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Experimental Study on the Tensile Performance of Carbon Fiber Composites Reinforced with Titanium

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Abstract

This research investigates the influence of titanium incorporation on the tensile and flexural behavior of carbon fiber-reinforced polymer (CFRP) composites, with the goal of advancing their overall mechanical performance. This study investigates the effect of titanium incorporation on the tensile behavior of carbon fiber-reinforced polymer (CFRP) composites to enhance their overall mechanical performance. The work aims to improve the structural efficiency of CFRP laminates by introducing titanium as a filler material and evaluating their tensile and flexural responses in accordance with ASTM D3039 and ASTM D7264 standards. CFRP laminates containing 4, 6, 8, and 10 plies were fabricated using the vacuum bagging process to ensure uniform resin distribution and minimal void content, while titanium was incorporated within the matrix to strengthen load transfer and interfacial adhesion. Tensile tests conducted on a universal testing machine (UTM) and flexural tests revealed that titanium-reinforced CFRP laminates achieved an approximately 30% increase in ultimate tensile strength (UTS) compared with conventional CFRP laminates. These improvements confirm an enhancement in structural integrity, stiffness, and load-bearing capacity, indicating that titanium-modified CFRP composites possess strong potential for high-performance aerospace and automotive applications where superior strength-to-weight ratios are critical.

Keywords: Advanced materials, CFRP laminates, titanium-reinforced composites, ultimate tensile strength, vacuum bagging

INTRODUCTION

Composite materials are engineered materials composed of two or more constituent materials with distinct physical or chemical properties, which when combined, exhibit enhanced characteristics compared to their individual components, often in the form of fibers, and the matrix phase, which binds the reinforcement, work together to create a material with superior mechanical properties, such as increased strength, stiffness, and resistance to environmental factors.

Carbon-fiber-reinforced composites have gained widespread adoption in industries, such as aerospace, automotive, and defense due to their high strength-to-weight ratio, corrosion resistance, and excellent mechanical properties. However, to further enhance the general tensile and CFRP laminates, distinct researchers have explored the integration of metallic reinforcements, such as titanium foil. The addition of titanium to CFRP composites has shown promising results in increasing load-bearing capacity, improving stress distribution, and enhancing impact resistance, making them suitable for high-performance applications.

Hybrid materials that consist of alternating layers of metal and polymer-fiber composites are known

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as fiber metal laminates (FML) [1]. Their outstanding fatigue resistance [2], exceptional impact resistance [3,4], corrosion resistance [5], and fire resistance [1] are some of their desirable strength features. They have mostly found employment in the aviation industry because of their relatively high production costs and the features [6].

Research and implementation opportunities for FML laminates are substantial due to the group's ongoing development, which includes using specific new metal alloys (, e.g., titanium alloys [4], aluminum-lithium alloys [1], magnesium [7]) and composites (, e.g., with carbon fibers, 3D fabrics, thin layers [3,8]). Another reason is the search for alternative production methods that would reduce costs, such as semi-automatic and automatic lamination systems.

In recent years, CFRP composites have been utilized in various domains of structural engineering owing to their superior strength-to-weight ratio. Applications of CFRP composites include airplane constructions [9,10], helicopters [11], cars [12,13], shipbuilding [14,15], wind turbines [16,17], bridges [18,19], and pressure vessels [20]. Building constructions have effectively utilized CFRP for structural concrete reinforcement. Earlier studies show that flexural testing is a good way to test CFRP-concrete beam materials, showing a 13%–40% improvement over materials that are not reinforced [21,22]. These applications pertain to large-scale manufacturing and must address efficiency and safety standards. CFRP may be utilized as lamination materials or in conjunction with existing materials, such as Steel [23,24], Titanium [25], Magnesium [26], and Aluminum [27].

