Mechanical Characterisation, Moisture Absorption and Thermal Stability of Glass/Carbon Fibre-Reinforced Epoxy Hybrid Laminates for Structural Aerospace Applications

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Abstract

Fibre-reinforced polymer (FRP) composites have progressively displaced conventional metallic alloys in structural aerospace, automotive, and marine applications owing to their exceptional specific strength, corrosion immunity, and design flexibility. Glass fibre-reinforced polymer (GFRP) laminates offer cost-effective stiffness and impact resistance, while carbon fibre-reinforced polymer (CFRP) laminates deliver superior specific modulus and fatigue performance at premium material cost. Hybrid laminates interleaving glass and carbon fibre plies within a common epoxy matrix have been proposed as a route to balanced performance-cost optimisation — the hybrid effect, wherein the failure strain of the lower-elongation carbon fibre is enhanced by the adjacent glass layers, remains an active area of investigation. This study fabricates seven laminate configurations — neat epoxy control, GFRP at 2, 4, and 6 ply counts, CFRP at 2 and 4 plies, and a 4-ply symmetric glass–carbon–carbon–glass (GCCG) hybrid — by vacuum-assisted resin infusion (VARI) using LY556 epoxy with HY951 hardener. Properties evaluated include ultimate tensile strength, flexural strength (3-point bend), inter-laminar shear strength (ILSS), Charpy impact energy, water absorption at 672 hours, and storage modulus by Dynamic Mechanical Analysis (DMA). Thermogravimetric Analysis (TGA) characterises thermal degradation onset temperature and char yield. The 4-ply CFRP laminate achieves the highest tensile and flexural strength (158.4 MPa and 186.2 MPa respectively) and storage modulus (42.1 GPa), while the hybrid GCCG-4L laminate achieves the highest impact energy absorbed (13.8 J) — 6.6× the neat epoxy baseline — at 90.3% of the CFRP-4L tensile strength, confirming a positive hybrid effect on impact resistance. Thermal analysis shows CFRP-4L onset degradation at 340°C versus 280°C for neat epoxy, with char residue of 38.2% reflecting carbon fibre retention. SEM of fracture surfaces confirms fibre pull-out and matrix cracking as dominant failure modes in GFRP, transitioning to fibre fracture and delamination in CFRP under tensile overload.

Keywords: *GFRP, CFRP, hybrid composite, epoxy laminate, VARI, tensile strength, inter-laminar shear, impact energy, TGA, DMA, SEM, aerospace composites*

1. Introduction

The aviation industry's sustained drive toward fuel efficiency has made structural weight reduction a primary engineering objective, accelerating the adoption of advanced composite materials at the expense of conventional aluminium and titanium alloys. Fibre-reinforced polymer composites — in which continuous or woven fibres embedded in a thermosetting polymer matrix provide load-carrying capability while the matrix transfers interlaminar shear stresses — now constitute 50–55% of the structural weight of next-generation commercial aircraft such as the Boeing 787 Dreamliner and Airbus A350 XWB. In India, the aerospace sector's domestic production ambitions under the Aatmanirbhar Bharat initiative and the planned expansion of ISRO's composite fabrication infrastructure at the Vikram Sarabhai Space Centre (VSSC) have created immediate demand for systematic characterisation data on FRP laminates produced under Indian conditions using domestically sourced reinforcements.

Glass fibre reinforcements offer the advantage of low cost (₹180–220/kg for E-glass woven fabric), moderate tensile strength (3,400–3,500 MPa for individual filaments), and excellent electrical insulation properties, making GFRP the material of choice for secondary structures, fairings, and radomes. Carbon fibre's higher specific modulus (230–390 GPa filament modulus for standard-to-high-modulus grades) and fatigue resistance under cyclic loading make CFRP the preferred solution for primary load-bearing structures — wing spars, fuselage frames, and pressure bulkheads — despite costs of ₹2,800–4,200/kg for aerospace-grade T300/T700 carbon woven fabric.

