
Research article

Effect of stacking sequence on the mechanical performance of hybrid carbon/glass fiber reinforced polymer composite laminates—A comprehensive experimental study

Ganesh Radhakrishnan¹, Ahmed Ali Salim Al Burtamani¹, Ali Jamil Humaid Al Daraai¹, Abdul Aziz Mohammed Al Ismaili¹, Asim Hamed Saif Al Hadhrami¹ and Kadhavoor R. Karthikeyan^{2,*}

¹ Mechanical & Industrial Section, College of Engineering and Technology, University of Technology and Applied Sciences, 611 Nizwa, Oman

² Department of Applied Mathematics and Science, National University of Science and Technology, Muscat P.O. Box 620, Oman

* **Correspondence:** Email: karthikeyan@nu.edu.om; Tel: +968-95159288.

Abstract: In this study, carbon (C)/glass (G) fiber reinforced polymer laminates were fabricated through the hand lay-up process. Our purpose was to investigate the influence of stacking sequence on their mechanical performance. Different stacking configurations such as G/G/G/G, G/C/C/C/C/G, C/C/G/G/C/C, and G/C/G/C/G with mixed construction of glass and carbon fibers such as randomized and mat type were used to tailor the properties of the laminates for specific mechanical behavior. The results highlighted that the stacking sequence played a crucial role in determining the composite's mechanical behavior, offering valuable insights for optimizing design and performance. The least porosity was observed for G/C/C/C/C/G & G/G/G/G composite laminates, which might be due to the arrangement of similar fiber mats on successive layers that increased the density appreciably and reduced the porosity. With much higher diffusion rates, carbon fibers were observed to possess a larger potential for water uptake than glass fibers. Maximum tensile strength of about 18.6 kN was observed for G/C/C/C/C/G laminate and least tensile strength of 3.9 kN for G/G/G/G laminate. Compared to other composite laminates, the laminate with stacking sequence C/C/G/G/C/C resulted in high load carrying capacity against compression. The randomized glass fiber and woven carbon fiber had an enhanced interlocking behavior, which resulted in improved resistance against transverse loading. Laminates containing carbon fibers in the outer or middle layers performed better under impact loading and inter-laminar shear loading due to their superior load-bearing capacity, crack arresting behavior,

and higher shear resistance of carbon fibers. Even with the delamination damage of the laminates, carbon fibers at the outer layers protected the laminate better than others. It was observed from ANOVA results that the stacking sequence had a strong influence on the mechanical and machining behavior of laminates.

Keywords: hybrid composites; stacking sequence; hand layup; tensile strength; inter-laminar shear; fiber rupture; delamination

1. Introduction

Carbon/glass fiber reinforced polymer (C/GFRP) composites (C: carbon fiber and G: glass fiber) are sophisticated hybrid materials that combine the advantageous qualities of carbon fibers and glass to create constructions with a great mix of durability, cost effectiveness, and mechanical performance. Glass and carbon fibers are stacked or alternately arranged in these composites, which embed in a polymer matrix such as thermoplastics, polyester, or epoxy. C/GFRPs are becoming more and more popular in civil engineering, automotive, marine, and aerospace applications, where cost and performance are crucial because of their customized mechanical behavior. Because of their hybrid nature, engineers might create parts that satisfy precise specifications for strength, weight, and durability without having to pay the higher prices of pure carbon fiber systems. C/GFRPs provide a flexible answer to challenging design problems since they also assist to alleviate problems like brittleness in pure carbon fiber reinforced polymer (CFRPs) and lower strength in pure GFRPs. These composites do, however, have drawbacks, such as intricate failure processes, possible delamination at the fiber interface, and recycling issues. Nagaraja et al. [1] had examined how stacking sequences influence the mechanical properties of carbon-glass/epoxy hybrid composite laminates made via resin infusion. Two laminates were evaluated: laminate 1 (C/G/G/C/G/C) with carbon fabric on the exterior, and laminate 2 (G/C/G/C/G/C/G) with glass fabric on the exterior. Laminate 1 demonstrated superior tensile strength and modulus compared to laminate 2, which contributes to the higher strength and stiffness of carbon fibers on the outer layers. Flexural testing revealed that laminate 1 also has 53% greater flexural strength than laminate 2, due to better resistance to bending loads provided by exterior carbon fibers. Fracture analysis showed that laminate 1 primarily fails by fiber breaking, whereas laminate 2 experiences interface decohesion and delamination, suggesting weaker fiber-matrix adhesion. Rajanna et al. [2] explored the mechanical properties of hybrid composites made from E-glass and carbon fibers in an epoxy matrix, using the resin infusion technique. Two stacking sequences were analyzed: stack-1 (C₁G₂C₁G₂C₁) with carbon fibers at the outer layers and alternating glass layers, and stack-2 (G₃C₄G₇C₆G₅C₁G₁) with alternating glass and carbon layers throughout. In terms of tensile strength, stack-1 performed better due to stronger interlayer bonding. For flexural strength, stack-2 showed superior results, as the carbon fibers near the surface more effectively resist bending stresses. When it came to compressive strength, stack-1 again excels, benefiting from the stability provided by glass fibers positioned at the core. In the study by Abdalla et al. [3], the effect of glass fiber stacking sequences on the notch sensitivity and tensile strength of glass fiber-reinforced epoxy composites was investigated. Three stacking sequences were tested: [(0°/90°)], [(0°/90°), (45°/-45°)], [(0°/90°)], and [(45°/-45°)]. The results showed that [(0°/90°)] has the highest un-notched tensile strength, while [(45°/-45°)] has the lowest. Notch sensitivity is highest for [(45°/-45°)] and

lowest for $[(0^\circ/90^\circ), (45^\circ/-45^\circ), (0^\circ/90^\circ)]$. Failure modes include fiber breakage, delamination, and matrix cracking, with $[(45^\circ/-45^\circ)]$ showing severe delamination. Kumar et al. [4] explored the mechanical properties of hybrid polymer composites made from carbon and glass fibers arranged in different stacking sequences (GC, GCG, CGC). Using a cost-effective hand layup technique, laminates were fabricated and tested for tensile and flexural strength. The results showed that the CGC configuration (carbon-glass-carbon) achieves the maximum tensile strength and flexural strength. Analytical models in ANSYS aligned well with experimental data, showing acceptable errors. The research highlights the importance of stacking sequence in optimizing composite performance for structural applications like automotive and aerospace components. Dong et al. [5] investigated the flexural properties of carbon/glass fiber-reinforced hybrid composites, focusing on how stacking sequences affect performance. Experiments and simulations showed that placing glass/epoxy layers on the compressive face enhances flexural strength (positive hybrid effect), while placing them on the tensile face reduces it (negative hybrid effect). Sandwich structures with carbon/epoxy skins and glass/epoxy cores-maintain strength while reducing costs. Hafiz and their team [6] studied the impact response of hybrid carbon-glass/epoxy composites with different stacking sequences under low-velocity impact. Hybrid laminates showed smaller load drops, higher maximum load, and less deflection compared to single-fiber laminates. Carbon-outside hybrids (C/G/C/G) exhibited the best performance, with higher energy absorption and reduced damage. The results highlight the importance of stacking sequence in optimizing impact resistance. In a study by Jesthi et al. [7], the mechanical properties of hybrid polymer matrix composites with symmetric inter-ply sequences of carbon/glass fibers, specifically [G2C2G], and [CG3C], were investigated. The tensile strength and flexural strength of [G2C2G] improved by 6% and 23%, respectively, compared to the pure glass fiber reinforced polymer composite. Dubey et al. [8] investigated the drilling performance of hybrid laminated composites made from carbon and glass fibers with different stacking sequences and found that the stacking sequence strongly influences the machinability of the composite laminates.

The literature review demonstrates that research from different parts of the world has contributed many scientific outcomes in the field of fiber reinforced polymer (FRP) composites fabricated with different stacking sequences. The inconsistencies of the results create an avenue for further research. The highlight of this study is that we attempt to fabricate the hybrid polymer composite reinforced with carbon fibers and glass fibers and characterize the same for their mechanical and machining performance. Efforts are also made to optimize the stacking sequence of composite laminate for better machinability feature using Analysis of Variance (ANOVA). The details of the experiment and results are discussed in detail in the following sections.

2. Materials and methods

In this study, C/GFRP composite laminates were fabricated for different stacking sequences, where the matrix consisted of an epoxy resin (poly epoxides) and a thermosetting polymer, mixed with a hardener in a 1:1 ratio, and the reinforcement materials used were glass mats with random orientation fibers and carbon fiber woven type mats, with average thicknesses of 0.75 and 0.25 mm, respectively. The properties of the matrix and reinforcement materials are presented in Table 1. The fabrication process employed was the hand lay-up method, chosen for its simplicity and reliability at room temperature and normal atmospheric conditions. The composition in each stacking sequence is shown in the Table 2, which included (i) G/G/G/G: all four layers with glass fiber mats; (ii) G/C/C/C/G:

six layers with two glass fiber mats at the outer layer and four layers of carbon fiber mats at the center; (iii) C/C/G/G/C/C: 6 layers with two successive carbon layers at each outer surface with two layers of glass fiber mats at the core; and (iv) G/C/G/C/G: five layers with glass and carbon fiber mats at alternate layers. Layers of carbon fiber mats and glass fiber mats were stacked as per the design shown in Figure 1, while epoxy resin was uniformly applied to each layer using a roller, continuing until the laminate reached a desirable thickness. Once stacking was completed, a large dead weight of approximately 0.5 kN was placed on the top of the stacking, and the structure cured for 24 h. A sheet of polyethylene film was used each at the top and bottom side of the stacking to ensure that the laminate could be removed easily after curing. After curing, the specimens were cut and prepared for tests as per ASTM (American Society for Testing and Materials) standards for the physical and mechanical behavior. The edges of the specimens were finished using flat file and emery sheets before testing. Our primary objective was to analyze the influence of stacking sequence of the fiber layers on the mechanical properties and machining behavior of the resulting composite laminates. The fabricated C/GFRP composite laminates underwent a series of mechanical characterizations, including measurements of mass density, porosity, water absorption, tensile strength, compressive strength, flexural strength, impact strength, inter-laminar shear strength, and delamination. Specimens for each mechanical test were prepared in accordance with the relevant ASTM standards: density and porosity (ASTM D792), water absorption (ASTM D570), tensile strength (ASTM D3039), compression strength (ASTM D3410), flexural strength (ASTM D790), impact strength (ASTM D256), and inter-laminar shear strength (ASTM D2344). The details of the tests and procedures are explained in the following sections.

