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The Impact of Laminations on the Mechanical Strength of Carbon-Fiber Composites for Prosthetic Foot Fabrication

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Abstract: Carbon-fiber composites are considered to be one of the suitable materials for the fabrication of prosthetic feet. However, commercially available composites-based prosthetic foot designs present several problems for lower limb amputees, such as low tensile strength, reduced impact resistance, high cost, and weight structure. Modulating the mechanical properties of carbon-fiber composites using a simplified method can help reduce these issues. Therefore, our present research aims to identify the impact of increasing the concentration of carbon fiber in the fabrication of carbon-fiber composites by using the hand layup method without the vacuum bagging technique. To improve the mechanical strength of carbon-fiber laminates, an increasing number of carbon-fiber layers are used in sample preparation. This study aims to determine the tensile strength of the laminates with a different number of carbon-fiber laminations. For the preparation of the sample specimen, black 100% 3 K 200 gsm carbon fiber with a cloth thickness of 0.2 mm and tensile strength of 4380 Mpa was laminated with two parts of epoxy resin Araldite® LY556 and Aradur hardener at a ratio of 100:30 to make the test specimen. The results indicated an overall improvement in the tensile strength of carbon-fiber laminates owing to the increase in the number of carbon-fiber layers in successive samples. The maximum achieved tensile strength through the present experimental protocol is 576.079 N/mm^2, depicted by a prepared specimen of 10 layers of carbon fiber. Secondly, an increase in the deformation rate has also been observed by increasing the loading rate from 2 mm/min to 5 mm/min during the tensile testing of fabricated samples. These sample carbon-fiber composites can be used in the fabrication of prosthetic feet by controlling the experimental conditions. The fabricated prosthetic foot will assist in rehabilitating lower-limb amputees.

Keywords: carbon-fiber composites; tensile strength; deformation rate; prosthetic foot

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1. Introduction

Lower-limb amputations severely affect quality of life by restraining body functions such as movement. Lower-limb prosthetics rehabilitate not only mobility but also the well-being of amputees. One of the primary factors in rehabilitating lower limb amputees is the prosthetic foot. For this purpose, several prosthetic foot designs have been introduced since the SACH (Solid-Ankle Cushion-Heel) foot was developed in 1957 [1]. SACH has been prescribed to disabled patients because it could lower the impact loading at heel strike.

Nevertheless, this commonly used prosthetic foot can store and release a small amount of elastic energy [2]. Other earlier prosthetic foot designs consisting of wood, metal, and vulcanized rubber presented various issues for amputees, such as lack of durability and discomfort. Previously, problems with prosthetic foot designs, including the Shape and Roll foot, Niagara Foot, and Jaipur foot, were investigated by several studies [3–5], stating similar issues of reduced durability and increased weight. Owing to problems with formerly used prosthetic foot materials, carbon-fiber composites were considered a suitable alternative, as stated by previous research [6]. Nolan [7] supported using composite materials for designing prosthetic feet because of their energy storage capacity, which provides a rehabilitative advantage to amputees requiring a high activity level.

Similarly, Campbell [8] also supported using carbon fiber and glass fiber in prosthetic applications for their low density, lightweight quality, and high strength. Recently, another study in Vietnam also provided evidence that carbon-fiber laminated prosthetic feet store elastic energy, helping the body move forward and reducing the impact force on residual limbs [9]. This property increases the flexibility of the prosthetic foot, thus mimicking the working of a natural foot.

Carbon fiber has been a primary choice for industrial uses for over a century. Their excellent strength-to-weight and stiffness-to-weight ratios make them suitable for the automotive, aerospace, and prosthetic industries. According to Sau-Fun et al. [10], previously, wood and metal were utilized as the preferred materials for constructing and fabricating prosthetic devices. However, Maruo et al. [11] suggested that such prosthetic materials presented issues such as reduced resistance to moisture and corrosion, and dampness. Similarly, another study stated that prosthetic applications require durable and stable materials such as synthetic fibers to provide comfort and control to amputees. Scholz et al. [12] related the supremacy of these composite materials over other materials to their biocompatibility and strength-to-weight characteristics.

Furthermore, Liu et al. [13] also claimed that the enhanced characteristics of fiber composite materials make them suitable for the prosthetic industry and industries such as sports, aeronautics, and aerospace. In recent studies, various other forms of composites, such as polypropylene (PP)-based nanocomposites, have also been tempered with nanoclay, basalt fibers, and graphene to be used in the aerospace industry [14,15]. Another form of composites known as fiber laminated metals (FML) has also been studied to investigate their impact on the mechanical strength of aircraft components. The results depicted an overall increase in tensile strength using fiber laminated metals [16]. Modulating fiber composites with different techniques can enhance their mechanical properties, making them suitable for various manufacturing industries [17].