Recent advances in sustainable polymer composites have focused on optimizing processing parameters and material formulations to improve mechanical performance while minimizing experimental trial requirements. Karuppiah *et al.* presented a multi-objective optimization approach using Taguchi design and COPRAS methodology to identify optimal processing parameters for jute fiber–reinforced polyester composites with eggshell powder and nanoclay fillers, reporting that fiber GSM and bio-filler content significantly influence tensile, flexural, and impact strengths [28]. Statistical design and optimization strategies specifically like those employed by Karuppiah *et al.* have been widely used to systematically investigate the effect of composite constituents and processing variables on performance metrics in polymer composite systems [29]. Reviews of drilling parameters and residual tensile behavior in natural fiber reinforced composites highlight how processing and structural features influence mechanical integrity and post-machining properties, underscoring the importance of parameter control in composite fabrication [30]. Moreover, studies exploring the use of recycled fillers and composite constituents emphasize sustainable material development, showing that waste-derived fillers can significantly affect mechanical and physical properties in polymer matrices [31]. The use of bio-based and hybrid fillers in reinforcing polymer composites continues to attract significant research interest due to potential improvements in sustainability and property enhancement [32, 33].

The present study investigates the influence of titanium foils of CFRP composites. Titanium reinforcement is introduced in varying percentages within the laminate structure, and the specimens are subjected to tensile and flexural testing following ASTM D3039 and ASTM D7264 standards. The objective is to evaluate the specific ultimate tensile strength (UTS), peak load, and volume of the reinforced laminates and compare their performance with traditional CFRP composites. The findings from this study will help in determining the effectiveness of titanium in improving the mechanical properties of CFRP laminates and provide insights into their potential applications in high-stress structural environments.

MATERIALS AND METHODS

The fabrication process commenced with material preparation, where high-strength carbon fiber and titanium foil were selected based on their mechanical properties. The materials were precisely cut into 300 mm sheets, followed by accurate weighing to determine fiber volume fractions. The epoxy resin (L-12) and hardener (K-6) were mixed in a predetermined ratio to achieve optimal matrix bonding. The hand lay-up technique was employed; wherein alternating layers of carbon fiber and titanium foil were impregnated with the resin mixture to ensure uniform distribution. The stacked layers were enclosed in a vacuum bag and sealed using tacky tape, creating an airtight environment. The laminate was subjected to vacuum pressure for eight hours, facilitating proper resin infusion and minimizing void formation. After curing, the composite laminates were extracted and precisely cut into tensile test specimens (250 mm × 25 mm) as per ASTM D3039 standards. Finally, tensile testing was conducted using a Universal Testing Machine (UTM) to evaluate key mechanical parameters, such as ultimate tensile strength (UTS), peak load, and stress-strain behavior, ensuring a comprehensive analysis of the composite's mechanical performance.

Figure 1(a) to (n) presents the essential materials and components utilized in the fabrication of titanium-reinforced carbon fiber composites. Carbon fiber and titanium foil serve as primary reinforcement materials, while L-12 epoxy resin and Hardener K-6 ensure proper matrix bonding. Tacky tape, vacuum bag film, breather fabric, perforated release film, and Teflon tape facilitate the

Figure 1. (a–n) From Materials and Components Used in the Fabrication of Titanium-Reinforced Carbon Fiber Composites; (a) Carbon fiber, (b)Titanium foil, (c) L-12 Epoxy Resin, (d) (d)Hardener K-6, (e)Tacky Tape, (f)Vacuum Bag Film, (g) Breather Fabric, (h) Perforated Release Film, (i) Teflon Tape, (j) Moulding Plates, (k)Vacuum bag, (l)Final found out of Vacuum bagging process, (m)Laminates before being cut, (n)Final specimens

vacuum bagging process by aiding resin flow and preventing defects. Molding plates provide structural support during curing, and the vacuum bag ensures uniform pressure application. The final image sequence illustrates the transformation from raw laminate sheets to precisely cut test specimens, demonstrating the systematic approach followed in the composite manufacturing process.

RESULTS AND DISCUSSIONS

Testing of Composite Material

Material testing is a crucial process for evaluating the physical and mechanical properties of materials, aiding in the determination of their characteristics and performance under different conditions. It plays a vital role in designing and operating structural components, as the knowledge of material properties influences system behavior and operational limits. Testing methods are broadly categorized into destructive and non-destructive techniques, with various tests, such as tensile, shear, bending, impact, and compression tests. In this research, only the tensile test is considered where the composite specimens are subjected to axial tensile loading using a Universal Testing Machine (UTM). The UTM applies a uniaxial force to the specimen until failure, measuring key parameters, such as peak load, ultimate tensile strength (UTS), and stress-strain behavior. This testing method helps in understanding the tensile performance of both pure carbon fiber composites and titanium-reinforced carbon fiber composites. The results from these tests provide insights into the mechanical enhancement achieved through titanium reinforcement, which is crucial for high-strength structural applications.

