ceramic materials [5]. Reinforcement materials, such as glass, carbon, or aramid fibers, are used in combination with different types of resins that serve as the matrix in fiber-reinforced composites.

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Received Date: November 15, 2024
Accepted Date: January 21, 2025
Published Date: June 05, 2025

Citation: Purna Surendernath, Pothamsetty Kasi V. Rao, M.V. Satish Kumar. Effect of Hybridization on Tensile and Flexural Strengths of Carbon, Glass and Steel Fiber Composites: A Comparative Study. Journal of Polymer & Composites. 2025; 13(Special Issue 4): S621–S635p.

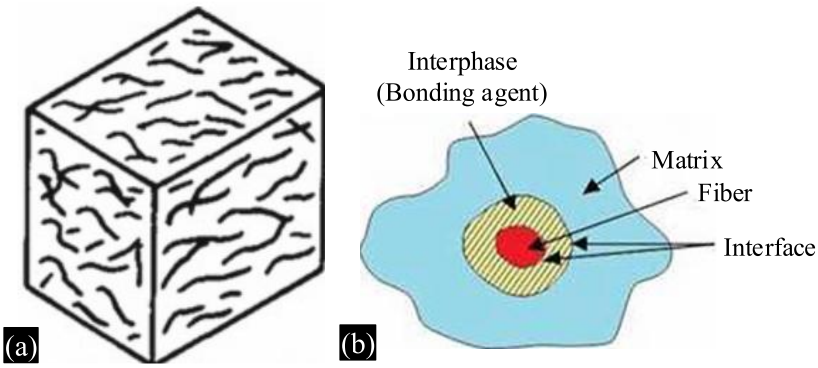

Figure 1. (a) Illustration of Fiber Composite [5], (b) Composite Material Structure [3].

Fiber Reinforced Polymer (FRP) composites are non-uniform and directionally dependent, making them incapable of undergoing plastic deformation [6].

Among FRP composites, Carbon fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP) and steel fiber reinforced polymer (SFRP) composite materials, have found significant increase in replacing the conventional material with better strength and low weight [3]. Carbon Fiber Reinforced Polymer (CFRP) composites utilize carbon fibers as the reinforcing material, typically paired with a polymer matrix. This type of composite offers several advantages, including an exceptionally high tensile strength-to-weight ratio, high tensile modulus-to-weight ratio, a low coefficient of thermal expansion, superior fatigue strength, and excellent thermal conductivity. CFRPs can achieve specific strengths of up to 4500 MPa, along with stiffness, damping capabilities, and an almost zero thermal expansion coefficient [7]. Figure 2(a) illustrates a CFRP composite laminate. Glass Fiber Reinforced Polymer (GFRP), depicted in Figure 2(b), is known for its impressive strength-to-weight ratio, corrosion resistance, and versatility in a wide range of applications. SiO2 can be incorporated into glass fibers, either as continuous or short fibers. S-type glass contains higher levels of silicon and aluminum compared to E-type glass, with each type offering specific properties suited to different applications [8].

Figure 2. (a) Carbon Fiber [9] (b) Glass Fiber [10] (c) Steel Fiber Composite [11].

Steel reinforced polymers (SRP) are less expensive composites that are currently considered for numerous applications in civil engineering, such as bridge and building repair. These composites typically comprise steel wires arranged into cords, which are woven into a fabric and then embedded within a polymer matrix. A microscopic cross-sectional image of such a cord is shown in Figure 2(c). Notably, the steel cords used in SRP can be obtained from the same manufacturing process used for making the reinforcement of automobile tires [11].

Despite of numerous benefits, the properties of non-hybrid composites, made with only one type of fiber is often limited by their inherent weaknesses. As a result, the concept of hybridization was emerged which combines two or more different types of fibers to improve the mechanical properties of composite to suit for the intended applications [12]. In the past literature, focus is made on individual properties of steel, glass and carbon fiber composites, but little focus was given to the properties of hybridized composites. In this study, how hybridizing different fibers can improve both tensile and flexural properties is addressed. The objective of this study is to investigates different combinations of carbon, glass, and steel fibers of PMCs and their effects on tensile and flexural strengths. This paper presents a thorough comparative analysis of fiber-reinforced polymer composites, both with and without hybridization.

Importance of Polymer Matrices in Hybrid Fiber Composites

The polymer matrix is more than just a binder in hybrid fiber composites; it is a key component that determines how effectively the fibers work together, protects the fibers from environmental and mechanical degradation, and significantly influences the mechanical, thermal, and processing characteristics of the composite. A well-chosen polymer matrix enhances the hybrid composite's overall performance, making it suitable for demanding applications in industries like aerospace, automotive, and construction.

