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Optimal Replacement of Glass Fabric with Carbon Fabric in Epoxy Matrix Composite

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ABSTRACT

The aim of this study is to investigate the optimum replacement of glass fabric with carbon fabric in epoxy matrix composites, focusing on achieving comparable mechanical properties while reducing manufacturing costs. The glass and carbon fabric-reinforced epoxy matrix hybrid composites are prepared with varying hybrid ratios of reinforcements (ratio of carbon fabric to total fabric) using the vacuum pump-assist hand lay-up technique. The composite samples are made in the shape of a plate. To analyze the tensile and flexural strengths of the fabricated composite samples, they are cut into corresponding dimensions as per ASTM standards. The effect of varying sequences of laminas and numbers of glass fabric and carbon fabric laminas on the mechanical properties of the composite is studied and compared, respectively. The improvements of 53.82% and 98.67% in the tensile strength and flexural strength, respectively, are noticed with an increment of the hybrid ratio from 0 to 1. The obtained results of the composites with various hybrid ratios can be used to select an optimal flexural strength as well as tensile strength in relation to a specific application and cost.

1. Introduction

A composite material can be defined as a combination of two or more materials that results in better properties than those of the individual constituents. In comparison to alloys, each constituent of the composite retains its own chemical, physical, and mechanical properties [1]. The main advantages of composite materials are their high strength and stiffness combined with their low density, i.e., they allow a weight reduction in the finished part (high strength-to-weight ratio) [2,3]. The composite materials are combinations of two phases: one is called the reinforcement phase, and the second is called the matrix phase [4,5]. Reinforcements are mostly used in the form of fiber and particulates. Metal, polymer, and ceramic materials are used as matrix materials; based on these matrix materials, they are called metal matrix composite (MMC), polymer matrix composite (PMC), and ceramic matrix composite (CMC), respectively [1,2,6]. A detailed classification of composites according to different aspects is shown in Fig. 1.

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Composite materials have generated significant attention in various industries due to their excellent mechanical properties and flexibility of use [7–10]. Among the comprehensive selection of composites, epoxy-based matrix materials reinforced with synthetic fibers have emerged as a promising candidate due to their high strength, stiffness, and thermal stability [11–13]. In particular, carbon fiber-reinforced epoxy composites have gained prominence for their superior mechanical properties, making them perfect for applications in the aerospace, marine, automotive, and sporting goods industries [14]. However, the high cost of carbon fibers has led researchers to investigate alternative reinforcements, such as glass fibers, which propose a more cost-effective solution with slightly compromised performance [15,16].

