EFFECT OF BRAID ARCHITECTURE AND RESIN TRANSFER PROCESS ON THE MECHANICAL PROPERTIES OF 3D BRAIDED COMPOSITE

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ABSTRACT

This study investigates the effect of braid architecture and resin transfer process on the mechanical properties of 3D braided carbon composites. PAN-based carbon fibres (300D, tensile strength 3.2 GPa, modulus 340 GPa) were used to fabricate biaxial and triaxial braided structures on a 16-carrier Maypole braiding machine. The braid angle was varied by employing different take-up roller teeth (36T, 42T, and 50T), producing braid angles in the range of approximately 53°–70°. The braided preforms were evaluated in dry form and after impregnation epoxy resin using a dosing pump–based resin transfer technique.

Tensile strength, tensile modulus, and flexural strength were determined to assess the mechanical performance. The results indicated that decreasing braid angle significantly improved tensile strength and modulus for both architectures due to enhanced fibre alignment along the loading direction. Triaxial braids consistently exhibited superior tensile and flexural performance compared to biaxial braids, owing to the presence of axial yarns that enhanced load transfer and structural stability. Resin treatment substantially improved mechanical properties, with increases of up to approximately 70–80% in tensile strength and notable enhancement in stiffness and bending load capacity. The highest mechanical performance was achieved for triaxial composites produced at the lowest braid angle (50T). Overall, the findings confirm that braid architecture, braid angle, and resin transfer processing play a critical role in tailoring the mechanical behaviour of 3D braided carbon composites. Optimized triaxial configurations combined with effective epoxy impregnation are recommended for high-performance structural applications requiring enhanced strength, stiffness, and flexural resistance.

.INTRODUCTION

Carbon fibre–reinforced composites have gained widespread acceptance across aerospace, automotive, marine, and structural applications due to their outstanding mechanical and chemical properties, including high tensile strength, low density, excellent thermal resistance, and superior chemical inertness. These composites are broadly classified into thermoset and thermoplastic systems. Thermoset matrices, particularly epoxy resins, are widely preferred because of their superior interfacial bonding and mechanical performance, whereas thermoplastic matrices such as polyester and polypropylene are used where recyclability and processing flexibility are required.

99

Carbon fibre composites can be manufactured through various textile preform architectures, including woven, knitted, nonwoven, and braided structures in both two-dimensional (2D) and three-dimensional (3D) forms. Among these, braided composites exhibit enhanced toughness and fatigue resistance compared to conventional filament-wound structures. Unlike woven fabrics, which possess orthogonal interlacements, braided structures can be engineered over a wide range of braid angles (typically 10°–85°), enabling tailored mechanical performance [1]. Furthermore, braided composites demonstrate improved interlaminar shear strength and reduced susceptibility to delamination under fatigue loading due to their integrated architecture [1]. The inherent structural continuity of braids allows efficient load distribution throughout the reinforcement, contributing to superior impact resistance and structural integrity [2].

Braiding is an established textile manufacturing technique involving the intertwining of three or more yarn systems at defined angles, where each yarn passes alternately over and under others without forming adjacent twists. This structural configuration enhances transverse modulus, transverse strength, damage tolerance, dimensional stability, and near-net-shape manufacturing capability [3]. The mechanical performance of braided composites is primarily influenced by parameters such as braid angle, braid type (biaxial or triaxial), and architectural configuration. Sun et al. [4, 5] investigated the compressive and uniaxial tensile behaviour of four-step 3D braided composites under high strain rates and reported pronounced rate-dependent properties. Among available techniques, the Maypole braiding machine is extensively used for producing tubular braided preforms.

Although significant research has addressed various applications of braided composites, limited literature is available on 3D carbon braided tubes considering variations in braid architecture and resin transfer techniques. In particular, comparative studies evaluating biaxial and triaxial 3D carbon braided tubes with varying braid angles and diameters, both in dry form and after resin impregnation, remain scarce. Therefore, the present study aims to investigate the influence of braid architecture and resin transfer processing on the mechanical performance of 3D braided carbon composites.