Prosthetic utilization has been significantly dependent on carbon fibers due to their ability to store energy and their adaptability, according to Dziaduszewska et al. [18]. The properties of carbon fibers can be manipulated by fabricating carbon-reinforced composites using epoxy resins and woven carbon fibers. Oleiwi et al. [19] explained that the lamination process could incorporate specific tensile properties and rigidity by controlling the specific angles and altering the matrix. Using various lamination techniques, blended polymer frameworks can be constructed to be utilized for the manufacturing of prosthetic limbs, as depicted by an experimental protocol designed by Abbas et al. [20]. Nowadays, the rapid prototyping system uses metal, plastic, or other material laminations to fabricate orthotic and prosthetic devices [21].

Several theoretical and experimental studies have been carried out to improve the mechanical properties of carbon-fiber composites. Jweeg et al. [22] have characterized two different fiber-type composite materials resulting in better performance outcomes for unidirectional fibers. Similarly, Abbas et al. [20] supported the improved mechanical properties of carbon-fiber composites by increasing the number of layers in carbon-fiber laminates during the manufacturing process. A recent study conducted by Khare et al. [23] also depicted that flexural strength increases by 17% when using 15% carbon-fiber reinforcements. Likewise, Rahmani et al. [24] supported the fact that the mechanical strength in composites can be improved by manipulating the interlaminar properties and strengthening the resin matrix. Hadi et al. [25] demonstrated a greater impact of the reinforcement material on improved tensile strength rather than the direction of polymer laminates. Muhammed et al. [26] suggested a relationship between the tensile strength and weight percentage of the reinforcement material that enhances certain properties, including elasticity, yield strength, and ultimate strength, by changing the weight percentage of the fiber composites.

Over previous decades, several cost-effective techniques were presented for the fabrication of carbon-fiber composites to improve their mechanical properties. Such techniques include hand layup, compression molding, vacuum bagging, and vacuum-assisted resin transfer molding to manufacture epoxy-based composites, as described by Pulikkalparambil et al. [27]. The improvement of prepared composites' properties depends on the suitability and efficacy of the selected technique. For instance, Muralidhara et al. [28] previously developed carbon-fiber laminates using the hand layup method followed by vacuum bagging, producing a significant improvement in the mechanical performance of the carbon-fiber composites. However, the tensile and flexural strength of the material was significantly enhanced by vacuum bagging compared to the hand layup method. Chen et al. [29] provided a different perspective regarding the wet hand layup method's limitations compared to fiber 3D printing (F3DP). The study concluded that the hand layup method fabricated prostheses with great flexure rather than tensile strength.

In this work, a simplified hand layup method has been utilized to fabricate carbon-fiber laminates to test the suitability of carbon fibers for prosthetic purposes. Carbon-fiber layers were subsequently increased in the prepared carbon-fiber laminates to test the impact of increasing the fiber content over the mechanical strength. The previous study conducted by Al-Khazraji et al. [30] depicts the suitability of such laminates for prosthetic sockets. The present study will focus on the suitability of such materials for designing a prosthetic foot prototype.

2. Materials and Methods

2.1. Materials

To test the mechanical strength of carbon-fiber laminates, the following materials have been used for the preparation of samples:

1. Black 100% 3 K 200 gsm carbon-fiber cloth with tensile strength 4380 Mpa (thickness = 0.2 mm);
2. Two parts epoxy resin Araldite® LY556;
3. Hardener Aradur® 22962;
4. Mold releasing wax;
5. Plywood for mold preparation.

2.2. Experiment Protocol

Specimen Preparation

A 100% 3 K 200 gsm carbon-fiber cloth with a thickness of 0.2 mm was cut into dimensions of 24 × 2.5 mm to prepare several layers of carbon-fiber lamination. To prepare the required samples of laminates for tensile testing, the carbon-fiber cloth with 0.2 mm thickness was stacked to up to 10 layers. For the preparation of each sample, 2, 6, and 10 carbon fabric layers were laminated using epoxy resin in a ratio of 100:30 by volume. The thickness of each sample varied owing to the difference in the number of carbon-fiber laminations. In a drying oven, these laminated samples were cured at a high temperature of between 80 °C and 120 °C.

For the preparation of carbon-fiber laminates, the fibers were kept at the orientation of 0° and 90°. Further, for constructing the laminates, two parts of an epoxy resin with the properties listed in Table 1 were applied using a paintbrush to acquire an equal distribution of resin between the subsequent layers of carbon fiber.