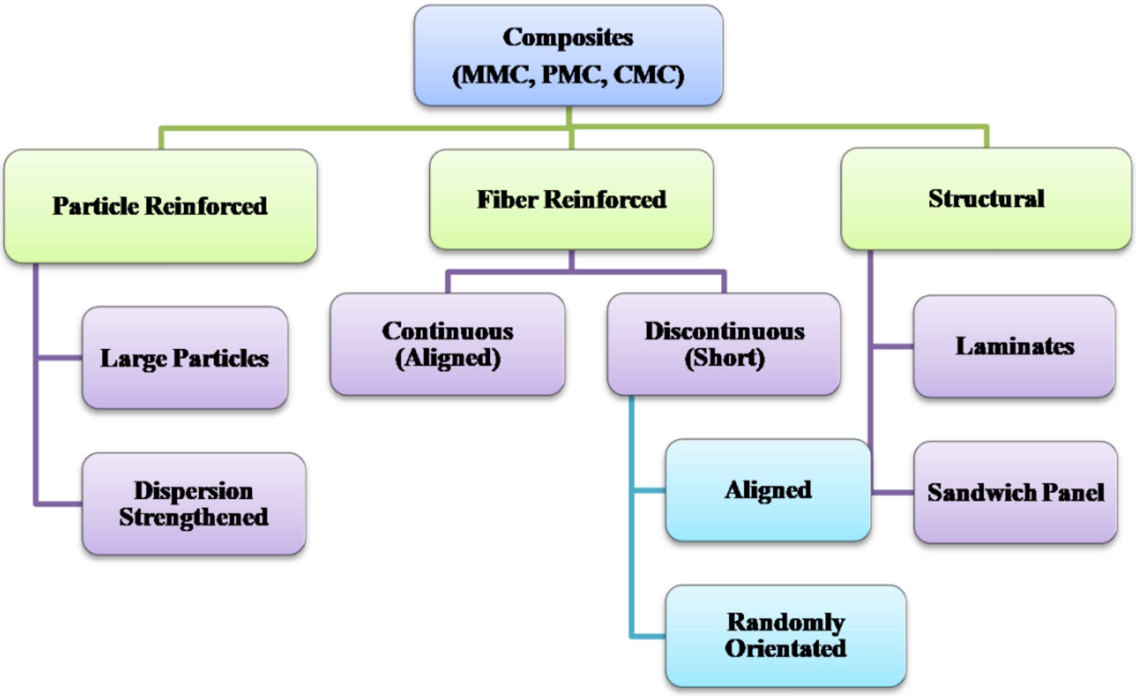

Fig. 1. Classification of composite materials

A significant amount of research is devoted to understanding the mechanical behavior of epoxy matrix composites reinforced with various synthetic fibers. Zhou et al. [17] conducted extensive studies on the mechanical properties of carbon nanofiber (CNF)-filled epoxy composites, highlighting the significant improvements in tensile and flexural strength achieved with the addition of CNF. Similarly, Su et al. [18] explored the friction and wear properties of carbon fabric composites, emphasizing the influence of environmental factors and nanoparticle fillers on tribological performance. Maurya et al. [19] determined the effect of SiC reinforcement on the mechanical behavior of the AA6061 matrix. They used the stir-casting method to develop composites. They noted that the 8 wt.% SiC-reinforced AA6061 composite has enhanced mechanical properties. In their further study, they developed friction stir additive manufactured hybrid composites by using AA6061, TiC, and sludge dust [20,21]. They used different weight percentages of TiC and sludge dust to improve the mechanical and microstructural properties of AA6061. They observed that the AA6061 reinforced with 5 wt.% of TiC and 5 wt.% of sludge dust hybrid composites have improved mechanical and microstructural properties. Dwivedi et al. [22] used eggshells, sludge, and chromium to reinforce the AA5052 by stir casting to develop hybrid composites. They enhanced the tensile strength, compressive strength, and hardness of the AA5052 with reinforcements. SiC and B_4C particulates were used by Patel et al. [23–27] to develop lightweight composite materials. These composites have superior hardness, wear resistance, compressive strength, and corrosion resistance. Polymer composites also have a good ability to provide protection against adverse environments [28]. Al-Qrimli et al. [29] investigated the mechanical performance of woven carbon/epoxy composites through experimental testing and finite element modeling, providing insights into the performance of these materials under loading conditions. Huang et al. [30] reported that the winding of carbon fiber-reinforced polymer composite on the wooden rod improved the compressive strength of the rod. Lee et al. [31] found an improvement in the flexural response of the wooden bar by incorporating a carbon fiber-reinforced polymer composite. Similarly, Pardhi and Patel [32] investigated the effect of glass fiber-reinforced polymer composite winding on the aluminum tube on its torsional strength. They revealed that the composite-winded aluminum tube has enhanced torsional strength compared to the same mass of aluminum tube. Lu et al. [33] reported that the E-glass fiber-reinforced polymer composites sustain their mechanical characteristics at elevated temperatures. Abolfazli et al. [7] compared the compressive strengths of basalt, glass, and carbon fiber-reinforced polymer composite tubes compressive strengths at elevated temperatures. They determined that the carbon fiber-reinforced composite has a higher compressive strength than the other composite tubes. Huang et al. [34] obtained improved flexural strength by incorporating flax-glass fiber-reinforced hybrid composite skins on the wooden beam. Additionally, Li et al. [35] proposed a novel approach for evaluating impact damage tolerance in composites using electrical resistance measurements, representing its effectiveness in assessing the safety performance of these materials. Research on carbon fabric-based polymer composites has provided important insights into the internal structure and mechanical properties of these materials. Studies by Karahan et al. [36] and Zhou et al. [17] expounded on the structural characteristics and mechanical behavior of carbon fabric-used polymer composites, highlighting their potential for use in structural applications. Different fabrication techniques, including hand lay-up, vacuum-assisted resin transfer molding, injection molding, filament winding, and compression molding, can be employed to produce composite materials with customized properties. These techniques offer divergent advantages in terms of processing flexibility, mechanical performance, and cost-effectiveness [37,38]. Sandwich panels have good energy-absorbing ability [39–43]. However, polymer composites are also used in their skin for protection against extreme loadings [44–46]. Studies by Zhang et al. [47], Mridha et al. [48], and Hussain et al. [49] investigated the effects of different fabrication techniques on the mechanical properties and fracture behavior of composite materials, highlighting the significance of process parameters and filler reinforcement in achieving the desired feat. Additionally, Tekinalp et al. [50] explored additive manufacturing techniques for fabricating short fiber-reinforced composites, representing considerable improvements in mechanical performance and microstructure compared to traditional manufacturing methods. Recent studies have focused on improving the interlaminar strength and tribological properties of carbon fabric and/or glass fabric-reinforced polymer composites through the inclusion of nanoparticulate fillers, such as Al_2O_3, SiO_2, carbon nanotubes, and Si_3N_4, to alleviate brittleness and develop wear resistance [18,51,52]. Aljidda et al. [53] discovered that the use of a glass fiber-reinforced polymer composite improved the flexural strength of a reinforced concrete bar. Mukhtar and Jawdhari [54] used the carbon fiber-reinforced polymer composite to improve the flexural strength of a reinforced concrete beam. Carbon fibers represent a promising alternative to glass fibers in composite applications, offering enhanced mechanical and tribological properties because of their structured alignment and load-carrying capacity [4,15,55,56]. Nugraha et al. [57] determined that hybrid composites are demandable materials for aerospace and aircraft applications due to their excellent strength. Torabizadeh and Fereidoon [58] reported that the use of glass fiber-reinforced polymer composite skin as face sheets of sandwich panels improved energy absorption under impact loads. Mack et al. [59] also suggested using hybrid composites as the skins of sandwich panels to obtain better impact resistance. The orderly arrangement of carbon fabrics improves integrity and strength, making them suitable for various industrial applications [31,60]. Carbon fabric-reinforced polymer composites are also used with metallic plates in designing armor-grade panels for protection against bullet impacts, projectile impacts, and blast pressures [61–63].

This comprehensive literature survey depicts that composite materials provide enhanced mechanical and tribological properties as well as reduced weight as compared to monolithic plates. Carbon and glass fabrics were used by many researchers to fabricate lightweight composites. However, the effect of hybridization with different ratios on the mechanical properties of the composite is not adequately described in the literature. It is therefore difficult to select a cost-effective composite material as per the required strength. However, the present research work aims to investigate the feasibility of replacing glass fabric with carbon fabric in epoxy matrix composites. This study identifies the optimal combination of carbon and glass fabrics in the epoxy matrix to achieve cost-effective composite materials with comparable mechanical properties to their carbon fabric-reinforced epoxy matrix composites. Tensile and flexural tests have been performed on efficiently fabricated composites to evaluate their mechanical performance. Scanning electron microscopy (SEM) analysis has also been done to understand the failure phenomenon of the composite.

2. Materials, Fabrication, and Experimentation

2.1. Materials

In the presented work, hybrid composites composed of epoxy, E-glass wove fiber (fabric), and carbon woven fiber (fabric) are fabricated. The E-glass fabric and the carbon fabric are used as reinforcement, and epoxy resin is used as the matrix. These used materials are shown in Fig. 2. The used glass fiber and carbon fiber in the form of a fabric type are supplied by Hindustan Fiber Glass Works, Kolkata, India. In the present study, plain weave carbon and glass fabrics are used because plain weave fabric provides higher structural rigidity as compared to twill weave and unidirectional fabric. Twill-weave fabric may be preferred where complex shapes are required, and unidirectional fiber can be used if high strength is required in any specific direction. A carbon fiber is a material consisting of fibers about 7 micrometers in diameter and composed mostly of carbon atoms. Carbon fabrics are stronger than steel and lighter than aluminum [64,65]. However, in the present work, carbon fabric is used as a reinforcement in epoxy matrix composites. The glass fabric is cheaper than the carbon fabric and has reasonable strength, which also makes it of great interest in the research. Epoxy resin is a lightweight thermoset polymer that also provides a uniform load distribution over the structural parts [66]. However, a type of epoxy LY-556 resin (density 1.1 g/cc) is used in the present investigation with a hardener HY-951 supplied by Haripa India, Kolkata, India. The mixing ratio of this epoxy and hardener is 10:1.