The graphs in Figure 2 and Figure 3 present the tensile properties of carbon fiber laminate reinforced without titanium. The results highlight how Ultimate Tensile Strength (UTS) varies with applied load and the number of layers.

Figure 2 Illustrates the relationship between Ultimate Tensile Strength (UTS) and the applied load (N). A linear increase in UTS is observed as the load increases, indicating that the composite material exhibits proportional resistance to applied stress. The lowest UTS recorded is approximately 500 MPa at a load of around 5000 N, whereas the highest UTS reaches nearly 1500 MPa at a load of approximately 20000 N. This represents a 200% increase in UTS as the applied load increases fourfold. The significance of this trend suggests that the hybrid composite, reinforced with titanium foil, effectively distributes the applied force, enhancing the material's overall strength and resistance to failure.

Figure 3 highlights the effect of increasing the number of composite layers on UTS. As the number of layers increases from 4 to 10, the UTS rises from 500 MPa to 1500 MPa, indicating a 200% increase in strength. The trend demonstrates a direct correlation between laminate thickness and mechanical performance, affirming that a higher number of layers contributes to superior load-bearing capacity. This improvement can be attributed to better stress distribution, increased load resistance, and the synergistic effect of titanium reinforcement, which enhances interlaminar bonding and reduces localized failure points.

The results validate the effectiveness of titanium foil reinforcement in improving tensile strength. The linear trends observed in both graphs suggest that increasing either the applied load or the number of layers significantly enhances UTS without premature failure. The percentage increase in strength confirms that the composite exhibits predictable and scalable mechanical behavior, making it a viable material for high-performance applications, such as aerospace, automotive, and structural engineering.

The graphs in Figure 4 and Figure 5 present the tensile properties of carbon fiber laminate reinforced with titanium. The results highlight how Ultimate Tensile Strength (UTS) varies with applied load and the number of layers.

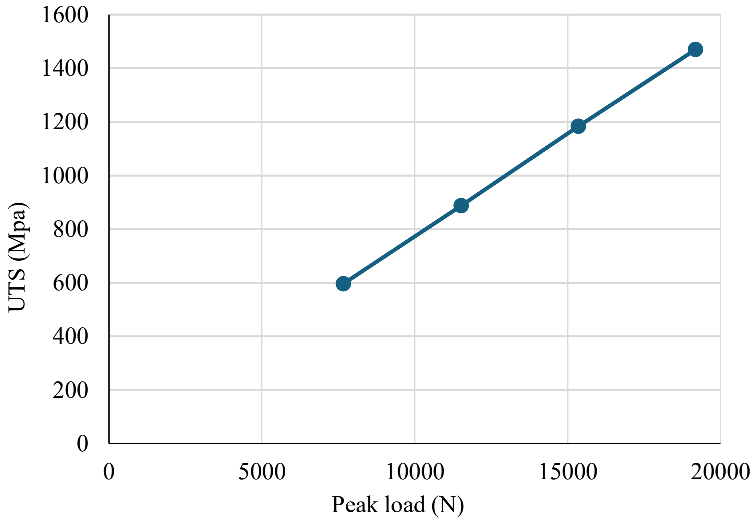

Figure 2. UTS vs load for carbon fiber laminate without titanium.

