

Development and Mechanical Characterization of Hybrid FRP Composites Reinforced With Coconut Fiber and Carbon Fiber

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Abstract: *The growing demand for lightweight, high-strength, and environmentally sustainable materials has led to increased interest in hybrid fiber-reinforced polymer (FRP) composites. This project focuses on the development and mechanical characterization of hybrid FRP composites reinforced with coconut fiber and carbon fiber. Coconut fiber, a natural and biodegradable material, offers advantages such as low cost, availability, and good energy absorption, while carbon fiber provides high strength, stiffness, and excellent fatigue resistance. By combining these two fibers, a hybrid composite material is developed to achieve a balance between mechanical performance and sustainability. In this study, composite laminates are fabricated using Epoxy Resin LY556 with Hardener HY951 as the polymer matrix through a controlled hand layup manufacturing process. Different fiber stacking sequences and weight fractions are considered to evaluate their influence on the overall performance of the hybrid composite. Mechanical characterization is carried out using standard ASTM testing methods to determine properties such as tensile strength, flexural strength, impact resistance, and hardness. The experimental results are analyzed to understand the interaction between natural and synthetic fibers and their contribution to load-bearing capability and durability. The results demonstrate that hybridization of coconut fiber with carbon fiber significantly improves the mechanical properties compared to composites reinforced with natural fibers alone, while also reducing the overall cost and environmental impact compared to purely synthetic composites. These hybrid FRP composites have potential applications in automotive components, lightweight structural parts, marine structures, and other engineering fields where a combination of strength, weight reduction, and sustainability is required.*

Keywords: Hybrid FRP composites, Coconut fiber, Carbon fiber, Natural fiber composites, Mechanical characterization, Tensile strength, Impact resistance, Polymer matrix composites, Epoxy Resin LY556, Sustainable materials.

I. INTRODUCTION

Fiber-reinforced polymer (FRP) composites have become indispensable in modern engineering owing to their outstanding strength-to-weight ratios, corrosion resistance, and design flexibility. Industries ranging from aerospace and automotive to civil engineering and marine structures have adopted FRP composites as primary structural materials. The continuing drive toward sustainable, eco-friendly engineering has further expanded interest in hybrid FRP systems that combine natural and synthetic fibers within a common polymer matrix.

Natural fibers such as coconut coir, jute, sisal, flax, and bamboo are abundant, renewable agricultural by-products. Among these, coconut coir fiber is particularly attractive because of its high cellulose content, good moisture resistance, low bulk density (approximately 1.15–1.46 g/cm³), acceptable tensile strength (120–200 MPa), and excellent energy absorption capacity due to its cellular microstructure. The use of coir reduces dependence on petroleum-derived synthetic fibers and lowers the environmental footprint of the final composite.



Carbon fiber is the benchmark high-performance synthetic reinforcement, offering tensile strengths exceeding 3500 MPa, a tensile modulus of 230–250 GPa, near-zero moisture absorption, and exceptional fatigue resistance. In this study, a bidirectional twill-weave carbon fabric (200 GSM, 3K tow, 1000 mm width, 0.2 mm ply thickness) is used, which offers excellent drapability and uniform fiber distribution in both warp and weft directions.

Hybridization involves combining two or more fiber types in a single composite system to achieve a synergistic balance of properties that cannot be attained by any single-fiber composite. By incorporating carbon fiber layers into a predominantly coir fiber laminate, the tensile stiffness and flexural strength are dramatically improved, while the natural fiber layers contribute to impact toughness, damping, and cost reduction. This positive hybrid effect has been widely reported in literature for various natural–synthetic fiber combinations.

This work investigates four hybrid laminate configurations with varying coconut and carbon fiber weight fractions, fabricated using Epoxy Resin LY556 and Hardener HY951. Mechanical characterization is performed under tensile (ASTM D638), flexural (ASTM D790), impact (ASTM D6110), and hardness (ASTM E18) test conditions, providing a systematic understanding of the influence of fiber hybridization ratio on the mechanical behavior of the composite.