Table 1. Properties of the matrix and reinforcement.

No.	Property	Epoxy	Carbon fiber	Glass fiber	Steel
1	Density (kg/m ³)	1200–1250	1800	2580	8000
2	Tensile strength (MPa)	11.14	5880	3445	400–550
3	Elastic modulus (GPa)	3.1	228	76	207
4	Flexural strength (MPa)	25.29	-	-	370–520
5	Thermal conductivity (W/mK)	0.2	70	1.35	25
6	Hardness (Moh scale)	-	-	6.5	4

Table 2. Compositions of fabricated laminates.

No.	Epoxy (wt.%)	Glass fiber (wt.%)	Carbon fiber (wt.%)	Stacking sequence
1	50	50	0	G/G/G/G
2	50	25	25	G/C/C/C/C/G
3	50	25	25	C/C/G/G/C/C
4	50	37.5	12.5	G/C/G/C/G

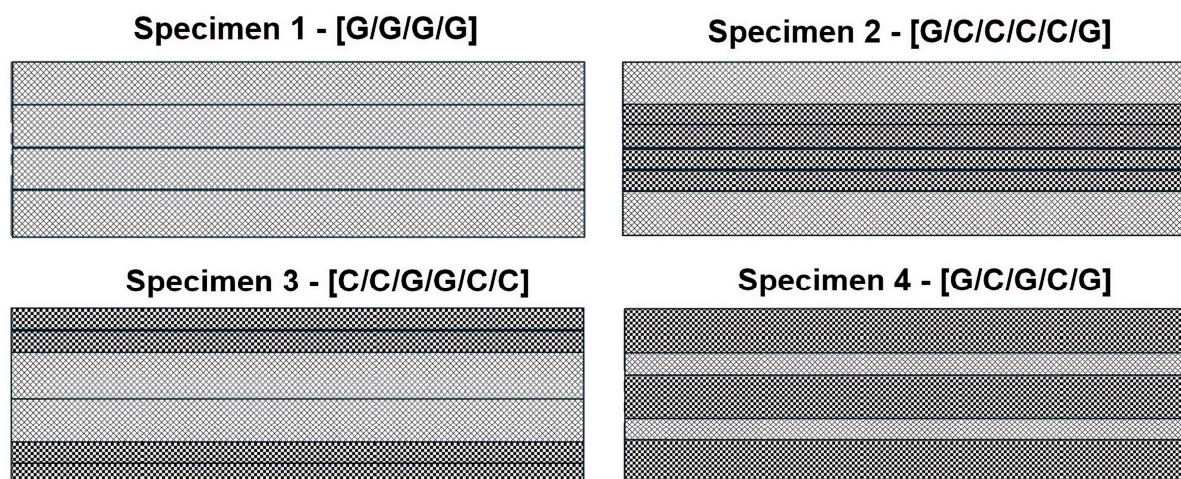


Figure 1. Stacking sequence of composite laminate specimens.

Porosity refers to the proportion of void space relative to the total volume of a material and typically arises during the manufacturing process through various mechanisms. In composite laminates, porosity negatively impacts strength and stiffness. For the fabricated C/GFRP laminates, porosity was evaluated by comparing theoretical and experimental density values. The water absorption test was conducted to determine the amount of water absorbed by a material under specified conditions. For this test, the specimens were first weighed in their dry state, then immersed in distilled water and 0.9% NaCl solution separately at room temperature for 24 h. Water and NaCl were used to analyze the water absorption and osmotic potential capacity of the fabricated laminates. After immersion, the specimens were removed, gently dried with a lint-free cloth, and reweighed. To ensure the reliability of the results, each test was performed three times using identical specimens of the same composition, and the average value was recorded. This analysis aimed to assess the moisture absorption capacity of the C/GFRP laminates and the role of stacking sequence.

The experimental setup for the tests are shown in Figure 2. The laminates were tested at room temperature for tensile strength using a 50 kN-capacity Universal testing machine (Make: EZ 50, Supplied by Lloyd Instruments, Germany). It had a dual-column rigid frame with adjustable crossheads and movable grips (manual/pneumatic) to fit specimens. The tensile test was done with a gripping length of 25 mm on both the sides and a strain rate of 5 mm/min, and the data was recorded using the Data Acquisition (DAC) system attached to the machine. The tensile strength of the laminates was determined from the stress strain behavior. The stiffness and the elastic modulus of the laminates were also determined from the tensile behavior. The compression test was performed on the laminates to evaluate how composite materials like C/GFRP behave under compressive loads, which is important for understanding their resistance to crushing or buckling. The compression test was carried out in the same machine used for the tensile test. The specimen dimensions were: thickness 3 mm, width 25 mm, and length 140 mm. The compression test was done with a gripping length of 50 mm on both sides and a strain rate of 5 mm/min. The compression strength was computed for all the stacking sequences from the stress-strain behavior of the laminates. The flexural of the C/GFRP laminates was determined using a Universal Testing Machine (UTM) of 20 kN capacity (Model: WP 300, supplied by Gunt Hamburg, Germany) at room temperature. The laminate was supported with a span length of 100 mm and subjected to a three-point bending test. The loading rate was controlled at 1 kN/s. The applied load and the corresponding deflection was recorded using a DAC system attached to the machine. The impact

strength of a fiber-reinforced composite laminate (as determined by ASTM D256 standards) referred to its ability to absorb and resist a sudden, forceful impact or blow without experiencing catastrophic failure. The impact strength was measured using a Pendulum Impact Tester (Model: WP 410–, 300 Nm, supplied by Gunt Hamburg, Germany). Inter-laminar Shear Strength (ILSS) is one of the critical mechanical properties that measures the strength of adhesion or bonding between the individual layers (plies) in a composite laminate structure. It determines the ability of a material to resist shear stresses that might lead to inter-laminar failure modes, such as delamination or separation between the plies, which could significantly reduce the laminate's structural integrity and load-bearing capability. The most widely adopted experimental method for evaluating ILSS is the Short Beam Shear (SBS) test, conducted according to ASTM D2344 standards, which employs a three-point bending configuration to generate shear stress within the specimen. In this study, the ILSS test was performed in a manner similar to that of the flexural strength test, but with a reduced support span of 40 mm, ensuring that shear failure predominates over flexural failure during testing. The ILSS test was carried out using a 20-ton capacity Universal Testing Machine (Model: WP 300, supplied by Gunt Hamburg, Germany). The delamination test was carried out to evaluate the drilling-induced damage in the composite laminate. This test can be considered a measure of machinability of the composite laminate. Our main objective for this test was to study the influence of stacking sequence of fiber plies in the laminate on the extent of damage in the hole geometry. The drilling on the composite laminates was carried out in a drilling machine (A 3-1, Pillar drilling machine, supplied by Ajax M/c tools, UK). A high speed steel (HSS) drill bit of 5 mm diameter was used for the drilling, and the drilling operation on the laminate was carried out at room temperature and in dry conditions. The process parameters and their levels considered during drilling are presented in Table 3. The holes were drilled on the laminate for full factorial design i.e., all the possible combinations of stacking sequence, feed, and spindle speed. Nine holes for the combination of speeds and feeds were drilled in each laminate. The dimensionless metric called the delamination factor (DF) is the performance measure of this delamination test, which is the ratio between the maximum diameter of the deformed hole to its nominal diameter. The nominal diameter of the hole was 5 mm, and the maximum diameter that enclosed the delamination zone coincided with the center of the hole diameter. The maximum diameter was measured as the average of the measurement of three orientations across the delamination zone to avoid error and ensure accuracy of the results. The experimental set up for the delamination test and delamination zone was shown in Figure 3. The DF values were analyzed with ANOVA to determine the level of significance of the process parameters. The optimized combinations of the process parameters were determined by the Response Optimizer tool using Minitab V. 22 software. The main effect plot, interaction plot, probability plots, and surface plots were obtained to justify the results of ANOVA.



Figure 2. Experimental set up for the (a) tensile test, (b) compression test, and (c) flexural test.

Table 3. Process parameters and their levels during drilling.