The hand layup method was used to fabricate the required carbon-fiber samples and the wooden molds to assist in curing the samples. The hand layup process is depicted in Figure 1. The hand layup method is one of the most significant processes in the composite manufacturing industry. This process helps build high-performance composite materials with enhanced mechanical as well as structural properties [31]. Carbon-fiber composites are fabricated layer by layer and incorporated with epoxy resin. The hand layup process consists of carbon-fiber composites, including layers of well-aligned fiber reinforcements with the matrix material. The prepared carbon-fiber laminates can be used for various applications, including sports goods, automotive, and prostheses. For the fabrication of a prosthetic foot prototype, the first step is the design construction using SolidWorks 2017 software. Three parts of the prosthetic foot (sole, keel, and heel) are designed using the approximate measurements of an average foot size (24.5 cm).

Table 1. Properties of epoxy resin and hardener.

Properties	Epoxy Resin Araldite® LY556	Hardener Aradur® 22962
Viscosity at 25 °C (ISO 12058–1)	10,000–12,000 mPa s	5–20 mPa s
Density at 25 °C (ISO 1675)	1.15–1.20 g/cm^3	0.89–0.90 g/cm^3
Flash Point (ISO 2719)	>200 °C	≥110 °C
Storage Temperature	2–40 °C	2–40 °C
Epoxy content (ISO 3000)	5.30–5.45 eq/kg	——
Epoxy equivalent (ISO 3000)	183–189 g/eq	——

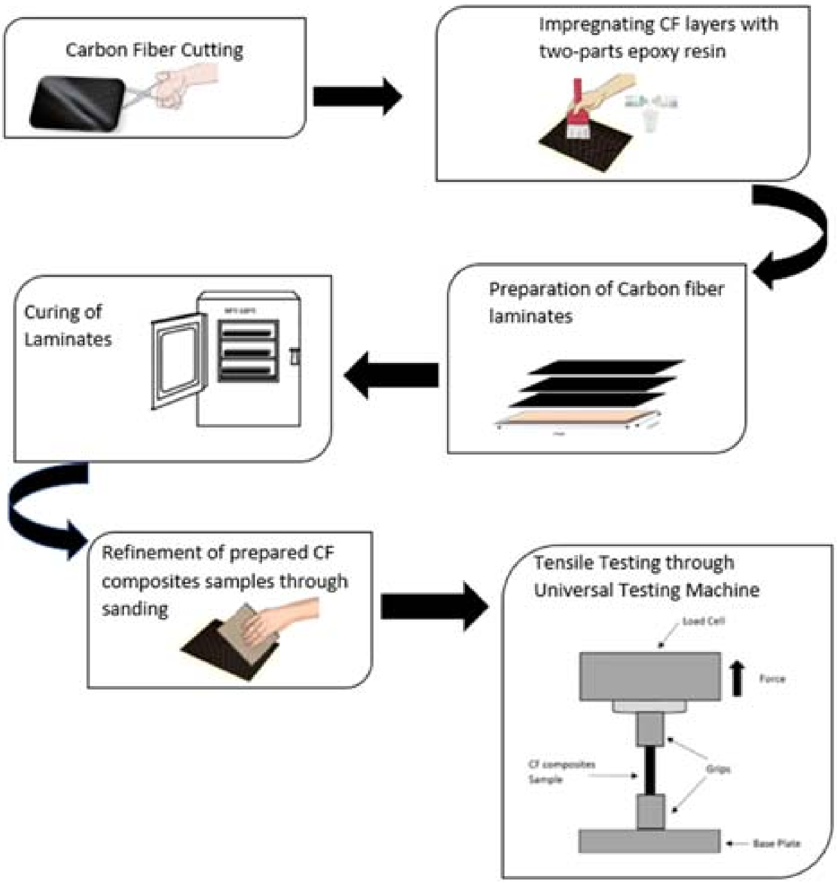


Figure 1. Hand Layup Process for producing carbon-fiber composite samples.

Laminates are cured in the drying oven at temperatures of 80 °C to 120 °C. The prepared samples are then subjected to shear cutting and sanding to refine the laminated samples. The process is repeated for several samples to fabricate the required number of samples used in the universal testing machine. Table 2 depicts the experimental protocol for sample fabrication.

Table 2. Experimental protocol.

