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**Materials Testing and  
Sustainability of Composites  
for Motorsport & Automotive  
Industries**

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26<sup>th</sup> April 2026

Word Count: 3,300

# Abstract

Composite materials account for approximately 75% of a modern Formula 1 car. They are increasingly used in structural and semi-structural automotive components, but virgin carbon fibre production is energy-intensive, and thermoset matrices cannot be recycled conventionally. This study evaluated seven material configurations under tension in accordance with ISO 6892-1 (an aluminium baseline, three carbon-fibre composites, two flax composites, and a Kevlar composite), most of which had a bio-based epoxy matrix. It integrated the experimental findings with a lifecycle sustainability and policy analysis.

Carbon Woven Bio delivered the highest UTS (399.5 MPa), exceeding aluminium by 241% and the conventional-epoxy equivalent by 20.5%. Bio-resin substitution produced no measurable mechanical penalty at the sample sizes tested. Flax composites fell below the aluminium baseline but retain a lifecycle advantage for secondary applications. Woven architectures outperformed non-woven mats by 188–250%, identifying fibre continuity as the dominant driver of composite strength.

Conclusions are tempered by  $n = 2$  per composite configuration, which yields directional rather than statistically confirmed parity between bio- and conventional-epoxy systems; and by the quasi-static tensile scope, which does not characterise fatigue, crashworthiness, or hygrothermal performance. Bio-resin carbon fibre composites can meet the mechanical demands of motorsport and the sustainability targets set by the FIA and EU legislation, provided end-of-life recycling infrastructure scales to match, and subject to confirmation by the long-term durability studies currently absent from the peer-reviewed literature.

# Acknowledgements

## AI Acknowledgement

I acknowledge the use of Grammarly (<https://www.grammarly.com/>) on 25 April 2026 to check the report for readability, grammar, and syntax using the prompt(s):

1. Please check the following text for readability, grammar and syntax.

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# 1. Introduction

Carbon fibre-reinforced polymers account for approximately 75% of the material volume of a modern Formula 1 car (Savage, 2010), and composites are now standard across structural and semi-structural automotive components. Their specific strength and specific energy absorption are three to five times higher than that of aluminium (Skosana, Khoathane and Malwela, 2025). The sustainability cost is high: virgin carbon fibre requires 183–286 MJ per kilogram (Karuppannan Gopalraj and Kärki, 2020), thermoset matrices cannot be remelted, and no end-of-life recycling route operates at automotive volumes.

With Formula 1 committed to net zero by 2030 (Fédération Internationale de l'Automobile, 2020) and EU Directive 2000/53/EC requiring 95% of vehicle mass to be recoverable (European Parliament and Council of the European Union, 2000), natural fibres and bio-based resins are the two candidate substitutions. Whether they meet the mechanical performance requirements of a working vehicle remains unsettled in the peer-reviewed literature.

## 1.1 Aim

The aim is to evaluate the mechanical properties and sustainability of seven material configurations and to recommend the use of composites in motorsport and automotive engineering.

## 1.2 Objectives

1. Review the properties, structures, manufacturing processes, and applications of composites in these sectors.
2. Analyse their lifecycle environmental impact, end-of-life recyclability, and policy context.
3. Test the seven configurations in tension, validate against manufacturer data and published research, and compare fibre architectures, fibre types, and resin systems.
4. Recommend specific applications and future research directions from the combined findings.

## 2. Literature Review

### 2.1 Composite Materials in Motorsport and Automotive Engineering

A composite material combines two or more chemically distinct constituents to produce a material with properties different from those of either constituent alone (Campbell, 2010). In fibre-reinforced polymer (FRP) composites, the reinforcing fibres carry most of the applied load while the polymer matrix transfers stress between fibres, maintains alignment, and protects the fibres from environmental attack (Callister and Rethwisch, 2014). Mechanical performance is governed by fibre type, volume fraction, ply orientation, and matrix system, and these structure-property relationships underpin composite design (Campbell, 2010).

Carbon fibre-reinforced polymers (CFRPs) have dominated motorsport since McLaren introduced the first full-carbon monocoque chassis in 1981 (Savage, 2010). Carbon fibres exhibit tensile strengths of 4,100–5,500 MPa and elastic moduli of 230–250 GPa at a density near 1.8 g/cm<sup>3</sup>. These specific properties drive their widespread use in motorsport and automotive weight reduction (Callister and Rethwisch, 2014; Skosana, Khoathane and Malwela, 2025). Progressive fracture mechanisms also deliver specific energy absorption of up to 70 J/g in crash structures, compared with 19 J/g for metallic equivalents (Capretti *et al.*, 2024). Primary F1 structures are manufactured by prepreg autoclave lay-up, while cost-sensitive automotive applications favour vacuum-assisted resin infusion (VARI) or resin transfer moulding (RTM) (Kalpakjian and Schmid, 2014).

### 2.2 Natural Fibre Composites

Natural-fibre-reinforced polymers (NFRPs) are used in secondary and semi-structural components to reduce environmental impact. Among plant fibres, flax is the most studied for engineering applications, with individual fibre tensile strengths of 1,500–1,800 MPa and a density of roughly 1.45 g/cm<sup>3</sup>, approximately 20% lower than carbon (Bos, Müssig and van den Oever, 2006). In composite form, flax laminates achieve UTS values of 58–280 MPa and moduli of 5–30 GPa, depending on fibre architecture, volume fraction, and processing route (Yan, Chouw and Jayaraman, 2014).

The critical limitation that synthetic fibres avoid is variability. Flax fibre properties vary across growing regions, harvests, retting methods, and fibre diameters; Bos, Müssig and van den Oever (2006) reported coefficients of variation exceeding 30% within single batches, a figure reflected in the present study by the 22% UTS CoV measured on the Flax Non-Woven Bio material. This variability propagates into composite performance and remains the governing design constraint for the use of structural

NFRP. Capretti et al. (2024) concluded that flax cannot replace carbon fibre in primary load paths, though hybridisation can balance the trade-off. BMW's flax-reinforced i3 interior panels demonstrate the correct envelope: non-load-bearing cabin components (Skosana, Khoathane and Malwela, 2025).