Process parameter	Levels
Spindle speed (rpm)	77, 123, 200
Feed (inch/rev)	0.004, 0.007, 0.009
Stacking sequence	G/G/G/G, G/C/C/C/C/G, C/C/G/G/C/C, G/C/G/C/G

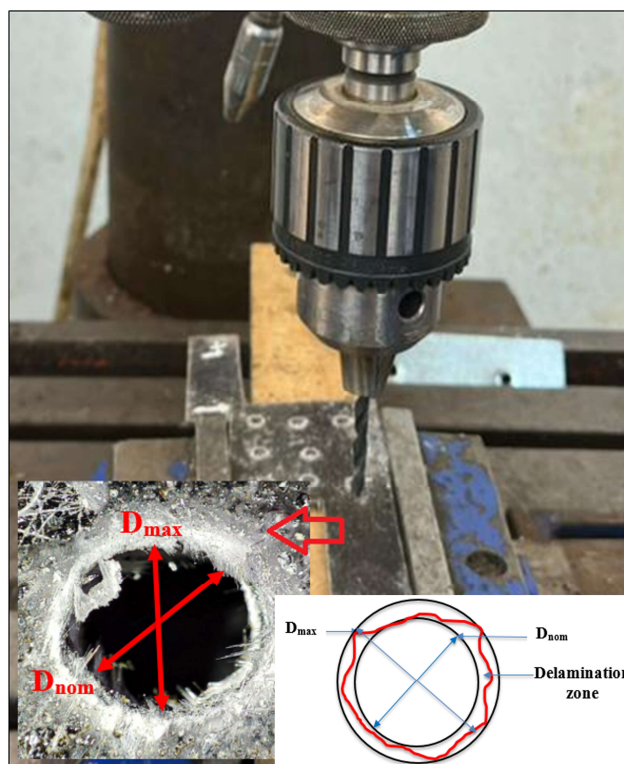


Figure 3. Experimental set up for the delamination test with delamination zone.

3. Results

The mechanical and machining characteristics of the composite laminates and the role of stacking sequence, including its optimized conditions, are discussed in this section. Despite uniform spreading of epoxy throughout the fiber mats, porosity existed due to the fabrication method used in this work. The mass density of the laminates computed experimentally and theoretically and the corresponding porosity are shown in Figure 4a. The stacking sequence of carbon and glass fiber mats influenced the density significantly. The least porosity was observed for specimens 2 and 1. This may be due to the arrangement of the same fiber mats on successive layers, increasing the density appreciably and reducing the porosity. Alternate arrangements of glass and carbon fiber mats resulted in increased porosity through restricted flow of epoxy and ineffective bonding between the layers [9]. The stacking sequence played a large role in weight gain in composite samples, according to water absorption data, as shown in Figure 4b. Composites with glass fibers positioned in or close to the core layers experienced negligible weight gain. Carbon fiber composites, however, showed higher water absorption when positioned near the surface. This suggested that fiber type and position are significant in water absorption. With much higher diffusion rates, carbon fibers possess a larger potential for water uptake than that of glass fibers [10]. This would imply that carbon laminates are more prone to degradation over time in water; this is a critical parameter to keep in mind while designing composites for humid or marine environments.

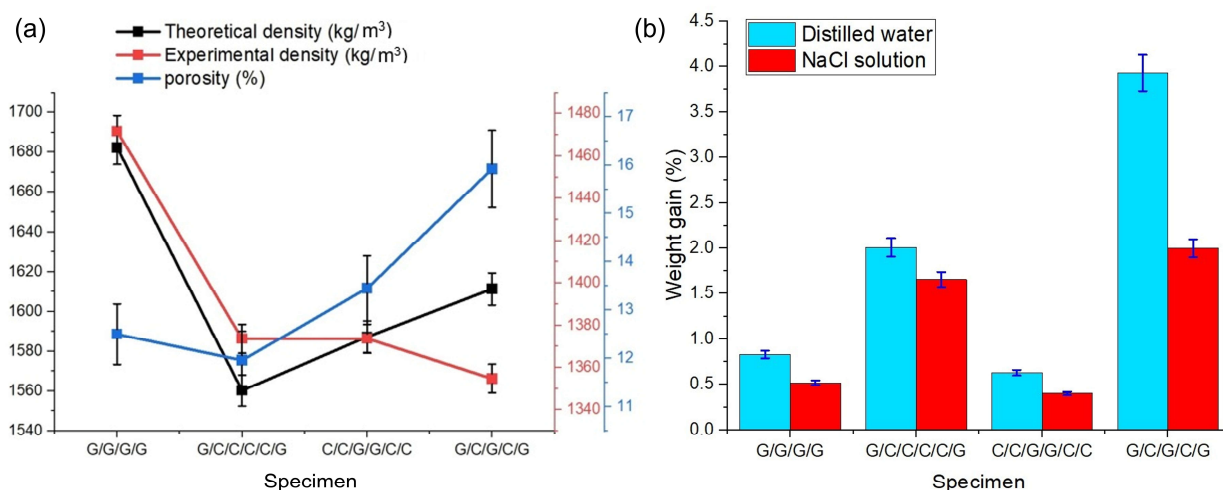


Figure 4. (a) Density and porosity and (b) weight gain of laminates.

The stress-strain behavior of the composite laminates under tension is shown in Figure 5a. It is observed from the figure that the stacking sequence of glass fiber and carbon fiber across the thickness of the laminate significantly influenced the tensile behavior. Moreover, hybrid composite laminates performed better and resulted in high tensile strength compared to that of single glass fiber reinforced polymer composite laminates. Maximum tensile strength of 18.6 kN is observed for the G/C/C/C/C/G laminate in Figure 5b, and the least tensile strength of 3.9 kN is shown for the G/G/G/G laminate. A distinct feature under tension is seen from the results for the hybrid composite laminate. It can be also stated that similar fiber mats in the adjacent layers resulted in higher tensile characteristic than that of dissimilar fiber mats in the adjacent layers. The main contribution to the tensile strength of the composite laminate was by carbon fiber than that of glass fiber. Despite the high tensile strength for the G/C/C/C/C/G laminate, the elongation was restricted to 1.05%, which might be due to the enhanced brittleness by the addition of carbon fibers at a larger quantity than that of glass fibers [11–13]. Moreover, the presence of glass fibers in the core region of laminates resulted in more plasticity with elongation corresponding to 1.7% to 2.4% than that of its presence at the edges. An apparent transition from a ductile to brittle characteristic was seen among the hybrid composite laminates with the changes in the stacking sequence of fiber mats. The corresponding modulus of elasticity of the laminates is shown in Figure 5c, complementing the results in Figure 5b,c. The maximum Young's modulus was obtained for the laminate G/C/C/C/C/G, which was around 8 GPa. The failure modes observed on the laminates after the tension test revealed that, with single reinforcement, the laminates were failed by delamination, whereas the failure was a combination of shear, delamination and fiber fracture in hybrid composite laminates. The brittle characteristic of the G/C/C/C/C/G laminate was the reason for its failure under a fiber rupture.

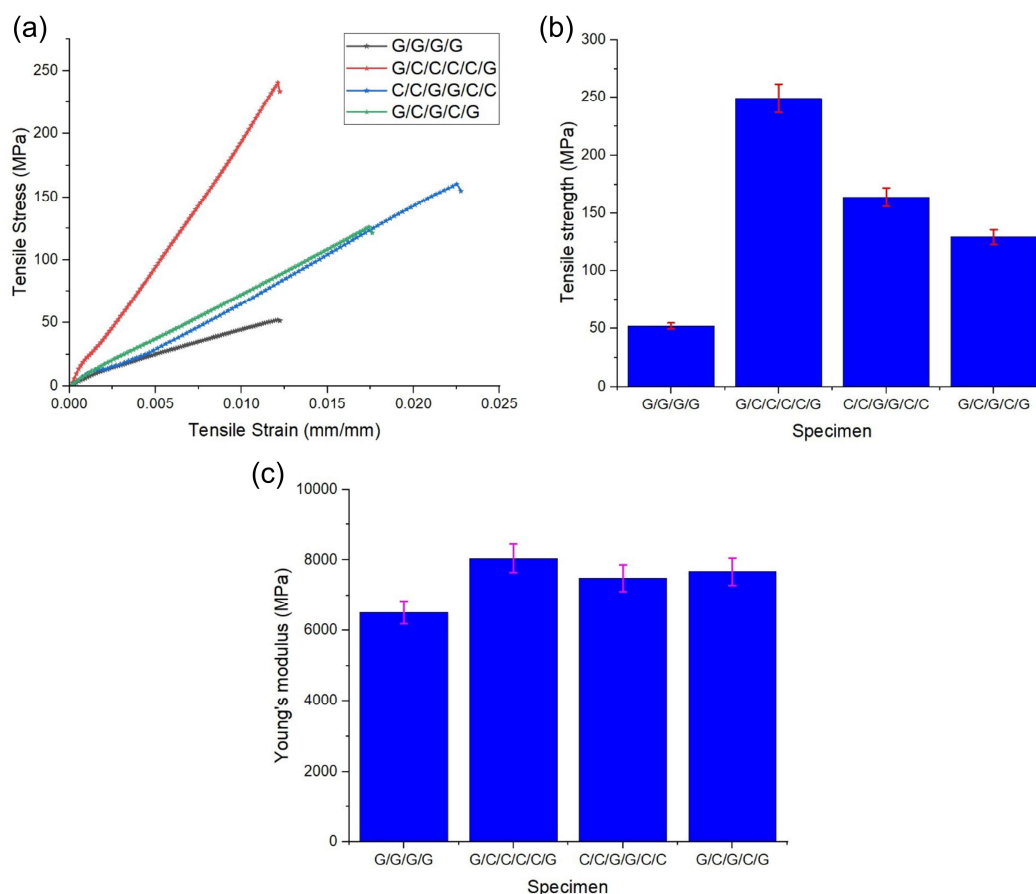


Figure 5. (a) Tensile behavior, (b) tensile strength, and (c) Young's modulus of laminates.

