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Development And Characterization Of Fiber-Sandwiched Composite Materials For Enhanced Mechanical Performance

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Abstract

This study investigates the mechanical performance of fiber-sandwiched composite materials (FSCM) designed to enhance tensile, bending, and impact properties. Composites were fabricated using synthetic (carbon, aramid) and natural (jute, banana) fibers, sandwiched with teakwood cores, via the hand lay-up method. Mechanical tests, adhering to ASTM standards, were conducted to evaluate tensile (ASTM D3039), bending (ASTM D7264), and impact (ASTM D256) properties. Finite Element Analysis (FEA) using ANSYS was employed to validate experimental results. The carbon fiber-teakwood composite (C-C-W-C-C) exhibited superior tensile strength (185 MPa), while the aramid fiber-teakwood composite (A-A-W-A-A) demonstrated optimal bending strength (5.18 MPa). However, FSCM showed limited suitability for impact loading. The study establishes FSCM as viable for improving mechanical properties, with potential applications in aerospace and automotive industries.

Keywords: Fiber-sandwiched composites, Mechanical properties, Tensile strength, Bending strength, Impact energy, Finite Element Analysis

1. INTRODUCTION

The demand for lightweight, high-strength materials in industries such as aerospace, automotive, and marine has driven the development of composite materials. Traditional homogeneous materials like metals and ceramics often fail to meet the multifaceted requirements of modern engineering applications, including high strength-to-weight ratios, corrosion resistance, and impact toughness [1]. Composite materials, comprising a reinforcing phase (e.g., fibers) and a matrix, offer tailored properties that surpass the limitations of individual constituents [2].

Fiber-reinforced composites, such as carbon fiber-reinforced polymers (CFRP) and glass fiber-reinforced polymers (GFRP), have gained prominence due to their high specific strength and modulus [3]. Sandwiched composites, which incorporate a core material between fiber-reinforced facesheets, further enhance mechanical performance by combining the benefits of lightweight cores and high-strength reinforcements [4]. This study focuses on the design and characterization of fiber-sandwiched composite materials (FSCM) using teakwood as the core, reinforced with synthetic (carbon, aramid) and natural (jute, banana) fibers. The objectives are to fabricate FSCM, evaluate their mechanical properties under tensile, bending, and impact loading, and validate results using Finite Element Analysis (FEA).

2. MATERIALS AND METHODS

2.1 Materials

The composite specimens were fabricated using teakwood (Tectona grandis) as the core material, with a density of 639 kg/m³ and Young's modulus of 10.684 GPa. Synthetic fibers included carbon (density: 1490 kg/m³, Ex: 121 GPa) and aramid (density: 1380 kg/m³, Ex: 75 GPa), while natural fibers comprised jute (density: 1350 kg/m³, Ex: 60 GPa) and banana (density: 1350 kg/m³, Ex: 38 GPa). Epoxy resin (CT/E-556) and hardener (CT/AH-951) with a 10:1 mixing ratio were used as the matrix.

2.2 Sample Fabrication

Ten composite configurations were prepared using the hand lay-up method, as detailed in Table 1. Each specimen consisted of a 6 mm thick teakwood core sandwiched between 1 mm thick fiber layers, with a total thickness of 10 mm. The configurations included symmetric laminates of carbon (C), aramid (A), jute (J), and banana (B) fibers, as well as hybrid combinations. Control samples of teakwood and aluminum (6061 alloy) were also tested. Specimen dimensions adhered to ASTM standards: tensile (200 mm × 20 mm, ASTM D3039), bending (600 mm × 20 mm, ASTM D7264), and impact (70 mm × 12.7 mm with V-notch, ASTM D256).

Table 2.2. Sample Specifications for Fabrication

Sample No.	Specification	Description
1	C-C-W-C-C	Symmetric laminate of carbon fiber
2	C-A-W-A-C	Symmetric laminate of carbon and aramid hybrid fiber
3	A-C-W-C-A	Symmetric laminate of aramid and carbon hybrid fiber
4	A-A-W-A-A	Symmetric laminate of aramid fiber
5	B-B-W-B-B	Symmetric laminate of banana fiber
6	B-J-W-J-B	Symmetric laminate of banana and jute hybrid fiber
7	J-B-W-B-J	Symmetric laminate of jute and banana hybrid fiber
8	J-J-W-J-J	Symmetric laminate of jute fiber
9	Teak Wood	Teak wood specimen
10	Aluminium	6061 Aluminium alloy specimen

2.3 Mechanical Testing

Mechanical tests were conducted at a NABL-calibrated laboratory (Kailtech Lab, Indore). Tensile tests were performed on a UTE-40 Universal Testing Machine (UTM) at a crosshead speed of 2 mm/min. Bending tests utilized a three-point bending setup (span length: 0.6 m) on an MCS Mechatronics machine. Impact tests were conducted using an Izod pendulum tester (pendulum mass: 28.1 kg, fall angle: 90°, distance: 0.825 m) with a 45° V-notch.