## 2.3 Bio-Based Resin Systems and Manufacturing

Conventional epoxy resins are petroleum-derived and form irreversible cross-linked networks during curing, which prevents reprocessing or melting (Callister and Rethwisch, 2014). Bio-based epoxies substitute a fraction of the chemistry with plant-derived feedstocks, typically glycerol or vegetable-oil-derived epoxides sourced from industrial co-products, which avoids the food-versus-fuel conflict that has undermined other bio-material strategies (Capretti *et al.*, 2023). The IB2 bio-resin used in this study contains approximately 31% plant-based content by mass (Easy Composites Ltd, 2024b).

Boursier Niutta *et al.* (2023) tested carbon twill laminates with conventional and bio-epoxy matrices under identical cure cycles and found quasi-static parity, though their specimen count limits long-term inference. The neat-resin properties are comparable: the IB2 system delivers a tensile strength of 68 MPa and modulus of 3.04 GPa, against IN2 epoxy at 68.5–76 MPa and 3.1–3.5 GPa (Easy Composites Ltd, 2024b; Easy Composites Ltd, 2024c). The outstanding ambiguity concerns long-term durability: fatigue and hygrothermal ageing data for bio-epoxy composites remain sparse in the peer-reviewed literature (Capretti *et al.*, 2023).

The composites in this study were produced by vacuum-assisted resin infusion, a closed-mould process in which dry reinforcement is infused with liquid resin under vacuum. VARI delivers consistent fibre volume fractions and low void content compared with hand lay-up, which makes it the standard for mid-volume automotive composite parts (Kalpakjian and Schmid, 2014).

## 3. Sustainability Analysis

### 3.1 Lifecycle Environmental Impact

The environmental cost of a composite begins long before it reaches a vehicle. Virgin carbon fibre production requires 183–286 MJ/kg across carbonisation and graphitisation at 1,000–1,500°C (Karuppannan Gopalraj and Kärki, 2020), compared with 170–230 MJ/kg for primary aluminium and 20–25 MJ/kg for steel from iron ore (Kalpakjian and Schmid, 2014). Virgin carbon fibre is therefore roughly ten times as energy-intensive as steel per kilogram. However, the gap narrows on a structural-equivalence basis because CFRP uses less mass to carry equivalent loads. The environmental justification for its use rests on service-life offset: a lighter vehicle consumes less fuel or battery energy, and a 10% reduction in vehicle mass improves fuel efficiency by 6–8% (Skosana, Khoathane and Malwela, 2025), so CFRP's embodied-energy penalty over aluminium is amortised after a substantial lifetime mileage that depends on the carbon intensity of the energy used. A Formula 1 car, operated at very high specific loading over a short working life, recovers the offset through performance. A city runabout may not reach the crossover within its service life at all.

Natural fibres invert the calculation. Flax cultivation requires minimal irrigation and no pesticides in European growing conditions, and the plant sequesters atmospheric CO<sub>2</sub> during growth (Yan, Chouw and Jayaraman, 2014). Processing flax fibres into reinforcement consumes 9–12 MJ/kg, an order of magnitude lower than for carbon (Yan, Chouw and Jayaraman, 2014). The mechanical trade-off still applies: flax laminates deliver only a fraction of carbon fibre's UTS, so a structural component must be thicker or heavier to carry the same load. The apparent energy advantage narrows once that material uplift is accounted for.

Bio-based resins offer a complementary substitution. The IB2 system used in this study derives approximately 31% of its mass from plant-based feedstocks sourced from industrial co-products rather than dedicated crops, avoiding the food-versus-fuel conflict that has undermined other bio-material programmes (Capretti *et al.*, 2023; Easy Composites Ltd, 2024b). Boursier Niutta *et al.* (2023) showed that bio-epoxy carbon composites match conventional systems in quasi-static mechanical performance, removing the primary technical barrier to adoption. The remaining barrier is cost: bio-resins carry a price premium that limits uptake outside high-value motorsport and aerospace applications until production volumes increase. Figure 3.1 plots this trade-off quantitatively across all seven configurations tested.