The compression test results of the composite laminates are presented in Figure 6. The maximum compressive load for the C/C/G/G/C/C laminate was 5.85 kN. On the other side, the least compressive load at 1.43 kN was obtained for the G/G/G/G composite laminate. A higher compressive strength of 68.39 MPa was observed for the G/C/C/C/C/G composite laminate, complementing the result of the tensile strength for the same stacking sequence. The carbon fiber mat in the core region of the composite laminate had the capacity of withstanding a greater crushing load than that of glass fibers. The maximum elongation of 7.5% was found for the G/C/C/C/C/G composite laminate despite its strength, which might be due to the enhanced interlocking and cohesion between the carbon layers at the core across the cross section of the laminate. The composite laminate with a stacking sequence of alternate carbon and glass fiber layers under great crushing load exhibited very poor resistance and failed due to crushing of the fibers. Compared to other composite laminates, the laminate with a stacking sequence C/C/G/G/C/C resulted in a high load carrying capacity against compression with no significant failure, which could have attributed to the fact that the randomized glass fibers in the core of the laminate construction resulted in higher resistance against crushing. The composite laminates with stacking sequences G/C/C/C/C/G and G/C/G/C/G failed by crushing completely under compression compared to that of other laminates. This might be due to the poor resistance of woven carbon fiber mats compared to that of randomized glass fibers against a crushing load. The predominant failure mode was inter-laminar shear that occurred between the fibers within the composite laminate [14]. The carbon fibers in the laminate were subjected to buckling under compression, resulting in abrupt failure of the laminate. On the other side, the glass fibers, due to

random orientation, supported the laminate to some extent against the compression load in other stacking sequences.

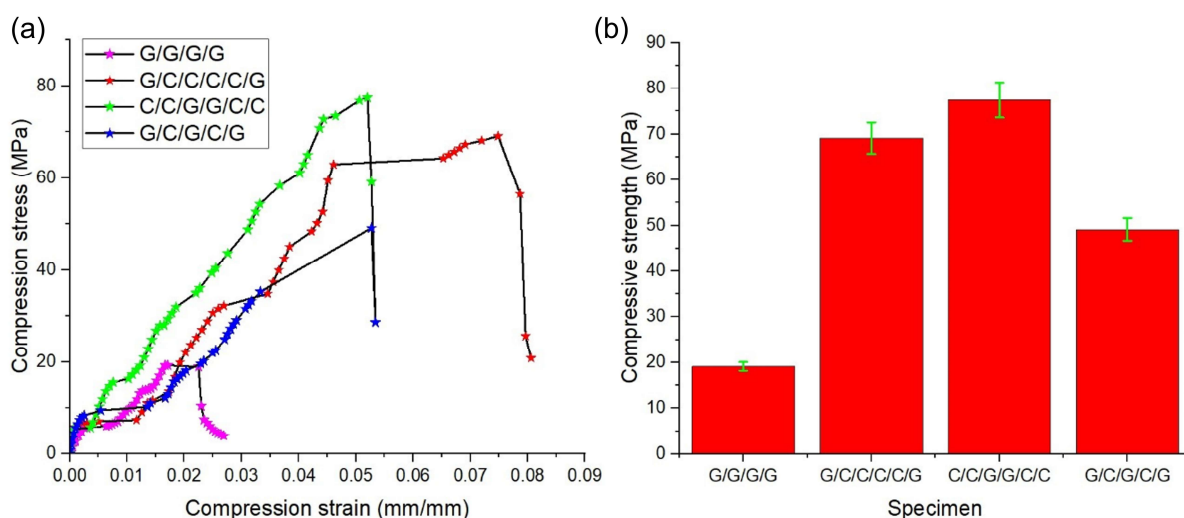


Figure 6. (a) Compressive behavior and (b) compressive strength of laminates.

The flexural performance of the composite laminates constructed with various stacking sequences is shown in Figure 7. The load-deflection curves revealed that there was a significant influence of the stacking sequence of the fiber layers on the flexural load capacity of the composite laminate. Using hybrid fibers such as glass and carbon in the composite had a drastic improvement in the flexural strength compared to that of pure glass fiber reinforced composite laminate. The flexural strength of the G/G/G/G composite laminate was around 160 MPa, whereas the flexural strength of the G/C/C/C/C/G composite laminate was 360 MPa, which was about a 125% increase. The randomized glass fiber and woven carbon fiber had an enhanced interlocking behavior, which resulted in improved resistance against transverse loading. Similarly, adjacent glass fibers or carbon fibers in the laminate construction had better flexural strength than the alternate fiber layers throughout the cross section of the laminate. The poor performance of the G/C/G/C/G composite laminate under flexural load was due to the poor cohesion between the layers, which reduced the resistance against flexural load abruptly and ended with a flexural strength of 60 MPa, which was almost six times lower than that of the G/C/C/C/C/G composite laminate.

The impact performance of the hybrid composite laminates with various stacking sequences is shown in Figure 8. The results indicated that the stacking arrangement of the fiber layers significantly affected the impact resistance of the composite specimens. The crack initiation and propagation across the width of the composite specimen varied with respect to the stacking sequence of hybrid glass and carbon fibers in it. Among all configurations, the C/C/G/G/C/C laminate exhibited the highest impact strength of 0.40 J/mm², corresponding to an absorbed impact energy of 12 J. This improvement was mainly attributed to the higher stiffness and energy absorption capacity of carbon fibers, which could effectively resist crack propagation during impact loading. In contrast, the G/G/G/G laminate showed the lowest impact strength of 0.23 J/mm², which was almost 74% lesser than that of laminate with sequence C/C/G/G/C/C, demonstrating the relatively weak impact resistance of glass fiber composites compared to hybrid ones. The G/C/C/C/C/G laminate achieved an intermediate performance with an impact strength of 0.30 J/mm², while the G/C/G/C/G laminate recorded 0.27 J/mm². The presence of

glass fibers at the outer surfaces led to premature failure due to their brittle nature, resulting in lower energy absorption. Overall, the results revealed that laminates containing carbon fibers in the outer or middle layers performed better under impact load due to their superior load-bearing capacity and crack arresting behavior. On the other hand, laminates with glass fibers on the outer layers exhibited reduced impact performance because of lower inter-laminar toughness and weaker fiber-matrix adhesion. The randomized fibers in glass fiber mat and woven carbon fiber mat led to the variation in resistance across the impact load [15,16].

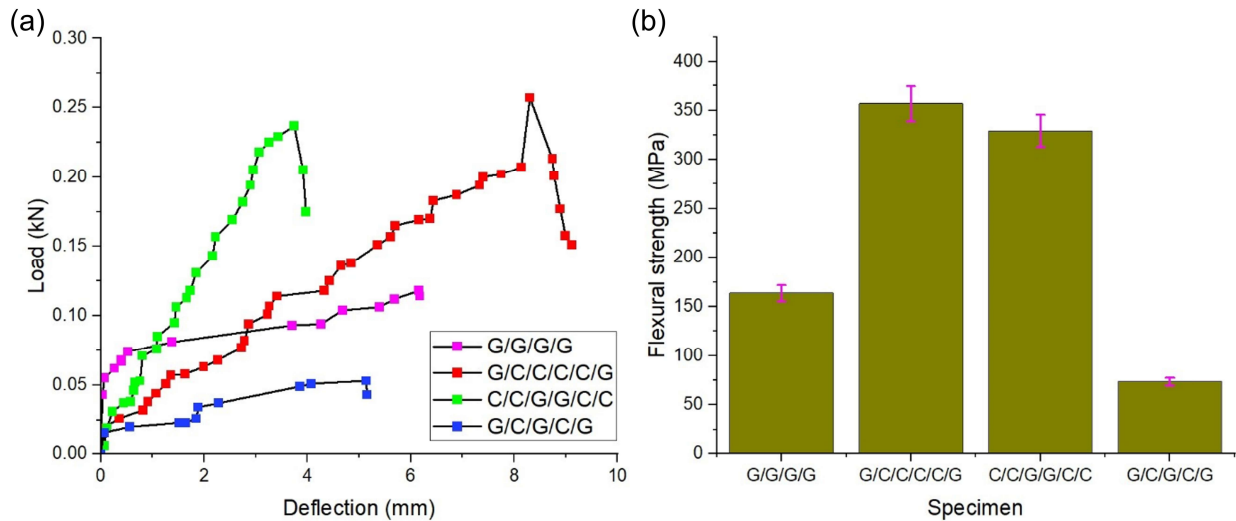


Figure 7. (a) Flexural behavior and (b) flexural strength of laminates.

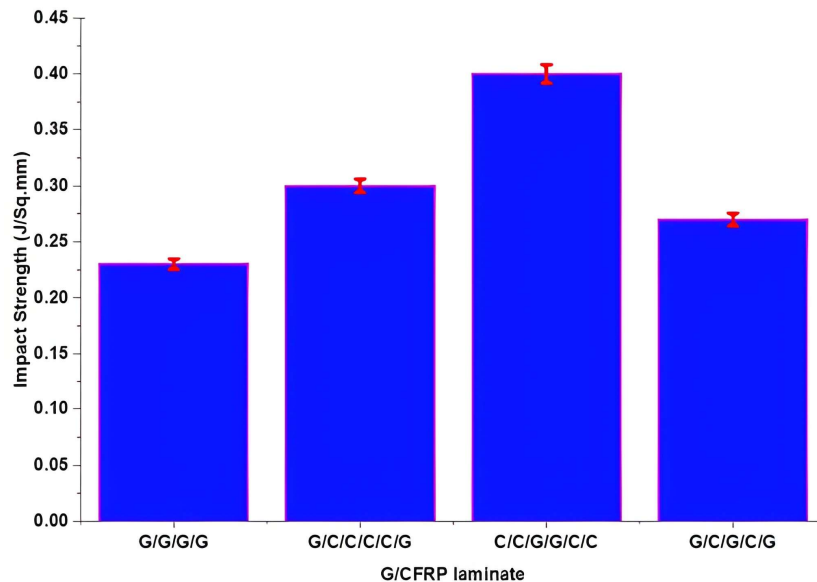


Figure 8. Impact behavior of laminates.