LITERATURE REVIEW

Boopalan et al. [13] investigated and compared the mechanical and thermal properties of raw jute and banana fiber reinforced epoxy hybrid composites. Research study showed that addition of banana fiber in jute/epoxy composites of up to 50% by weight results in increasing the mechanical and thermal properties and decreasing the moisture absorption property. Umair et al. [14] investigated the effect of different ply layups on the static and fatigue behaviour of hybrid glass/carbon fibre composite joints. The results indicate that the double scarf-II (GF on outside) is the best of the four designs examined for high stress-high fatigue applications, such as in tidal turbines or larger wind turbines. Dong [15] Conducted experimental and numerical study on flexural properties of symmetric carbon and glass fibre reinforced hybrid composite laminates. The study showed that the hybrid composite has comparable flexural strength and modulus as the full carbon composite when up to half of the plies are glass/epoxy and placed on the inside of the composite. Dipen K R et al. [16] reviewed detailed classification of the existing types of GFs and CFs, highlighting their basic properties. It was observed that flexural strength and ultimate tensile strength of the GFRP and CFRP composites were enhanced with an improvement in the CF and GF content of fiber weight portions. Guermazi et al. [17] investigated the characterization of glass/epoxy, carbon/epoxy and hybrid laminated composites. The mechanical properties of the carbon/epoxy composites were considerably higher than those of the glass/epoxy. Moreover, the hybrid structure presented intermediate mechanical properties. Jun Hee [18] Song evaluated the tensile properties of carbon/glass and carbon/aramid fibers. It was observed that the pairing materials did not lead to a large increase of tensile strength due to the domination of carbon fiber, but the mechanical properties of specific laminates were clearly changed by the particular pairing sequence used. Sriram et al. [19] examined the strength behavior of reinforced concrete containing steel and ramie fibers, comparing it with control concrete. Cementitious composites were added to both the control and hybrid fiber-reinforced concrete (HFRC). The study focused on composites using hooked-end steel fibers and ramie fibers, which offer numerous applications in the construction industry, highlighting the synergistic effects achieved through the combination of these fibers. Kumar et al. [20] examined the influence of hybridization on compressive instability failure in composites by adjusting the volume fraction of glass fiber. The study specifically addressed the failure mechanisms associated with compressive instability in these hybridized composites. He, F., et al. [21] reviewed studies on the mechanical performance of concrete reinforced with a hybrid fiber blend of polypropylene and steel after exposure to thermal damage. Their analysis covers the mechanisms of deterioration and examines the influence of testing conditions on results. Key mechanical parameters of hybrid fiber-reinforced concrete, such as compressive elastic modulus, compressive strength, flexural strength, and fracture toughness, were evaluated in relation to temperature changes. GuruRaja et al. [22]

studies tensile strength, tensile modulus, & peak load of the hybrid composites by varying orientations viz 0°/90°, 45°/45° and 30°/60°. They reported that angle ply orientation at 0°/90° showed significant increase in tensile properties. Further, the results indicated that carbon-glass hybrid composites offered the merits of synthetic fibers. Said et al. [23] used ANSYS software to evaluate the impact of hybridization on the tensile strength of FRP composites based on maximum stress failure criteria.

Dahil et al. [24] investigated the tensile strength and impact toughness of inter-layer hybrid composites composed of unidirectional carbon fiber and twill-woven E-glass fabric in an epoxy resin matrix, both with and without surface cracks. They conducted tensile loading and low-velocity Charpy impact tests. Murugana et al. [25] studied the static mechanical properties and dynamic mechanical properties of hybrid composite laminates. Experiments were conducted and results indicated that hybrid laminate with carbon fibre as enveloping layer, H2, performs better than other hybrid arrangement, H1 and proves to be good alternative for glass laminate. Umair et al. [26] optimized the flame retardant (FR) and mechanical properties of hybrid jute-glass/epoxy composites. In the second phase of their study, two jute-glass hybrid epoxy composites were produced using an optimal concentration of ZrP particles (3%), and their mechanical properties—tensile, flexural, and impact strength—along with flame retardancy were evaluated. Abebe et al. [27] investigated the mechanical and water absorption properties of hybrid polymer matrix composites (HPCs) created by hand layup, reinforced with E-glass fiber and wool. The research aimed to enhance the mechanical properties and water resistance of hybrid composites using polyester resin. Erkendirci et al. [28] analyzed the tensile strength and impact resistance of epoxy hybrid composites with three, five, and seven layers, reinforced with carbon-S2-glass (CG) and carbon-Kevlar-49 (CK) and filled with alumina (Al O). Wu et al. [29] compared the tensile and compressive properties of carbon/glass interlayer and intralayer hybrid composites. Results indicated that tensile and compressive strengths for interlayer and intralayer hybrid composites are greater than the theoretical values, which demonstrates that strength conforms well to the positive hybrid effect. Abd El-baky et al. [30] studied the tensile and flexural properties of jute-glass-carbon fibers reinforced epoxy hybrid composites. Results showed that the hybridization process can potentially improve the tensile and flexural properties of jute reinforced composite.

METHODOLOGY

The experimentation was initiated with the careful selection of fibers for the construction of both non- hybrid and hybrid laminates. Non-hybrid composites were prepared using a single type of fiber, such as carbon, glass, or steel, whereas hybrid composites were developed by combining different fibers, such as glass+steel, carbon+steel, and glass+carbon+steel. These fibers were chosen to understand the mechanical properties of both types, with non-hybrid laminates serving as a baseline for comparison. Following the selection of fibers, an epoxy resin and hardener were prepared as the matrix to bind the fibers together. Single fibers were layered for non-hybrid laminates, while alternating layers of different fibers were used in hybrid laminates to ensure an even distribution of materials within the composite.

After the lay-up process, the laminates were compressed to remove any trapped air bubbles that could weaken the material. The consolidated laminates were then cut into standardized specimens for mechanical testing. To evaluate the mechanical performance, tensile strength testing (according to ASTM D3039 standards) and flexural strength testing (according to ASTM D790 standards) were conducted. These tests measured the composites' ability to withstand forces that would pull them apart or cause them to bend, providing insights into their overall durability. Finally, the mechanical properties of the hybrid laminates were compared with those of the non-hybrid composites, allowing the impact of fiber integration on the material's properties to be assessed comprehensively. Figure 3 illustrates the flow diagram of the experiment.