II. MATERIALS & METHODOLOGY

A. Carbon Fiber Reinforcement

The synthetic reinforcement used in this study is a bidirectional twill-weave carbon fiber fabric with a 3K tow (3000 filaments per tow) and an areal density of 200 GSM. The fabric roll width is 1000 mm and the nominal ply thickness after layup is 0.2 mm. The twill-2/2 weave architecture provides superior drapability over complex contours compared to plain weave, and the balanced 0°/90° fiber orientation delivers isotropic in-plane stiffness. Carbon fiber filaments have an individual diameter of approximately 5–7 μm , a tensile modulus of 230 GPa, and a tensile strength of 3500–4500 MPa. Moisture absorption is essentially zero (<0.02%), ensuring dimensional stability under humid operating conditions.

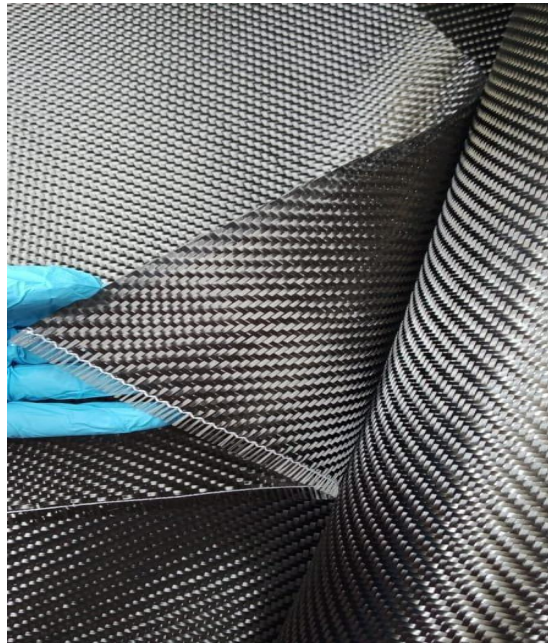


Fig. 1 Carbon Fiber Bidirectional Twill Fabric – 200 GSM, 3K, Width 1000 mm, Thickness 0.2 mm

B. Coconut (Coir) Fiber Reinforcement

Coconut coir fiber mats were sourced from locally available husked coconuts. The coir fiber is extracted from the mesocarp of the coconut fruit and consists primarily of cellulose (32–43%), lignin (40–45%), and hemicellulose (0.15–



0.25%). In its raw form, the fiber surface is coated with waxy deposits and natural oils that reduce adhesion with polymer matrices. To improve interfacial bonding, the fibers were subjected to alkali treatment: immersion in a 5 wt% sodium hydroxide (NaOH) solution at room temperature for 6 hours, followed by thorough washing with distilled water and drying in a hot-air oven at 70°C for 24 hours. Alkali treatment removes surface impurities, increases surface roughness, and exposes reactive hydroxyl groups that enhance mechanical interlocking with the epoxy matrix.



Fig. 2 Alkali-Treated Coconut Coir Fiber Mat Used as Natural Fiber Reinforcement

C. Epoxy Resin Matrix (LY556 / HY951)

Epoxy Resin LY556 (diglycidyl ether of bisphenol-A, DGEBA) was used as the polymer matrix with Hardener HY951 (aliphatic polyamine) as the curing agent, blended in a 10:1 weight ratio per manufacturer specifications. LY556 offers low viscosity (700–1200 mPa·s at 25°C) for excellent fiber wet-out during hand layup, outstanding adhesion to both carbon and natural fibers, and a pot life of approximately 25–30 minutes at ambient temperature. Post-curing at 60°C for 2 hours ensures complete cross-linking, maximizes glass transition temperature ($T_g \approx 130^\circ \text{C}$), and achieves a cured tensile strength of approximately 80 MPa and tensile modulus of 3.5 GPa.

