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Evaluating Fiber Volume Fraction and Defects in Fiber Reinforced Polymer Composites for T Joint applications

Sachin Yadav[1,]*, Ramkisan S. Pawar[2], Vithoba. Tale[3], Amogh Sambare[4], Ritesh Fegade[5], Somnath Kolgiri[6]

Abstract

Fiber-reinforced polymer (FRP) composites have been integral to industries such as aviation, aerospace, shipbuilding, and automotive due to their strength, durability, lightweight, and corrosion resistance. This study examines the production and microstructural analysis of polymer composites using FRP and manual lamination methods. While manual lamination is quick and economical, it relies on operator skill, resulting in low mechanical properties. Microstructure analysis via 3D optical and scanning electron microscopes revealed that structural defects, including voids and pores from incomplete matrix infiltration, significantly reduce composite strength. Comparative analysis showed composite laminates had twice as many defects as FRP. Evaluating fiber volume fraction in the matrix, influenced by microstructural space selection, is vital for assessing composite quality. This research highlights the importance of advancing manufacturing processes to reduce defects and improve the structural integrity of composite materials. Microstructural analysis plays a vital role in achieving this optimization. To investigate the composite T-joints, Scanning Electron Microscopy (SEM) along with Energy Dispersive X-ray Spectroscopy (EDS) were utilized. These methods offered in-depth information about the elemental composition, distribution, and bonding characteristics at the joint interface. To evaluate the mechanical performance of the composite T-joints, a series of mechanical tests were conducted, including tensile testing, three-point bending tests, Shore hardness tests, and water absorption tests. The combined results offer a comprehensive understanding of the structural integrity, durability, and environmental resistance of the composite T-joints, contributing to their potential application in load-bearing and moisture-prone environments.

Keywords: Composite materials, PVC (polyvinyl chloride), epoxy matrix, composite T-joint

***Author for Correspondence**
Sachin Yadav

[1]Assistant Professor, Department of Mechanical Engineering, Parvatibai Genba Moze College of Engineering, Wagholi, Pune, Maharashtra, India
[2]Principal, Department of Mechanical Engineering, Padmabhooshan Vasantdada Patil Institute of Technology, Bavdhan, Pune, Maharashtra, India
[3]Associate Professor, Department of Mechanical Engineering, Rajarshi Shahu College of Engineering, Tathawade, Pune, Maharashtra, India
[4]Assistant Professor, Department of Mechanical Engineering Deen Dayal Upadhyay KAUSHAL Kendra, Dr Babasaheb Ambedkar Marathwada University, Chh. Sambhajinagar, Maharashtra, India
[5]Associate Professor, Department of Mechanical Engineering, Parvatibai Genba Moze College of Engineering, Wagholi, Pune, Maharashtra, India
[6]Principal, Department of Mechanical Engineering, Parvatibai Genba Moze College of Engineering, Wagholi, Pune, Maharashtra, India

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INTRODUCTION

The use of fiber-reinforced polymer composites for industrial applications commenced in the 1930s. Initially, shipbuilding Industry started using composites mainly consisting of glass fibres and PVC foam [1]. Later on, fiber-reinforced plastics, due to their specific advantages, were mostly used in simple technological applications to complete structures. The primary factors that influence the choice of composites for various applications involve their strength, durability, weight, corrosion resistance, etc. Polymer composites, unlike metals, are characterized by their lightweight nature and superior corrosion resistance. If compared with ceramics, they are considered the most promising materials primarily due to their low energy production demands and high impact strength [2, 13].

The widespread integration of polymer composite into industries such as aviation, aerospace, shipbuilding and automotives is driven by these characteristic features [3, 18–20]. However, the future application of composite requires careful consideration during their design phase to achieve optimal properties and considerable lifespan. Therefore, tailoring these crucial properties of polymer composite involves combining matrix and fiber in specific proportions.

Proper fiber alignment in composite matrix plays a crucial role in defining strength and modulus of elasticity of final structure. Therefore, selection of manufacturing method is vital [4, 15–17]. During the design process, specifying final application working conditions and direction of loading with respect to fibre orientations needs to be addressed carefully.

The optimal effect is achieved when fibers are aligned in one direction, providing high strength in that specific direction. However, when fibers are woven into fabrics, the overall strength of the composite is lower but equal in all directions. Therefore, both the application and manufacturing methods of polymer composites must be considered when selecting a suitable polymer matrix [5, 20–22].