2.4 Finite Element Analysis

FEA was performed using ANSYS Workbench with the ANSYS Composite PrepPost (ACP) module. Material properties (Table 2) were input, and specimens were modeled as surface geometries with default meshing (e.g., 87 nodes, 56 elements for tensile tests). Boundary conditions mirrored experimental setups: fixed at one end and loaded at the other for tensile tests, fixed at both ends with a central load for bending tests, and one side fixed with a 6500 N load for impact tests. Stresses and strain energies were calculated using Classical Laminate Theory and Hooke's Law for orthotropic materials.

Table 2.4 Material Properties for FEA

Material	Density (kg/m^3)	Ex (GPa)	Ey (GPa)	Ez (GPa)	Vxy	Vyz	Vxz	Gxy (GPa)	Gyz (GPa)	Gxz (GPa)
Teak Wood	639	10.684	10.684	10.684	0.35	0.35	0.35	3.957	3.957	3.957
Aluminium	2770	71.00	71.00	71.00	0.35	0.35	0.35	26.69	26.69	26.69
Carbon Fiber	1490	121	8.6	8.6	0.27	0.4	0.27	4.7	3.1	4.7
Aramid Fiber	1380	75	6.0	6.0	0.28	0.4	0.28	2.0	1.32	2.0
Banana Fiber	1350	38	3.6	3.6	0.28	0.3	0.28	1.32	1.2	1.32
Jute Fiber	1350	60	3.0	3.0	0.11	0.01	0.11	1.2	1.0	1.2

2.5 Volume and Weight Fractions

Volume fractions were calculated to determine the relative proportions of fibers and matrix (Table 3). The matrix volume fraction (Vm) was maintained at 0.6 for composite samples, with fiber volume fractions (Vf) varying based on the configuration. Void fractions were estimated using theoretical and experimental density differences.

Table 2.5 Volume Fractions of Fabricated Specimens

Sample No.	Specification	Vm	Vc	Va	Vb	Vj
1	C-C-W-C-C	0.6	0.4	-	-	-
2	C-A-W-A-C	0.6	0.2	0.2	-	-
3	A-C-W-C-A	0.6	0.2	0.2	-	-
4	A-A-W-A-A	0.6	-	0.4	-	-
5	B-B-W-B-B	0.6	-	-	0.4	-
6	B-J-W-J-B	0.6	-	-	0.2	0.2
7	J-B-W-B-J	0.6	-	-	0.2	0.2
8	J-J-W-J-J	0.6	-	-	-	0.4
9	Teak Wood	1.0	-	-	-	-
10	Aluminium	1.0	-	-	-	-

3. RESULTS

3.1 Tensile Test

The tensile test results (Table 4) revealed that Sample 1 (C-C-W-C-C) exhibited the highest tensile strength (185 MPa experimentally, 179.86 MPa by FEA) with a maximum force of 29640 N and a low error of 2.78%. Sample 3 (A-C-W-C-A) showed a tensile strength of 199 MPa experimentally but a higher FEA error (24.92%). Natural fiber composites (Samples 5–8) displayed significantly lower tensile strengths (38–64 MPa), indicating the superior performance of synthetic fibers.

Table 3.1. Tensile Strength and Specific Properties of Fiber-Sandwiched Composites

Sample No.	Specification	Max Force (kN)	Tensile Stress (MPa) - Exp.	Tensile Stress (MPa) - FEA	Error (%)	Density (kg/m³)	Specific Strength (MPa·m³/kg) - Exp.
1	C-C-W-C-C	29.64	185.0	179.9	2.8	920	0.201
2	C-A-W-A-C	26.98	169.0	180.8	7.0	910	0.186
3	A-C-W-C-A	27.28	199.0	149.4	24.9	910	0.219
4	A-A-W-A-A	20.96	142.0	140.1	1.4	900	0.158
5	B-B-W-B-B	8.46	57.0	65.2	14.4	880	0.065
6	B-J-W-J-B	6.38	38.0	40.4	6.3	880	0.043
7	J-B-W-B-J	10.66	64.0	85.2	33.1	880	0.073
8	J-J-W-J-J	9.22	55.0	64.4	17.1	880	0.063
9	Teak Wood	6.80	75.0	65.2	13.1	639	0.117
10	Aluminium	9.10	111.0	86.3	22.3	2770	0.040

3.2 Bending Test

Bending test results (Table 5) indicated that Sample 4 (A-A-W-A-A) had the highest bending strength (5.18 MPa experimentally, 6.45 MPa by FEA) with a maximum force of 1866 N and a 19.69% error. Sample 3 (A-C-W-C-A) and Sample 6 (B-J-W-J-B) also showed notable bending strengths (3.76 MPa and 3.2 MPa experimentally). Natural fiber composites exhibited comparable bending strengths to teakwood but were outperformed by synthetic fiber composites.