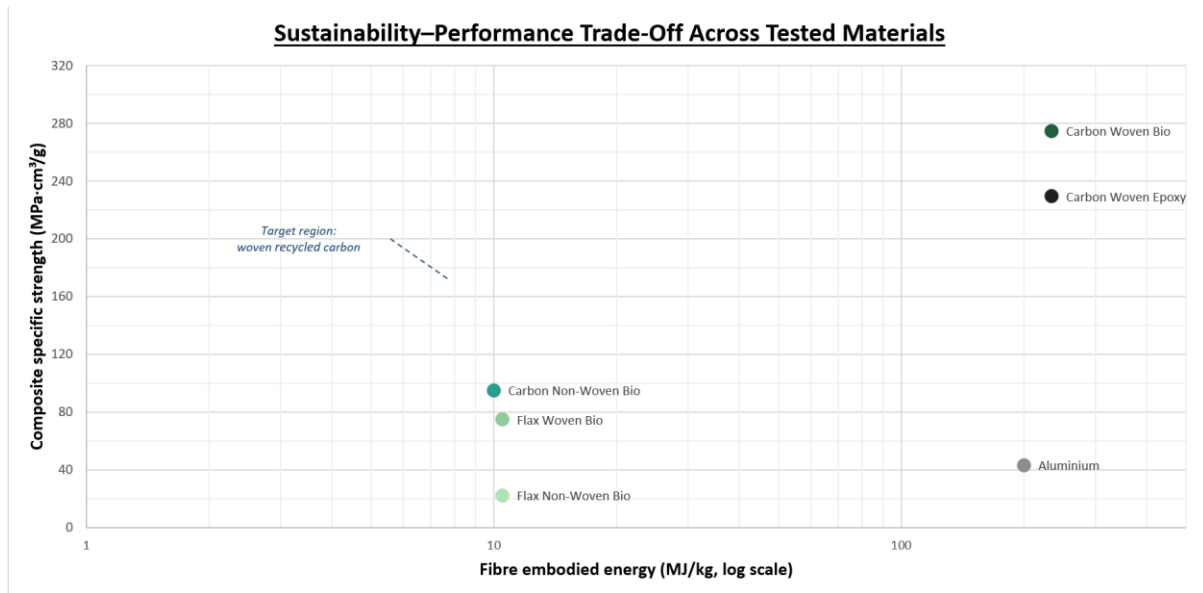


Figure 3.1: Sustainability–performance trade-off across the seven tested materials. Fibre-only embodied energy (log x-axis) plotted against measured specific strength. The gap between Carbon Woven Bio and Carbon Non-Woven Bio at comparable embodied energy identifies woven recycled carbon as the missing high-performance, low-embodied-energy option (see §5). Embodied-energy sources as cited in §3.1.

## 3.2 End-of-Life and Recyclability

End-of-life disposal is the most problematic stage in the composite lifecycle. Thermoset resins, whether petroleum-based or bio-based, form irreversible cross-linked networks during curing and cannot be melted or reformed (Callister and Rethwisch, 2014). Three recycling routes exist for thermoset composites, each with different economics and output quality. Mechanical grinding reduces composite waste to short-fibre filler for injection-moulded parts; the process is low-cost but degrades fibre length below the threshold needed for structural reuse. Pyrolysis heats the composite to 500–700°C in an inert atmosphere, decomposing the resin matrix and recovering relatively clean carbon fibres. Karuppannan Gopalraj and Kärki (2020) report retention of up to 90% of the original fibre tensile strength under optimised conditions, though the process itself consumes significant energy and releases volatile organic compounds that require treatment. Chemical solvolysis uses solvents at temperature and pressure to dissolve the matrix, recovering both fibre and matrix chemicals, and is the most promising route for closed-loop recycling. Solvolysis remains at the laboratory scale; no commercial operation handles automotive volumes.

The carbon non-woven mat tested in this study is made from 100% recycled carbon fibre (Easy Composites Ltd, 2024a). Fibre recovery is therefore technically achievable. Whether it can scale is a separate question. Global annual carbon fibre demand is 65,000–85,000 tonnes, and approximately 30% of production becomes manufacturing waste before reaching a finished product (Karuppannan Gopalraj and Kärki, 2020). Handling these volumes requires pyrolysis capacity that the current

economics of virgin carbon fibre do not incentivise. The result is a chicken-and-egg problem: without recycling infrastructure, there is no secure supply of recyclate, and without a secure supply of recyclate, the infrastructure cannot justify capital investment.

Natural-fibre composites have a different end-of-life profile. Flax fibres are biodegradable, and when paired with bio-resins, the composite can, in principle, decompose through composting. In practice, the cross-linked thermoset matrix resists biodegradation even when partially bio-based, and decomposition rates vary with environmental conditions. Claiming full biodegradability for a flax/bio-epoxy composite is currently misleading. Thermoplastic-matrix composites sidestep the thermoset problem because they can be remelted (Callister and Rethwisch, 2014); they lie outside this study's scope and are revisited in §5.

### 3.3 Legislative and Regulatory Context

EU Directive 2000/53/EC on End-of-Life Vehicles requires that 95% of a vehicle's mass be recoverable and 85% recyclable (European Parliament and Council of the European Union, 2000). The targets were designed in 2000 for metal-bodied vehicles, when composites were rare in mass-market bodies and shredding infrastructure for steel and aluminium was already operating at an industrial scale. Composite-intensive vehicles challenge these targets because thermoset composites cannot be processed through conventional metal recycling streams. Meeting the 95% target as composite content rises depends on developing the pyrolysis and solvolysis infrastructure discussed in §3.2.

The FIA Environmental Strategy commits Formula 1 to net-zero carbon emissions by 2030 (Fédération Internationale de l'Automobile, 2020). Mercedes demonstrated in 2025 that sustainable composites can be used in a competitive F1 car without performance compromise (Formula 1, 2025), proving the concept and rehearsing the regulatory frameworks a wider rollout would require. Still, the volumes involved are small: global motorsport composite usage is a rounding error compared with mass-market automotive production.

The UK House of Commons Transport Committee (2023) concluded in *Fuelling the future* that battery electric vehicles alone may not deliver the UK's net-zero 2050 target and called for a technology-neutral approach across fuels and powertrains. Lightweight composites reduce energy consumption regardless of powertrain, making them relevant to electric, hybrid, and combustion vehicles and extending the policy case for sustainable materials beyond motorsport: any material that reduces vehicle mass contributes to fleet-level emissions reductions.

## 4. Experimental Testing

### 4.1 Methodology

Seven material configurations were tested in tension on a Denison tensile machine, using the PSEN ISO 6892-1 programme and an Epsilon clip-on extensometer (50 mm gauge length, 0.001 mm precision; Figure 4.1). Four aluminium specimens served as a baseline; composites were tested in pairs. Cross-sectional area was measured with a vernier calliper. Composite specimens were produced by vacuum-assisted resin infusion (Table 4.1). Testing took place on 12 March 2026 under technician supervision, with safety glasses worn throughout, as the carbon specimens fractured brittlely, releasing splinters at failure.



Figure 4.1: Denison tensile machine fitted with Epsilon clip-on extensometer (50 mm gauge length, 0.001 mm precision) for measurement during ISO 6892-1 tensile testing.