Nowadays, most researchers are exploiting single-species and multiple-species fibers in a polymer matrix in order to enhance their properties. In this case, microstructural examination of these structures is necessary to gain insights into the effects of multiple species fibers on polymer composite structure. The mechanical behavior of materials is strongly affected by their microstructural features, making their understanding essential [6, 27–30]. Such insights support the design of materials with enhanced strength and durability for diverse applications. Also, it will aid in optimizing the manufacturing process to enhance the overall performance of these composites. The objective of our work is to perform experimental analysis of glass fiber reinforced on PVC foam matrix for T joint applications. Natural fibers such as *Grewia monticola* have recently gained attention as potential reinforcements in polymer composites due to their renewable origin, low density, and favorable mechanical and chemical characteristics. Studies have shown that proper physico-chemical characterization of such fibers is essential to ensure their suitability for structural and semi-structural composite applications [23]. Kenaf and banana fibers have been explored as reinforcements for epoxy-based composites, particularly because of their eco-friendliness and good mechanical behavior even after moisture absorption. These investigations highlight the need to evaluate durability and wear performance when using natural fiber-reinforced composites in humid or saline environments [24].

MATERIALS

Polymer Composites with PVC Foam: A Versatile and Lightweight Material

Polymer composites incorporating PVC (Polyvinyl Chloride) foam offer a promising combination of the versatility of polymers with the lightweight and structural integrity provided by foam reinforcement. PVC foam is extensively used as a core material in sandwich structures due to its low density, high stiffness, and excellent chemical resistance. PVC foam, when embedded within polymer matrices like epoxy or polyester resins, improves the overall mechanical performance of composites. This enhancement makes the material highly applicable across industries such as aerospace, marine, construction, and automotive [7].

The addition of PVC foam to the polymer matrix improves the specific strength and stiffness of the composite while maintaining a lightweight structure. Because of its ability to reduce weight while maintaining performance, PVC foam is widely preferred in lightweight structural applications. In addition, it enhances the thermal and acoustic insulation characteristics of composites, broadening their potential uses. During fabrication, PVC foam offers excellent formability, enabling the creation of customized designs and complex geometries.. The foam can be infused or laminated with the polymer matrix using techniques such as vacuum bagging, resin transfer molding (RTM), or infusion processes to ensure proper adhesion and distribution of forces within the composite structure [8, 34–36]. Overall, polymer composites with PVC foam offer a cost-effective solution with excellent mechanical properties, lightweight characteristics, and versatility, making them a preferred choice for a wide range of industries and applications. Emerging research has identified aerial root fibers from species such as *Ficus retusa* as sustainable alternatives to synthetic fibers in composite manufacturing. Their mechanical and thermal properties make them promising candidates for reducing dependence on petroleum-derived reinforcements [25]. Agro-waste-derived materials, such as microcrystalline cellulose obtained from citrus peel residues, have been shown to provide valuable reinforcement potential in polymer composites. Such approaches not only enhance composite performance but also promote sustainable material development by utilizing bio-based waste streams [26].

Polymer Composites with PVC Powder

Polymer composites with PVC powder offer a unique set of properties and advantages for various applications. When combined with a polymer matrix, such as epoxy or polyester resin, PVC powder enhances the mechanical, thermal, and chemical resistance properties of the composite material [9].

One of the key benefits of using PVC powder in polymer composites is its ability to improve the impact strength and toughness of the material. Its ability to provide durability and withstand impacts makes it highly suitable for use in construction materials, sporting equipment, and automotive parts. Moreover, the addition of PVC powder improves the fire-retardant characteristics of composites, extending their application to areas where fire safety is essential, including electrical housings and building materials.

The incorporation of PVC powder into polymer composites also offers advantages in terms of cost-effectiveness and ease of processing. PVC powder is readily available and relatively inexpensive compared to other reinforcing materials, making it an attractive option for manufacturers looking to reduce production costs without compromising on quality. PVC powder can be uniformly incorporated into polymer matrices through conventional techniques like extrusion, compression molding, and injection molding. This processing flexibility enables the production of intricate components with reliable dimensional stability and consistent mechanical performance [10–11, 31–33]. Consequently, polymer composites reinforced with PVC powder present a cost-effective and adaptable solution, offering improved mechanical, thermal, and chemical characteristics. Such composites are widely utilized in sectors including construction, automotive, electronics, and consumer goods, where durability, efficiency, and performance are essential.

Hybrid Configurations in Polymer Composites

There are several configurations for hybrid polymer composites, as depicted in Figure 1. One approach involves stacking layers of different fiber types, as shown in Figure 1(a), which is the simplest and most cost-effective method of hybrid composite manufacture. Another configuration involves interweaving different fiber types into fabric layers, as illustrated in Figure 1(b). Also, hybrid composites can be created by mixing two types of fibers on a fiber scale, resulting in an intrayarn hybrid, as depicted in Figure 1(c).