MATERIAL AND METHODS

Braiding sample preparation

In this study PAN based carbon fibre is used with the specifications of fibre were 300D linear density with tensile strength 3.2 GPa and tensile modulus 340GPa. The braided samples of carbon fibre were made on Maypole braiding machine with 16 horn gears or bobbin. The biaxial and triaxial samples were made by using different take up rollers 36T, 42T, 50T. These take up rollers decide the braiding angle of the braiding structure. As the teeth of take-up roller are increased the

braiding angle decreased significantly. Process variables are given below in table-1 and the figure-1 shows the carbon braided sample that is prepared for the study.

Table 1 - Process Variables for Braiding Samples

Teeth	Biaxial		Triaxial	
	Angle (A^0)	Diameter (mm)	Angle (A^0)	Diameter (mm)
36T	70.19	3.73	68.61	4.65
42T	55.85	3.90	62.35	4.45
50T	53.53	4.05	52.62	4.38

Figure 1- Microscopic View of Carbon Braided Sample

Resin molding on the braided samples

The samples were treated with compatible epoxy thermo-set resin (reinforced polymer) named Araldite 230-1 CY and hardener, a curing agent was Aradur N - 951 HY. The resin epoxy is used as the resin matrix to efficiently hold the fiber is place. In the earlier studies the technique used for resin transfer were based on VARTM (Vacuum Assist Resin Transfer Molding) principal. But the samples made for the experimental purposes were three dimensional round shaped and VARTM technique were found not suitable for resin transfer. Because, VARTM mainly used for molding of woven or two dimensional fabrics are. When the VARTM did not work then another technique dosing pump was used. With the dosing pump for spotless penetration of resin inside the braided structure, PVC pipes of 6mm and 8mm diameter were taken for the biaxial and triaxial respectively.

Procedure for the resin transfer

First the resin solution was prepared in 10:1 ratio (ten parts of resin and one part of hardener) and then manually stirrer it about 15 to 20 min. continuously till the solution got well mixed. Then the braided samples were passed through the hollow PVC pipe, biaxial from 6mm diameter pipe and triaxial form 8mm dia. pipe respectively because triaxial have bigger diameter than biaxial. The samples were tied from one end with high tenacity yarn and drawn the specimen through pipe. There-after the pipes were fixed on the outlet nose of the dosing pump, and the inlet nose of the pump dipped into the resin solution. Then the pump started and it picked up the resin from the inlet side and inject at the outlet side. In the dosing pump, a piston moves in too n fro which creates the suction and dosing or injecting, when it moves in backward direction it creates suction and in forward direction it creates high pressure dosing. The dosing pressure was kept on trial and error basis $4kg/cm^2$, at this pressure the resin completely impregnated into the specimen.

TEST METHODS

The resin-moulded carbon braided composite specimens were evaluated for tensile properties, including breaking strength and tensile modulus, using an Instron Universal Testing Machine in accordance with ASTM D3039. The gauge length was maintained at 200 mm, with a full-scale load capacity of 5000 N. The crosshead speed was set at 2 mm/min, and five specimens were tested to ensure reproducibility of results.

Flexural properties were determined through a three-point bending test conducted as per ASTM D790. A three-point bending fixture was attached to the Instron Universal Testing Machine for this purpose. The specimens were supported at both ends over a span length of 77 mm and loaded centrally using a loading nose. To prevent slippage during testing, the total specimen length was kept at 110 mm. The test was performed at a crosshead speed of 20 mm/min, and five observations were recorded. Flexural strength values were obtained up to the point of specimen failure.

RESULTS AND DISCUSSION

Tensile strength

The tensile strength behaviour of 3D braided carbon structures was significantly influenced by braid architecture, braid angle, and resin treatment as shown in table 4.1 and fig 4.1. Untreated biaxial and triaxial braided samples exhibited a clear dependence of tensile performance on braid angle. Tensile strength of biaxial braids as well as triaxial braids increases as braid angle decreases. This trend indicates that decreasing braid angle enhances axial load-bearing capacity, as fibres become more aligned with the tensile loading direction.