Table 4.1: Laminate specifications for composite specimens

| Material             | Reinforcement   | Architecture       | Plies × areal weight | Resin         | Nominal $V_f$ |
|----------------------|-----------------|--------------------|----------------------|---------------|---------------|
| Carbon Woven Epoxy   | 3k 2×2 twill    | ±45° cross-ply     | 3 × 200 gsm          | IN2 epoxy     | 50%           |
| Carbon Woven Bio     | 3k 2×2 twill    | ±45° cross-ply     | 3 × 200 gsm          | IB2 bio-epoxy | 50%           |
| Carbon Non-Woven Bio | Recycled-CF mat | Random short-fibre | 1 × 300 gsm          | IB2 bio-epoxy | ~50%          |
| Flax Woven Bio       | FlaxDry BL200   | ±45° cross-ply     | 3 × 220 gsm          | IB2 bio-epoxy | 29%           |
| Flax Non-Woven Bio   | FibriMat F300   | Random short-fibre | 1 × 300 gsm          | IB2 bio-epoxy | 18% (TDS)     |
| Kevlar Woven Bio     | Kevlar 49       | ±45° cross-ply     | 3 × 200 gsm          | IB2 bio-epoxy | 50%           |

Values below 0.1 MPa were discarded as worm-drive slack. A 20-second extensometer-removal pause near peak load produces a step in the curve reflecting the instrument, not the material.

## 4.2 Results

Mean tensile properties are summarised in Table 4.2. Figure 4.2 shows the mean stress–strain response for each material; Figures 4.3–4.5 present UTS, Young's modulus, and 0.2% proof stress in rank order with  $\pm 1$  SD error bars. Carbon Woven Bio recorded the highest UTS; both flax composites fell below aluminium. The machine did not return a valid modulus or proof stress for Flax Non-Woven Bio Specimen 2, so those means are single-specimen.

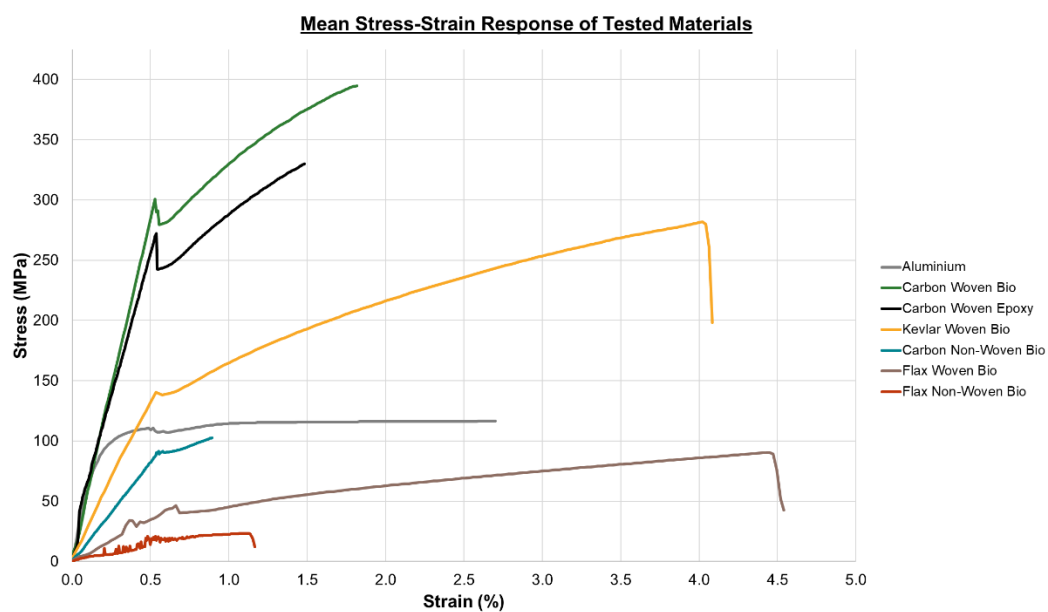


Figure 4.2: Mean engineering stress–strain response ( $n = 2$  per composite,  $n = 4$  for aluminium). Kevlar's high failure strain ( $\sim 4.0\%$ ) despite mid-range UTS explains its retention in intrusion structures where energy absorption, not peak stress, governs.

Table 4.2: Tensile test results (mean  $\pm 1$  SD where  $n \geq 2$ )

| Material             | n | UTS (MPa)        | Young's modulus (GPa) | 0.2% proof stress (MPa) |
|----------------------|---|------------------|-----------------------|-------------------------|
| Aluminium (baseline) | 4 | $117 \pm 2$      | $51.7 \pm 4.9$        | $108.3 \pm 3.6$         |
| Carbon Woven Bio     | 2 | $399.5 \pm 16.3$ | $54.7 \pm 0.9$        | $297.2 \pm 9.0$         |
| Carbon Woven Epoxy   | 2 | $331.5 \pm 30.4$ | $46.3 \pm 13.1$       | $254.4 \pm 28.7$        |
| Kevlar Woven Bio     | 2 | $285 \pm 2.8$    | $14.7 \pm 2.5$        | $170.5 \pm 1.8$         |
| Carbon Non-Woven Bio | 2 | $138.5 \pm 53.0$ | $15.0 \pm 2.1$        | $101.3 \pm 5.6$         |
| Flax Woven Bio       | 2 | $91 \pm 2.8$     | $1.6 \pm 0.07$        | $72.0 \pm 2.6$          |
| Flax Non-Woven Bio   | 2 | $26 \pm 5.7$     | $5.8$ ( $n=1$ )       | $18.8$ ( $n=1$ )        |