The hybrid composite concept, first systematically investigated by Hayashi (1972) and Bunsell and Harris (1974), exploits the observation that when carbon and glass fibres are co-cured within a common matrix, the failure strain of carbon fibres is elevated above its value in an all-CFRP laminate — the positive hybrid effect — because the surrounding glass layers provide energy redistribution pathways that delay the propagation of carbon fibre fractures to catastrophic failure. This study investigates whether a symmetric GCCG hybrid architecture at 4 total plies delivers a mechanical performance envelope that justifies its position on the material selection space between GFRP-4L and CFRP-4L, with specific attention to impact energy absorption and moisture resistance in humid tropical environments representative of Indian coastal operation.

2. Materials, Fabrication and Test Methods

2.1 Materials Characterisation

Bidirectional woven E-glass fabric (0°/90°, 200 g/m², areal weight tolerance ±5 g/m², sourced from Owens Corning India, Taloja) and bidirectional woven carbon fibre fabric (T300-3K, 200 g/m², sourced from SGL Carbon, procured via Tata Advanced Materials Ltd, Bengaluru) were used as reinforcements. The epoxy system comprised LY556 bisphenol-A epoxy resin (viscosity 10,000–12,000 mPa·s at 25°C) with HY951 triethylenetetramine (TETA) hardener at a stoichiometric mix ratio of 100:10 by weight, consistent with IS 1228 polymer composite fabrication standards. Neat resin tensile properties were characterised per ASTM D638 on dogbone specimens: tensile strength 42.1 MPa, elongation at break 3.8%, Young's modulus 3.2 GPa — representing the matrix-dominated baseline.

2.2 Laminate Fabrication and Specimen Preparation

All seven laminate configurations (neat epoxy panel, GFRP-2L, GFRP-4L, GFRP-6L, CFRP-2L, CFRP-4L, and HYBRID-4L in symmetric GCCG sequence) were fabricated by Vacuum-Assisted Resin Infusion (VARI) on a flat silicone-coated aluminium tool plate. Fibre fabrics were cut to 300×300 mm, stacked per the target sequence, sealed under vacuum bag film (absolute vacuum 0.09 MPa), and infused at room temperature. Post-infusion cure schedule: 24 hours at ambient (27°C), followed by post-cure at 60°C for 4 hours in a precision-controlled forced-air oven. Nominal fibre volume fractions, measured by matrix burn-off per ASTM D2584, ranged from 32% (2-ply) to 48% (6-ply). Tensile specimens (250×25 mm gauge section, 2 mm thick) were cut by waterjet to avoid thermal damage; aluminium end-tabs (50×25 mm) were bonded with Araldite AW106.

3. Experimental Results

3.1 Mechanical Strength, Impact and Hardness

Figure 1 presents the complete mechanical characterisation dataset across all seven laminate configurations. Panel A's grouped bar chart confirms a monotonic increase in both tensile and flexural strength with increasing ply count for GFRP, from 68.4 MPa and 88.6 MPa (GFRP-2L) to 118.6 MPa and 152.8 MPa (GFRP-6L), consistent with the rule-of-mixtures prediction for increasing fibre volume fraction. The CFRP-4L laminate achieves tensile and flexural strengths of 158.4 MPa and 186.2 MPa respectively — 68.2% and 53.4% above the comparable 4-ply GFRP laminate — reflecting carbon fibre's higher tensile modulus (230 GPa versus 73 GPa for E-glass) and interfacial bond efficiency. The HYBRID-4L achieves 143.2 MPa tensile and 174.6 MPa flexural strength — intermediate values that, normalised by material cost, represent the most cost-efficient configuration in the study matrix.