The inter-laminar shear strength (ILSS) of the composite laminates was significantly influenced by the stacking sequence of the fibers, as shown in Figure 9. The results indicated a difference in shear resistance among the configurations of the laminate. The G/G/G/G laminate exhibited the lowest shear strength, with an ILSS of 3.91 MPa and a maximum shear load of 125 N. This laminate, consisting of

pure glass fibers, demonstrated poor resistance to shear, confirming that glass fibers alone provided limited inter-laminar bonding. On the other hand, the C/C/G/G/C/C laminate showed the highest shear strength, with an ILSS of 16.13 MPa and a maximum shear load of 516 N, representing a significant improvement. The high shear strength of this laminate could be due to carbon fibers being placed at the outer layers, which were stronger and stiffer than glass fibers, enhancing the laminate's shear resistance. The G/C/G/C/G laminate and G/C/G/G/C/G laminate exhibited moderate shear strengths of 6.41 and 6.34 MPa, respectively, outperforming the glass-only laminate but not reaching the strength of the carbon-dominant laminate [16]. The results highlighted that laminates with carbon fibers on the outer layers, such as the C/C/G/G/C/C laminate, offered superior shear strength due to the stiffness and shear resistance provided by the carbon fibers [17–20]. The significant difference in shear strength for the laminates emphasized the importance of fiber placement, i.e., the glass fibers and carbon fibers, its orientation, and its woven structure in the mat in optimizing the inter-laminar shear performance of composite laminates.

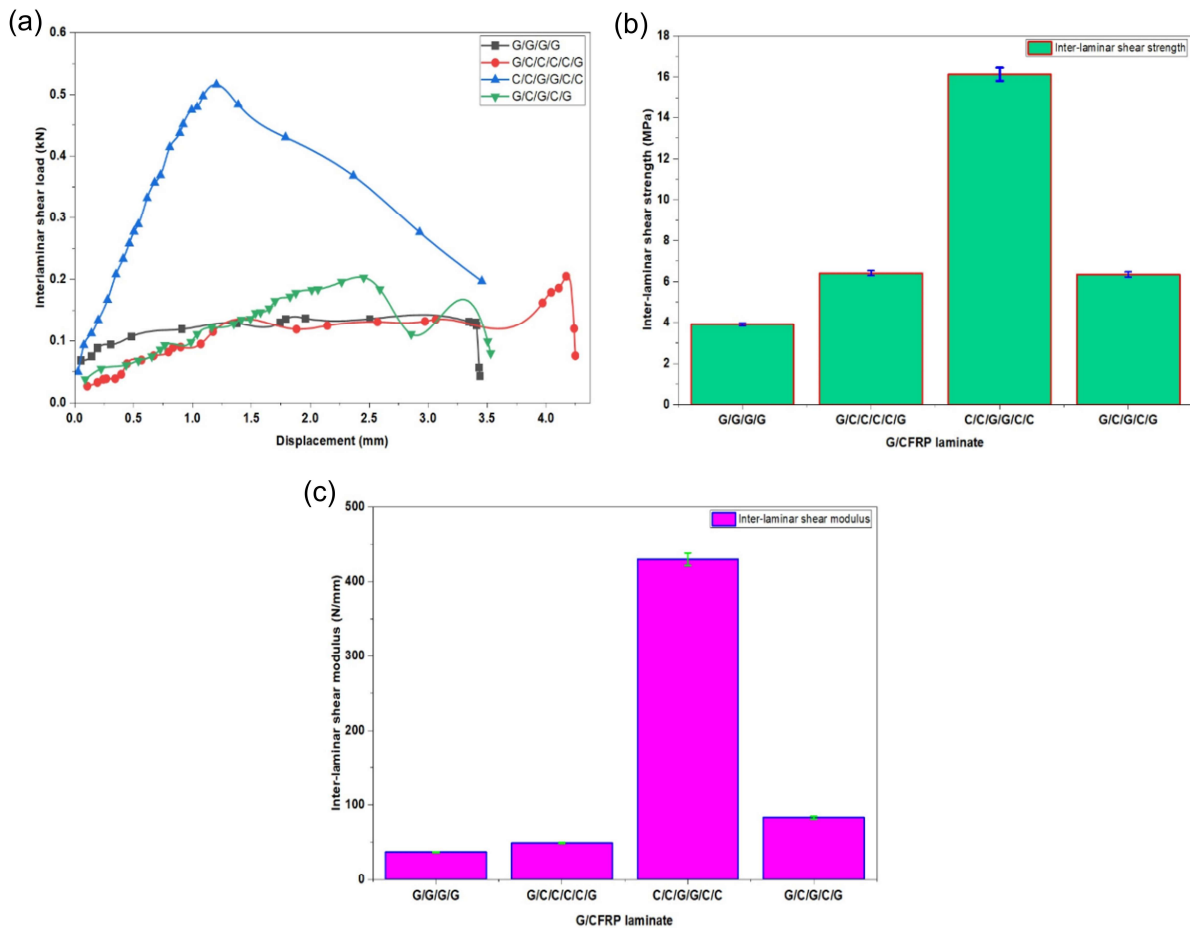


Figure 9. (a) Inter-laminar shear behavior, (b) inter-laminar shear strength, and (c) inter-laminar shear modulus of laminates.

The estimated DF at each drilled hole for the four composite laminates with different stacking sequences are shown in Figure 10. The maximum DF resulted in a spindle speed of 77 rpm and feed of 0.004 inch/rev, and the minimum DF was observed for the holes drilled at a maximum feed of 0.009 inch/rev and spindle speed of either 123 or 200 rpm. The observations of DF for all the

laminates revealed that at lower spindle speed, the cutting of fibers across the cross section was not clean, and there was possible heat generation at the localized spot, i.e., near the circumference of the hole, due to longer contact time between the tool and the laminate. On the contrary, with lower feed, even though the punching force on the laminate from the drill tool was lower, the stacking sequence of hybrid glass and carbon fibers resulted in unequal resistance during machining, which increased the delamination damage on the laminate. The heterogeneous structure of the laminate and variation in the machinability characteristic of glass and carbon fibers together resulted in higher delamination.

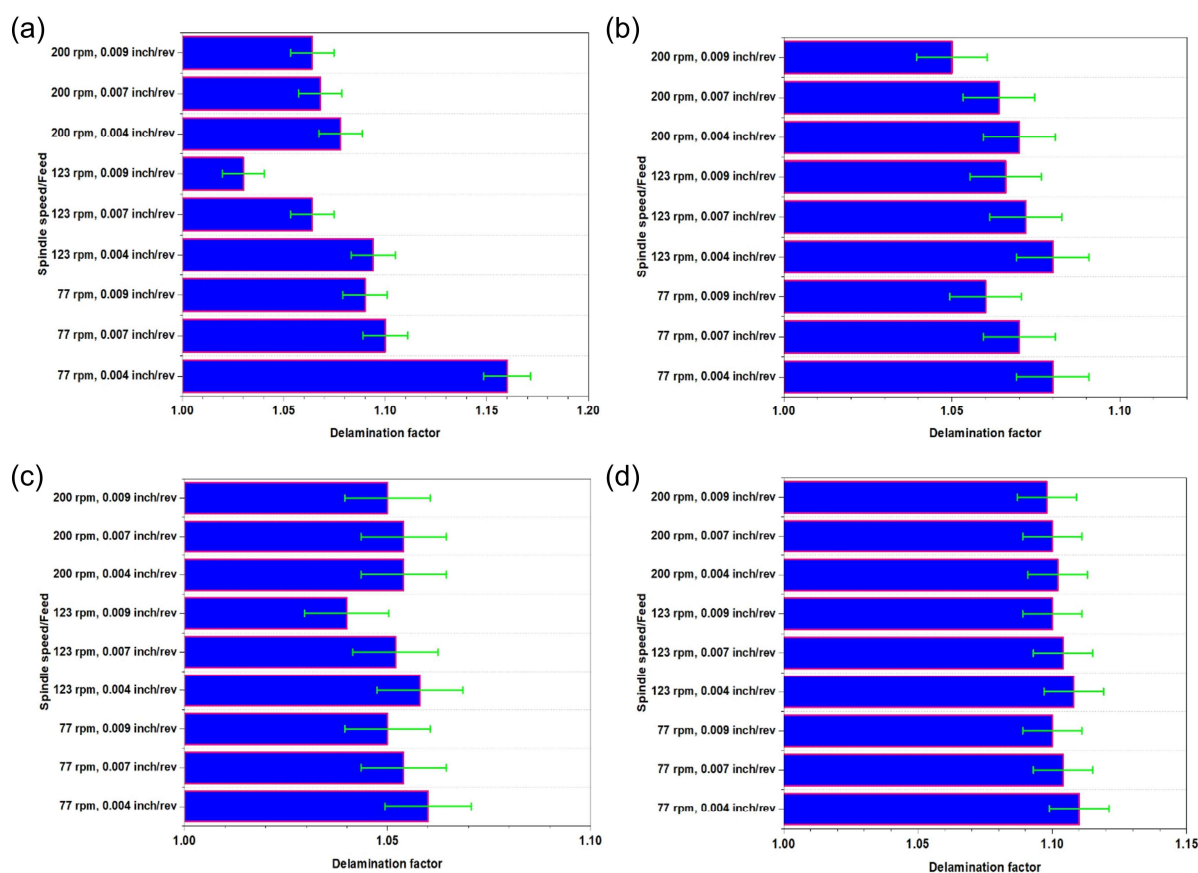


Figure 10. Delamination factor at various speeds and feeds for (a) G/G/G/G, (b) G/C/C/C/C/G, (c) C/C/G/G/C/C, and (d) G/C/G/C/G laminates.