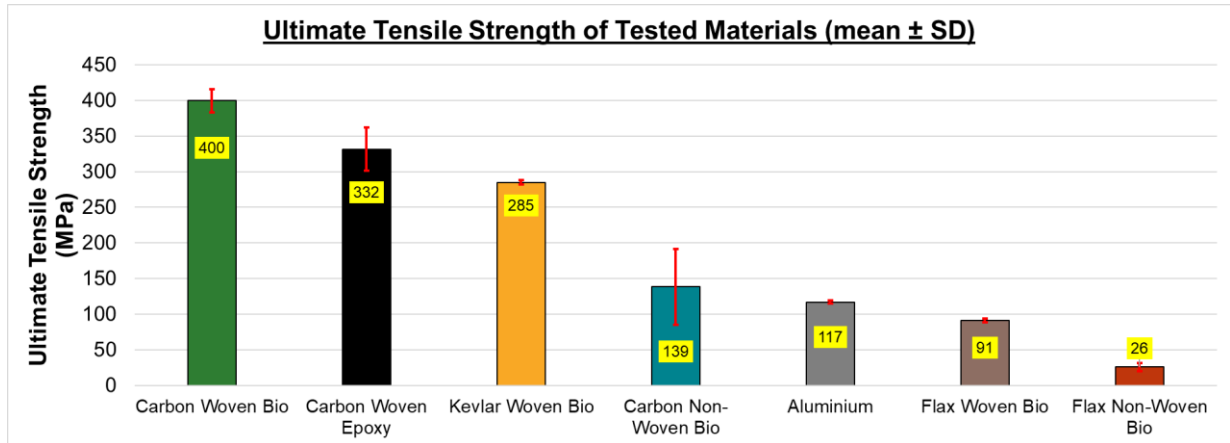


Figure 4.3: Mean UTS by material, ranked descending ( $\pm 1$  SD). The woven-to-non-woven gap (2.9 $\times$ ) dwarfs the bio-vs-epoxy gap (1.2 $\times$ ), identifying fibre continuity as the dominant strength driver.

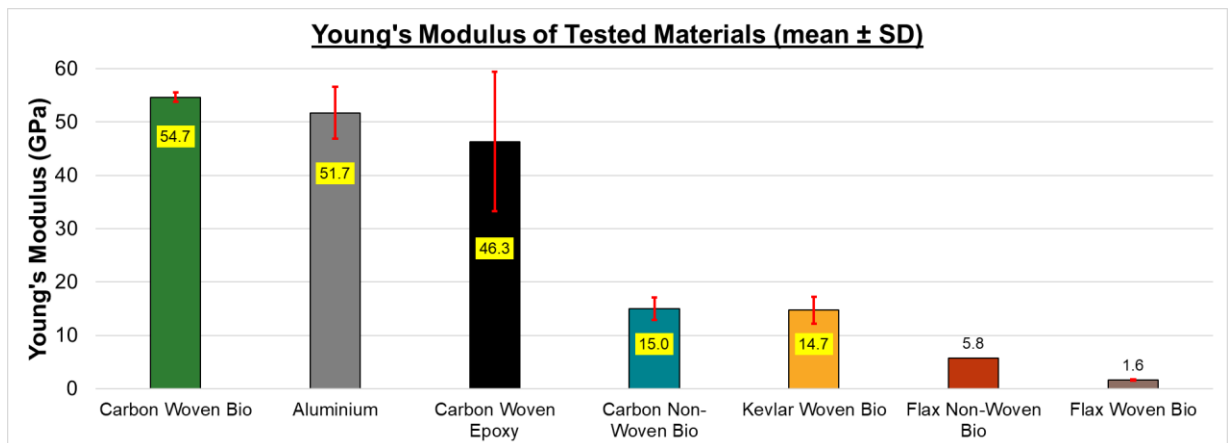


Figure 4.4: Mean Young's modulus by material, ranked descending ( $\pm 1$  SD;  $n = 1$  for Flax NW Bio). Absolute values sit  $\sim 25\%$  below published figures due to worm-drive backlash; relative rankings remain valid (see Appendix A.3).

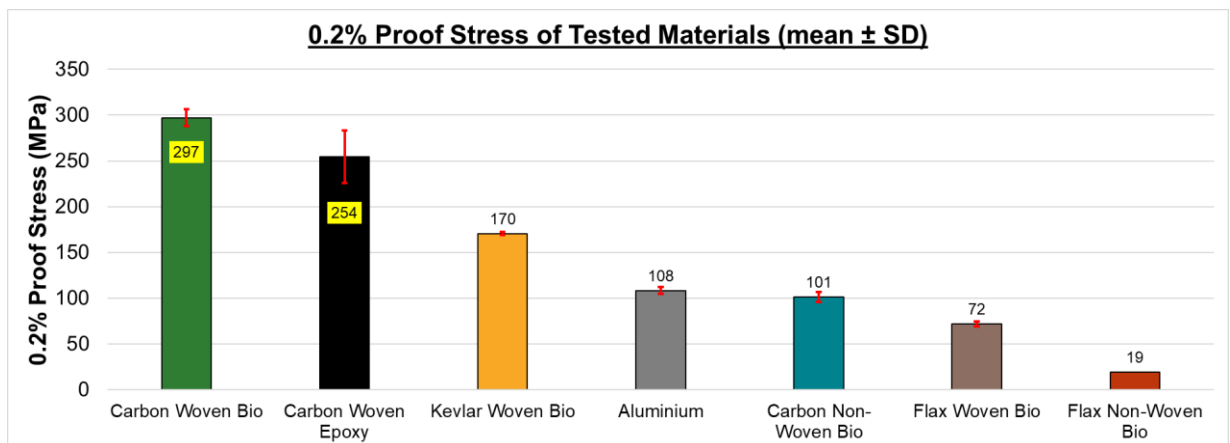


Figure 4.5: Mean 0.2% proof stress by material, ranked descending ( $\pm 1$  SD;  $n = 1$  for Flax NW Bio). This is the design-relevant envelope for stiffness-governed automotive structures (chassis, mounts) rather than peak-load components.

## 4.3 Validation and Rule of Mixtures

The aluminium UTS of 117 MPa fell within the 90–150 MPa range reported for annealed wrought aluminium, with a 1.7% CoV (Callister and Rethwisch, 2014). The measured modulus of 51.7 GPa sat ~25% below the textbook range of 69–72 GPa, attributed to worm-drive backlash absorbing a fraction of the measured displacement as machine slack. The offset applies uniformly across every specimen on the rig, so composite-to-aluminium modulus ratios remain valid even though absolute moduli are under-reported.