2.2. Fabrication Method

The glass fabric and carbon fabric-reinforced epoxy matrix hybrid composites are fabricated through the hand lay-up process, which represents a meticulous and controlled methodology intended to produce materials with tailored properties. One of the key innovations in our fabrication process was the incorporation of mold connected to a vacuum pump during the hand lay-up process, as shown in Fig. 2. This vacuum-assisted cure played a pivotal role in controlling air inclusion and eliminating excess epoxy [67]. The connected vacuum pump created an environment where trapped air was efficiently removed, enhancing the overall quality of the fabricated composite. Simultaneously, the evacuation of excess epoxy contributed to a more precise and controlled resin-to-fiber ratio, addressing common challenges associated with conventional hand lay-up processes [68]. This advanced technique allowed us to achieve a higher degree of uniformity and consistency in the development of composite materials. The fabrication process commenced with the application of a releasing agent to the surface of the mold. This critical step ensured the seamless removal of the composite samples from the mold, facilitating subsequent testing and analysis. Following the mold preparation, a matrix material composed of epoxy resin and hardener was thoroughly mixed in 10:1 to achieve a homogenous blend [52]. The resin system (formed by epoxy and hardener) holds the fibers together in fiber-reinforced composites. This process ensures appropriate load transmission and establishes the mechanical characteristics of the composite. While toughness, durability, wear resistance, and overall structural performance are mostly influenced by the resin system, the fibers offer strength and stiffness. This prepared matrix material was then carefully applied to the mold and spread uniformly to guarantee proper impregnation of the reinforcing fibers. After that, the fabrication process is completed in four steps, as shown in Fig. 3. These four steps are first reinforcement layer placement, resin wetting, repeated reinforcement layer placement, and curing.

Five distinct composite samples, denoted as S_1, S_2, S_3, S_4, and S_5, are fabricated by systematically varying the hybrid ratio. Figure 3 shows the sequence of glass fabric and carbon fabric in hybrid composites. Each composite laminate is made of four plies. The hybrid ratio represents the proportion of carbon fabric in the E-glass fabric and/or carbon fabric-reinforced epoxy matrix composite, with values ranging from 0 to 1. This variation was undertaken to investigate the impact of different hybrid compositions on the final composite material properties. The hybrid ratios chosen were 0, 0.25, 0.50, 0.75, and 1, offering a comprehensive analysis of the mechanical properties of the hybrid composites. Each composite sample represented a unique combination of reinforcing fabrics, allowing us to explore the synergistic effects and trade-offs associated with different hybridizations. The designations and fabric layer sequence in composites are given in Table 1. In this table, “G” and “C” represent the glass fabric layer and carbon fabric layer, respectively, in the fabricated composite. The composite samples S_2, S_3, and S_4 represent hybrid composites due to the combined use of glass and carbon fabrics. Following the completion of the hand lay-up process, the composite samples are allowed to cure for a period of 48 hours. The curing time was carefully selected to ensure adequate cross-linking of the epoxy resin and the development of the desired mechanical properties. Crucial elements that directly affect a fiber-reinforced composite's mechanical characteristics are the curing temperature and duration. They control the resin matrix's level of polymerization and cross-linking, which influences characteristics including toughness, strength, stiffness, and thermal stability. Achieving optimality for these characteristics guarantees that the composite performs to the best of its abilities.

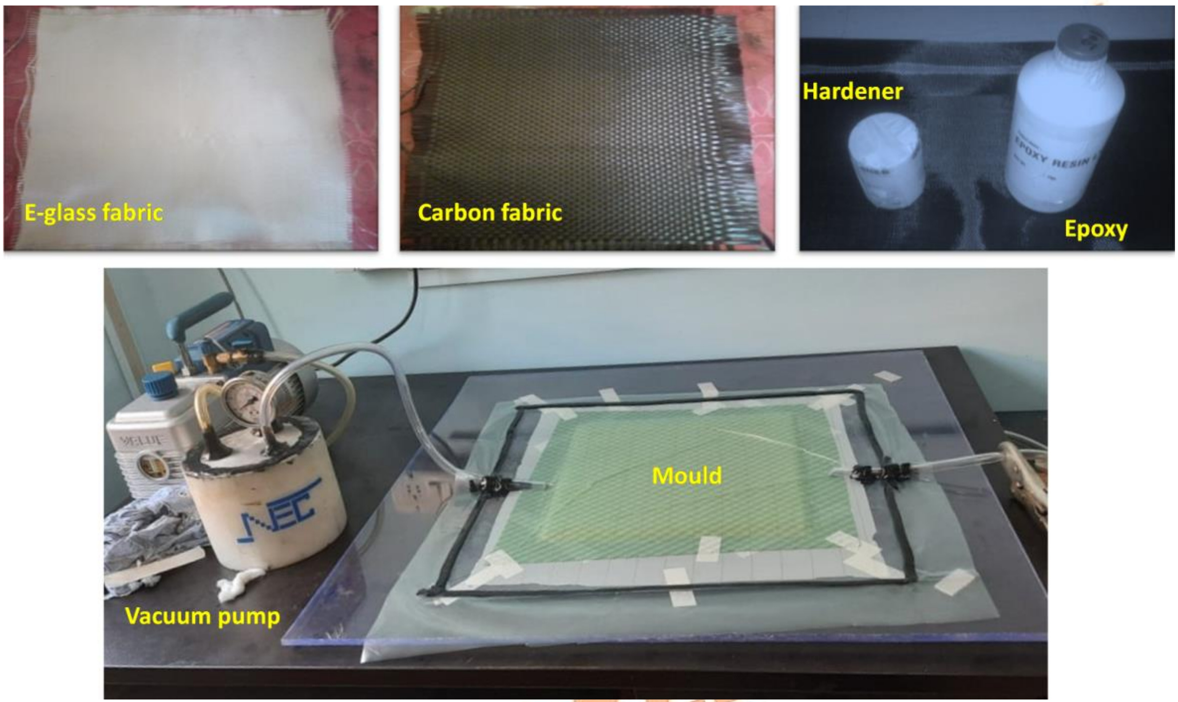

Fig. 2. Raw materials of composite fabrication and hand lay-up mold connected with vacuum pump