Overall, compared to glass fibers, the higher cooling capacity of carbon fibers resulted in a lower rate of heat generation and lower DF. The carbon fibers at the outer layer protected the laminate with lesser DF than that of glass fibers. The extent of delamination damage on the composite laminates were also observed from the optical micrographs for more visual clarity in the effect. The optical micrographs of the drilled hole at maximum and minimum delamination effect for various stacking sequences are shown in Figure 11. A higher order pull-out of the fibers was observed from the optical micrographs at maximum DF. The laminates with higher glass fiber content were subjected to higher order shear and pull out compared to that of laminates with higher content of carbon fibers.

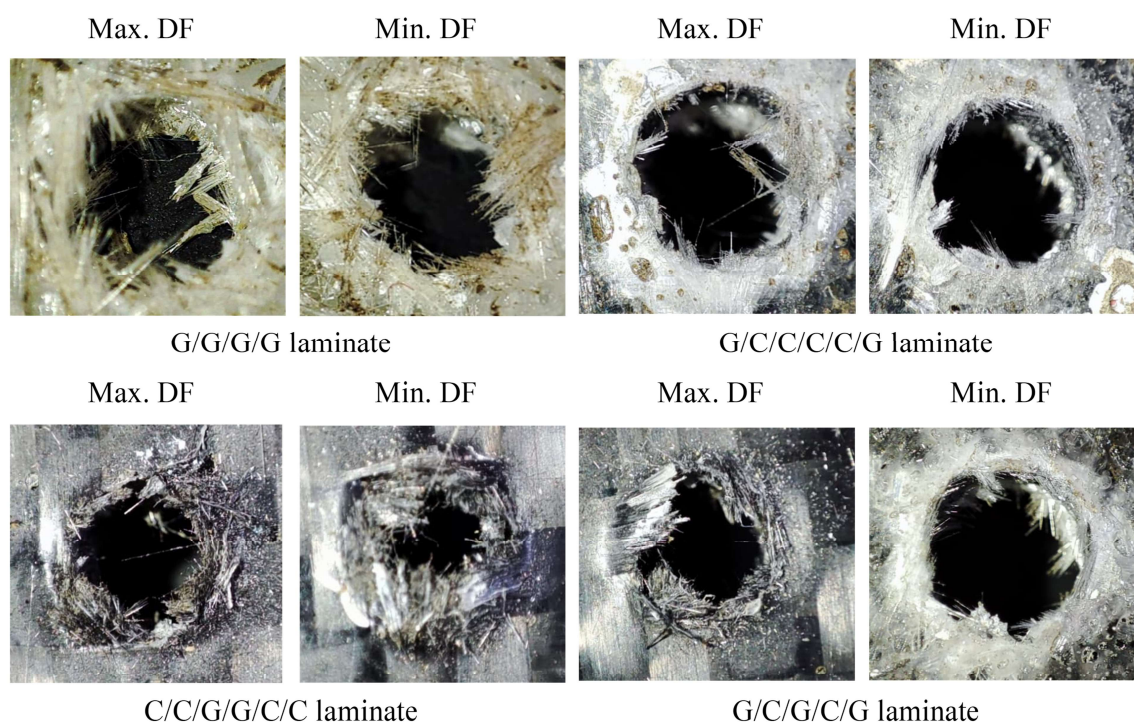


Figure 11. Optical micrographs of drilled holes exposing the delamination zone in laminates.

The data used for ANOVA are shown in Table 4, and their means at various levels are shown in Table 5. It was observed from the means that the stacking sequence had a strong influence on the delamination damage followed by the feed and spindle speed. The results of ANOVA are presented in Table 6. The lowest p-value of 0.008 (<0.05) was obtained for the stacking sequence, and the highest p-value of 0.661 (>0.05) was obtained for the spindle speed. The contribution of stacking sequence stood highest at 95.57% for the delamination damage of the composite laminates during drilling, confirming that the stacking sequence played a vital role in the machining performance of the composite laminates compared to that of the machining process parameters considered during machining. The Pareto chart and normal probability plot for the responses are shown in Figure 12a,b. The influence of stacking sequence on the response was very high, at a standardized effect of >14 , which was very high compared to that of the mean standardized effect of 2.78 for the process. The probability plot confirmed that the responses were very close to the fit line; a strong support for the accuracy of the results. In the residual plots shown in Figure 12c,d, the scattered distribution of errors across the fit and trial runs confirmed the accuracy and consistency of the results. The main effect plot of the control factors against the means is shown in Figure 13, revealing that the stronger influence on the delamination was from the stacking sequence. From the interaction plot shown in Figure 14, a stronger interaction was observed between spindle speed and feed, whereas the interaction between the stacking sequence and machining parameters were significantly less.

Table 4. L9 orthogonal array with factors and response.

No.	Stacking sequence	Spindle speed (rpm)	Feed (inch/rev)	Delamination factor
1	G/C/C/C/C/G	77	0.009	1.06
2	G/C/C/C/C/G	123	0.007	1.072
3	G/C/C/C/C/G	200	0.004	1.07
4	C/C/G/G/C/C	77	0.007	1.054
5	C/C/G/G/C/C	123	0.004	1.058
6	C/C/G/G/C/C	200	0.009	1.05
7	G/C/G/C/G	77	0.004	1.11
8	G/C/G/C/G	123	0.009	1.1
9	G/C/G/C/G	200	0.007	1.1

Table 5. Response table for the means.

Level	Stacking sequence	Spindle speed (rpm)	Feed (inch/rev)
1	1.067	1.075	1.070
2	1.054	1.077	1.075
3	1.103	1.073	1.079
Delta/rank	0.049/1	0.003/3	0.009/2

Table 6. ANOVA results for the DF.

Source	DF	Adj. SS	Adj. MS	F-value	P-value	Contribution (%)
Stacking sequence	2	0.003908	0.001954	118.81	0.008	95.57
Spindle speed (rpm)	2	0.000017	0.000008	0.51	0.661	0.415
Feed (inch/rev)	2	0.000132	0.000066	4.00	0.200	3.22
Error	2	0.000033	0.000016	-	-	0.807
Total	8	0.004089	-	-	-	100

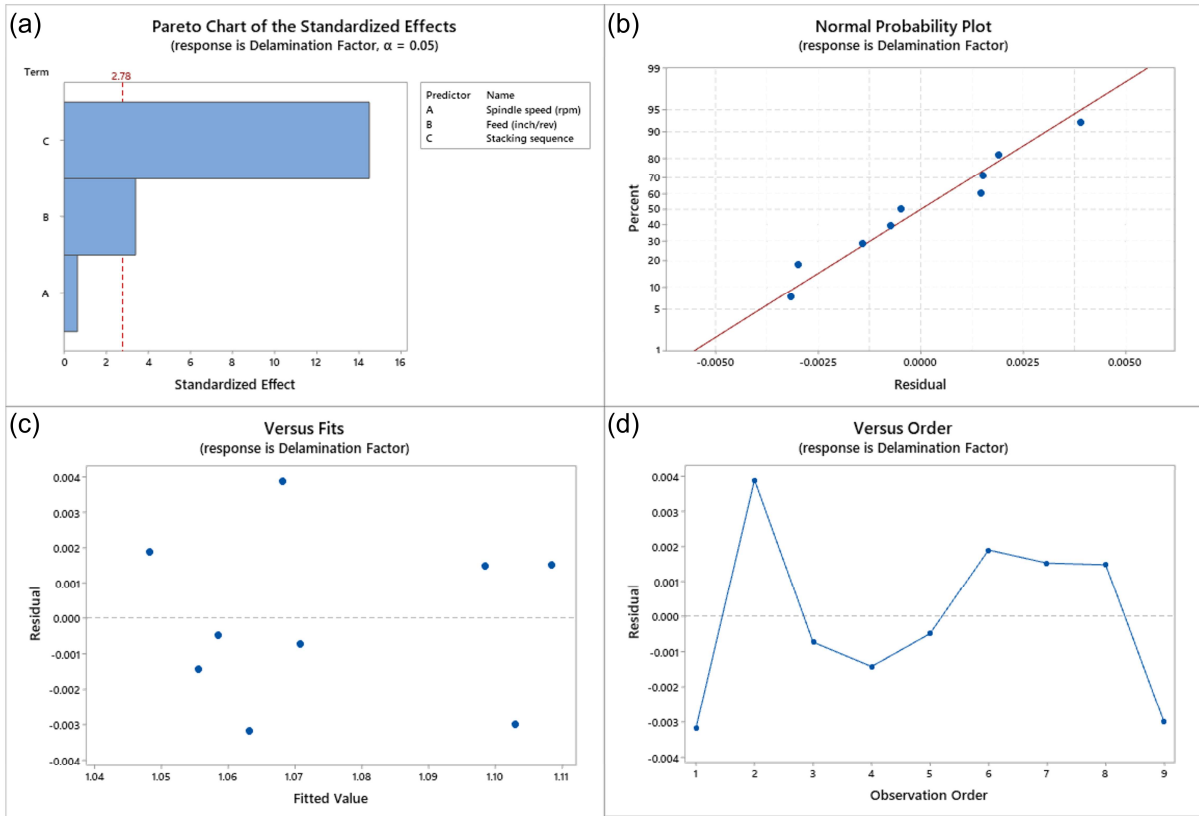


Figure 12. (a) Pareto chart, (b) normal probability chart for the responses, (c) residual vs fits, and (d) residual vs order for the responses.