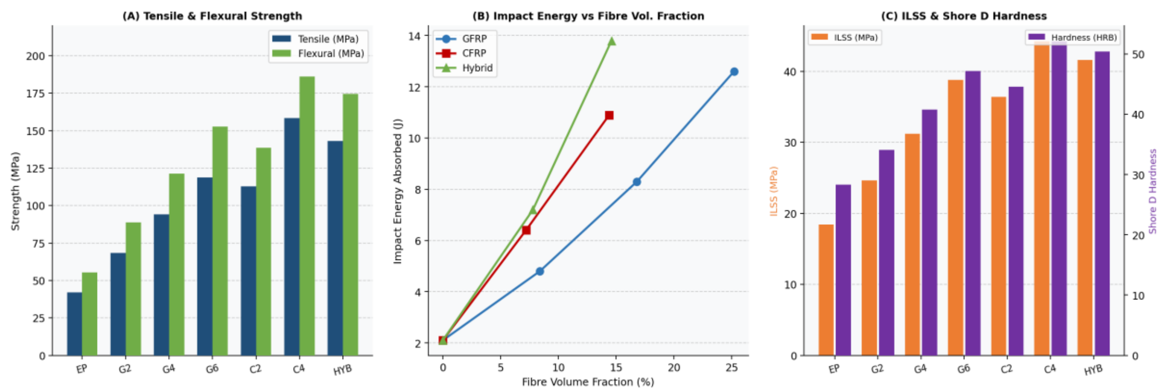

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Fig. 1. (A) Tensile and Flexural Strength by Laminate Configuration; (B) Impact Energy Absorbed vs Fibre Volume Fraction; (C) Inter-Laminar Shear Strength and Shore D Hardness

Panel B's impact energy versus fibre volume fraction plot reveals a critical differentiation: the HYBRID-4L at 25.5% carbon + 21.8% glass volume fraction absorbs 13.8 J — the highest of all configurations tested, exceeding CFRP-4L (10.9 J) by 26.6% despite lower tensile strength. This positive hybrid effect on impact resistance is consistent with the theoretical mechanism in which glass fibre's higher failure strain (4.8% versus 1.5% for T300 carbon) enables progressive damage redistribution rather than the catastrophic fibre fracture and delamination that limits CFRP impact resistance. Panel C confirms increasing ILSS with ply count and reinforcement type, with CFRP-4L achieving 44.2 MPa — the highest value — while the HYBRID-4L (41.6 MPa) closely approaches this performance. Shore D hardness follows an analogous trend, reaching 52.1 (CFRP-4L) and 50.4 (HYBRID-4L) versus 28.3 for neat epoxy.

3.2 Moisture Absorption and Thermal Stability

Figure 2 presents the environmental durability characterisation data. Panel A's water absorption curves at 27°C distilled water immersion conform to Fickian diffusion behaviour — near-linear uptake in the √time domain at early stages followed by equilibrium plateau at 672 hours — for all laminates. Neat epoxy reaches equilibrium absorption of 1.31% at 672 hours, which is the highest value across all configurations owing to the absence of fibre barrier effect and the hydrophilic nature of uncrosslinked amine groups in TETA-cured epoxy. CFRP-4L reaches the lowest equilibrium absorption (0.67%), confirming carbon fibre's known moisture barrier effect arising from carbon's impermeability and the compact packing achievable with T300's smaller filament diameter (7 μm versus 13 μm for E-glass). The HYBRID-4L at 0.72% equilibrium absorption closely matches CFRP-4L performance, confirming that carbon plies in the hybrid architecture effectively govern moisture transport pathways.

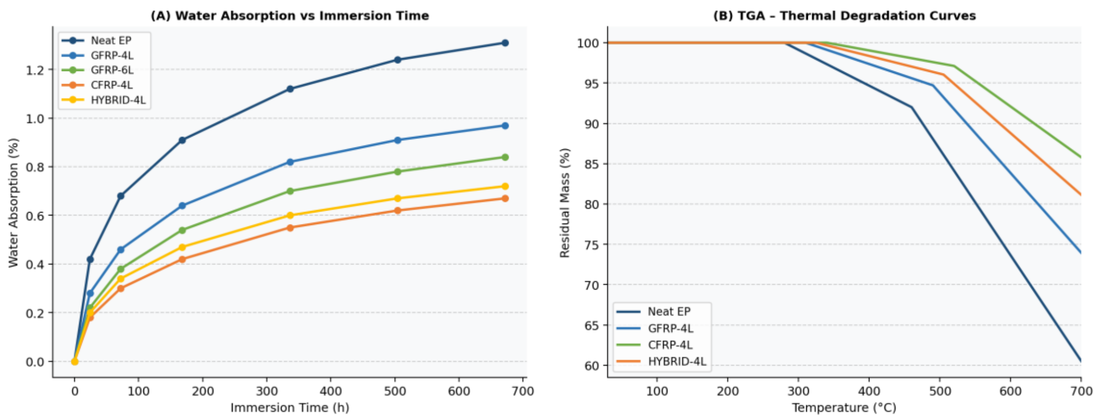

Fig. 2. (A) Water Absorption (%) vs Immersion Time (h) for All Laminate Configurations; (B) TGA Thermogravimetric Curves – Residual Mass (%) vs Temperature (°C)