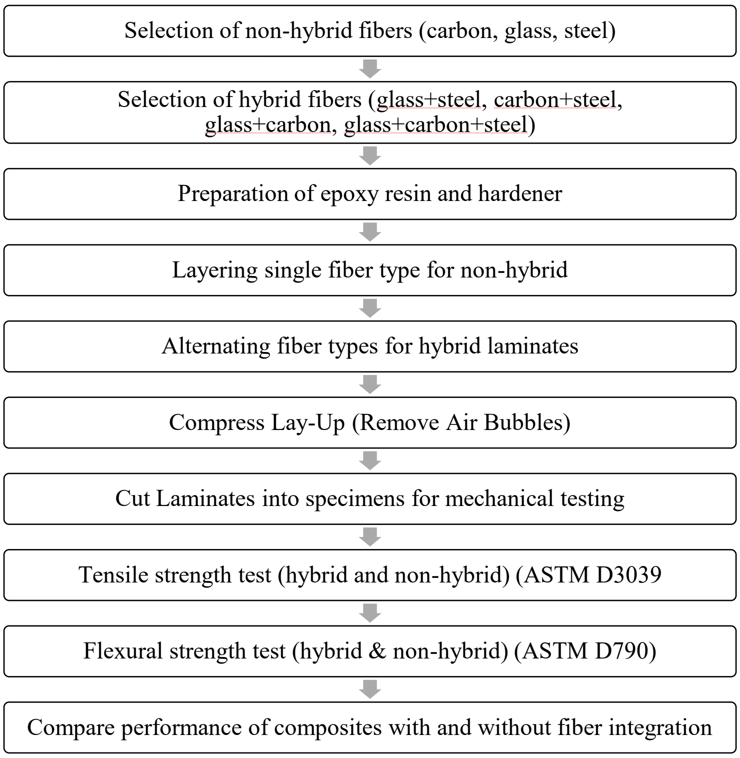

Figure 3. Flowchart for the Experimentation

MATERIALS

In the present work three specimens are prepared for each of Carbon, Glass and Steel laminates as per ASTM standards. The Bi-Directional Carbon Fabric (420 gsm), Bi-Directional Glass Fabric (420 gsm) and Bi-Directional Steel Mesh are shown in Figure 4. The synthetic fiber physical properties are shown in the Table 1. Whereas the common materials required for preparation of all the specimens (Epoxy Resin - LY 556; Epoxy Hardener -HY 951 and Wax Polish) are shown in Figure 4.

Figure 4. (a–f) Resins and hardener used in fabrication.

Table 1. Physical properties of Synthetic fiber

Property	Glass Fiber	Carbon Fiber
Density	2.5–2.6 g/cm³	1.6–1.9 g/cm³
Young's Modulus	70–90 GPa	230–600 GPa
Thermal Conductivity	1–1.4 W/m·K	20–100 W/m·K
Coefficient of Thermal Expansion	5–10 µm/m°C	-0.1 to 1.5 µm/m°C
Specific Strength	Moderate	High
Moisture Resistance	Good, but can degrade in alkaline environments	Excellent
Electrical Conductivity	Non-conductive	Conductive

COMPOSITE PREPARATION

The preparation of composite material using hand lay-up technique includes the standard steps. The process begins by applying a release agent, such as anti-adhesive gel, to the mold surface to prevent the polymer from sticking to the mold's bottom and sides. Next, appropriate layers of fiber are placed into the mold, followed by a resin layer, which is spread evenly over the fibers using a brush. Care is taken to ensure the resin is applied uniformly, creating a smooth surface. A thin plastic sheet is then placed over each layer, and pressure is applied using a roller to eliminate air bubbles and ensure the resin is evenly distributed across the fibers. This process is repeated until the desired material thickness is achieved. The mold is then left at room temperature for 24 to 36 hours to cure, after which the composite can be removed from the mold. Figure 5 shows the hand lay-up process.