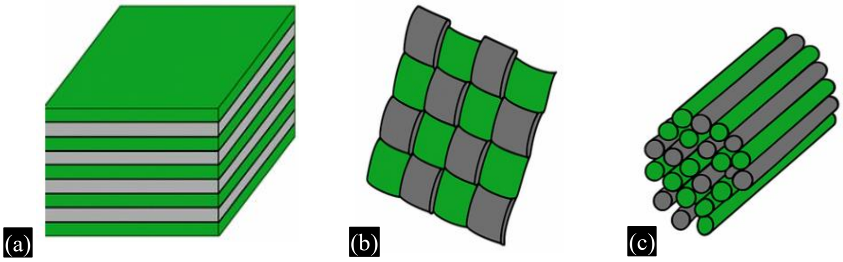


Figure 1. The three main hybrid configurations [12]. (a) layer-by-layer, (b) yarn-by-yarn, (c) fibre-by-fibre

MANUFACTURING TECHNOLOGIES FOR COMPOSITE MATERIALS

Currently, numerous manufacturing technologies are continuously being developed and enhanced. The most widely used manufacturing technique for composite materials is the wet hand lay-up lamination method, also known as contact pressing. This method is faster and cheaper compared to vacuum infusion.

The principle of hand lay-up, as shown in Figure 2, involves manually applying resin and dry fabric reinforcement into a mold fitted with a release agent. The process begins with applying a layer of resin, followed by a layer of reinforcement. The resin is then pressed into the reinforcement using a roller until it is sufficiently wet and free of air bubbles. The layering steps are continued successively until the composite reaches the required thickness. After curing at room temperature, the final product is removed from the mold.

Advantages of this method include its ease of execution, the ability to create shapes and dimensions with unlimited variability, and minimal manufacturing expenses. However, hand lay-up lamination also has disadvantages, such as low productivity, only one finished surface, and a final product that heavily depends on the operator's skill and attention to detail.

Specifications and Fabrication of Composite Specimens

Specified properties of the fabrics used for composite manufacture are listed in Table 1. Two types of composites were prepared for mechanical testing: one with carbon fiber reinforcement and the second with a composite laminate impregnated with epoxy resin.

For preparation of composite T-joint specimens, six fabric layers were used to achieve a thickness of approximately 15 mm, matching the size of the mold. A laminated desk served as the mold, covered with a release agent and polished to prevent resin adhesion during curing. Epoxy resin compatible with all three fabric types, was used as the hardener in a weight ratio of 100 parts resin to 40 parts hardener. This resin, known for its low viscosity, ensured effective fiber wetting and resulted in a lightweight composite. It cures quickly at room temperature, with a density ranging from 1.01 to 1.23 g/cm^3 at 25°C. The layering process involved applying resin to the mold, placing a fabric layer, and wetting it with more resin. This sequence was repeated until the desired specimen thickness was achieved. After curing at room temperature for about 24 hours, the finished plates were removed from the mold and cut into individual test specimens using machine saw methods.

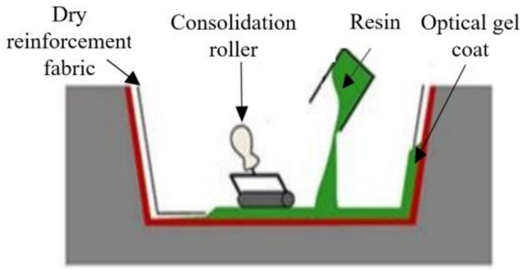


Figure 2. Principle of hand lay-up method [14].

Table 1. Specification of the Fabric

Property	**Fibre Reinforced Polymer (FRP)**	**Composite Laminate**
Weave	Plain	Plain
Areal Density $[g\cdot cm^{-2}]$	160	164
Density $[g\cdot cm^{-3}]$	1.76	1.76/1.44
Fibre Specification	HS 3K 200 tex	HS 3K 200 tex / 2 200 121 tex
Producer	Toray	Toray / Twaron

MECHANICAL TESTING

Mechanical properties were assessed through static tensile and bending tests. Table 2 provides a comparison of these mechanical properties obtained from testing the composite T-joint specimens.

Density analysis for the composition of PVC + Epoxy + Glass Fiber involves determining the density of the composite material formed by combining these components. Such analysis plays a key role in determining the mass and volumetric properties of the composite.