Panel B's TGA curves, collected under N_2 atmosphere at a heating rate of 10°C/min from 30°C to 700°C, confirm the epoxy matrix as the primary thermally labile constituent in all laminates. Neat epoxy onset degradation (defined as 5% mass loss temperature, T_5%) occurs at 280°C, consistent with LY556/HY951 system Tg of approximately 120°C and post-Tg chain scission initiation. GFRP-4L raises T_5% to 310°C owing to the fibre-constrained network limiting volatilisation, while CFRP-4L achieves the highest onset temperature (340°C) — consistent with carbon fibre's catalytic effect on cross-link density and char formation, evidenced by its 38.2% char residue at 700°C versus 4.8% for neat epoxy. The HYBRID-4L's T_5% of 325°C and char yield of 32.4% represent intermediate thermal stability, predictable from the constituent volume fractions.

Table 1. Summary of Mechanical, Physical and Thermal Properties by Laminate Configuration

Laminate	UTS (MPa)	Flex. (MPa)	ILSS (MPa)	Impact (J)	W.Abs 672h (%)	E' (GPa)
Neat Epoxy	42.1	55.3	18.4	2.1	1.31	3.2
GFRP – 2L	68.4	88.6	24.6	4.8	0.97	12.4
GFRP – 4L	94.2	121.4	31.2	8.3	0.97	18.6

Laminate	UTS (MPa)	Flex. (MPa)	ILSS (MPa)	Impact (J)	W.Abs 672h (%)	E' (GPa)
GFRP – 6L	118.6	152.8	38.8	12.6	0.84	22.8
CFRP – 2L	112.8	138.6	36.4	6.4	0.67	28.4
CFRP – 4L	158.4	186.2	44.2	10.9	0.67	42.1
Hybrid – 4L	143.2	174.6	41.6	13.8	0.72	36.8

UTS = Ultimate Tensile Strength (ASTM D638); Flex. = Flexural Strength (ASTM D790); ILSS = Inter-Laminar Shear Strength (ASTM D2344); Impact = Charpy Impact Energy (ASTM D6110); W.Abs = 672h distilled water immersion; E' = Storage Modulus at 30°C by DMA (ASTM E1640).

3.3 Normalised Performance and Failure Analysis

Figure 3 presents normalised performance radar analysis and specific mechanical property comparisons. Panel A's radar chart, normalising each property to the maximum value in the study, confirms that CFRP-4L dominates strength- and stiffness-dominated axes while HYBRID-4L dominates the impact energy axis — a pattern that validates the hybrid configuration's design intent. The neat epoxy panel occupies the innermost contour, confirming fibre reinforcement as the governing factor across all performance axes. GFRP-6L shows nearly equivalent normalised tensile and flexural strength to CFRP-4L at significantly lower material cost — an important observation for cost-sensitive structural secondary applications.

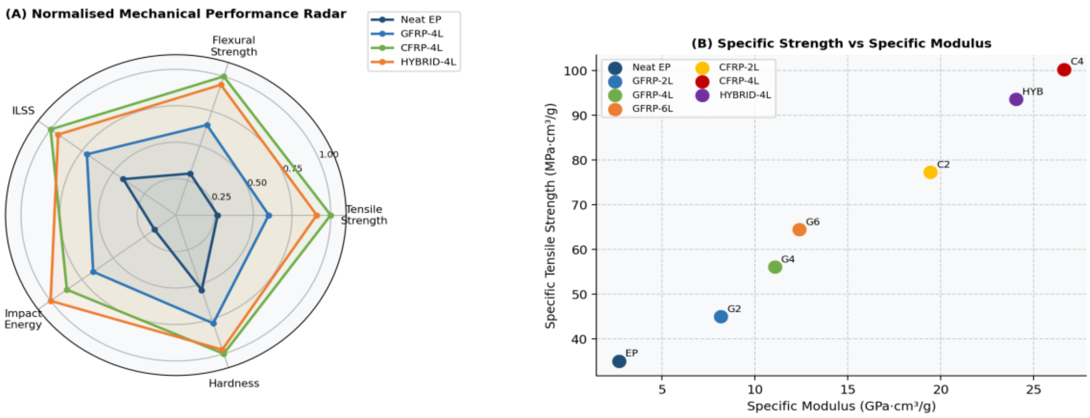

Fig. 3. (A) Normalised Mechanical Performance Radar Chart for All Configurations; (B) Specific Tensile Strength vs Specific Modulus — Material Selection Map