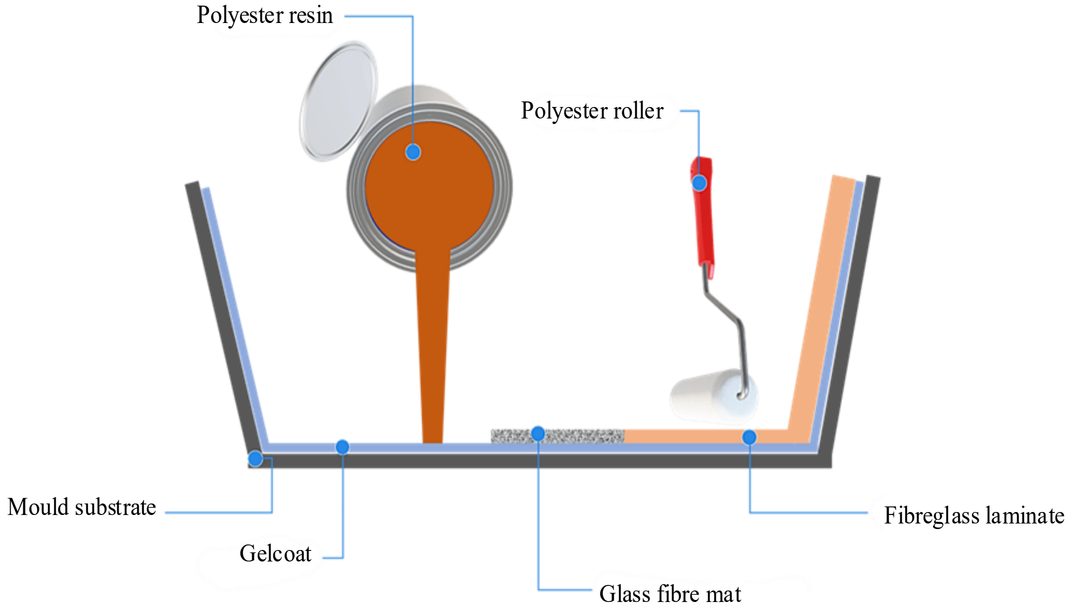

Figure 5. Hand Lay-Up Process.

RESULTS AND DISCUSSION

Figure 6(a) shows the specimens prepared using hand lay-up technique. The essential evaluation of polymers and their composites through mechanical and physical analyses is critical for identifying material characteristics. These analyses play a vital role in designing and assessing items, ensuring quality, establishing performance criteria for applications, and determining appropriate manufacturing methods. The material is put through mechanical and physical testing to make sure it meets with performance standards set by the industry, particularly for the troposphere, automotive, consumer, medical, and defence sectors. Mechanical testing of polymeric materials comprises examination of mechanical behaviour like rigidity and strength in order to assess its possible applicability for the development of a composite's structure. Tensile (tension), flexural, and impact testing are the most

Journal of Polymer & Composites
Volume 13, Special Issue 4
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

typical types of standardised mechanical testing for polymer composites. To do the testing the fabricated composite material is been cut into ASTM Standards shapes for testing. Figure 6(b) shows the specimens were cut as per ASTM standards using CNC machine.

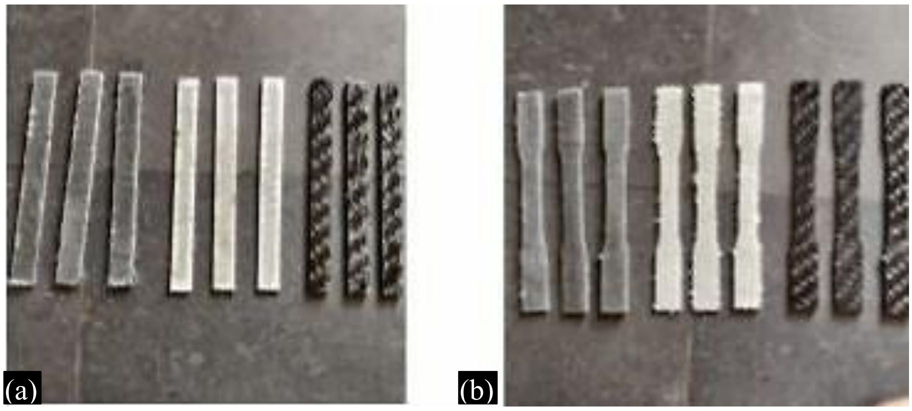

Figure 6. (a) Prepared Specimens (b) Specimens as per ASTM standards.

Tensile Test (ASTM D 638)

Tensile testing is a destructive testing procedure that provides details on the yielding power, flexibility, and tensile qualities of a metallic object. It establishes the highest level of stretching or elongation that a sample of plastic or composite material can bear before cracking. According to standards such as ASTM D 638, basic tension or flat-sandwich tension testing is commonly used for tensile testing of composite materials.

Three specimens are prepared as per ASTM standards, as shown in Figure 7 for tensile strength.

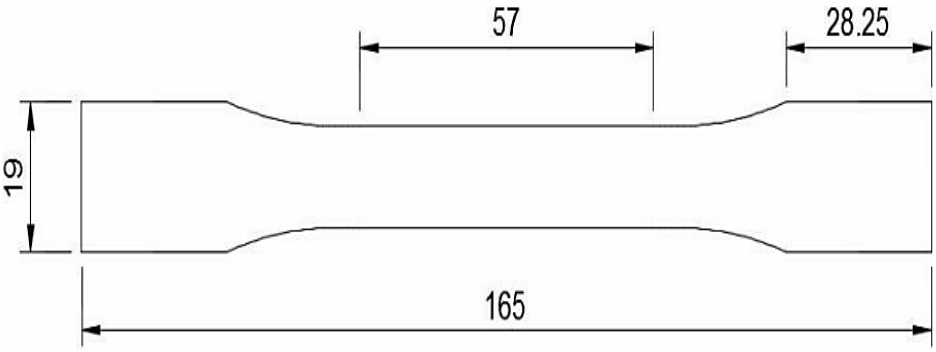

Figure 7. Tensile testing Specimen ASTM standard.

Flexural Testing (ASTM D 790)

Flexural testing, also known as transverse beam testing or flexure testing, assesses how substances react to basic beam stress. It is typically applied to substances with some elasticity, including composite, timber, and polymeric materials. In its simplest form, a bend test is executed on a universal testing device by employing a sample on two fixed anvils then bending it with applied force on one or more loading anvils to assess its goods. A 4-point bend test provides pressure using two extreme anvils placed equivalently away from the centre, as opposed to a 3-point bend test, which applies stress with a single upper anvil in centre. In a 3-point test, a very tiny section of uniform stress is concentrated beneath its centre loading point. In a 4-point test, there is a zone of uniform stress among inner span loading points. According to the variety of test sample, a variety of different flex fixtures may be employed. Figure 8 depicts the schematics for the beam's bending test.