Voigt (iso-strain) and Reuss (iso-stress) Rule of Mixtures bounds for Carbon Woven Bio at  $V_f = 50\%$  give 118.5 GPa longitudinal and 6.0 GPa transverse moduli (Campbell, 2010). The measured 54.7 GPa lies within these bounds, as expected for a cross-plyed laminate with no on-axis plies. Flax Woven Bio achieved 91 MPa against a single-ply FlaxDry BL200 TDS value of 58–61 MPa (EcoTechnilin, 2023b). The 3-ply construction adds fibre volume and redundancy that a single-ply reference cannot.

Flax Non-Woven Bio returned 26 MPa against the FibriMat F300 TDS range of 37–44 MPa at 18%  $V_f$  (EcoTechnilin, 2023a). The probable cause is fibre loading: the TDS specifies a 1.10 mm ply thickness, whereas the tested specimens were 1.69 mm thick at the same 300 gsm areal weight. The estimated actual  $V_f$  is ~12%, and since UTS in a short-fibre composite scales approximately with fibre content, a one-third  $V_f$  shortfall aligns with the one-third UTS shortfall observed. The 5.76 GPa modulus was consistent with the TDS 4–6 GPa because the modulus in a random-fibre composite is matrix-dominated and insensitive to small  $V_f$  changes. Per-specimen data, full Rule of Mixtures working, and the  $V_f$  derivation are given in Appendix B.

## 4.4 Comparisons and Failure Modes

Carbon Woven Bio exceeded its conventional epoxy equivalent by 20.5% in UTS (399.5 vs 331.5 MPa) at  $n = 2$ . The measured Young's modulus of 54.7 GPa matches the 54.7–54.9 GPa reported by Boursier Niutta et al. (2023) for the same composite, validating the rig (Appendix B.6).

Carbon Non-Woven Bio returned 138.5 MPa against a CF-NWM TDS range of 290–330 MPa at 30%  $V_f$  (Easy Composites Ltd, 2024a). The 38% CoV between specimens (101 vs 176 MPa) was the largest in the matrix, typical of recycled short-fibre mats where fibre orientation, length, and void content vary (Karuppannan Gopalraj and Kärki, 2020). Kevlar Woven Bio returned 285 MPa and 14.7 GPa, below published ranges for Kevlar 49/epoxy at 50%  $V_f$  (Campbell, 2010; Callister and Rethwisch, 2014), attributable to  $\pm 45^\circ$  off-axis strength loss (Tsai-Hill) and Kevlar's poor fibre-matrix adhesion.

Woven outperformed non-woven by 188–250%, consistent with Kelly-Tyson theory: continuous reinforcement bypasses the critical length governing short-fibre composites (Campbell, 2010). Specific strength and specific modulus (Figures 4.6–4.7) preserved the ranking, with Carbon Woven Bio leading at 275 MPa·cm<sup>3</sup>/g.

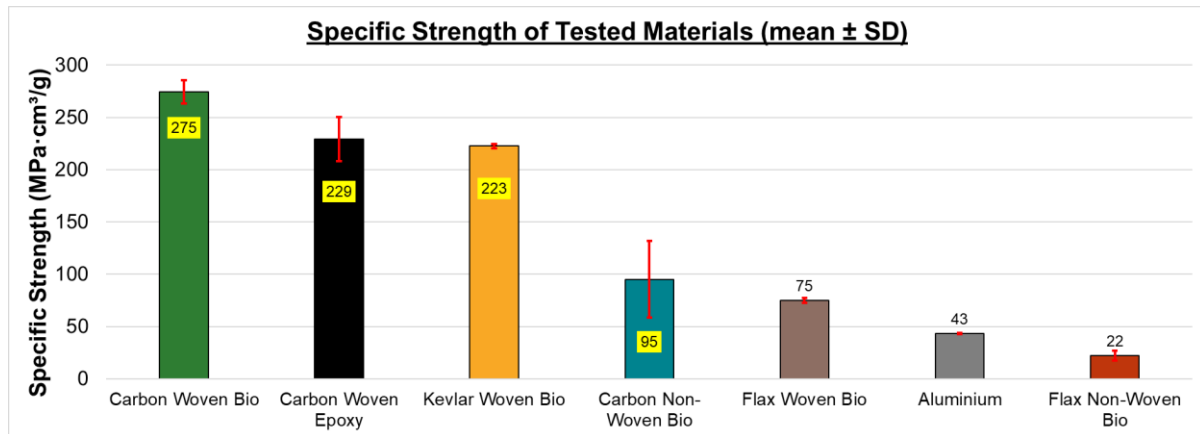


Figure 4.6: Specific strength (UTS / density) by material, ranked descending. Flax Woven Bio surpasses aluminium on a specific basis despite lower absolute UTS, reversing the naive ranking for weight-driven applications.