TABLE I: PROPERTIES OF CONSTITUENT MATERIALS

Property	Carbon Fiber (3K Twill)	Coconut Coir Fiber	Epoxy LY556 (Cured)
Density (g/cm ³)	1.76	1.15–1.46	1.20
Tensile Strength (MPa)	3500–4500	120–200	~80
Tensile Modulus (GPa)	230–250	4–6	3.5
Elongation at Break (%)	1.4–1.8	15–30	5–8
Moisture Absorption (%)	<0.02	8–15	<0.5
Fabric / Form	200 GSM Twill	Woven Coir Mat	Liquid Resin
Ply Thickness (mm)	0.2	0.4–0.5	N/A
Tow / Width	3K / 1000 mm	Variable	N/A



III. FABRICATION METHOD

A. Laminate Configuration Design

Four laminate configurations were designed with varying proportions of coconut fiber (C) and carbon fiber (CF) plies to systematically investigate the effect of hybridization ratio. Each laminate consists of four fiber plies stacked in specific sequences within the epoxy resin matrix. The fiber volume fraction was maintained at approximately 40% across all configurations to isolate the influence of fiber type from fiber content.

TABLE II: HYBRID LAMINATE STACKING CONFIGURATIONS

Laminate	Stacking Sequence	Coconut (%)	Carbon (%)	Expected Characteristic
Laminate A	C / C / C / C	100	0	Max. impact toughness, low stiffness
Laminate B	C / C / C / CF	75	25	Improved strength, high toughness
Laminate C	C / CF / C / CF	50	50	Balanced hybrid – optimal overall
Laminate D	CF / CF / CF / C	25	75	Max. stiffness, reduced impact

B. Hand Layup Fabrication Process

All composite laminates were fabricated using the room-temperature hand layup technique owing to its simplicity, low tooling cost, and suitability for various fiber architectures. A flat aluminium mould (350 mm × 350 mm × 5 mm) was thoroughly cleaned and coated with three applications of mould-release wax to prevent laminate adhesion.

Epoxy Resin LY556 and Hardener HY951 were carefully weighed in a 10:1 ratio by mass and mixed with a mechanical stirrer for 3–5 minutes, ensuring homogeneous blending while minimizing air entrapment. The mixed resin had a pot life of approximately 25 minutes at ambient conditions (25°C, 55% RH). The layup procedure began with a thin resin coat on the mould, followed by sequential placement of fiber plies as per each laminate's stacking sequence. Each ply was thoroughly wetted with epoxy by brush and manually rolled using a serrated aluminium roller to consolidate plies, eliminate inter-ply air pockets, and ensure complete fiber wet-out. Fig. 3 illustrates the hand layup process.

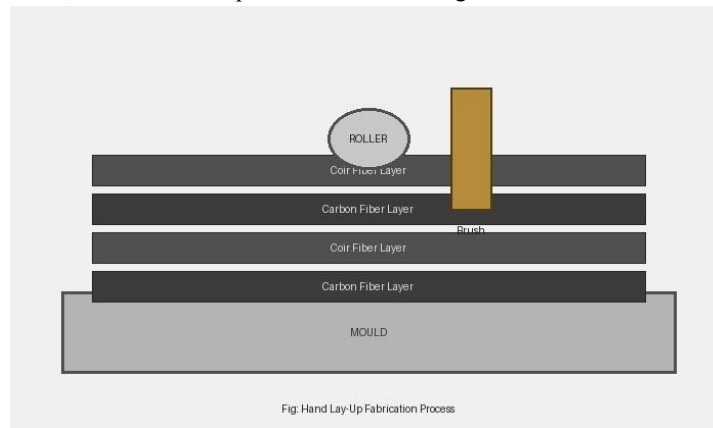


Fig. 3 Hand Layup Fabrication Process – Fiber Ply Stacking, Resin Application, and Roller Consolidation

After layup, the mould was sealed with a top plate and cured under a uniform dead weight of 5 kg/m² at room temperature (25°C) for 24 hours, then post-cured at 60°C for 2 hours to ensure complete epoxy cross-linking. After cooling, cured laminates were demoulded to a nominal thickness of 3.0 ± 0.2 mm. Test specimens were cut using a water-cooled diamond saw with edges ground to remove machining damage.