The process of density analysis involves analyzing the components of a composite material, such as PVC, epoxy resin, and glass fiber, using a precise weighing scale. The volume of each component is calculated, with irregular shapes like glass fiber, using displacement or geometric methods. The composite material is formed by mixing the components in the desired ratios, ensuring uniform distribution. Density is then determined using various formulas, which is crucial for understanding the material's properties, including strength and durability.

From Table 3, the calculated values are:

- Composite Weight in Air = 4.7116 g
- Composite Weight in Water = 4.6263 g
- Relative Density = Weight in Air / Weight in Water
- Relative Density = 4.7116 / 4.6263
- Relative Density = 1.01 g/cm³

This calculation provides the density of the composite material expressed in mass per unit volume, such as grams per cubic centimeter (g/cm³).

By conducting density analysis, manufacturers and researchers can optimize the composition of PVC + Epoxy + Glass Fiber composite to meet specific requirements related to weight, strength, and other mechanical properties.

Microstructure Evaluation by 3D Microscopy

Electron microscopy is a more challenging but far more detailed method for the microstructure study of investigated specimens. As in the case of 3D microscopy, the microstructure of carbon composite (Figure 4) and composite with hybrid reinforcement was also assessed using electron scanning microscopy.

Delamination and edge-related damage in composite laminates were examined using a stereo microscope before conducting SEM analysis, as illustrated in Figures 3 and 4. The combination of high stiffness and strength-to-weight ratio makes composite materials well-suited for a wide range of structural applications.. It is essential to predict their failure behavior under loading.

Table 2. Comparison of mechanical properties of selected composite T-joints.

Property	**Fibre Reinforced Polymer (FRP)**	**Composite Laminate**
Tensile Strength σt [MPa]	452.2 ± 56.4	350.7 ± 15.0
Tensile Modulus E [GPa]	29.9 ± 1.6	22.3 ± 1.6
Total Strain εt [GPa]	2.9 ± 0.4	2.7 ± 0.3
Flexural Strength σ [MPa]	336.2 ± 15.0	288.3 ± 10.0

Table 3. Theoretical density

Parameter	**Glass Fiber (g/cm³)**	**Epoxy (g/cm³)**	**PVC (g/cm³)**
Density	2.54-2.60	1.2-1.3	1.48

Figure 5 shows that EDS can be used to identify the composing elements of a material's surface. The higher the peak (Si K) at 24.57% weight and 17.14% atomic concentration indicates a higher concentration of that element. While EDS cannot provide details about chemical bonding, it is widely used for both qualitative and quantitative elemental analysis. The system automatically detected elements such as C k, O k, Si k, Fe k, Ti k, etc. Also, we manually verified the presence of K, Si, Ti, Fe, Mg, Na, and Al. Among these, only Na and Ti were detected in small amounts originating from the PAAm.

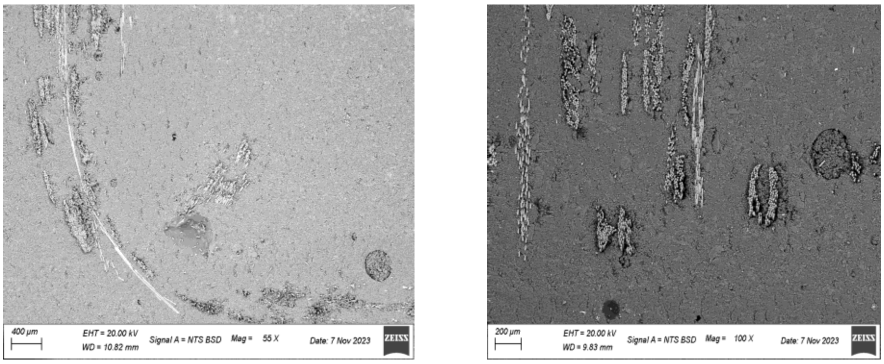


Figure 3. SEM analysis of defects in the microstructure of the FRP.