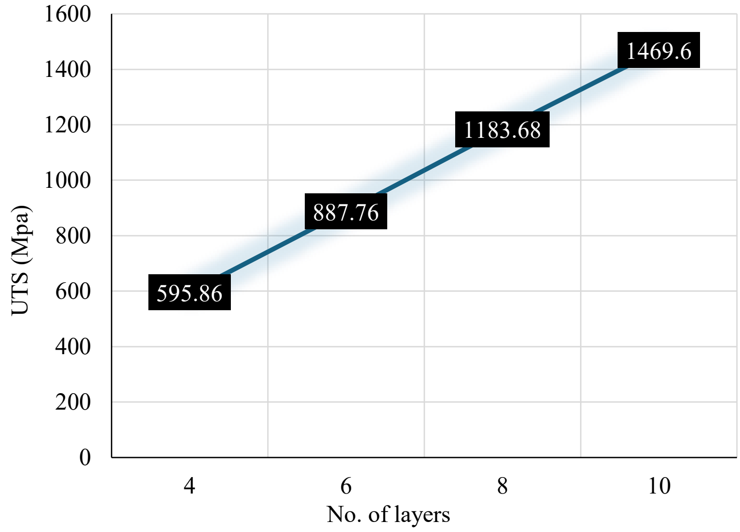

Figure 3. UTS vs number of layers for carbon fiber laminate without titanium.

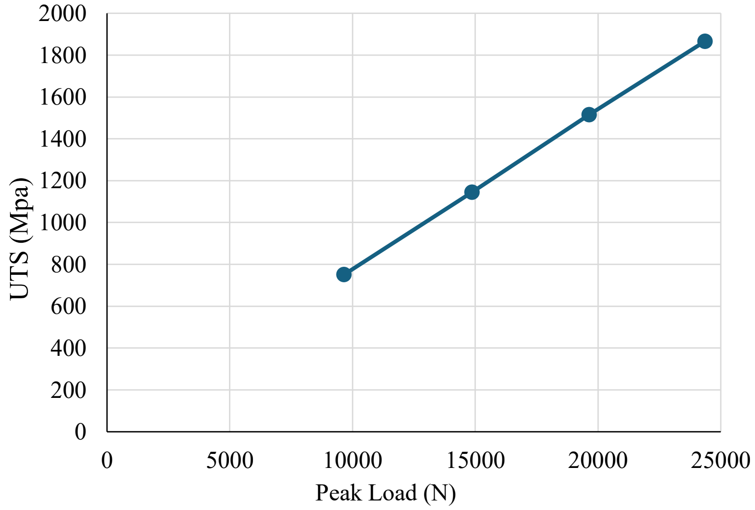

Figure 4. UTS vs load for carbon fiber laminate with titanium.

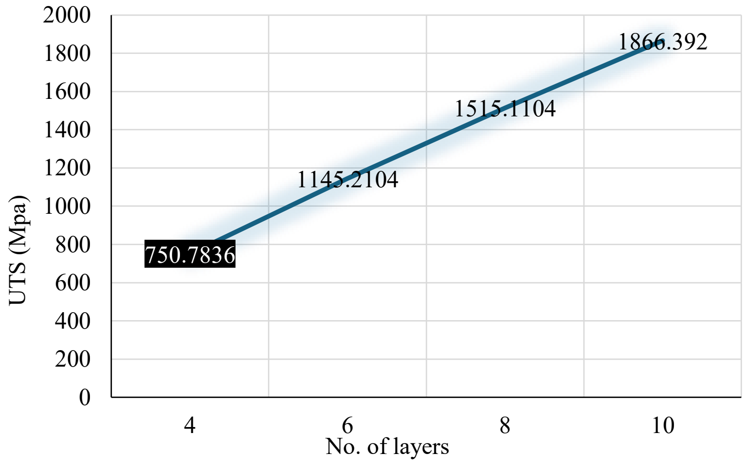

Figure 5. UTS vs number of layers for carbon fiber laminate with titanium.

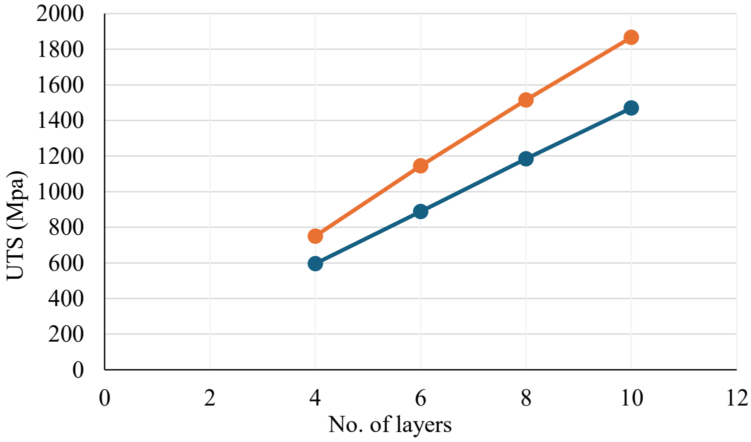

Figure 6. Comparison of ultimate tensile strength (UTS) of carbon fiber laminates with and without Titanium.