A comparison between braid architectures reveals that triaxial braids consistently demonstrated higher tensile strength than biaxial braids under corresponding process conditions. The superior performance of triaxial structures can be attributed to the presence of axial yarns, which directly contribute to load carrying along the tensile axis and improve structural stability. The additional yarn system also promotes more efficient stress redistribution within the braided network.

Resin impregnation through a dosing pump–based resin transfer process significantly enhanced tensile strength in both architectures. After treatment, biaxial samples showed tensile strengths of 2287 N, 2900 N, and 3275 N for 36T, 42T, and 50T, respectively. Corresponding triaxial samples exhibited even higher values of 3287 N, 3583 N, and 3925 N. The improvement in tensile strength after resin treatment ranged approximately from 60% to 78%, depending on braid type and angle. This enhancement is primarily due to improved fibre–matrix interfacial bonding, reduced fibre slippage, and more effective stress transfer between filaments. The cured thermoset matrix also increased structural rigidity and minimized internal deformation during loading.

The highest tensile strength (3925 N) was obtained for the triaxial braid at the lowest braid angle (52.62°, 50T) after resin treatment, demonstrating the combined beneficial effect of optimized fibre orientation and matrix reinforcement. Overall, the results confirm that both braid architecture and resin transfer processing parameters play a crucial role in determining the tensile performance of 3D braided carbon composites. Lower braid angles and triaxial configurations, when combined with effective epoxy impregnation, provide superior tensile properties suitable for high-performance structural applications.

Table 4.1- Tensile Strength of Carbon Biaxial and Triaxial Braid with Different Braid Angle and Resin Treatment

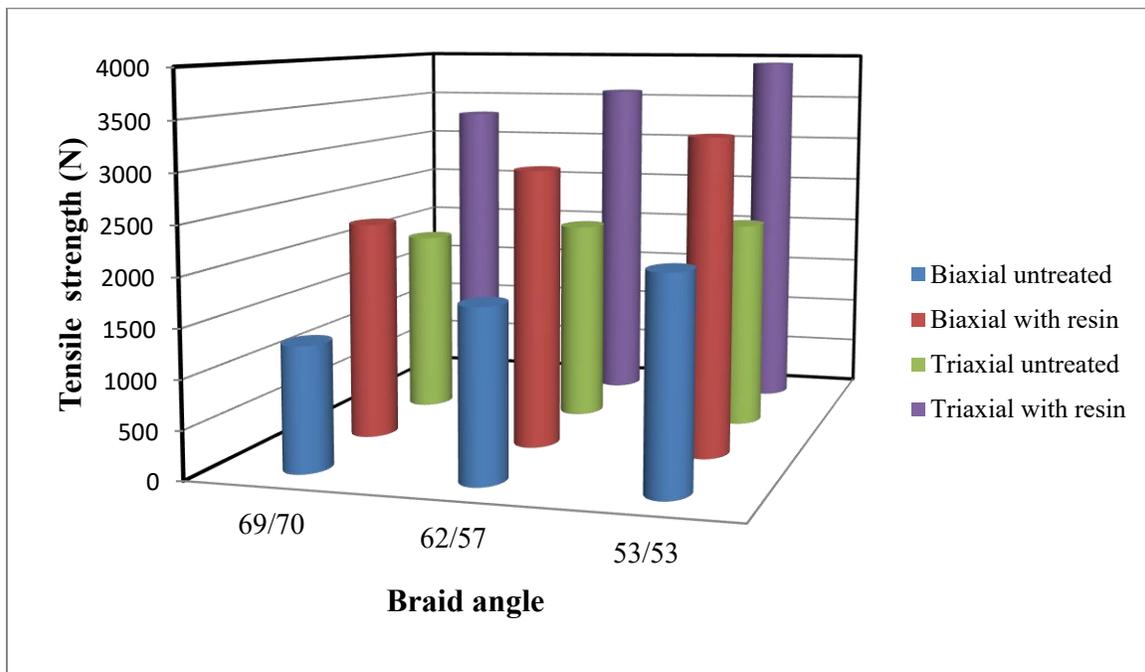| Teeth	Biaxial			Triaxial		
	Angle (A^0)	Before treatment (N)	After treatment (N)	Angle (A^0)	Before treatment (N)	After treatment (N)
36T	70^0	1283	2287	69^0	1950	3287
42T	57^0	1750	2900	62^0	2133	3583
50T	53^0	2150	3275	53^0	2200	3925