Araldite® LY556/Aradur® 22962	Number of CF Laminations	Load Rate
100:30	2 layers 4 layers	2 mm/min, 2 mm/min
	2 layers	5 mm/min
	6 layers	5 mm/min
	10 layers	5 mm/min

2.3. Tensile Testing

Tensile testing is one of the crucial steps in determining the mechanical strength of a particular material, which is carbon-fiber laminates in the present case. A universal testing machine is used to apply a uniaxial load on the sample until the point of failure, as shown in Figure 2. The acquired result from the tensile testing can be utilized to select suitable materials for quality control or prosthetic applications. The mechanical testing also predicts the properties of the material being tested. These properties include maximum elongation or reduction in the cross-sectional area and ultimate strength. For this purpose, the specimen is loaded in a controlled manner in the grip section of the universal testing machine (UTM). The materials are prepared and tested according to the ASTM D3039 standard, which provides the guidelines for testing the laminated type of composite material [32]. The maximum capacity of the universal testing machine is 20 KN, which worked on the electronic control servo mechanism. The gauge length for each sample was kept at approximately 80 mm. Furthermore, the material was subjected to tensile testing at 5 mm/min.

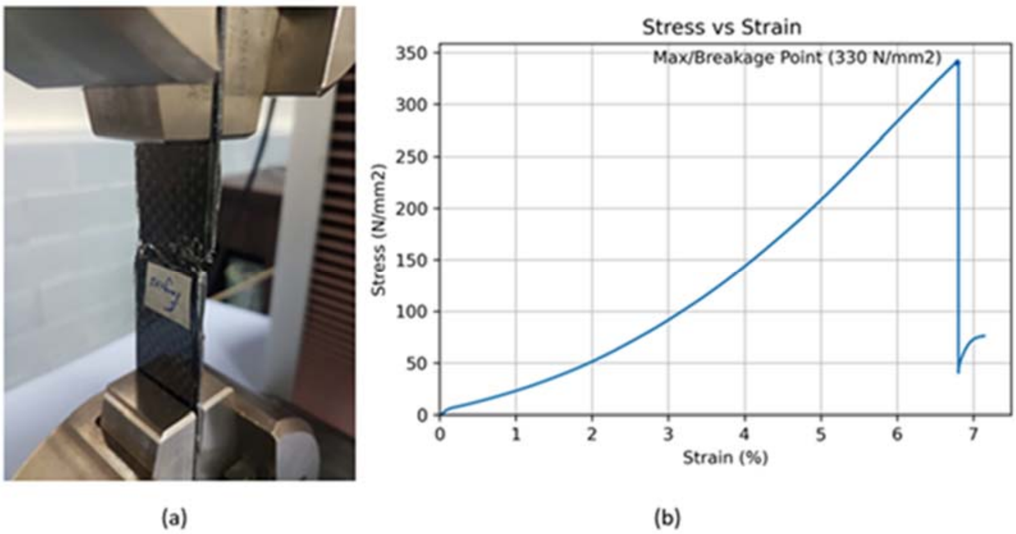


Figure 2. (**a**) Tensile Test for carbon-fiber composites in UTM (**b**) Mechanical behavior of carbon-fiber composites in UTM.

2.4. Design Concept of Prosthetic Foot

For the fabrication of a prosthetic foot prototype, the first step is the design construction using SolidWorks 2017 CAD software (version 25, Dassault Systèmes, Waltham, MA, USA). Three parts of the prosthetic foot (sole, keel, and heel) are designed using the approximate measurements of an average foot size (24.5 cm). The sole, keel, and heel dimensions are 24.5 cm $\times$ 9 cm, 19.2 cm $\times$ 7 cm, and 8.3 cm $\times$ 5 cm, respectively. The thickness of each part was kept equal to 0.7 cm, as the prosthetic footplates were manufactured using the same number of carbon-fiber layers. Figure 3 illustrates the CAD design and fabricated prosthetic foot prototype.