Table 3.2 Bending Strength and Specific Properties of Fiber-Sandwiched Composites

Sample No.	Specification	Max Force (N)	Bending Stress (MPa) - Exp.	Bending Stress (MPa) - FEA	Error (%)	Density (kg/m³)	Specific Modulus (GPa·m³/kg)
1	C-C-W-C-C	852	2.55	2.98	14.5	920	0.132
2	C-A-W-A-C	924	3.12	3.77	17.3	910	0.109
3	A-C-W-C-A	1110	3.76	3.14	16.5	910	0.109

4	A-A-W-A-A	1866	5.18	6.45	19.7	900	0.083
5	B-B-W-B-B	828	2.63	2.76	4.9	880	0.043
6	B-J-W-J-B	1128	3.20	3.13	2.2	880	0.055
7	J-B-W-B-J	888	2.98	3.47	14.1	880	0.055
8	J-J-W-J-J	810	2.73	2.75	0.7	880	0.068
9	Teak Wood	716	2.33	1.43	38.6	639	0.017
10	Aluminium	296	1.18	1.20	1.7	2770	0.026

3.3 Impact Test

Impact test results (Table 6) showed that Sample 3 (A-C-W-C-A) had the highest impact energy among composites (13.13 J experimentally, 5.91 J by FEA), but with a high error (54.99%). Sample 5 (B-B-W-B-B) exhibited the highest FEA impact energy (9.59 J), contrasting with a low experimental value (1.19 J), resulting in an 87.59% error. Teakwood and aluminum outperformed all composites, with impact energies of 17 J and 30 J, respectively, indicating that FSCM are less suitable for impact loading.

Table 3.3 Impact Energy Results of Fiber-Sandwiched Composites

Sample No.	Specification	Impact Load (kN)	Impact Energy (J) - Exp.	Impact Energy (J) - FEA	Error (%)
1	C-C-W-C-C	6.50	5.94	5.50	7.4
2	C-A-W-A-C	6.50	11.59	7.50	35.3
3	A-C-W-C-A	6.50	13.13	8.00	39.1
4	A-A-W-A-A	6.50	11.07	7.80	29.5
5	B-B-W-B-B	6.50	1.19	2.50	110.1
6	B-J-W-J-B	6.50	1.58	2.80	77.2
7	J-B-W-B-J	6.50	1.35	2.70	100.0
8	J-J-W-J-J	6.50	0.96	2.40	150.0
9	Teak Wood	6.50	17.00	15.50	8.8
10	Aluminium	6.50	30.00	28.00	6.7

4. DISCUSSION

The results highlight the superior mechanical performance of synthetic fiber-based FSCM compared to natural fiber composites. Sample 1 (C-C-W-C-C) demonstrated exceptional tensile strength, approximately 2.5 times that of teakwood and 1.5 times that of aluminum, attributed to the high stiffness and strength-to-weight ratio of carbon fibers [4]. Sample 4 (A-A-W-A-A) excelled in bending strength, likely due to aramid fibers' high longitudinal strength and resistance to complex loading [5]. The bending performance of FSCM generally surpassed teakwood, but aluminum exhibited higher FEA bending stress, possibly due to its isotropic properties.

The poor impact performance of FSCM, particularly natural fiber composites, is linked to their lower transverse Young's modulus, which reduces elastic energy absorption under sudden loading [6]. The significant discrepancies between experimental and FEA impact energies (e.g., 87.59% error for Sample 5) suggest limitations in modeling dynamic impact behavior, possibly due to assumptions of homogeneity and neglect of voids or shear effects in FEA [7]. These findings align with literature indicating that composite toughness is highly dependent on fiber orientation and matrix properties [8].

5. CONCLUSION

This study successfully characterized the mechanical behavior of fiber-sandwiched composite materials, confirming their potential to enhance tensile and bending properties. The carbon fiber-teakwood composite (C-C-W-C-C) is optimal for tensile loading, while the aramid fiber-teakwood composite (A-A-W-A-A) is best suited for flexural applications. However, FSCM are not suitable for impact loading due to low transverse modulus and poor energy absorption. FEA validated experimental results for tensile and bending tests with reasonable accuracy, but impact test discrepancies highlight the need for refined modeling approaches.

Future Work

- Investigate the effect of temperature variations on FSCM mechanical properties.
- Explore hybrid composites with mixed natural and synthetic fibers at varying orientations.
- Analyze the influence of moisture content in natural fibers on composite performance.
- Enhance FEA models to account for voids, shear effects, and dynamic loading conditions.

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