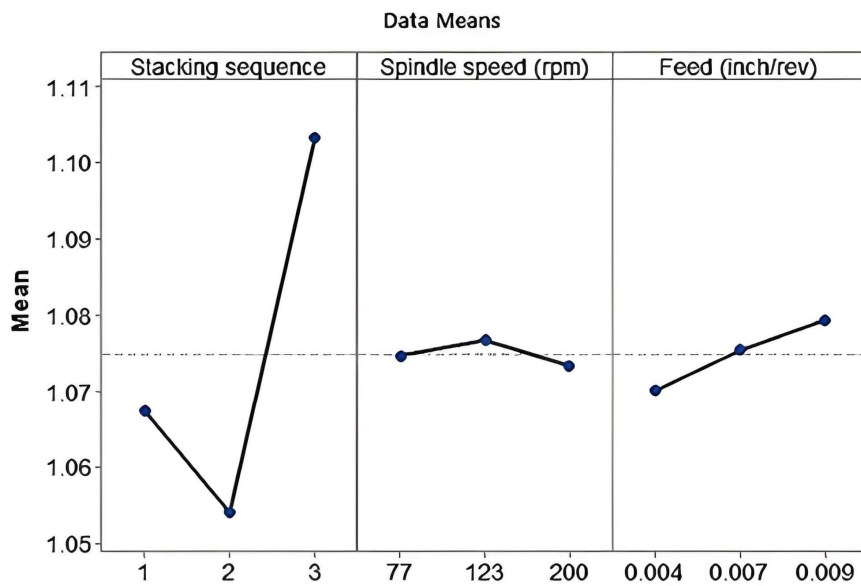


Figure 13. Main effect plot for delamination factor against their factors.

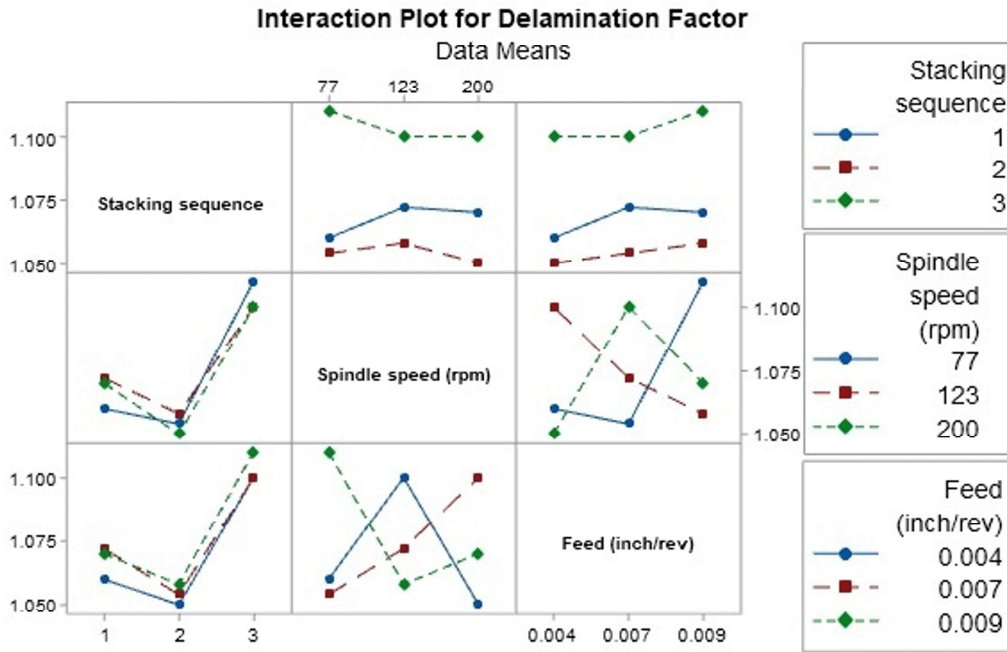


Figure 14. Interaction plot for the delamination factor against their factors.

Finally, the contour plots for the DF against the combinations of the control variables are shown in Figure 15, which complements the results shown previously. The parameters and results of the response optimizations are presented in Tables 7 and 8, respectively, and the optimized parameters for the response, DF, are shown in Table 9 with confidence interval (CI) and prediction interval (PI) values and Figure 16. The lowest feed of 0.004 inch/rev, highest spindle speed of 200 rpm, and the stacking sequence C/C/G/G/C/C were an optimized set of parameters for the best response.

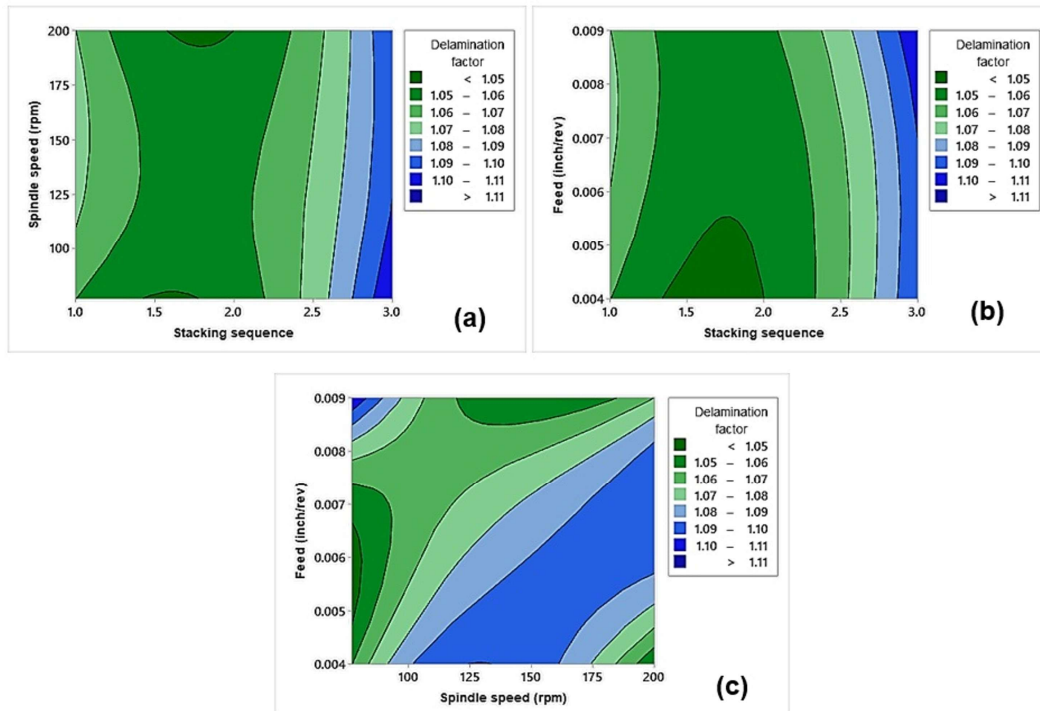


Figure 15. Surface plots for the delamination factor against their factors.

Table 7. Parameters for response optimization.

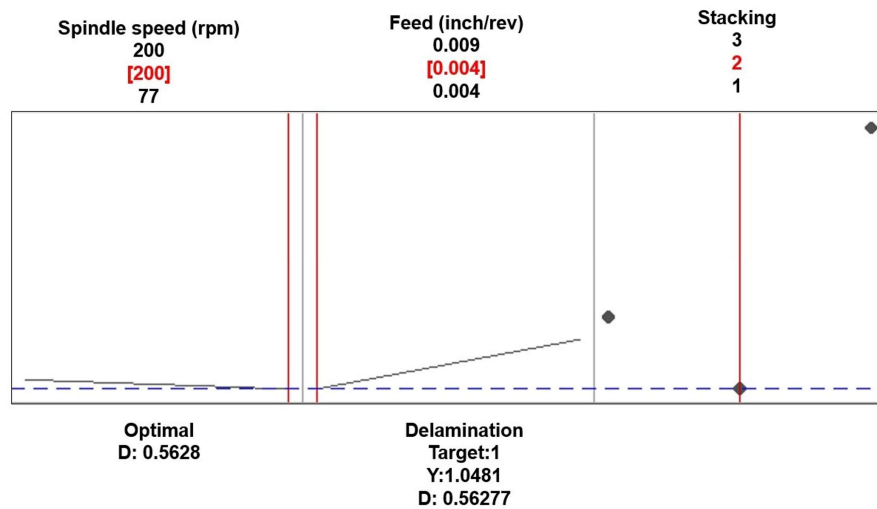
Response	Goal	Lower	Target	Upper	Weight	Importance
DF	Target	0.9	1	1.11	1	1

Table 8. Solution for response optimization.