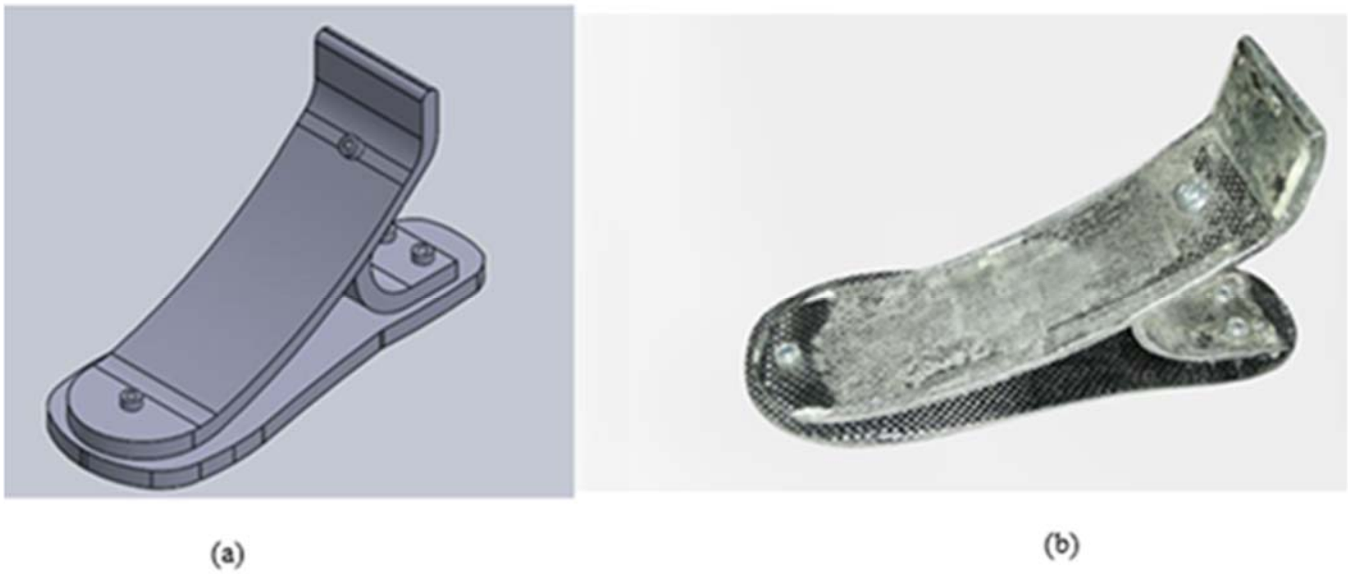
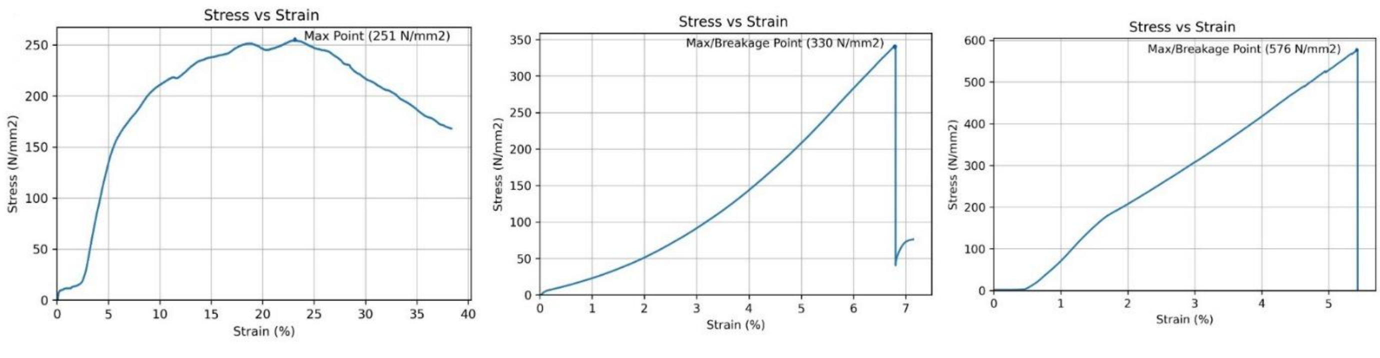


Figure 3. (**a**) CAD design for prosthetic foot prototype (**b**) Fabricated prosthetic foot prototype.

3. Results

The mechanical strength of three specimens of carbon-fiber laminates were tested using the universal testing machine. The first sample was prepared using two carbon-fiber layer reinforcements (0°/90°) and epoxy resin in a ratio of 100:30 by volume and tested to determine the maximum stress capacity. This two-layered sample exhibited a mechanical strength of 251 N/mm^2 before the failure of the carbon-fibers in the sample. Figure 4a depicts the ultimate tensile strength along with the failure of the tested sample.



(**a**) (**b**) (**c**)