IV MECHANICAL TESTING

A. Tensile Testing (ASTM D638)

Tensile testing was conducted on a 100 kN computer-controlled Universal Testing Machine (UTM) per ASTM D638 (Type I). Dog-bone specimens (165 mm × 19 mm × 3 mm, 50 mm gauge length) were tested at a crosshead speed of 5



mm/min. Load-extension data were continuously recorded to compute tensile strength (σ_t), elongation at break (ϵ_b), and Young's modulus (E). Five specimens per configuration were tested and mean values with standard deviations are reported.

B. Flexural Testing (ASTM D790)

Three-point bending tests were performed on the same UTM per ASTM D790. Rectangular specimens (130 mm \times 13 mm \times 3 mm, span-to-depth ratio 16:1) were loaded at 2 mm/min. Flexural strength (σ_f) and flexural modulus (E_f) were computed using classical beam bending formulae. Specimens were oriented with the service-tension face downward to replicate actual loading conditions.

C. Impact Testing (ASTM D6110)

Charpy impact tests were performed on a 300 J pendulum machine per ASTM D6110. V-notched specimens (64 mm \times 12.7 mm \times 3 mm; notch: 45°, 2 mm deep) were tested at a striker velocity of 3.46 m/s. Impact strength (kJ/m²) was calculated by dividing the absorbed energy by the net cross-sectional area at the notch. Five specimens per laminate were tested.

D. Hardness Testing (ASTM E18)

Rockwell hardness (HRR scale: 60 kg minor load, 100 kg total load, 12.7 mm ball indenter) was measured per ASTM E18 on 50 mm \times 50 mm \times 3 mm polished coupons. Three readings per specimen were averaged. Fig. 4 shows the UTM setup used for tensile testing.

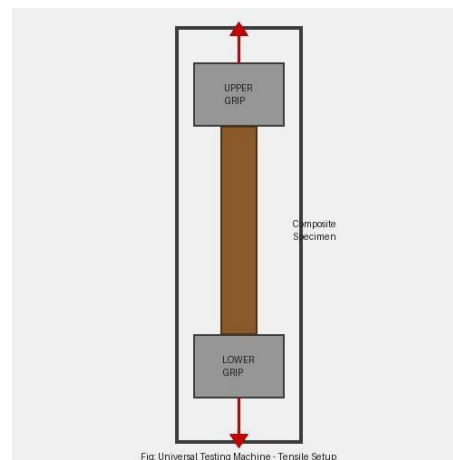


Fig. 4 Universal Testing Machine (UTM) Setup for Tensile Testing of Hybrid FRP Specimens (ASTM D638)

V. RESULTS AND DISCUSSION

A. Tensile Properties

Tensile strength and Young's modulus values for all laminate configurations are presented in Table III. Laminate A (100% coir) recorded the lowest tensile strength of 68.4 MPa and modulus of 4.2 GPa, consistent with the inherent limitations of natural fiber composites in terms of fiber-matrix adhesion and fiber orientation uniformity. Progressive substitution of coir plies with carbon fiber plies caused a monotonic increase in both properties.

Laminate	Tensile Strength (MPa)	Tensile Modulus (GPa)	Flexural Strength (MPa)	Flexural Modulus (GPa)	Elongation (%)
A (CCCC)	68.4 \pm 3.2	4.2 \pm 0.3	82.6 \pm 4.1	3.8 \pm 0.2	2.8
B (CCCF)	135.2 \pm 5.8	18.6 \pm 1.1	148.4 \pm 6.2	12.4 \pm 0.8	2.1
C (CCFF)	198.5 \pm 6.4	47.3 \pm 2.3	215.7 \pm 7.8	38.6 \pm 1.6	1.6
D (CFFF)	312.6 \pm 8.1	98.4 \pm 3.9	338.2 \pm 9.4	86.5 \pm 2.8	1.2

TABLE III: TENSILE AND FLEXURAL PROPERTIES OF HYBRID FRP LAMINATES



Laminate C (50% coir / 50% carbon, symmetric CCF sequence) achieved a tensile strength of 198.5 MPa, a 190% improvement over Laminate A. Laminate D (75% carbon) reached the highest tensile strength of 312.6 MPa, a 357% improvement, owing to the dominant influence of the high-modulus carbon fiber layers. The alternating sequence in Laminate C allows each carbon ply to be flanked by energy-absorbing coir plies, promoting progressive damage and load redistribution – a key characteristic of the positive hybrid effect.