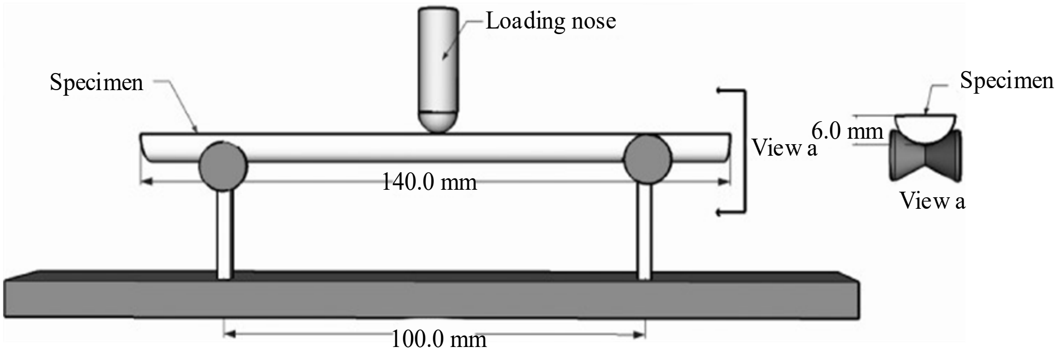

Figure 8. Schematics of Flexural test of the beam

The universal testing apparatus was used to conduct the Flexural test in this work. The composite material was initially cut in line with ASTM specifications. According to ASTM Standards, the specimen is sliced into the testing size, as seen in Figure 9.

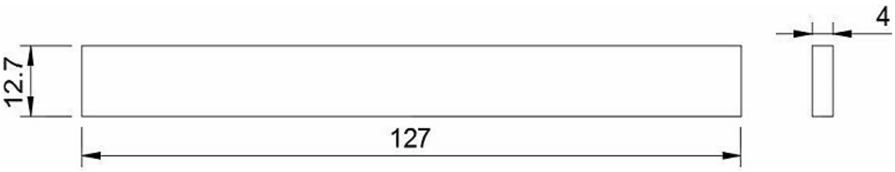

Figure 9. Flexural testing Specimen ASTM standard.

Tensile & Flexural testing for carbon, glass and steel PMC

The value of tensile & flexural strength of a specimen may vary slightly due to manual errors in hand layup method, all the observed values are shown in Table 2. To take care of these variations of three specimens with same laminates prepared and there tensile & flexural is observed. The best of the three values is considered as their tensile & flexural strength.

The tensile test findings vary by little, not more than 5 N/mm^2, and are essentially similar from sample to sample. In terms of tensile strength, the carbon sample has the greatest value (426.49 N/mm^2). Glass and steel have far lower tensile strengths than carbon. The graph, which is shown in Figure 10, clearly compares the tensile strengths of carbon, glass, and steel. It is evident from the graph below that carbon matrix composite has a substantially greater tensile strength than glass and steel.

Table2. Tensile & Flexural Strength for Carbon, Glass and Steel Matrix composite material.

	Tensile Strength			Flexural strength		
	Carbon	***Glass***	***Steel***	***Carbon***	***Glass***	***Steel***
Specimen 1	421.95	208.27	47.92	217.86	212.54	61.07
Specimen 2	425.69	212.35	49.66	230	210.39	32.37
Specimen 3	426.49	210.14	48.56	244.76	213.32	46.5

On the other hand, the flexural test results are generally consistent from sample to sample and variation is not more than 10 N/mm^2. The carbon sample has the highest value (244.76 N/mm^2) for flexural strength. The graph in Figure 10 compares the flexural strengths of steel, glass, and carbon in a concise manner. It is evident from the graph below that carbon matrix composite has a substantially greater flexural strength than glass and steel matrix composite. Glass has lower flexural strengths compared to carbon where as steel has much less flexural strength among all the three composites.

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Volume 13, Special Issue 4
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

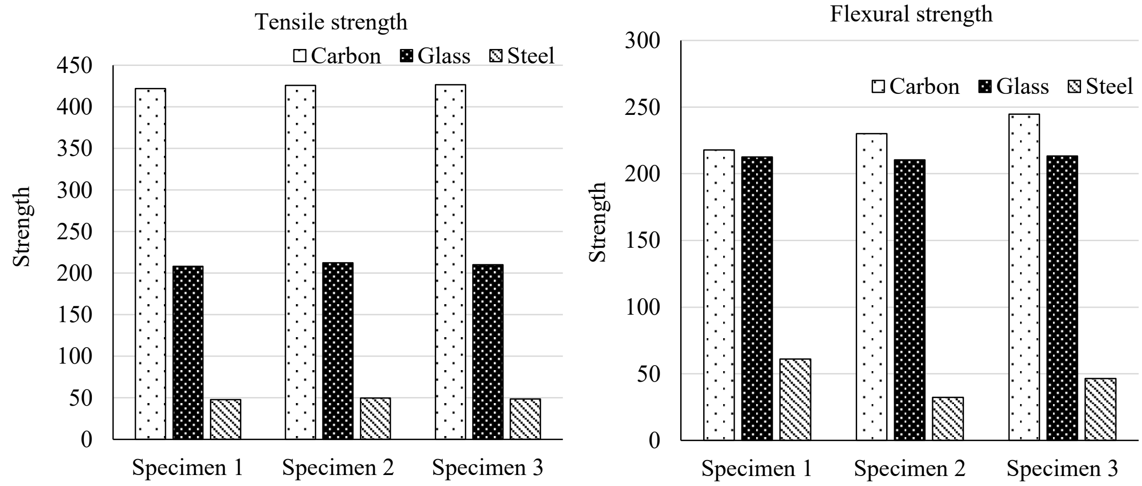

Figure 10. Tensile and Flexural Graph for Non-Hybrid composite.