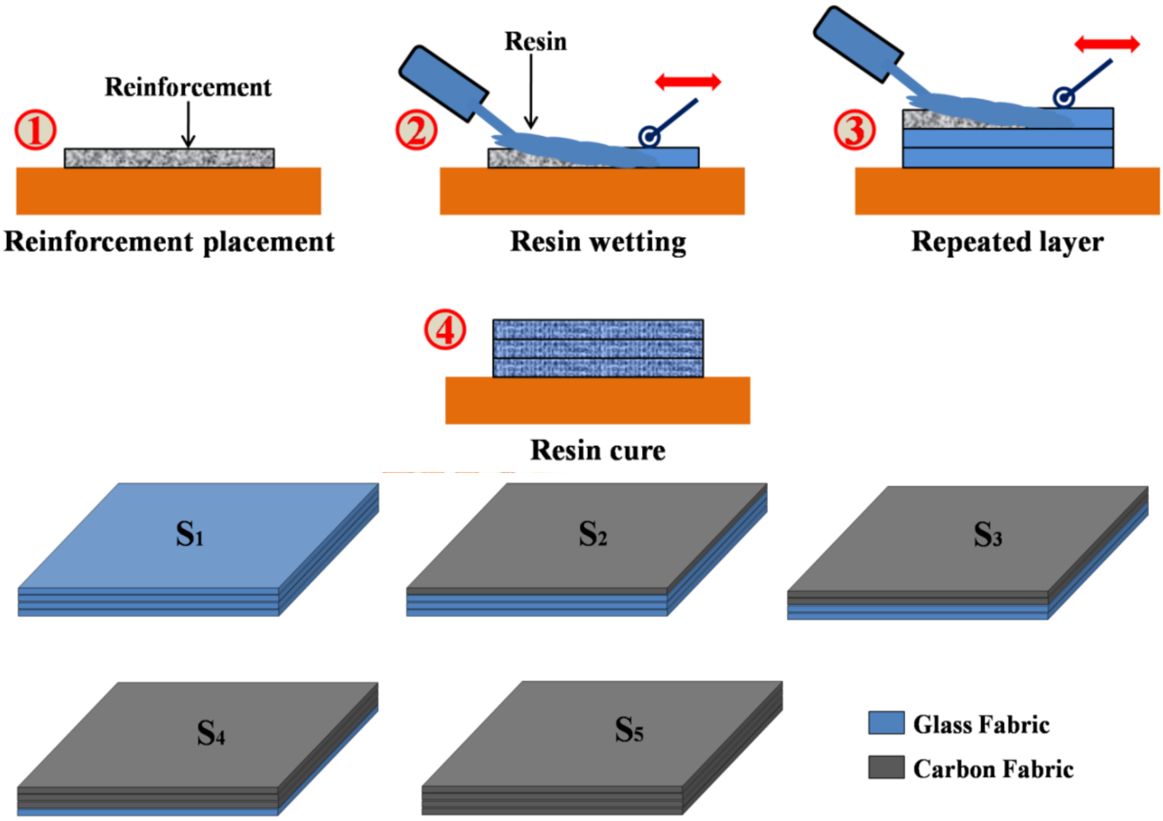

Fig. 3. Composite fabrication process with the sequence of glass fabric and carbon fabric in the composite materials

The obtained composite materials exhibited a combination of the high-strength characteristics of carbon fabric and the cost-effectiveness of glass fabric [69,70]. A fabricated composite plate is shown in Fig. 4. In the present study, the weight percentages of the fibers and resin in the fabricated composites are approximately 40% and 60%, respectively. In general, a balanced ratio of fiber to resin improves stiffness and tensile strength because the resin bonds the fibers and evenly distributes stresses. However, because of the resin's reduced strength in relation to the fibers, too much resin may result in weaknesses like voids or poor adherence, which might impair mechanical performance. While toughness and resistance to the environment can be enhanced by increased resin content, maintaining the ideal balance between fiber content and resin content is essential to the overall structural integrity and performance of the composite.

Table 1. Designations for fabricated composites with a fabric layer sequence

Composite	Hybrid ratio	Layer sequence	Glass fabric %	Carbon fabric %
S_1	0.00	G-G-G-G	100	0
S_2	0.25	C-G-G-G	75	25
S_3	0.50	C-C-G-G	50	50
S_4	0.75	C-C-C-G	25	75
S_5	1.00	C-C-C-C	0	100

2.3. Testing and Characterization

To assess the physical and mechanical properties of the fabricated composites, test specimens of appropriate dimensions as per American Society of Testing and Materials (ASTM) standards are precisely cut from each composite plate by using an abrasive water jet machine. The specimens cut out from a fabricated composite plate are represented in Fig. 5. These specimens are subjected to tensile and flexural tests. The tensile and flexural tests are performed at room temperature. The results of these tests provided valuable insights into the structural performance, strength, and durability of the hybrid composites across different hybrid ratios. Also, after performing mechanical testing, the SEM characterization of the fractured composite sample is performed to understand the failure mechanism of the composite. The comprehensive analysis of the physical and mechanical properties aims to contribute to the understanding of hybrid composite behavior and guide the selection of optimal hybrid ratios for specific engineering applications.

Fig. 4. A composite plate fabricated through a vacuum pump assists the hand lay-up method.

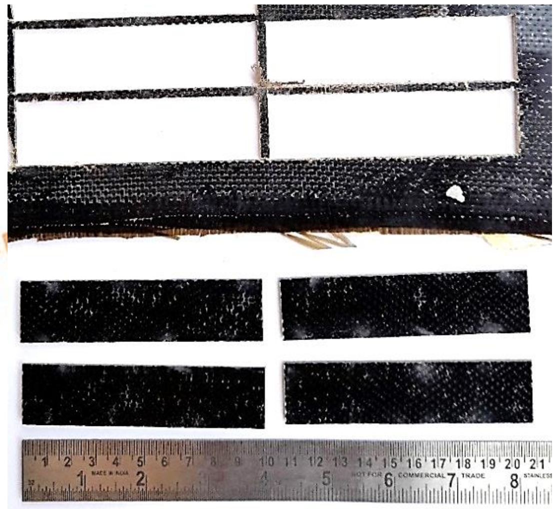

Fig. 5. Specimens with appropriate dimensions cut from a composite plate

2.3.1. Mechanical Testing

Mechanical testing is essential for evaluating the fundamental properties of composite materials, helping in material development, and ensuring quality control for various applications in engineering, design, and construction. The characterization of the mechanical performance of composites is crucial for determining their suitability for specific structural applications [69]. In the presented work, tensile and flexural tests are performed to evaluate the mechanical performance of the fabricated composite materials.

Tensile testing is a widely used method for assessing how composite materials behave under tension, providing valuable insights into their mechanical properties. By subjecting a specimen to a controlled tensile force until failure, engineers and quality managers can determine parameters such as tensile strength, modulus of elasticity, and elongation at break. ASTM D3039 outlines the geometry for tensile test specimens of fiber-reinforced polymer composites. Tensile tests are performed on flat specimens prepared according to ASTM D3039-76 standards. The specimens have dimensions of 125 mm× 13 mm× 5 mm. This test is conducted on a Universal Testing Machine (UTM) at a constant crosshead speed of 1 mm per minute to ensure consistent results. Flexural tests are also performed on the same UTM. Flexural testing evaluates the combined effects of tensile, compressive, and shear properties when a bending load is applied to a specimen. The ASTM D2344 standard specifies the procedure for conducting flexural tests, commonly known as three-point bend tests, on polymer matrix composite materials. The dimensions of the flexural test specimens are standardized to ensure consistency in testing and analysis. The specimens are prepared according to ASTM D2344-84 standards, having dimensions of 100 mm × 25 mm × 5 mm. The used UTM for mechanical characterizations of the fabricated composite is shown in Fig. 6.