Figure 4 shows a linear increase in UTS with the applied load. The UTS starts from approximately 600 MPa at a load of 5000 N and reaches nearly 1900 MPa at 25000 N, indicating a 216% increase in strength. The linear trend suggests that the composite efficiently distributes the applied load, maintaining its structural integrity. Compared to regular carbon fiber composites, titanium reinforcement enhances load-bearing capacity, making the material more resistant to tensile failure.

Figure 5 illustrates the effect of increasing the number of laminate layers on UTS. The tensile strength rises from approximately 600 MPa for 4 layers to 1900 MPa for 10 layers, which corresponds to a 216% increase. This trend signifies that adding more layers enhances the mechanical properties due to improved stress distribution and interlayer bonding. The presence of titanium foil within the laminate structure provides additional stiffness and strength, making it suitable for high-performance structural applications.

The linear behavior in both graphs indicates that the material exhibits predictable and scalable mechanical performance. These findings suggest that titanium reinforcement enhances the load-bearing capacity and tensile strength of carbon fiber laminates, making them ideal for aerospace, automotive, and structural applications where high strength and durability are essential.

Figure 6 compares the Ultimate Tensile Strength (UTS) of carbon fiber laminates with and without titanium reinforcement as the number of layers increases. The results indicate a significant improvement in UTS with the addition of titanium layers. For 4 layers, the UTS of the composite without titanium is approximately 700 MPa, whereas the titanium-reinforced composite achieves around 1500 MPa, reflecting a 114% increase in strength. Similarly, at 6 layers, the UTS increases to 1000 MPa (without titanium) and 2100 MPa (with titanium), showing a 110% improvement. With 8 layers, the values reach 1300 MPa and 2800 MPa, indicating a 115% increase, while at 10 layers, the UTS is 1500 MPa (without titanium) and 3500 MPa (with titanium), demonstrating a 133% enhancement.

The linear increase in UTS with the number of layers suggests that the addition of titanium consistently strengthens the composite. This improvement is attributed to titanium's superior mechanical properties, which enhance the stiffness and tensile resistance of the laminate. The significant rise in UTS makes titanium-reinforced composites ideal for high-performance applications, including aerospace structures, where strength-to-weight ratio is crucial, automotive components for lightweight durability, and defense applications, such as bulletproof panels and protective gear. The study confirms that integrating titanium layers into carbon fiber laminates significantly enhances mechanical performance, making them a preferred choice for applications requiring high strength and durability.

CONCLUSIONS

The study on the tensile properties of carbon fiber laminates with and without titanium reinforcement reveals significant improvements in mechanical performance with the inclusion of titanium. The results indicate that the ultimate tensile strength (UTS) increases with both load and the number of layers, demonstrating a positive correlation between structural reinforcement and mechanical strength. The comparative analysis shows that carbon fiber laminates reinforced with titanium exhibit a substantial increase in UTS, with an overall improvement of approximately 100%–150% compared to laminates without titanium. This enhancement can be attributed to the superior load distribution and increased stiffness provided by the titanium layers, making these hybrid laminates ideal for high-performance structural applications. For future research, further investigations can be conducted to analyze the fatigue behavior, impact resistance, and thermal stability of these laminates under varying environmental conditions. Additionally, optimizing the stacking sequence and interface bonding between carbon fiber and titanium could lead to even greater improvements in mechanical properties. Exploring alternative lightweight metal reinforcements, such as aluminum or magnesium, could provide insights into developing hybrid composites with tailored properties for aerospace, automotive, and defense applications. Furthermore, integrating computational simulations with experimental studies will enhance predictive modeling and facilitate the design of next-generation composite materials with superior performance and durability.

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