HYBRIDIZATION OF COMPOSITES

Composite materials, particularly Polymer Matrix Composites (PMCs), have gained widespread use in fields such as aerospace and automotive due to their superior mechanical properties, including tensile and flexural strengths. In this study, three different types of fibers—carbon, glass, and steel—were used to create both standalone and hybrid PMC laminates. Hybridization of these fibers aims to optimize material properties by combining the strengths of individual fibers, leading to a balanced performance in stiffness, durability, fatigue resistance, and weight reduction. The values of tensile and flexural strength for hybridized composite material are shown in Tables 3 and 4.

Table 3. Tensile Strength for hybridized composite material

	Tensile Strength			
	Glass + Steel	***Carbon + Steel***	***Glass+carbon***	***Glass+carbon+steel***
Specimen 1	273.446	441.106	558.947	575.719
Specimen 2	263.669	437.073	514.952	578.887
Specimen 3	290.747	431.176	530.864	587.523
Average	275.95	436.45	534.92	580.71

Table 4. Flexural Strength for hybridized composite material.

	Flexural strength			
	Glass + Steel	**Carbon + Steel**	**Glass+carbon**	**Glass+carbon+steel**
Specimen 1	332.73	405.34	443.88	490.9
Specimen 2	330.46	410.56	432.15	489.3
Specimen 3	239.63	218.56	445.48	486.04
Average	300.94	344.82	440.50	488.75

The hybridization results show notable improvements in both tensile and flexural strengths when compared to non-hybrid composites. Specifically, the glass+carbon+steel hybrid achieved the highest average tensile strength of 580.71 N/mm², outperforming other hybrid configurations, including the carbon+steel (436.45 N/mm²) and glass+steel (275.95 N/mm²) composites. In terms of flexural strength, the glass+carbon+steel hybrid also excelled, with an average of 488.75 N/mm², reflecting a well-rounded improvement in load-bearing capabilities. The data suggests that hybridization not only amplifies the strengths of individual fibers but also mitigates their individual limitations, creating composites with a more uniform and enhanced performance profile. Figures 11 and 12 shows the bar graph that compares the tensile strengths and flexural strengths of hybridized steel, glass, and carbon.

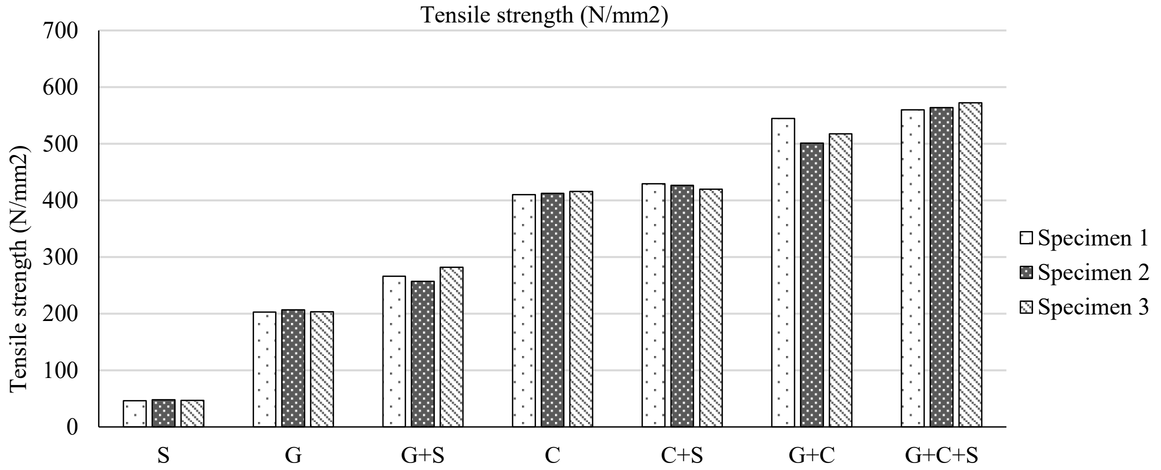

Figure 11. Tensile strength graph for hybrid composites.
***S – Steel, G- Glass, C- Carbon, G+S – Glass+Steel, C+S – Carbon + Steel, G+C – Glass + Carbon, G+C+S – Glass + Carbon + Steel*