2.3.2. Failure Behavior Characterization

After mechanical testing, the composite samples are examined using SEM to understand the failure phenomena and microstructural changes induced by the applied loads. SEM analysis provides valuable insights into the fractured surfaces, fiber-matrix interactions, and other structural features. Also supporting the interpretation of mechanical test results and informing further material optimization efforts. The used SEM machine for damage behavior characterizations is also shown in Fig. 6.

Fig. 6. UTM was used for tensile and flexural tests, and SEM was used for fracture behavior characterization.

3. Results and Discussion

The thorough examination carried out on the glass-carbon fabric-reinforced epoxy composites clarifies the significant impact of replacing glass fabric with carbon fabric in the epoxy matrix composite on mechanical performance. The study involved a systematic assessment of five composites, denoted as S_1, S_2, S_3, S_4, and S_5, comprising different ratios of glass and carbon fabrics within the epoxy matrix. Composite S_1 is a pure glass fabric-reinforced epoxy composite, serving as a reference for comparison. Consequently, composites S_2 through S_5 are fabricated by sequentially replacing individual layers of glass fabric with carbon fabric within the epoxy matrix composite.

3.1. Mechanical Performance

Tensile and flexural tests on the fabricated composites are carried out to evaluate their mechanical performance. The tensile and flexural strengths of all the composites are compared to determine the optimal replacement of glass fabric with carbon fabric from the epoxy matrix composite.

The tensile strength of composite materials is mainly determined by the fiber strength as well as the fiber contents. Therefore, the variation in composite strength with the different fabric compositions is obvious. Table 2 shows the tensile strength of composites with different compositions (hybrid ratios).

Table 2. Tensile strength of fabricated composites with different hybrid ratios

Composite	Hybrid ratio	Tensile strength (MPa)	% increment in tensile strength with respect to the tensile strength of S_1
S_1 (G-G-G-G)	0.00	416.2	-
S_2 (C-G-G-G)	0.25	435.6	4.66%
S_3 (C-C-G-G)	0.50	473.3	13.72%
S_4 (C-C-C-G)	0.75	588.6	41.42%
S_5 (C-C-C-C)	1.00	640.2	53.82%

Table 3. Flexural strength of fabricated composites with different hybrid ratios

Composite	Hybrid ratio	Flexural strength (MPa)	% increment in flexural strength with respect to flexural strength of S_1
S_1 (G-G-G-G)	0.00	202.6	-
S_2 (C-G-G-G)	0.25	236.5	16.73%
S_3 (C-C-G-G)	0.50	282.7	39.54%
S_4 (C-C-C-G)	0.75	377.4	86.28%
S_5 (C-C-C-C)	1.00	402.5	98.67%

The results listed in Table 2 show that there is a gradual increase in tensile strength from 416.2 MPa to 640.2 MPa with increasing the hybrid ratio from 0 to 1, respectively, in the fabricated composites. This increasing trend in tensile strength with the increase in the hybrid ratio is mainly due to stronger interfacial bonding among carbon fabrics and epoxy matrix compared to the bonding between glass fabrics and epoxy matrix. Also, the carbon fibers are stronger and stiffer as compared to the glass fibers. Table 2 also shows the percentage change in the tensile strength of different composites with respect to the tensile strength of a pure glass fabric-reinforced epoxy matrix composite (S_1 composite). While examining the tensile test result, it has been noticed that the tensile strength of the S_2, S_3, S_4, and S_5 composites increases by 4.66%, 13.72%, 41.42%, and 53.82%, respectively, as compared to the tensile strength of the S_1 composite.

The variations in flexural strength of the fabricated composites of different hybrid ratios measured by using three-point bending tests are tabulated in Table 3. The results listed in Table 3 show that there is a gradual increase in the flexural strength of the fabricated composites from 202.6 MPa to 402.5 MPa with an increase in the hybrid ratio from 0 to 1, respectively. The better interfacial linkage between carbon fabrics and epoxy matrix than between glass fabrics and epoxy matrix is the cause of the increase in flexural strength with an increase in the hybrid ratio. This could also be because carbon fabric is stiffer than glass fabric. Table 3 also shows that the flexural strength of the composites S_2, S_3, S_4, and S_5 increases by 16.73%, 39.54%, 86.28%, and 98.67%, respectively, in comparison with the flexural strength of the S_1 composite.