Solution	Spindle speed (rpm)	Feed (inch/rev)	Stacking sequence	DF fit	Composite desirability
1	200	0.004	2	1.04810	0.562769

Table 9. Multiple response prediction.

Variable	Setting			
Spindle speed (rpm)	200			
Feed (inch/rev)	0.004			
Stacking sequence	2			
Response	Fit	SE fit	95% CI	95% PI
DF	1.04810	0.00284	(1.04021, 1.05598)	(1.03588, 1.06032)

**Figure 16.** Optimized response graph for the delamination of laminates.

4. Conclusions

The stacking of carbon and glass fibers significantly influenced the mechanical and machining behavior of the composite laminates. The physical, mechanical, and machinability attributes of the composite laminates were investigated, and the influence of stacking sequence on them were evaluated, including the optimization. The following conclusions can be drawn from the results:

- The least porosity was observed for specimens G/C/C/C/C/G & G/G/G/G. This may be due to the arrangement of same fiber mats on successive layers, increasing the density appreciably and reducing the porosity.

- With much higher diffusion rates, carbon fibers seem to possess a larger potential for water uptake than glass fibers.

- The highest tensile strength of 18.6 kN was observed for the G/C/C/C/C/G laminate, and the lowest tensile strength of 3.9 kN was shown for the G/G/G/G laminate. An apparent transition from a ductile to brittle characteristic was seen among the hybrid composite laminates with the changes in the stacking sequence of fiber mats.

- Compared to other composite laminates, the laminate with a stacking sequence C/C/G/G/C/C resulted in a high load carrying capacity against compression with no significant failure.

- The flexural strength of the G/G/G/G composite laminate was around 160 MPa, the flexural strength of the G/C/C/C/C/G composite laminate was 360 MPa, which was about a 125% increase. The randomized glass fiber and woven carbon fiber had an enhanced interlocking behavior, resulting in improved resistance against transverse loading.

- The laminates containing carbon fibers in the outer or middle layers performed better under impact loading due to their superior load-bearing capacity and crack arresting behavior. On the other hand, laminates with glass fibers on the outer layers exhibited reduced impact performance because of lower inter-laminar toughness and weaker fiber-matrix adhesion.

- The laminates with carbon fibers on the outer layers, such as the C/C/G/G/C/C laminate, offered superior inter-laminar shear strength due to the higher contribution of stiffness and shear resistance provided by the carbon fibers. The significant difference in shear strength between the laminates emphasized the importance of fiber placement in optimizing the inter-laminar shear performance of composite laminates.

- Compared to glass fibers, the higher cooling capacity of carbon fibers resulted in a lower rate of heat generation and DF. The carbon fibers at the outer layer protected the laminate with a lesser DF than that of glass fibers. Higher order pull-out of the fibers was observed from the optical micrographs at a maximum DF. Overall, the laminate with a stacking sequence C/C/G/G/C/C performed better in mechanical performance than that of other laminates.

- ANOVA results indicated that the lowest p-value of 0.008 (<0.05) was obtained for the stacking sequence, and the highest p-value of 0.661 (>0.05) was obtained for spindle speed. Thus, the influence of the stacking sequence was very strong compared to that of other process parameters. The material configuration of the laminate had a significant level of influence than that of the machining parameters considered in the delamination analysis. This may be due to the non-homogeneous and non-isotropic construction of the laminate.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgments

This study did not receive any external funding.

Author contributions

Ganesh Radhakrishnan: conceptualization; investigation; validation; methodology; data interpretation and visualization; writing original draft; manuscript review and editing; supervision. Kadhavoor R. Karthikeyan: conceptualization; investigation; validation; data interpretation and visualization; writing original draft; manuscript review and editing; supervision, project administration and funding acquisition. Ahmed Ali Salim Al Burtamani¹, Ali Jamil Humaid Al Daraai¹, Abdul Aziz Mohammed Al Ismaili¹, Asim Hamed Saif Al Hadhrami: conceptualization; investigation; methodology; experimentation; validation; data interpretation and visualization; writing original draft; manuscript review and editing; resource management for the project. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

References

1. Nagaraja KC, Rajanna S, Prakash GS, et al. (2020) The role of stacking order on mechanical properties of glass/carbon reinforced epoxy hybrid composites prepared by resin infusion technique. *Mater Today Proc* 22: 2446–2451. <https://doi.org/10.1016/j.matpr.2020.03.371>
2. Nagaraja KC, Rajanna S, Prakash GS, et al. (2020) Studying the effect of different carbon and glass fabric stacking sequence on mechanical properties of epoxy hybrid composite laminates. *Compos Commun* 21: 100425. <https://doi.org/10.1016/j.coco.2020.100425>
3. Abdalla GA, Elbadry EA, Aboraia M (2020) Effect of glass fiber stacking sequence on the notch sensitivity of glass fiber reinforced epoxy matrix composites. *Egypt J Chem* 63: 2977–2986. <https://doi.org/10.21608/ejchem.2020.19497.2186>
4. Kumar K, Mishra YK, Kumar J, et al. (2024) Exploration of stacking effects of carbon/glass fabric in polymer hybrid composites: Analysis of mechanical properties. *Discov Appl Sci* 6: 636. <https://doi.org/10.1007/s42452-024-06348-5>
5. Dong C, Davies IJ (2018) Effect of stacking sequence on the flexural properties of carbon and glass fibre-reinforced hybrid composites. *Adv Compos Hybrid Mater* 1: 530–540. <https://doi.org/10.1016/j.compositesb.2013.10.027>
6. Ali HT, Akrami R, Fotouhi S, et al. (2020) Effect of the stacking sequence on the impact response of carbon-glass/epoxy hybrid composites. *FU Mech Eng* 18: 69–77. <https://doi.org/10.22190/FUME191119010A>
7. Jesthi DK, Mandal P, Rout AK, et al. (2018) Effect of carbon/glass fiber symmetric inter-ply sequence on mechanical properties of polymer matrix. *Proc Manuf* 20: 530–535. <https://doi.org/10.1016/j.promfg.2018.02.079>
8. Dubey AD, Kumar J, Kyratsis P, et al. (2024) Stacking effect of carbon/glass fiber during drilling operation of laminated polymer composite. *Arch Metall Mater* 69: 589–598. <https://doi.org/10.24425/amm.2024.149787>

9. Cole DP, Henry TC, Gardea F, et al. (2017) Interphase mechanical behavior of carbon fiber reinforced polymer exposed to cyclic loading. *Compos Sci Technol* 151: 202–210. <https://doi.org/10.1016/j.compscitech.2017.08.012>
10. Avci H, Arikan H, Akdemir A (2004) Fracture behavior of glass fiber reinforced polymer composite. *Cement Concrete Res* 34: 429–434. <https://doi.org/10.1016/j.cemconres.2003.08.027>
11. Onal L, Adanur S (2002) Effect of stacking sequence on the mechanical properties of glass-carbon hybrid composites before and after impact. *J Ind Text* 31: 255–271. <https://doi.org/10.1106/152808302028713>
12. Radhakrishnan G, Mathialagan S (2022) Effect of fiber orientation on mechanical behavior of glass fiber reinforced polyethylene terephthalate foam sandwich composite. *Mater Today Proc* 62: 624–628. <https://doi.org/10.1016/j.matpr.2022.03.623>
13. Chen AY, Baehr S, Turner A, et al. (2021) Carbon fiber reinforced polymer composites: A comparison of manufacturing methods on mechanical properties. *Int J Lightweight Mater Manuf* 4: 468–479. <https://doi.org/10.1016/j.ijlmm.2021.04.001>
14. Liu X, Tey WS, Tan P, et al. (2022) Effect of the fibre length on the mechanical anisotropy of glass fibre-reinforced polymer composites printed by Multi Jet Fusion. *Virtual Phys Prototy* 17: 734–748. <https://doi.org/10.1080/17452759.2022.2059638>
15. Romanzini D, Ornaghi Junior HL, Amico II SC, et al. (2012) Preparation and characterization of ramie-glass fiber reinforced polymer matrix hybrid composites. *Mat Res* 15: 415–420. <https://doi.org/10.1590/S1516-14392012005000050>
16. Jagannatha TD, Harish G (2015) Mechanical properties of carbon/glass fiber reinforced epoxy hybrid polymer composites. *Int J Mech Eng Robot Res* 4: 131–137. Available from: <https://www.ijmerr.com/show-130-634-1.html>.
17. Radhakrishnan G, Breaz TO, Al Hinai AHH, et al. (2025) Effect of alumina microparticle-infused polymer matrix on mechanical performance of carbon fiber reinforced polymer (CFRP) composite. *J Compos Sci* 9: 360. <https://doi.org/10.3390/jcs9070360>
18. Bere P, Popescu A, Dudescu C, et al. (2017) Influence of the stacking sequence on the mechanical behavior of glass fiber reinforced polymer. *MATEC Web Conf* 112: 04006. <https://doi.org/10.1051/mateconf/201711204006>
19. Radhakrishnan G, Vaithilingam S, Tamilarasan VD, et al. (2025) Multi response optimization during machining of magnesium matrix nanocomposite reinforced with TiN nano particulates. *MJChem* 27: 361–369. <https://doi.org/10.55373/mjchem.v27i3.361>
20. Radhakrishnan G, Breaz D, Al Hattali AHMS, et al. (2023) Influence of aspect ratio on the flexural and buckling behavior of an aluminium sandwich composite: A numerical and experimental approach. *Materials* 16: 6544. <https://doi.org/10.3390/ma16196544>



AIMS Press

© 2026 the Author(s), licensee AIMS Press. This is an open access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>)