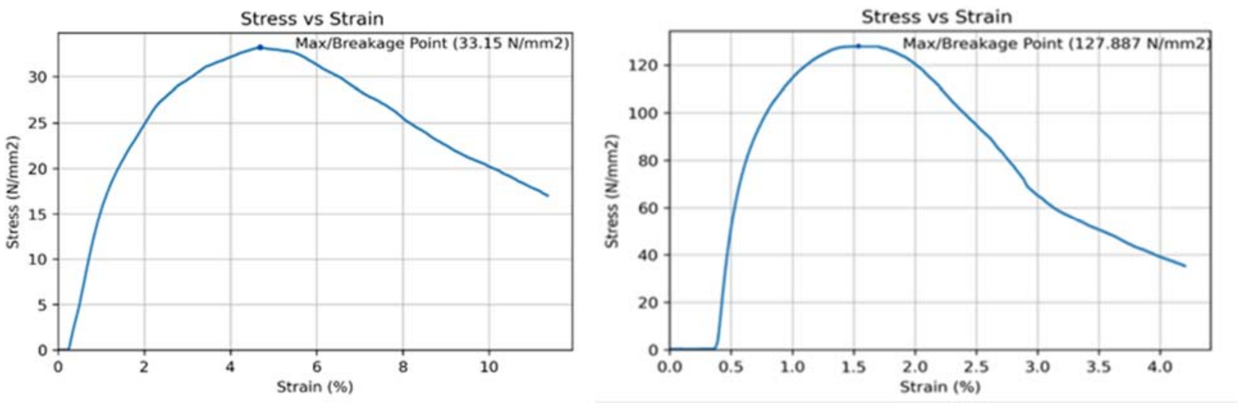
Figure 4. (**a**) Stress–strain Curve for Sample 1 (**b**) Stress–strain Curve for Sample 2 (**c**) Stress–strain Curve for Sample 3.

Similarly, the second laminated sample was prepared using the six layers of carbon fibers with the same ratio of two parts of epoxy resin. The increase in the number of CF layers increased the stress-enduring capability of the laminate. Table 3 shows the parameters obtained when tensile testing the carbon-fiber laminates along with the stress–strain curve generated by the universal testing machine. The stress–strain graph in Figure 4b shows a higher ultimate tensile strength for the sample in comparison to the previous one in Figure 4a. Secondly, the material breaks after reaching the yield point, which suggests the maximum load-bearing capability of the fibers. For this sample, 10 layers of carbon fiber were added along with the 100:30 of two parts epoxy resin. The mechanical properties of the sample are evident from the data and stress–strain curve in Figure 4c.

Table 3. UTM Generated Data for Carbon-fiber Composites.

Sample	Time (sec)	Stress (N/mm^2)	Strain (%)	Force (N)	Displacement (mm)	Stroke (mm)
	0	−0.06769	0	−2.26498	0	0
	0.1	−0.13361	0.044444	−0.54995	0.005333	0.005333
Sample 1	27.23	251.2207	18.88733	1034.025	2.266479	2.266479
	45.36	208.7001	31.47639	859.0095	3.777167	3.777167
	55.26	167.9828	38.35209	691.4171	4.60225	4.60225
	0	−2.85135	0	−98.3715	0	0
	0.1	−2.77994	0.002438	−95.9078	0.002146	0.002146
Sample 2	179.64	330.9781	6.805351	11,418.74	5.988708	5.988708
	188.58	75.94242	7.141951	2620.013	6.284916	6.284916
	188.4	75.85056	7.135014	2616.844	6.278812	6.278812
	0	−0.06769	0	−2.26498	0	0
	0.1	0.266715	0.006849	8.924802	0.005479	0.005479
Sample 3	52.1	576.079	5.426823	19276.75	4.341458	4.341458
	52.12	540.9233	5.429844	18100.37	4.34z3875	4.343875
	52.18	−0.29973	5.432031	−10.0295	4.345625	4.345625

Several samples showed abnormal behavior under the application of force by the universal testing apparatus. Figure 5a,b illustrate the stress–strain curve of the failure of several laminated samples. Most of these samples were tested at a lower load rate which resulted in different tensile behavior. Figure 5a,b depicts the stress–strain graph for the samples tested under a load rate of 2 mm/min in the Universal Testing Machine.



a **b**

Figure 5. (**a**) Stress–strain curve for two-layered sample (Failed Sample 1) (**b**) Stress–strain curve for four-layered sample (Failed Sample 2).

Prosthetic Foot Prototype Results

The prototype for the prosthetic foot was tested under a static load of 68,948 N/m^2 to check the displacement of footplates. Figure 6a shows the displacement under a load of zero. However, Figure 6b shows the displacement of footplates when a static load (68,498 N/m^2) was applied for a few minutes. The displacement recorded under the load is 10 mm in the heel section of the foot. The static loading on the fabricated prosthetic foot was performed to assess the stability. Various other methods such as cyclic loading, MTS testing, and ANSYS Static Structural Analysis can be used for further investigation of a prosthetic foot in terms of its range of motion [33]. However, due to the lack of the required apparatus for cycling loading, mechanical testing was performed using a static load.

Figure 6. (**a**) Initial 0 mm displacement in the heel section; (**b**) 10 mm displacement under static load.