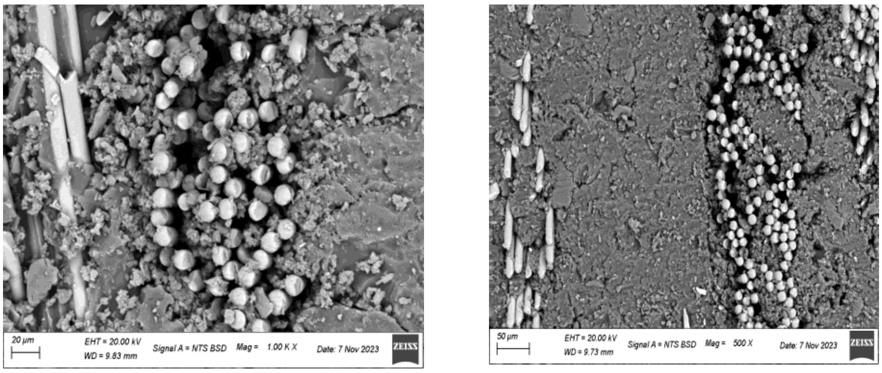
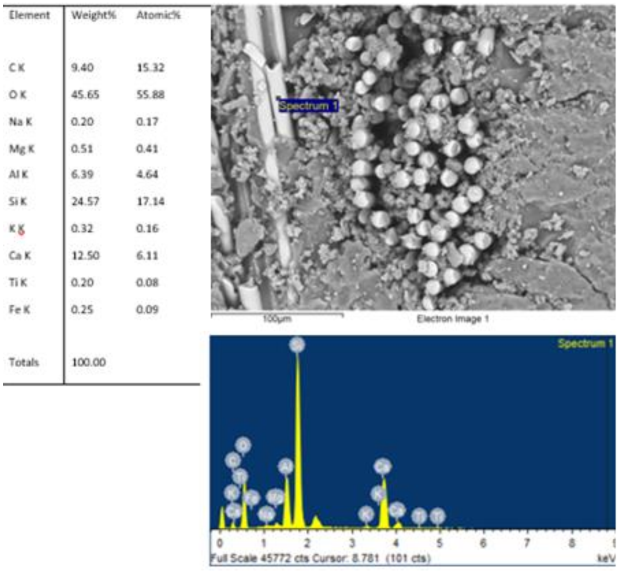


Figure 4. SEM analysis of defects in the microstructure of the Overlaminate.



Element	Weight%	Atomic%
C K	9.40	15.32
O K	45.65	55.88
Na K	0.20	0.17
Mg K	0.51	0.41
Al K	6.39	4.64
Si K	24.57	17.14
K K	0.32	0.16
Ca K	12.50	6.11
Ti K	0.20	0.08
Fe K	0.25	0.09
Totals	100.00	

Figure 5. X-ray spectrum is acquired, and elements are identified and labeled. The higher the peak, the higher the concentration of that element.

SEM analysis confirmed that the microstructure of the Fiber Reinforced Plastic (FRP) and the composite laminate contains numerous defects, primarily voids and pores, as depicted in Figure 4, Figure 5,. This is attributed to uneven fiber matrix penetration. Insufficient cohesion occurs at fiber ends or intersections, resulting in localized shear stress that aligns with tensile forces. Consequently, cracks develop, propagating through weak points between fibers, ultimately leading to matrix failure.

Experimental Stress Analysis

In the experimental stress analysis, tensile, 3-point bending, Shore, and water absorption tests were conducted. The tensile test was performed on a Universal Testing Machine with three different angles of the composite T-joint.

Tensile Test

In the static tensile test of the composite T-joint, the specimen is positioned on the load cell located at the top of the T-panel, and the load is applied directly to the upper part of the joint. Figure 6 illustrates the testing setup with the sample fixed in the machine. The base of the rig is a heavy section measuring 1800 mm in length. Required parameters and dimensions of the composite T-joint are input into the software. The ASTM D638 test method was used for testing the composite T-joint. Three different tests were conducted with the same dimensions of the composite T-joint, with only the filler angle being changed.

Load Vs Displacement

Figure 7 presents the load–displacement plot for one of the three tested specimens. An initial load of approximately 0.2 kN is observed, which results from pre-stressing and the self-weight of the two square steel tubes. The central portion of the load–displacement response shows an almost linear behavior up to about 5 kN.

ASTM D638 testing of the composite T-joint involves subjecting the specimen to a tensile load while recording its mechanical response. This test is carried out using a universal testing machine, commonly referred to as a tensile testing machine. Three different composite joints were tested under the same dimensions, with only the orientation of the angle of the triangle being changed. Due to changing the orientation of the angle, different loads and deflections were observed for each specimen shown in figure 7, 8 and 9.

Therefore, all three composite T-joints were compared to find the optimal angle of the triangle for sustaining higher loads. The table 4 below presents a comparison of load and deflection values for the three composite T-joints. From the results, it can be inferred that the 90°/45°/45° configuration exhibited superior strength when compared with the 90°/60°/30° and 60° joints.

The crack initiated from the interface between the over laminate and bottom skin through core A at about 8.389 KN after 12.72 mm displacement. The load versus displacement curve is shown in Figure 7, 8 and 9.

Figure 6. Composite T joint mounted on UTM for Tensile test.