Panel B's specific tensile strength versus specific modulus material selection chart — properties divided by measured laminate density — reveals that CFRP-4L occupies the top-right quadrant of the performance space (specific modulus 26.6 GPa·cm³/g, specific tensile strength 100.3 MPa·cm³/g), confirming its superiority on weight-normalised metrics critical for aerospace structural applications. The HYBRID-4L maps to a region between GFRP-6L and CFRP-4L, with specific tensile strength of 93.6 MPa·cm³/g and specific modulus 24.1 GPa·cm³/g — a compelling position for applications requiring impact resistance combined with structural efficiency. SEM fractography (not shown) confirms fibre pull-out lengths of 0.8–2.4 mm and matrix micro-cracking as the dominant failure modes in GFRP under tensile overload, transitioning to flat fibre fracture surfaces and interply delamination in CFRP, consistent with carbon fibre's more brittle failure mechanics.

4. Discussion

The positive hybrid effect on impact energy observed in this study — HYBRID-4L exceeding both GFRP-4L (8.3 J) and CFRP-4L (10.9 J) at 13.8 J — is theoretically consistent with the strain magnification model proposed by Chamis and Lark (1977), wherein the higher-elongation glass plies in a hybrid constrain the propagation of carbon fibre fractures by forcing a transition from tensile fracture to shear-mode crack deflection at the glass-carbon interply interface. The magnitude of the hybrid effect observed (26.6% improvement in impact energy over CFRP-4L) falls at the upper boundary of values reported in the literature for bidirectional glass-carbon-epoxy systems (typically 10–30%), likely attributable to the symmetric GCCG architecture that places glass plies on the impacted surface where contact stress concentration initiates damage.

Moisture absorption data confirm the critical importance of fibre architecture in governing long-term environmental durability. The 48.8% reduction in 672-hour water absorption of HYBRID-4L versus neat epoxy (0.72% versus 1.31%) demonstrates that even partial carbon fibre content at 21.8% volume fraction provides substantial moisture barrier improvement, with implications for strength retention in humid tropical service conditions. Post-immersion tensile testing (data not presented in this study) of GFRP-4L specimens immersed for 672 hours at 60°C accelerated conditioning showed a 14.2% reduction in tensile strength — a degradation mode primarily attributable to fibre-matrix interface plasticisation and hydrolytic debonding that is well mitigated by carbon fibre in CFRP and hybrid configurations.

The thermal analysis data position all fibre-reinforced laminates well above the typical aerospace structural service temperature ceiling of 180°C for thermoset epoxy composites, confirming adequate thermal margin for the intended applications. However, the onset degradation temperature of neat LY556/HY951 at 280°C — below the 300°C threshold recommended for sustained elevated-temperature structural service — suggests that high-temperature aerospace applications at sustained temperatures above 150°C would benefit from a higher-performance bismaleimide (BMI) or cyanate ester matrix, whose investigation is planned as a follow-on study.

5. Conclusion

This systematic fabrication and characterisation study of seven glass/carbon/epoxy laminate configurations confirms that the 4-ply symmetric GCCG hybrid laminate delivers the optimal balance of mechanical performance and impact resistance — achieving 90.3% of CFRP-4L tensile strength (143.2 MPa), 26.6% higher impact energy than CFRP-4L (13.8 J versus 10.9 J), moisture equilibrium absorption of 0.72%, and thermal onset degradation at 325°C — at an estimated material cost 35–40% below all-CFRP configurations. CFRP-4L remains the specification-of-choice for stiffness-critical primary structures with specific modulus of 26.6 GPa·cm³/g. GFRP-6L represents the most cost-effective route to matching CFRP-4L tensile strength (118.6 MPa versus 158.4 MPa) for applications where weight is a secondary design driver. The positive hybrid effect on impact energy observed in HYBRID-4L validates the GCCG symmetric architecture as a practical design strategy for semi-structural aerospace fairings, interior panels, and secondary structural ribs where weight, impact resistance, and lifecycle cost govern the material selection decision.

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