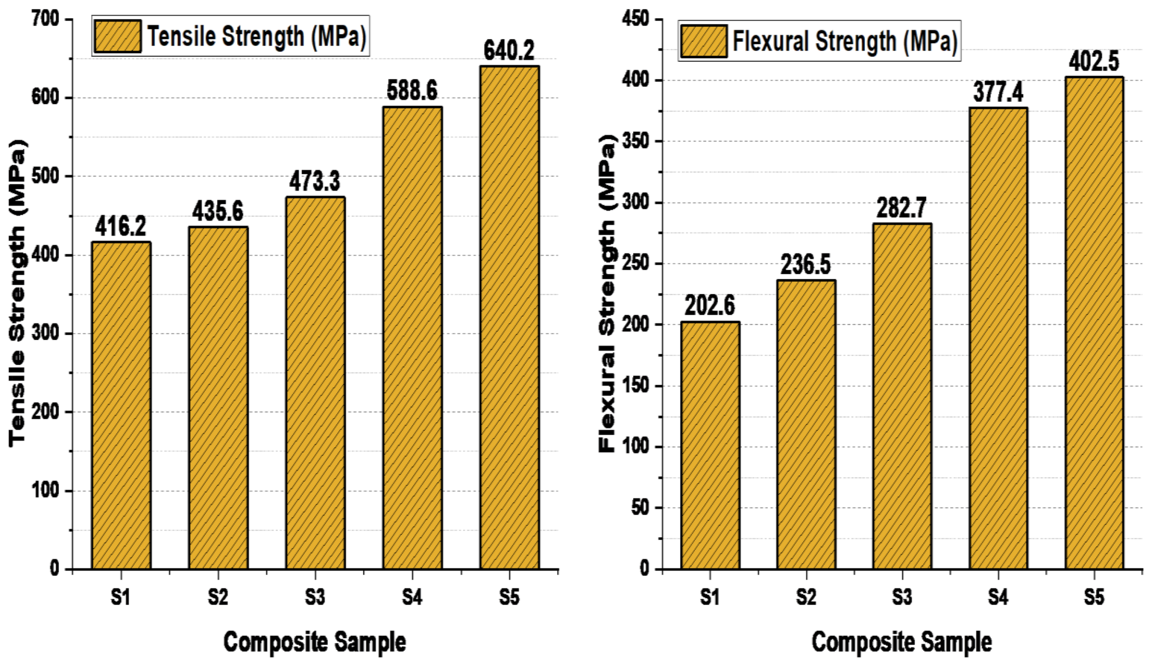

Fig. 7. Tensile and flexural strengths of fabricated composites

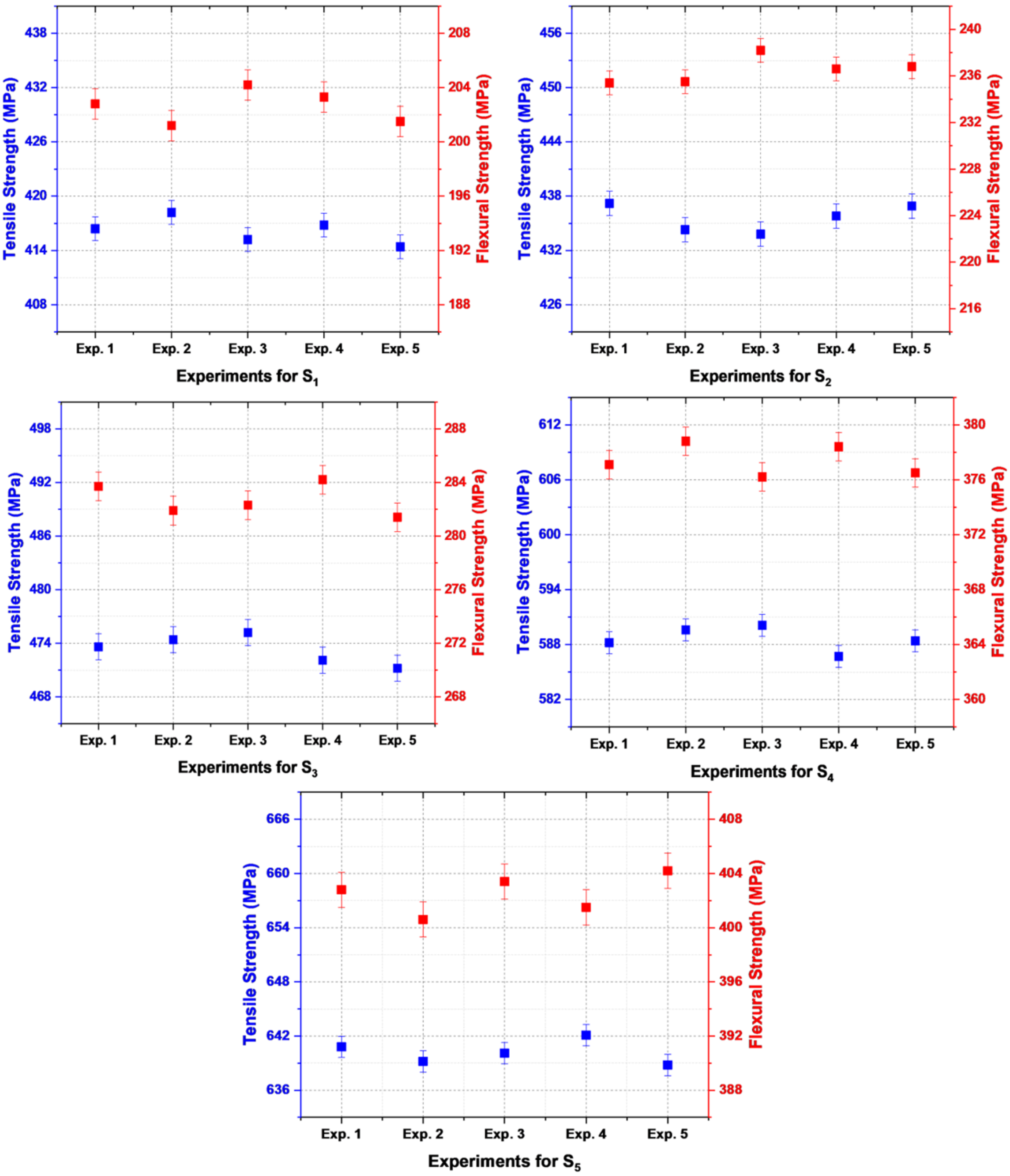

Fig. 8. Error bar chart for the tensile and flexural testing of five composites

Figure 7 indicates that the tensile and flexural strengths of the composite are significantly improved by replacing the glass fabric with the carbon fabric in the composite. The increment in both tensile and flexural strengths of replacing the glass fabric with carbon fabric in the composite can be attributed to several technical factors, such as a higher strength-to-weight ratio, increased stiffness, superior orientation and alignment, improved fatigue resistance, optimized composite structural design, and superior material compatibility. Carbon fibers possess higher tensile strength in comparison to glass fibers. So, when carbon fabrics replace the glass fabrics in the composite materials, the overall strength-to-weight ratio of the composite improves. This increase in strength allows the composite to sustain higher tensile loads. The stiffness and rigidity of the carbon fibers are also better than those of the glass fibers. The stiffness of a material is directly related to its flexural strength, which is its ability to resist deformation under bending. On incorporation of carbon fabrics, which offer higher stiffness, into the composite, the material becomes more resistant to bending forces, resulting in improved flexural strength.

The orientation of the reinforcing fabrics in the composite also plays an important role in determining the mechanical properties of the composite. Carbon fibers can be easily oriented and aligned more specifically within the composite matrix compared to glass fibers. The controlled orientation of the carbon fibers helps in better load distribution and alignment along the fibers, which improves the overall mechanical properties of the composite. Moreover, the carbon fibers exhibit better interfacial bonding with the epoxy matrix, leading to enhanced load transfer between the fibers and the matrix. By strategically replacing glass fabric layers with carbon fabric layers, the composite architecture can be optimized to maximize strength and stiffness while minimizing weight and cost.

To ensure robust and delegated data collection, five samples for each fabricated composite are tested for characterization of both tensile and flexural strengths. The obtained results are plotted in Fig. 8. Following the testing phase, we estimated the average tensile and flexural strengths of each composite by averaging the results obtained from the five samples. This approach allowed us to obtain a single value (mentioned in Tables 2 and 3 and shown in Fig. 7) that accurately represents the mechanical performance of each composite in both testing conditions.