Figure 4.1- Tensile Strength of Carbon Biaxial and Triaxial Braid with Different Braid Angle and Resin Treatment

Tensile modulus

The tensile modulus of 3D braided carbon structures was strongly influenced by braid angle, braid architecture, and resin treatment. For untreated samples, the tensile modulus increased with decreasing braid angle in both biaxial and triaxial configurations. This improvement in modulus with decreasing braid angle can be attributed to superior fibre orientation along the loading direction. As the braid angle decreases, a greater proportion of the fibre orientation contributes to axial stiffness, resulting in higher resistance to elastic deformation under tensile loading.

Comparison between braid architectures indicates that biaxial braids demonstrated slightly higher tensile modulus than triaxial braids in the dry state at corresponding braid angles. This may be due to tighter fibre packing and lower structural complexity in biaxial configurations, which can reduce initial structural compliance. In contrast, the additional axial yarns in triaxial braids, while beneficial for tensile strength, may introduce minor structural crimp or redistribution effects that slightly influence stiffness in the untreated condition.

Resin treatment significantly enhanced tensile modulus in both braid types. The percentage improvement in modulus ranged approximately between 50% and 75%, depending on braid angle and architecture. The significant increase in tensile modulus after resin impregnation is attributed to improved fibre–matrix interfacial bonding and reduced fibre mobility within the braided

104

structure. The cured thermoset matrix enhances structural consolidation, minimizes yarn slippage, and increases the overall rigidity of the composite. Furthermore, the dosing pump–based resin transfer process likely ensured uniform impregnation, reducing void content and enabling efficient stress transfer from matrix to fibre during elastic deformation.

The highest tensile modulus (255 MPa) was recorded for the triaxial composite at 50T (53.0°), indicating that the combined effect of lower braid angle and effective resin reinforcement yields superior stiffness.

Table 4.2- Tensile Modulus of Carbon Biaxial and Triaxial Braid with Different Braid Angle and Resin Treatment

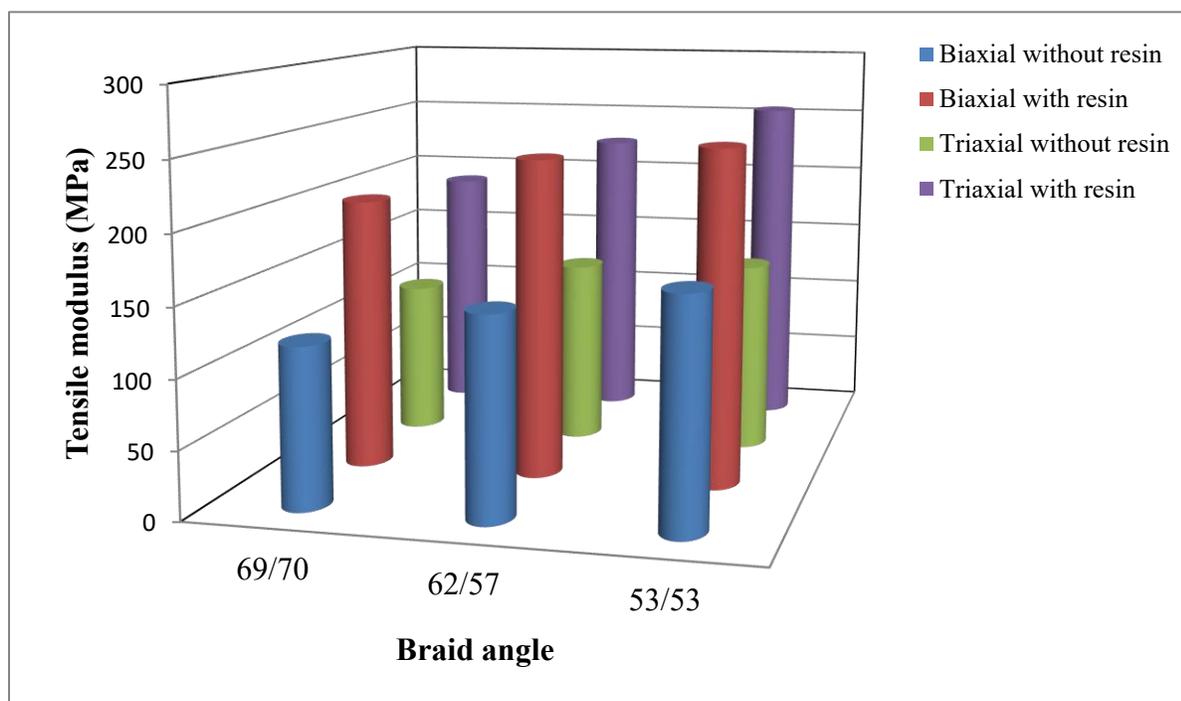| Teeth	Biaxial				Triaxial			
	Angle (A^o)	Dia. (mm)	Before treatment (MPa)	After treatment (MPa)	Angle (A^o)	Dia. (mm)	Before treatment (MPa)	After treatment (MPa)
36T	69^0	3.73	118	202	70^0	4.65	115	188
42T	62^0	3.90	147	237	57^0	4.45	138	225
50T	53^0	4.05	167	249	53^0	4.38	143	255