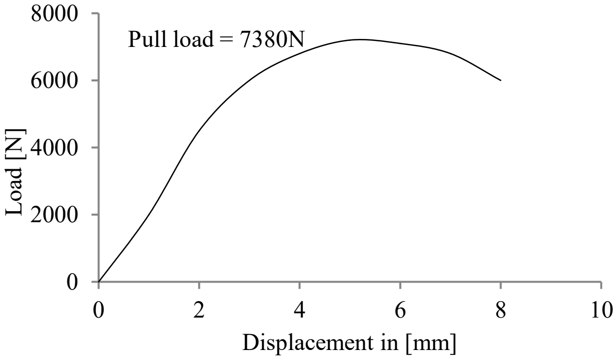


Figure 7. Load vs. displacement graph for 90°/60°/30° in Tensile test.

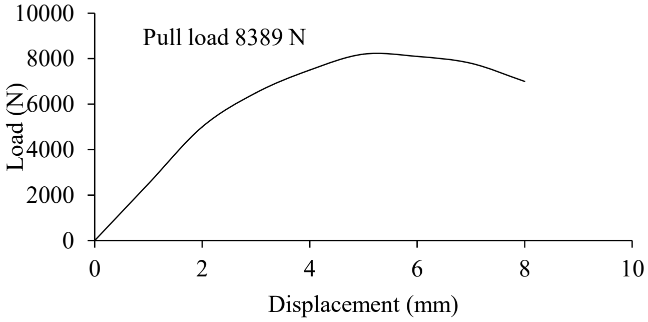


Figure 8. Load vs. displacement graph for 90°/45°/45° in Tensile Test.

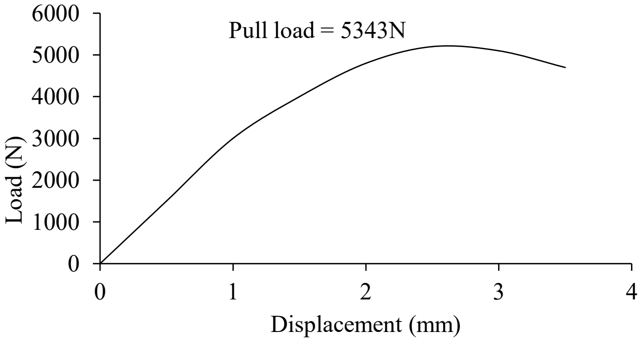


Figure 9. Load vs. displacement graph for 60° in Tensile Test.

Table 4. Comparison of Load and Deflection of Three Composite T-Joints in Tensile Test

Load [N]	**Displacement 90°/45°/45° [mm]**	**Displacement 90°/60°/30° [mm]**	**Displacement 60° [mm]**
0	0	0	0
1000	0.5	0.4	0.25
2000	0.8	1	0.7
3000	1	1.6	0.8
4000	1.5	2	0.9
5000	1.8	2.4	1.2
5343	1.9	2.5	5.22
6000	2.2	3.6	-
7000	2.4	5.8	-
7380	2.6	8.88	-
8000	4.4	-	-
8389	12.72	-	-

Three Point Bending Test

The three-point bending test was conducted on a universal testing machine. The applied velocity of the bending load was 2 mm/min. Figure 12 shows the load configuration for a beam in a three-point bending test. Load–displacement plots were obtained for each test specimen. The dimensions and all the procedures of the three-point bending test were in accordance with the standard ASTM D695. The three-point bending test conducted on the composite T-joint is illustrated in Figure. 10 and the load–displacement behavior for 90°, 60°, and 30° orientations obtained from the bend test is shown in Figure. 11. As illustrated in Figure 13, the 60° orientation exhibits a characteristic load–displacement behavior under flexural loading

Figure 10. Three-point bending test on composite T joint.

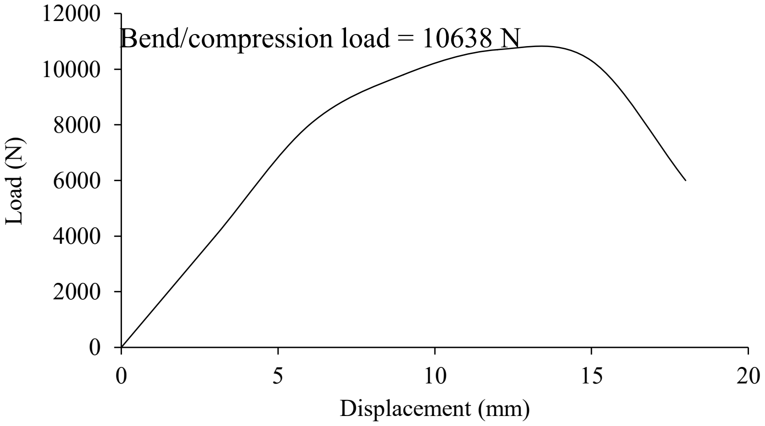


Figure 11. Load vs. displacement graph for 90°/60°/30° in bend test.