Moreover, to assess the reliability and consistency of the obtained results, as shown in Fig. 8, the standard deviation is computed for all fabricated composites for both tensile and flexural testing. For tensile strength, the standard deviation of the five samples tested for the S_1, S_2, S_3, S_4, and S_5 composites is 1.315, 1.358, 1.467, 1.188, and 1.178, respectively. For flexural strength, the standard deviations of the five samples tested for the S_1, S_2, S_3, S_4, and S_5 composites are 1.119, 1.019, 1.071, 1.029, and 1.296, respectively. These standard deviations serve as a measure of the distribution or variability of data points around the mean value, providing valuable insights into the consistency and repeatability of the experimental measurements.

By thoroughly analyzing both the average values and standard deviations of tensile and flexural strengths across the five composites, one can gain a comprehensive understanding of the mechanical behavior and performance variability within the fabricated composite materials. This thorough approach ensures the reliability and validity of the results.

The increment in the tensile and flexural strength of the S_2, S_3, S_4, and S_5 composites with respect to the S_1 composite is compared in Fig. 9. These results reveal a consistent increasing trend of tensile and flexural strength with each incremental substitution of glass fabric with carbon fabric. This study highlights the better mechanical performance of the composite offered by carbon fibers compared to glass fibers. The difference in mechanical properties across the composite samples can be recognized due to the unique characteristics of glass and carbon fabrics. While glass fibers offer a cost-effective reinforcement, carbon fibers exhibit better strength and stiffness, making them ideal for applications where high mechanical performance is paramount.

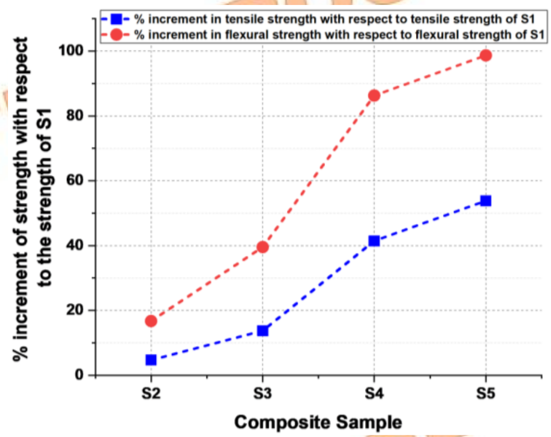

Fig. 9. Increment in the tensile and flexural strengths of S_2, S_3, S_4, and S_5 composites with respect to the S_1 composite

Figure 9 shows that replacing glass fabric layers with carbon fabric layers in a composite material has considerable effects on its tensile and flexural strengths. Initially, replacing one layer of glass fabric with carbon fabric has led to a moderate increase in tensile and flexural strength of 4.66% and 16.73%, respectively. Carbon fibers are known for their higher strength and stiffness compared to glass fibers, so incorporating even a single layer of carbon fabric has enhanced the overall mechanical properties of the composite. By replacing additional layers of glass fabric with carbon fabric, the tensile and flexural strengths of the composite are likely to increase further by 13.72% and 39.54%, respectively. With two layers of carbon fabric, the reinforcement provided by the stiffer and stronger carbon fibers becomes more prominent, resulting in a more extensive improvement in mechanical properties compared to just one layer of replacement. Replacing three layers of glass fabric with carbon fabric has led to a significant increase of 41.42% and 86.28%, respectively, in tensile and flexural strengths. The replacement of all the glass fabric layers with carbon fabric resulted in an increment of 53.82% and 98.67%, respectively, in tensile and flexural strength. With each additional layer of carbon fabric, the composite becomes progressively stiffer and stronger. However, there are diminishing returns beyond a certain point (3 layers), as the benefits of adding more carbon fabric layers are plateauing or becoming less evident.

The obtained tensile strength of the S_5 composite sample is very close to the literature [29] tensile strength of carbon fabric-reinforced epoxy matrix composite. Jafarzadeh and Nematzadeh [16] used carbon fabric-reinforced epoxy matrix composites to improve the flexural strength of glass fabric-reinforced epoxy matrix composites that incorporated reinforced concrete structures. If they replace the glass fabric with carbon fabric, they could improve the flexural strength without increasing the structural weight. Mukhtar and Jawdhari [54] directly used carbon fabric-reinforced epoxy matrix composite to improve the flexural strength of a reinforced concrete beam. If they want to compromise a little bit with flexural strength, then they should prefer the combination of both glass and carbon fabric. However, the findings of the present study help researchers optimize the performance of the structures as per requirements. Zhou et al. [17] and Chauhan and Bhushan [65] used CNF and carbon black particulates, respectively, to improve the tensile and flexural strengths of carbon fabric-reinforced epoxy matrix composites. However, to further improve the tensile and flexural strengths of each fabricated composite, additional reinforcement of CNF, carbon black, or their combinations can be used.

3.2. Failure Characterization

The SEM characterization exposed valuable insights into the fracture mechanisms and failure modes of the composite. The fractured composite sample S_3, which consists of two layers of glass fabric and two layers of carbon fabric embedded in an epoxy matrix, is examined through the SEM. The composite sample is fractured during mechanical testing, providing an opportunity to examine the microstructure of the fractured surface. SEM images are taken at magnifications of 310x, 1.20kx, and 1.60kx to capture extensive images of the fractured surface. These images are shown in Fig. 10, which represent the broken fibers and matrix morphology of the composite. At 310x magnification, an additional image was taken to visualize the top surface of the composite sample. By examining the images obtained at altered magnifications, as shown in Fig. 10, the distribution of broken fibers, matrix cracking, and interfacial bonding within the composite can be identified and analyzed. This detailed microstructural analysis provides significant information for understanding the mechanical behavior and performance of the composite under applied loading conditions, supporting the optimization of composite fabrication processes and the development of advanced composite materials for different engineering applications.