4. Discussion

In the present study, tensile testing of carbon-fiber laminates indicates that increasing carbon-fiber content for composite fabrication can enhance mechanical strength. The mechanical properties of different samples are depicted in Table 4. Furthermore, the stress–strain curves generated by the universal testing machine can help to determine the mechanical properties of the used material. The stress–strain curve shows a linear behavior at certain points and non-linear curvatures at the start of the mechanical test. The linear sections of these graphs indicate that increasing the load on the laminates increases the strain rate along with a deformation of the fibers present in the sample, resulting in breakage of the tested carbon-fiber laminates. It was suggested by Wang et al. [34] that the failure of composites occurs when carbon fibers in the samples are fractured. The failure points in the reported study were observed at 470 MPa and 800 MPa, respectively. These failure stress points show the functional failure point of the composite sample.

Table 4. Mechanical Strength of Tested Carbon-fiber Laminates.

CF Layers	Load Rate	Epoxy: Resin	Mechanical Strength (N/mm^2)
2	2 mm/min	100:30	33.15
4	2 mm/min	100:30	127.88
2	5 mm/min	100:30	254.51
6	5 mm/min	100:30	341.54
10	5 mm/min	100:30	576.07

However, the non-linear regions in the stress–strain curve indicate the viscoelastic nature of the matrix, along with the brittle failure of the composite sample. Secondly, the slope in the stress–strain graphs show the initial stiffness of the carbon-fiber composites. The lowest tensile strength is shown by the two-layered laminates tested at a loading rate of 2 mm/min. To improve the tensile strength, other two-layered laminates were tested at an increased loading rate of 5 mm/min. Khan et al. [35] have reported a direct dependency of fracture strain and stress on the load rate in the case of carbon-fiber composites.

The increase in the number of layers in successive samples indicated a direct impact on the tensile strength of the carbon-fiber laminates, as evident from Figure 7. The tensile strength is mainly affected by the type of fiber used in the composition of the laminate. Furthermore, the applied matrix also varies the properties of the composite by improving the adhesion bond between carbon-fiber layers [28]. The mechanical properties of the composite materials also depend on the fabrication technique.

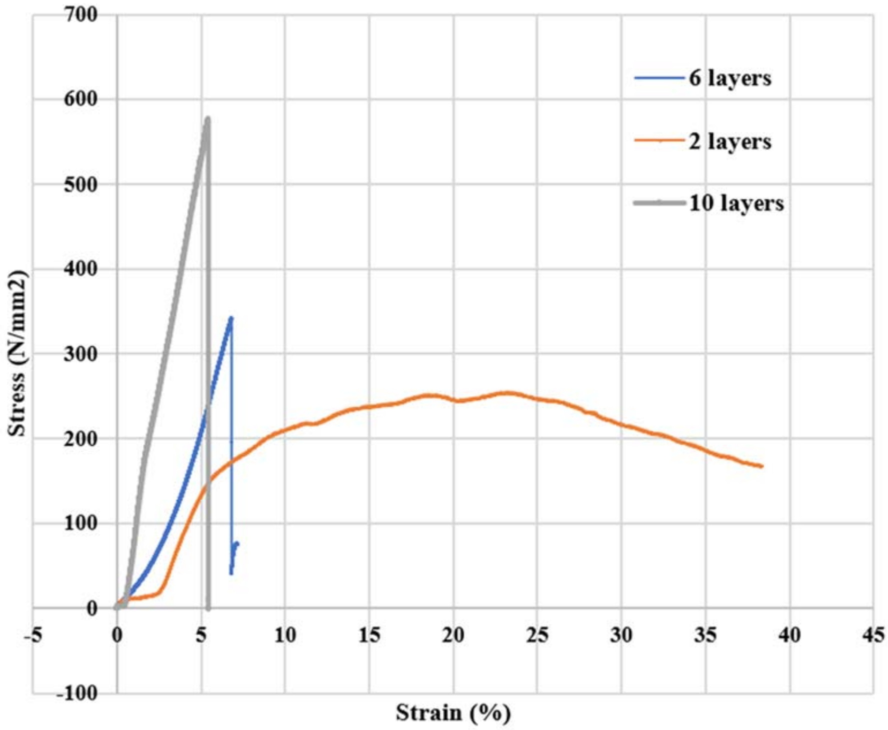


Figure 7. Stress–strain Superimposed scattered plot for tested carbon-fiber samples.