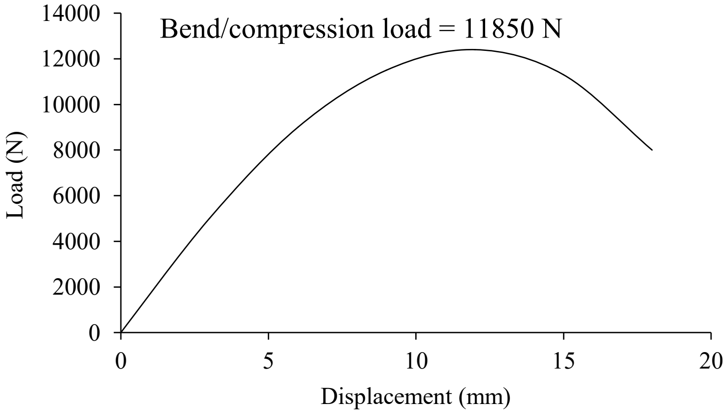


Figure 12. Load vs. displacement graph for 90°/45°/45° in bend test.

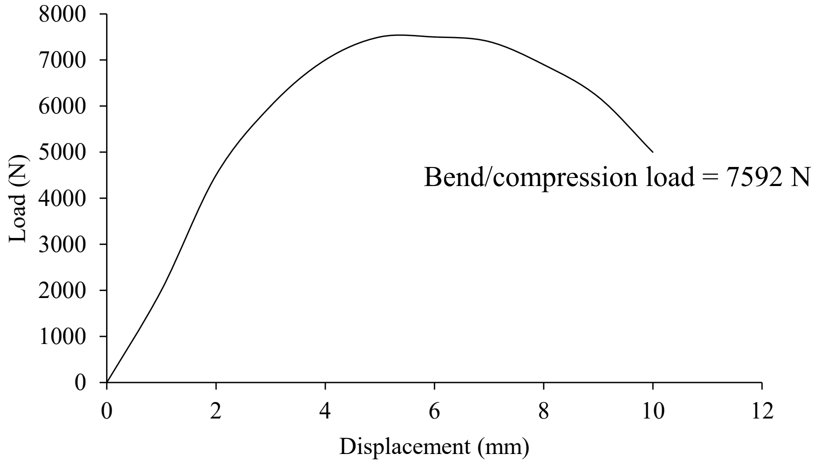


Figure 13. Load vs. displacement graph for 60° in bend test.

Table 5. Comparison of Load and Deflection of Three Composite T-Joints in Three-Point Bend Test

Load [N]	Displacement 90°/45°/45° [mm]	Displacement 90°/60°/30° [mm]	Displacement 60° [mm]
0	0	0	0
1000	1.2	1.4	0.5
2000	1.5	1.9	1.2
3000	2.2	2.3	1.6
4000	2.8	3	2
5000	3	4.1	2.5
6000	3.8	4.5	3.1
7000	4.2	4.7	3.9
7380	4.4	5.1	4.2
7592	4.5	5.2	9.4
8000	5.6	6	-
9000	5.9	7.5	-
10000	6	9	-
10638	10.2	19.39	-
11850	20.79	-	-

STM D695 testing of the composite T-joint is carried out by subjecting the specimen to a compressive (bending) load and evaluating its response under applied stress. This procedure is performed using a universal testing machine, also known as a tensile testing machine.

Three different composite joints were tested under the same dimension, with only the orientation of the angle of the triangle being changed. Due to the change in orientation of the angle, different loads and deflections were observed for each specimen. Therefore, all three composite T-joints were compared to find the optimal angle of the triangle for sustaining higher loads. The above Table 5 presents a comparison of load and deflection values for the three composite T-joints. The conclusion drawn is that the 90°/45°/45° T-joint provided better strength compared to the 90°/60°/30° and 60° T-joints in the three-point bending test.

Shore Test

To determine the hardness of the composite material, the standard states that ten measurements are taken, from which the average value is calculated. Before testing, the material is stored at a room temperature of 25°C for one hour. A total of three tests were conducted on the Base Composite, Triangular core at 90°/60°/30°, and Triangular Core at 90°/45°/45° degrees, as shown in Figure 14.

Table 6 shows the Comparison of Shore Hardness Test (ASTM D2240) of three different composite joints. The Base Composite and the 90°/45°/45° triangular core, and the 90°/60°/30° angle of the triangular core exhibited better hardness values.