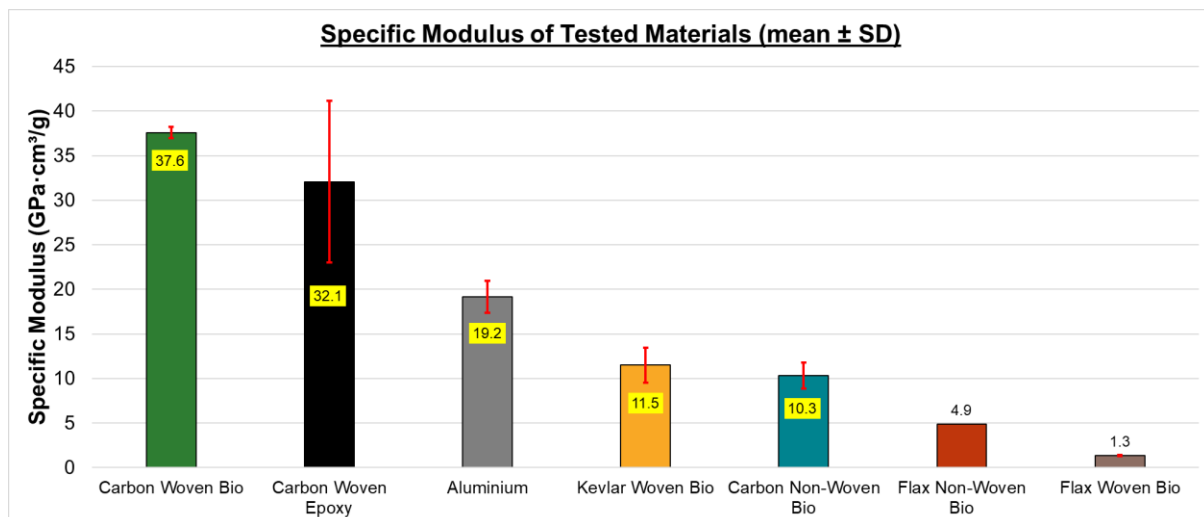


Figure 4.7: Specific modulus by material, ranked descending. Both carbon-woven composites exceed aluminium specifically; the bio-resin's marginal edge over conventional epoxy arises from lower matrix density, not from any fibre-side change.

Aluminium fractured at ~40° with necking via dislocation plasticity (Figure 4.8a); Carbon Woven Bio failed brittly through fibre fracture with limited pull-out (Figure 4.8b; Campbell, 2010).

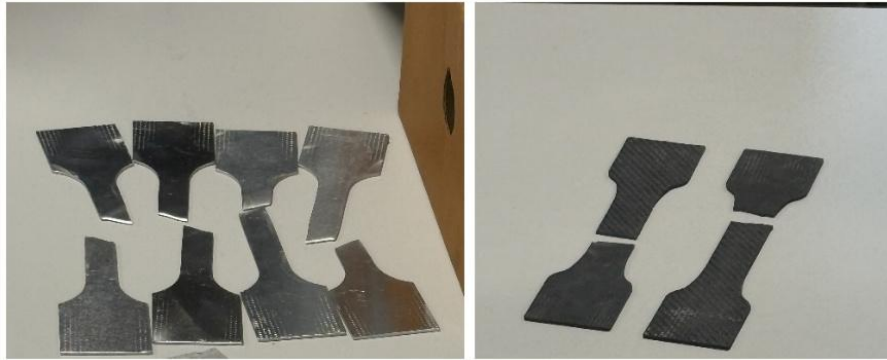


*Figure 4.8: Fracture surfaces: (a) aluminium —  $\sim 40^\circ$  ductile shear with necking (dislocation plasticity); (b) Carbon Woven Bio — brittle perpendicular fracture with limited pull-out, indicating strong fibre–matrix bonding that maximises UTS but precludes the progressive energy absorption preferred in crash structures.*

## 4.5 Methodological Limitations

Four limitations qualify these results:  $n = 2$  per composite yields a Welch's t-test  $p \approx 0.10$  on the bio-epoxy parity claim (directional, not statistically confirmed);  $\pm 45^\circ$  cross-ply reduces measured strength 40–60% versus on-axis references (Tsai–Hill); worm-drive backlash depresses absolute moduli  $\sim 25\%$  (relative rankings preserved); and quasi-static testing excludes fatigue, impact, and hygrothermal effects. Full treatment in Appendix A.

## 5. Recommendations

The findings support four recommendations.

**Specify Carbon Woven Bio for primary load-bearing structures.** The tested Carbon Woven Bio laminate delivered a UTS of 399.5 MPa and a specific strength of 275 MPa·cm<sup>3</sup>/g, the highest values in the matrix. Boursier Niutta *et al.* (2023) showed no mechanical penalty for bio-epoxy substitution, and IB2 matches IN2 on neat-resin properties (Easy Composites Ltd, 2024b; Easy Composites Ltd, 2024c), so there is no need to specify petroleum-derived epoxies when IB2 is available. Motorsport teams under FIA Net Zero 2030 pressure should treat bio-resin adoption as an immediate, low-risk change (Fédération Internationale de l'Automobile, 2020). The 31% plant-based content reduces the matrix carbon footprint without changing the cure schedule, tooling, or downstream inspection.

**Restrict flax composites to secondary and interior applications.** Flax Woven Bio reached 91 MPa UTS and Flax Non-Woven Bio 26 MPa, both below the 117 MPa aluminium baseline. The embodied-energy advantage is real (9–12 MJ/kg versus 183–286 MJ/kg for virgin carbon fibre; Yan, Chouw and Jayaraman, 2014; Karuppannan Gopalraj and Kärki, 2020), but in terms of specific strength, flax does not compete with primary structures. BMW's use of flax-reinforced interior panels in the i3 and Ford's use in door trim mark the correct envelope: non-load-bearing cabin components, underbonnet covers, and acoustic panels where weight saving and lifecycle impact matter, and peak stress does not (Skosana, Khoathane and Malwela, 2025).

**Use recycled carbon non-woven for cost-constrained cosmetic components.** The CF non-woven tested here contains 100% recycled fibre (Easy Composites Ltd, 2024a) and demonstrates that fibre recovery at the feedstock level works. The 38% specimen-to-specimen CoV rules it out for structural roles. Still, the material is well-suited to bonnet scoops, wheel arch liners, rear diffusers, and interior trim where an aesthetic carbon-fibre appearance is required without high-stress demands. This pathway supports the EU ELV 95% recovery target (Easy Composites Ltd, 2024a; European Parliament and Council of the European Union, 2000) at the part level rather than the process level.