Figure 4.2- Tensile Strength of Carbon Biaxial and Triaxial Braid with Different Braid Angle and Resin Treatment

Three point bending test

The flexural behaviour of 3D braided carbon structures was evaluated using a three-point bending test to assess the influence of braid architecture and braid angle on bending load-carrying capacity. The results indicate that braid configuration and fibre orientation significantly affect the flexural performance of both biaxial and triaxial braids.

For biaxial braids, the bending load increased with decreasing braid angle. The results suggest that lower braid angles enhance the structural rigidity under transverse loading conditions. As the braid angle decreases, fibres become more aligned along the axial direction, providing improved resistance to tensile stresses developed on the outer surface of the specimen during bending.

In comparison, triaxial braids demonstrated substantially higher bending loads than biaxial braids at corresponding take-up conditions. The superior flexural performance of triaxial braids can be attributed to the presence of axial yarns in addition to bias yarns, which contribute significantly to resisting tensile and compressive stresses generated during bending. The axial yarn system enhances structural continuity and improves stress distribution across the braid cross-section, thereby increasing flexural load capacity.

The increase in bending load with decreasing braid angle for both architectures is consistent with improved fibre alignment along the length of the specimen, which strengthens the tensile side of

106

the bent structure. Moreover, the larger braid diameters observed at lower braid angles may contribute to increased section modulus, thereby enhancing resistance to bending deformation.

Overall, the results clearly demonstrate that braid architecture plays a dominant role in flexural performance. Triaxial braided structures exhibit nearly double the bending load compared to biaxial structures under similar processing conditions. Furthermore, lower braid angles significantly improve flexural strength due to better fibre orientation and enhanced load-sharing mechanisms. These findings confirm that optimized braid architecture, particularly triaxial configuration with lower braid angles, is more suitable for applications requiring high flexural rigidity and structural stability in 3D braided carbon composites.