B. Flexural Properties

Flexural strength followed the same increasing trend with increasing carbon fiber content. Laminate A exhibited 82.6 MPa while Laminate D achieved 338.2 MPa. The improvements are attributed to the superior bending stiffness conferred by the carbon fiber plies, which exhibit higher resistance to inter-laminar shear and fiber microbuckling. Laminate C achieved 215.7 MPa flexural strength with a modulus of 38.6 GPa, confirming its suitability for applications requiring both bending resistance and impact tolerance.

C. Impact Resistance and Hardness

Impact strength showed an inverse trend: Laminate A exhibited the highest impact strength of 42.6 kJ/m², decreasing progressively to 24.2 kJ/m² for Laminate D. This behavior reflects the high energy-absorption capacity of coir fibers due to their porous cellular cross-section, high natural elongation at break (15–30%), and micro-fibrillar structure that promotes fiber bridging and crack deflection during impact. Carbon fiber, despite its high tensile strength, is inherently brittle (elongation ~1.4%), resulting in catastrophic fracture upon impact without significant plastic energy dissipation. Rockwell hardness (HRR) increased monotonically with carbon fiber content, from 62.4 HRR (Laminate A) to 93.5 HRR (Laminate D), consistent with the higher elastic moduli of carbon-rich laminates.

Laminate	Impact Strength (kJ/m ²)	Rockwell Hardness (HRR)	Failure Mode
A (CCCC)	42.6 ± 2.1	62.4 ± 1.8	Fiber pull-out, matrix cracking
B (CCCF)	36.8 ± 1.8	72.6 ± 2.1	Mixed delamination + pull-out
C (CCFF)	30.4 ± 1.6	83.2 ± 1.5	Delamination + carbon fracture
D (CFFF)	24.2 ± 1.2	93.5 ± 1.2	Brittle carbon fracture

TABLE IV: IMPACT STRENGTH AND ROCKWELL HARDNESS OF HYBRID FRP LAMINATES

VI. CONCLUSION

This study successfully developed and mechanically characterized four hybrid FRP composite laminate configurations using coconut coir fiber and carbon fiber bidirectional twill fabric (200 GSM, 3K, 0.2 mm thick) as reinforcements, and Epoxy Resin LY556/HY951 as the matrix, fabricated by the hand layup process. The following conclusions are drawn:

1. Tensile and flexural strengths increase monotonically with increasing carbon fiber content. Laminate D (75% carbon) achieved the highest tensile strength (312.6 MPa) and flexural strength (338.2 MPa), while Laminate A (100% coir) recorded the lowest values.
2. Impact strength decreases with increasing carbon fiber content due to the brittle nature of carbon fiber. Laminate A exhibited the best impact resistance (42.6 kJ/m²). Failure modes shift from progressive fiber pull-out in coir-dominant laminates to brittle carbon fracture and delamination in carbon-dominant laminates.
3. Rockwell hardness (HRR scale) increases with carbon fiber content, ranging from 62.4 HRR (Laminate A) to 93.5 HRR (Laminate D).
4. Alkali (NaOH) treatment of coir fibers significantly improves fiber-matrix interfacial adhesion, contributing to improved mechanical performance relative to untreated coir composites.



5. Laminate C (50% coir / 50% carbon, CCFF symmetric sequence) demonstrates the best overall balance: tensile strength 198.5 MPa, flexural strength 215.7 MPa, impact strength 30.4 kJ/m², and hardness 83.2 HRR. It is identified as the optimal hybrid configuration for cost-effective structural applications.
6. Hybridization of low-cost renewable coir fiber with high-performance carbon fiber fabric in an epoxy matrix is a practical and sustainable engineering approach, offering ~50% cost reduction compared to all-carbon composites while maintaining adequate structural performance for automotive, marine, and civil engineering applications.

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