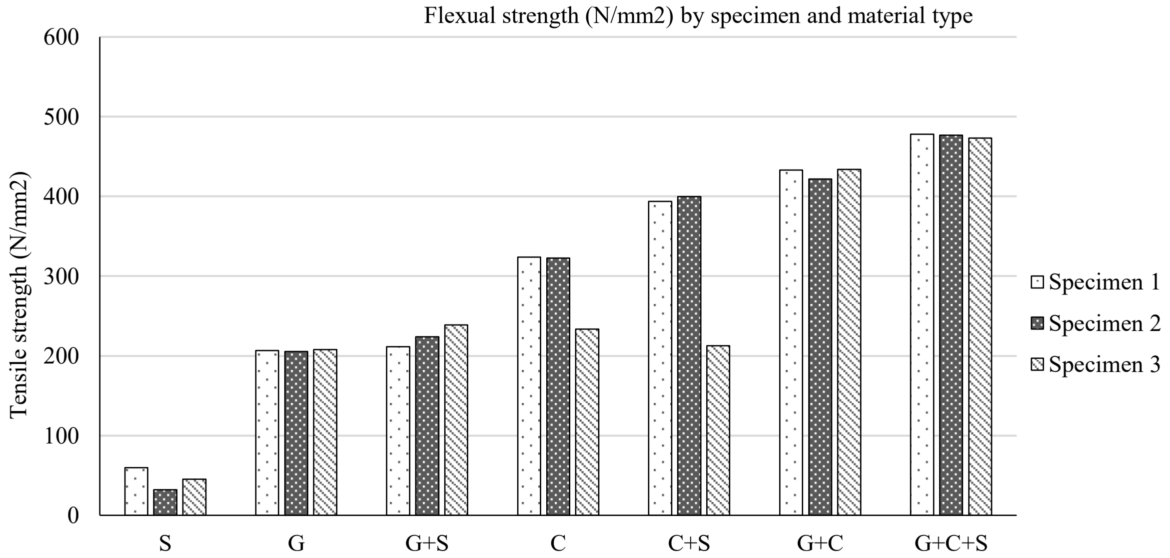

Figure 12. Flexural strength graph for hybrid composites.
***S – Steel, G- Glass, C- Carbon, G+S – Glass+Steel, C+S – Carbon + Steel, G+C – Glass + Carbon, G+C+S – Glass + Carbon + Steel*

TENSILE STRENGTH COMPARISON

Non-Hybrid Composites

Among the three non-hybrid composites, carbon fiber composites displayed the highest tensile strength, reaching 426.49 N/mm². Glass fiber composites followed with 212.35 N/mm², while steel composites exhibited the lowest tensile strength at 48.56 N/mm².

Hybrid Composites

Hybridization significantly enhanced the tensile properties. The glass+carbon+steel hybrid showed the highest tensile strength at 587.523 N/mm², a 37.8% increase over carbon composites alone. Other hybrids such as glass+carbon (558.947 N/mm²), carbon+steel (441.106N/mm²), and glass+steel (290.747 N/mm²) also displayed considerable improvements in tensile strength compared to individual fiber composites. Figure 13 indicates the average tensile values of hybrid composites.

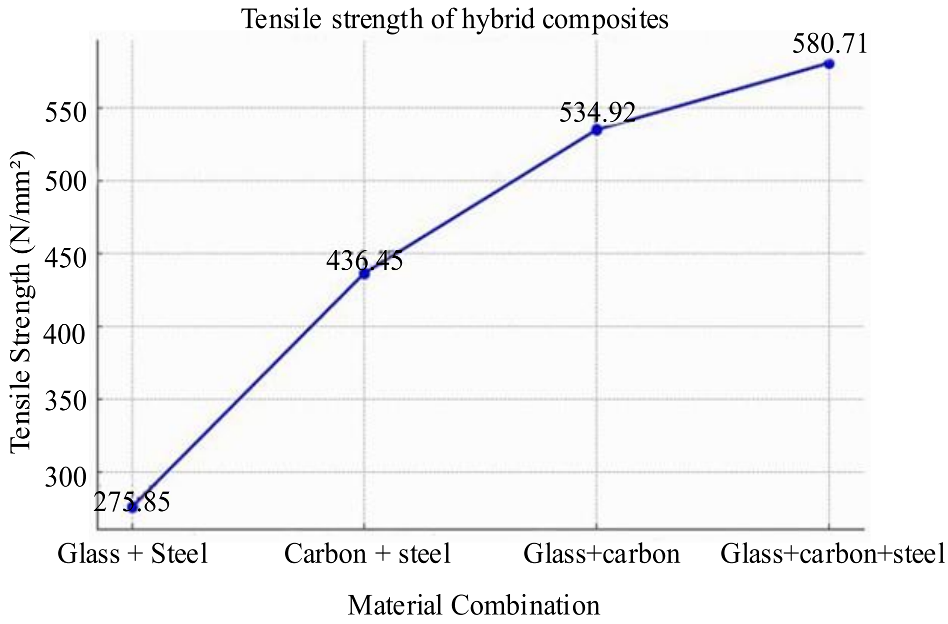

Figure 13. Average tensile values of hybrid composites

FLEXURAL STRENGTH COMPARISON

Non-Hybrid Composites

In terms of flexural strength, carbon fiber composites again outperformed the other materials with 244.76 N/mm². Glass fiber composites followed closely at 213.32 N/mm², while steel composites had a much lower flexural strength of 61.07 N/mm².

Hybrid Composites

Hybrid composites demonstrated enhanced flexural strength in all tested combinations. The glass+carbon+steel hybrid recorded the highest flexural strength at 490.9 N/mm², while the glass+carbon hybrid achieved 445.48 N/mm², both considerably higher than individual composites. The glass+steel and carbon+steel hybrids also showed increased flexural strength compared to steel and glass composites alone. Figure 14 indicates the average flexural values of hybrid composites.