As evident from the stress–strain curves, the yield point (maximum point for linear behavior) is followed by the tensile deformation of the sample resulting from the failure of fibers under stress. The cross plies (0°/90°) are the major regions initiating the cracks in the composite samples. The breakage occurs in those areas in fiber structure which have a lower tensile strength than the ideal tensile strength of the unidirectional composites. For instance, one of these breakage points is depicted in the stress–strain graph for sample 2, which is at 351.54 N/mm^2. Moreover, failure of the reinforced fiber composites can also occur due to the formation of hollow spaces and the uneven distribution of the carbon-fibers in the epoxy matrix. Another issue in the failure of the mechanical testing is the slippage of the fibers in the grip section of the UTM. Concerning the reduced tensile strength, Khan et al. [35] have reported a direct dependency of tensile strength over the loading rate. Our study supported this dependency by depicting a reduced tensile strength and failure behavior at a loading rate of 2 mm/min, as illustrated in Figure 5a,b.

The deflection of the heel section under a high static load (68,948 N/m^2) shows that the prosthetic foot can withstand higher stress conditions. The minimum deflection of 10 mm also shows the lower probability of delamination of the fabricated carbon-fiber plates under static load. The tested carbon-fiber laminates with high mechanical strength can be used for multiple prosthetic and orthotic purposes.

Our research depicted different behaviors in the mechanical strength of the woven carbon-fiber composites than previously reported. Our study also simplified the overall manual process of the hand layup method by eliminating the vacuum bagging process, which was a commonly used procedure in previous studies, depicted in Table 5. Using the hand layup method can increase the probability of forming an uneven matrix and fiber distribution, along with hollow sections which can lead to the failure of carbon-fiber composites. The difference in mechanical behavior and non-linearity can be due to factors such as experimental settings and manufacturing techniques. Such factors must be modulated to improve the tensile behavior of carbon-fiber composites in future studies. Furthermore, carbon-fiber composites are considered an expensive material for prosthetic applications, which can be a limitation in manufacturing carbon-fiber composites on an industrial scale.

Table 5. Comparison of Findings of Previous Studies.

Previous Studies	Materials	Fabrication Method	Tensile Strength	Conclusion
(Muralidhara et al. 2020)	Carbon fiber: T800CF/Ep, T700CF/Ep, and T300CF/Ep Epoxy Resin: Araldite LY1564 Hardener: Aradur 22962	Hand layup method with vacuum bagging process	Approximately 680 MPa, 630 MPa, and 330 Mpa.	(2–6) % increase in the mechanical strength by vacuum bagging in comparison to the hand layup method.
(Chen et al. 2021)	Unidirectional carbon-fiber sheets Two parts epoxy resin	Hand layup method	The mean tensile strength of 13 CF samples showed an average tensile strength equal to 164.57.	The hand layup method provided higher stiffness and mechanical strength in flexure.
(Pham et al. 2020)	Dry carbon-fiber fabric Polyester resin	Hand layup method with vacuum bagging	Specimen tensile strength was found to be 243 Mpa.	The manufactured prosthetic foot prototype will enable forward propulsion lowering the impact force upon residual organs.
[36] (Karthik et al. 2021)	Glass, carbon, and Kevlar fibers	Hand layup method with compression molding	A mixture of carbon and Kevlar fibers indicated the highest tensile strength of 385.09 Mpa.	Carbon-Kevlar-Carbon composites showed fewer surface defects under stress.

5. Conclusions

In this research, the hand layup process was used with no vacuum bagging apparatus to investigate the impact of increasing carbon-fiber content on the mechanical strength of carbon-fiber composites. Through the optimization of this process, carbon-fiber composite plates were fabricated, which were used to construct a prosthetic foot prototype. Mechanical testing of various layered carbon-fiber composites under different loading rates (2 mm/min and 5 mm/min) depicted different tensile strengths. The minimum number of carbon-fiber layers (n = 2) demonstrated the lowest tensile strength of 254.51 N/mm^2. Subsequently, a slight improvement in the mechanical strength was observed in the six-layered composite sample, demonstrating a tensile strength of 341.54 N/mm^2. However, the ten-layered sample had the highest tensile strength of equal to 576.07 N/mm^2. The Universal Testing Machine results suggested that increasing the number of CF laminations can improve mechanical strength. The acquired results were different from the previously reported data in terms of having lower tensile strength. The difference in the tensile behavior might be the result of different experimental procedures. The hand-layup method is effective in improving flexural strength and stiffness of the material rather than tensile strength as evidenced by previous studies reported in this study. Secondly, the breakage of the specimen normally occurs at the cross plies after reaching the yield point, indicating the maximum stress that the specimen can withstand. The fracture behavior depicted the brittle behavior of the tested material. By controlling the environmental conditions and experimental parameters in future studies, the mechanical strength of the prepared composite samples can be further enhanced.

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