Table 4.3- Flexural Strength of Carbon Biaxial and Triaxial Braid with Different Braid Angle and Resin Treatment

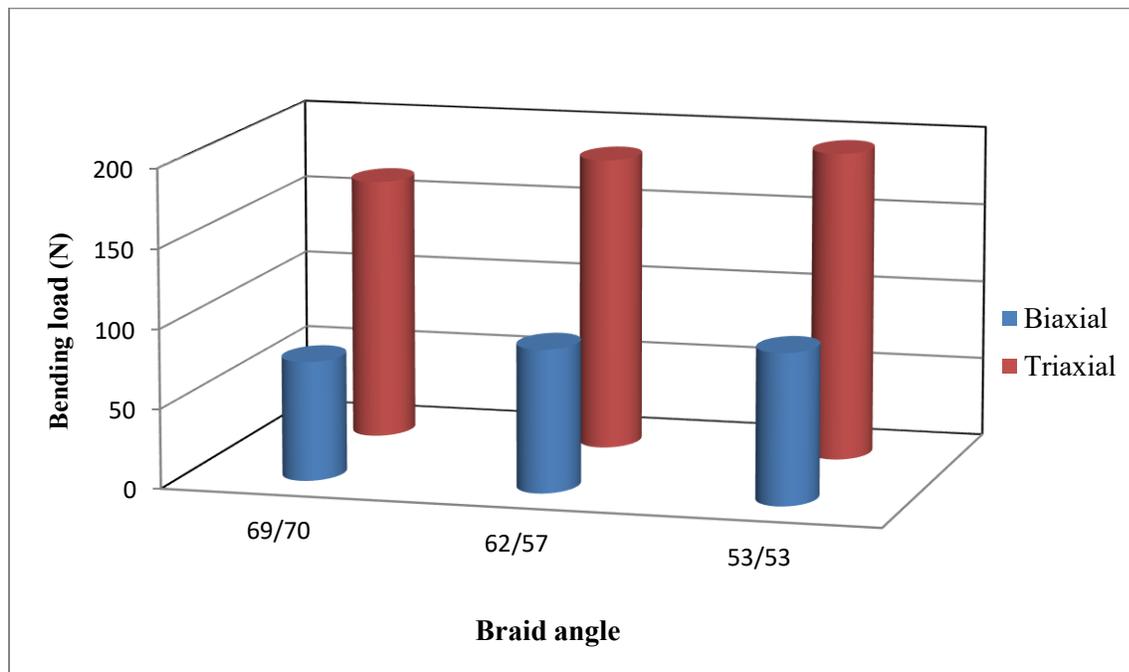| Take up Roller Teeth	Biaxial		Triaxial	
	Braid Angle (A⁰)	Bending Load (N)	Braid Angle (A⁰)	Bending Load (N)
36T	69^0	75	70^0	165
42T	62^0	90	57^0	185
50T	53^0	95	53^0	195

Figure 4.3- Flexural Strength of Carbon Biaxial and Triaxial Braid with Different Braid Angle and Resin Treatment

CONCLUSION

The present study investigated the effect of braid architecture and resin transfer process on the mechanical properties of 3D braided carbon composites, with particular emphasis on tensile strength, tensile modulus, and flexural strength. The experimental results clearly demonstrate that both braid configuration and braid angle significantly influence the mechanical performance of braided structures and their corresponding composites.

A consistent improvement in tensile strength, tensile modulus, and flexural load was observed with decreasing braid angle for both biaxial and triaxial braids. Lower braid angles enhanced fibre alignment along the loading direction, resulting in improved axial load-bearing capacity and higher stiffness. Among the two architectures, triaxial braids exhibited superior tensile and flexural performance compared to biaxial braids due to the presence of axial yarns, which contributed directly to stress transfer and improved structural integrity.

Resin impregnation through a dosing pump–based resin transfer process significantly enhanced mechanical properties. The treated composites showed substantial improvements in tensile strength and modulus compared to dry braids, confirming the effectiveness of matrix reinforcement in promoting fibre–matrix bonding, reducing yarn slippage, and ensuring uniform stress distribution. The resin-treated triaxial braid at the lowest braid angle (50T) demonstrated the

highest tensile strength, tensile modulus, and flexural load, indicating the combined beneficial effect of optimized fibre orientation and effective matrix consolidation.

Overall, the study establishes that mechanical performance of 3D braided carbon composites can be effectively tailored by controlling braid architecture, braid angle, and resin transfer parameters. Triaxial braided composites with lower braid angles and proper epoxy impregnation are particularly suitable for high-performance structural applications requiring enhanced strength, stiffness, and bending resistance.

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