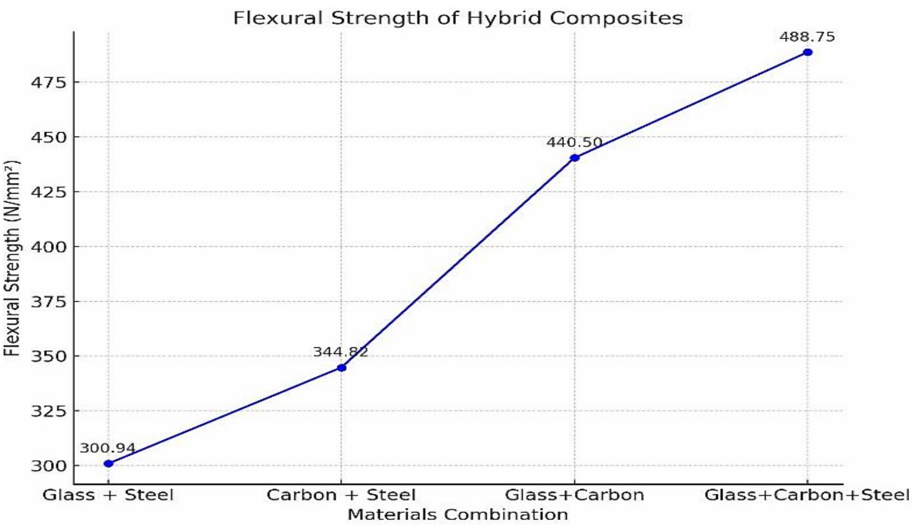

Figure 14. Average flexural values of hybrid composites

EFFECT OF HYBRIDIZATION ON MECHANICAL PROPERTIES

Hybridization amplifies the benefits of individual fibers by combining their strengths. The addition of steel fibers to glass or carbon improves load distribution and overall toughness, while the presence of carbon fibers enhances the stiffness and strength. The glass+carbon+steel hybrid composite demonstrated the most balanced properties, with significant increases in both tensile and flexural strengths. This synergy is especially advantageous in applications that demand a balance between stiffness and toughness.

Analysis of the Carbon-Based Composites

Non-Hybrid Carbon Composites

Carbon composites, known for their high strength-to-weight ratio, displayed the highest tensile (426.49 N/mm²) and flexural (244.76 N/mm²) strengths among the non-hybrid laminates. Their performance justifies their widespread use in high-performance applications like aerospace.

Hybrid Carbon Composites

When combined with steel or glass fibers, carbon-based hybrids showed marked improvement. The **carbon+steel hybrid** improved tensile strength by approximately 1.1%, and flexural strength increased by 2.5% compared to pure carbon composites. This suggests that hybridization with steel adds ductility without compromising stiffness.

Performance of Glass Fiber Composites

Non-Hybrid Glass Composites

Glass composites, while not as strong as carbon, provided moderate tensile (212.35 N/mm²) and flexural (213.32 N/mm²) strengths. Due to their lower cost and adequate mechanical properties, they are well-suited for applications with less stringent requirements.

Hybrid Glass Composites

Hybridization with carbon and steel fibers significantly boosted glass composite performance. The glass+steel hybrid improved tensile strength by about 38.4%, while the glass+carbon hybrid exhibited an even greater improvement in both tensile and flexural strengths, approaching those of carbon composites.

Steel Fiber Composites: Challenges and Improvements

Non-Hybrid Steel Composites

Steel-reinforced composites showed the weakest mechanical performance among the non-hybrid composites, with tensile strengths peaking at 49.66 N/mm² and flexural strengths at 61.07 N/mm². However, steel fibers provide excellent toughness and ductility, which are essential in impact resistance applications.

Hybrid Steel Composites

Hybridization dramatically improved steel composite properties. The glass+steel hybrid reached tensile strengths of 290.747 N/mm², demonstrating that even low-strength steel can benefit significantly from hybridization with stronger fibers like glass and carbon.

CONCLUSIONS

This study demonstrates that hybrid fiber-reinforced polymer composites, specifically combinations of carbon, glass, and steel fibers, offer significant mechanical enhancements over non-hybrid composites in terms of tensile and flexural strengths. Among non-hybrid composites, carbon fiber reinforced polymers displayed the highest tensile and flexural strengths, while steel fiber composites showed the lowest. However, the introduction of hybridization, particularly the glass+carbon+steel combination, resulted in remarkable improvements—showing a 37.8% increase in tensile strength and substantial gains in flexural strength over single-fiber composites. The study highlights that hybridization not only amplifies the benefits of individual fibers but also balances their mechanical properties, creating composites with greater strength, toughness, and stiffness. The superior performance of glass+carbon+steel hybrids underscores the synergistic potential of combining high-strength carbon with ductile steel and cost-effective glass fibers. These findings offer valuable insights for structural applications requiring lightweight, high-strength materials, particularly in aerospace, automotive, and civil engineering sectors.

Limitations

The hand layup method introduced variability in sample preparation, leading to minor inconsistencies in the tensile and flexural strength results. Additionally, the study was conducted under controlled laboratory conditions, which do not account for environmental factors like temperature fluctuations, UV exposure, and humidity that could affect the long-term performance of the composites in real- world applications.

Future scope

Future research could explore advanced manufacturing methods like resin transfer molding to enhance consistency and scalability, investigate new fiber combinations and orientations for optimized mechanical properties, and assess additional properties such as impact resistance and environmental durability to broaden application potential in industries like aerospace and automotive.

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