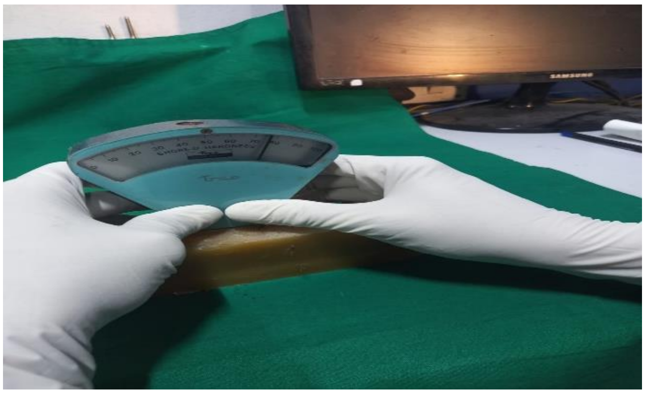


Figure 14. Checking Shore D hardness of Composite T-joint.

Table 6. Comparison of Shore Hardness Test for 90°/45°/45°, 90°/60°/30°, and 60°

Parameters	90°/45°/45°	90°/60°/30°	60°
Point 1	75	71	80
Point 2	77	73	79
Point 3	75	71	79
Point 4	74	72	80
Point 5	77	73	78
Point 6	75	74	79
Point 7	74	72	78
Point 8	77	73	80
Point 9	75	72	80
Point 10	76	71	79

Table 7. Water Absorption Test Results for TJ-1, TJ-2, and TJ-3

T-Joints	Length (L) (mm)	Height (H) (mm)	Thickness (t) (mm)	Initial Weight (g)	Final Weight (g)	Water Absorption (%)
TJ-1	200	70	6	10.0	10.0	0
TJ-2	200	70	6	10.0	10.3	0.3
TJ-3	200	70	6	10.0	10.4	0.4

Water Absorption Test

The maximum percentage of water absorption for the manufactured composite T-joint was investigated. The samples were completely submerged in salty water and were taken out of the water after 15 days of immersion. After wiping the surface moisture with a clean, dry cloth, the samples were weighed. Before conducting the water absorption test, the component's dimensions were 4.4 mm in length, 6.5 mm in height, and 1.4 mm in thickness.

Effect of Moisture on Composite Material

In order to investigate the effect of salty water on the composite material, the composite material was immersed in salty water for 150 days, and accordingly, specimen dimensions and strength were calculated. The details are mentioned in the Table 7 above.

The water absorption percentages of the three sample types TJ-1, TJ-2, and TJ-3 are contrasted in the table 3. TJ-1 and TJ-2 are identical in size, and after rising in weight from 10.0 to 10.0 grams, TJ-1 absorbs 0% of the water (0.0 grams). TJ-2's weight increased to 10.3 grams after absorbing 3% (0.3 grams) and TJ-3's weight increased to 10.4 grams after absorbing 4% (0.4 grams). In comparison to the TJ samples, the TJ-1 sample exhibits superior water resistance since it does not absorb any water and retains its initial weight of 10.0 grams.

CONCLUSIONS

Composite materials reinforced with fabric are heterogeneous, featuring a complex and often porous structure. Achieving homogenous distribution, even at the microstructural level, is challenging. Microphotographs provide the primary means to gather data on composite structure, facilitating direct assessment of reinforcement, matrix, or void morphology.

The study's objective was to produce and analyze the microstructure of polymer composite materials based on theoretical as well as practical knowledge. Using the Fibre reinforced composite (FRP) and manual lamination method, we produced composite materials with fiber-reinforced plastic and composite laminate. Although the composite laminate method is quick and economical, its accuracy relies on the operator's skill. These materials exhibited low mechanical properties, prompting microstructure analysis using a 3D optical microscope and a scanning electron microscope.

Analysis of the composites' microstructure indicates that mechanical properties are influenced by the fiber-to-matrix ratio and are affected by structural defects such as voids, holes, pores, and cracks. Voids and pores arise from incomplete matrix infiltration between fibers during production, contributing to reduced strength parameters. Comparing composite laminate with a Fibre Reinforced Composite (FRP), the composite laminate exhibited more defects. In contrast, the composite laminate displayed approximately half as many defects. Evaluating the volume fraction of fibers in the matrix yields approximate results, influenced by the selection of representative microstructural spaces for assessment. Assessing these factors is essential for evaluating the quality and performance of the composite material. By reducing such defects through improved manufacturing methods, the structural integrity of the final product can be significantly enhanced.

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