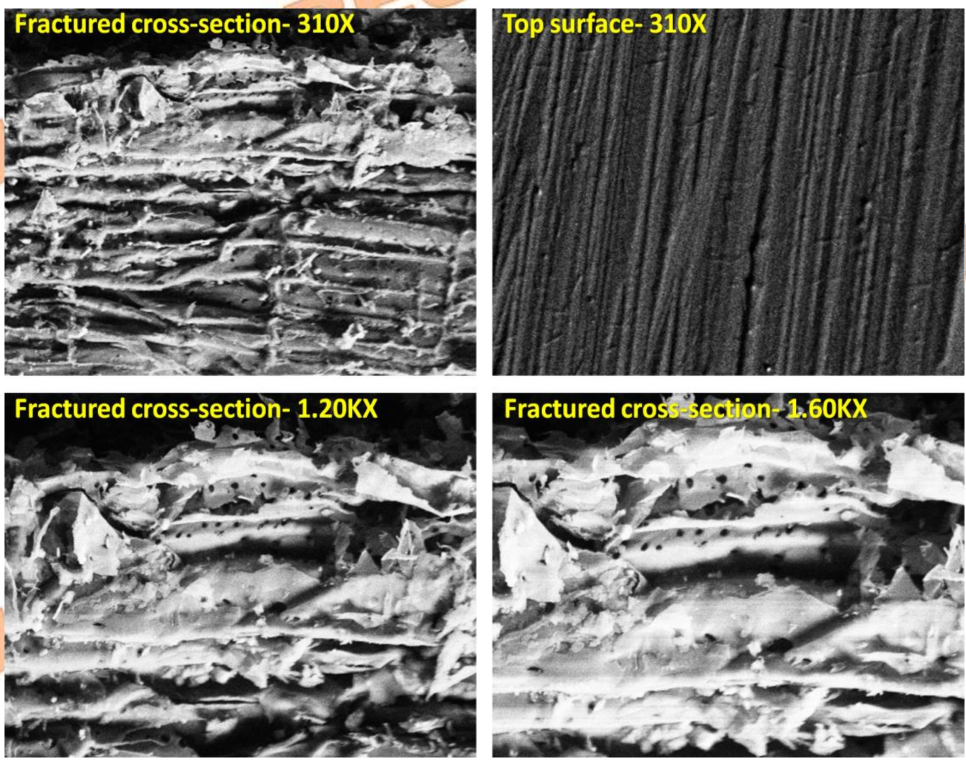

Fig. 10. SEM images of the S_3 hybrid composite with different magnifications

The mechanical performance of glass fabric and carbon fabric-reinforced composites can be greatly affected by variations in the surface finish. The bonding quality, fiber-matrix adhesion, and load transfer efficiency of the composites are influenced by their surface finish and are crucial for their mechanical properties, including strength and stiffness. As opposed to glass fabric, carbon fabric has a smoother surface quality. As a result of their smooth surface, carbon fabric-reinforced composites have superior fiber alignment and enhanced mechanical properties such as tensile strength and flexural strength. Because the glass fabric has a coarser surface, the glass fabric-reinforced composites, on the other hand, mechanically interlock better and naturally bind better with resins. Rougher finishes tend to be more flexible and impact-resistant than carbon fabric-reinforced composites, but they can also introduce more voids and stress concentrators, decreasing their long-term performance.

Overall, the study provides helpful insights into the trade-off between cost considerations and mechanical performance by presenting a comparative analysis of tensile and flexural strengths across fabricated composites of different hybrid ratios. Using this information, engineers and manufacturers may carefully select the ideal hybrid ratio of reinforcement in the composite, making it fit for a variety of applications or specifications. Further, the ability to customize the fiber composition of the composite enables stakeholders to optimize the material for a wide range of applications, balancing the need for mechanical strength with cost-effectiveness. This flexibility in material design allows decision-makers to make well-informed choices that line up with their project objectives and budget constraints.

4. Potential Applications

The possible uses of the fabricated carbon-glass fabric hybrid composites with varying hybrid ratios depend on their cost and mechanical properties. However, based on that, the potential applications of the fabricated composites are as follows:

- The high carbon fabric percentage composites (S_4 and S_5) have high strength and low weight; hence, these composites can be preferred for aerospace structural components, high-performance automotive parts (e.g., body panels and chassis), and premium sporting goods (like bicycles and rackets). However, these composites are costly compared to glass fabric-reinforced composites.
- Balanced carbon-glass fabric percentage composite (S_3) has intermediate strength with a cost reduction compared to high carbon fabric percentage composites (S_4 and S_5) and is lighter than S_2 and S_1 composites. However, it is suitable for general engineering applications such as marine structures and turbine blades.
- The high glass fabric percentage composites (S_1 and S_2) have lower strength and higher weight, but their cost is smaller. However, these can be used for making hulls and decks in boats, bumpers, and infrastructure reinforcement such as concrete beams.

5. Limitations

The fabricated composites with a higher carbon fabric percentage provide higher strength. However, the use of carbon fabric as a replacement for glass fabric in specific applications comes with several limitations. These key limitations are as follows:

- Higher cost: carbon fabric is significantly costlier than glass fabric.
- Reduced flexibility: carbon fabric-reinforced epoxy matrix composites are stiffer and less flexible than glass fabric-reinforced epoxy matrix composites, which leads to a disadvantage in applications where flexibility is required, such as surfboards and safety gear.
- Electrical conductivity: glass fabrics are insulators, but carbon fabrics are electrically conductive. Because of this characteristic, carbon fabric cannot be used in situations where electrical insulation is essential, such as in some electronic housings or as insulating materials in electrical infrastructure and aircraft.

6. Conclusions

The current research work depicts the optimum replacement of glass fabric with carbon fabric in epoxy matrix composites fabricated by the vacuum-pump-assisted hand lay-up method, which provides valuable insights into the hybridization phenomenon and its effects on the mechanical properties of the composite materials. The main findings of this study can be summarized as follows:

- The tensile strength of the hybrid composite exhibits an increase ranging from 4.66% to 53.2% across different hybrid ratios (0.25 to 1).
- The flexural strength of the hybrid composite experiences an increase ranging from 16.73% to 98.67% for 0.25 to 1 hybrid ratios.
- The carbon fabric remains the preferred choice for applications requiring high strength, and the glass fabric presents a viable alternative for situations where a slight reduction in tensile and flexural strengths is acceptable. Notably, the cost-effectiveness of glass fabric, which is approximately 20 times lower than carbon fabric, makes it an

attractive option for applications where cost considerations are paramount.

Further research in this area could focus on refining hybridization strategies, exploring alternative reinforcement materials, and investigating the long-term durability and reliability of hybrid composite structures.

In the present study, only the tensile and flexural strengths of the fabricated composites are analyzed. In the future, their impact strength, shear strength, or fatigue behavior can also be analyzed to identify their more suitable applications.

To combine characteristics like stiffness, strength, and impact resistance, further study into optimizing hybrid composite design may concentrate on adjusting fiber ratios and layup sequences. Additionally, sophisticated surface treatments may be used to improve fiber-matrix bonding. Performance may be increased, and faults can be decreased by creating stronger, more resilient matrix materials and improving production processes.

Furthermore, investigations on fatigue and environmental aging, in conjunction with hybridization with materials such as nanofibers, may improve durability. Important topics for additional research include sustainability initiatives, such as the use of eco-friendly materials and recycling techniques, as well as multi-scale modeling for design optimization.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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