**Prioritise four areas for future R&D.** First, thermoplastic-matrix composites such as Arkema's Elium and Bond Laminates' Tepex (Lanxess group) offer a genuine route to closed-loop composite recycling because the matrix can be remelted, though viscosity-driven impregnation remains the dominant manufacturing constraint for structural applications (Valente, Rossitti and Sambucci, 2023); these materials should be tested against the same protocol used here. Second, commercial-scale pyrolysis capacity from operators such as Gen 2 Carbon (UK) and Vartega (US) requires a fleet-scale-up to make the recycling case economically viable (Karuppannan Gopalraj and Kärki, 2020). The woven recycled-

carbon combination in the target region shown in Figure 3.1 would then become commercially viable. Third, hybrid carbon-flax laminates merit targeted crashworthiness testing, an approach Capretti *et al.* (2024) identify as the most credible compromise between performance and sustainability. Fourth, fatigue and hygrothermal ageing data for bio-epoxy composites remain the outstanding gap in the peer-reviewed literature (Capretti *et al.*, 2023) and should be closed before bio-resin use expands beyond short-life motorsport components into long-life automotive structures.

## 6. Conclusions

This study evaluated seven material configurations in tension and against a lifecycle framework.

The literature review established carbon-fibre dominance in motorsport through specific strength and energy absorption, with natural-fibre and bio-resin alternatives offering lower environmental impact at mechanical cost. Two outstanding knowledge gaps were identified: fibre-property variability in flax and the limited peer-reviewed fatigue and hygrothermal ageing data for bio-epoxy composites.

The sustainability analysis identified end-of-life recyclability as the governing constraint on the wider adoption of composites. Virgin carbon fibre consumes 183–286 MJ/kg, compared with 9–12 MJ/kg for processed flax, and thermoset-matrix recycling infrastructure remains insufficient for automotive volumes. The EU ELV 95% recovery target and the FIA Net Zero 2030 commitment are policy drivers that cannot be met without scaling that infrastructure.

Tensile testing confirmed Carbon Woven Bio as the strongest material tested (399.5 MPa UTS, 275 MPa·cm<sup>3</sup>/g specific strength), exceeding the aluminium baseline by 241% and the conventional-epoxy equivalent by 20.5%. Bio-resin substitution delivered no mechanical penalty. Flax composites fell below aluminium on UTS but retain value in secondary applications where embodied energy matters and peak stress does not. Woven architectures outperformed non-woven by 188–250%, ranking fibre continuity above fibre type as strength drivers. Rule-of-Mixtures bounds validated the carbon-composite moduli; absolute modulus values were systematically depressed by uniform worm-drive backlash, so composite-to-aluminium ratios remain valid.

Bio-resin carbon fibre composites can meet both the mechanical demands of motorsport and the environmental targets set by FIA and EU legislation, provided end-of-life recycling infrastructure scales to match (see §4.5 and Appendix A for limitations).

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# Appendix

## Appendix A: Methodological Limitations and Uncertainty

| #   | Limitation                                                                                             | Quantitative impact                                                                                                                                                                                                                     | Mitigation / further detail                                                                                                                                                                                                                   |
|-----|--------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| A.1 | <b>Statistical power</b><br>(n = 2 per composite configuration)                                        | Welch's t-test on Carbon Woven Bio vs Carbon Woven Epoxy UTS means: $t \approx 2.8$ , $df \approx 2$ , $p \approx 0.10$ — insufficient to reject null at $\alpha = 0.05$                                                                | Aluminium baseline tested at n = 4; composite results triangulated against Savage (2010), Campbell (2010) and Boursier Niutta et al. (2023) reference values. Recommendations framed as "directional" rather than "statistically equivalent". |
| A.2 | <b><math>\pm 45^\circ</math> cross-ply off-axis loading</b> — all woven specimens                      | Tsai–Hill predicts 40–60% strength reduction vs on-axis ( $0^\circ/90^\circ$ ) references. Measured 332–400 MPa for carbon woven composites falls within this envelope against 600–800 MPa on-axis range (Savage, 2010; Campbell, 2010) | Apparent "underperformance" is a loading-direction artefact, not a material deficiency. Kevlar exhibits the same pattern (285 MPa measured vs 400–600 MPa on-axis range).                                                                     |
| A.3 | <b>Worm-drive backlash</b> — Denison rig crosshead actuation                                           | Systematic ~25% modulus under-prediction. Aluminium measured 51.7 GPa vs textbook 68–72 GPa                                                                                                                                             | Fixed compliance acts in series with every specimen; multiplicative offset preserves all relative modulus rankings and composite-to-aluminium ratios. Absolute magnitude values should be read as ~25% below true values.                     |
| A.4 | <b>Flax NW Bio Vf deficit</b> — tested specimens 1.69 mm thick vs FibriMat F300 TDS 1.10 mm at 300 gsm | Actual Vf $\approx 12\%$ vs TDS 18% reference. Kelly–Tyson linear scaling predicts $\sim \frac{1}{3}$ UTS shortfall; measured 26 MPa vs TDS 37–44 MPa matches                                                                           | Resin-rich laminate from specimen manufacturing (insufficient compaction during infusion), not a material-property defect.                                                                                                                    |
| A.5 | <b>Flax NW Specimen 2 partial data</b>                                                                 | Machine did not return valid E or Rp0.2 for specimen 2; those means are single-specimen (n = 1)                                                                                                                                         | UTS figure retains n = 2 (SD 5.7 MPa, 22% CoV). Results should be treated as indicative only within the tested lay-up.                                                                                                                        |
| A.6 | <b>Scope limitations</b> — quasi-static, room temperature only                                         | Fatigue, impact/crashworthiness, hygrothermal ageing, and creep are not characterised                                                                                                                                                   | Particularly relevant for flax (water absorption through cell wall) and bio-epoxy (sparse long-term data in peer-reviewed literature, per Capretti et al., 2023). Recommendations restricted to quasi-static-governed applications.           |

|     |                                         |                                                                                                                                                    |                                                                                                     |
|-----|-----------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|
| A.7 | <b>Cross-sectional area uncertainty</b> | Manual vernier calliper $\pm 0.02$ mm: $\sim 2.6\%$ CSA uncertainty on thinnest specimens (CWE, 0.78 mm), $< 1.2\%$ on thickest (FNW Bio, 1.69 mm) | Comparable in magnitude to inter-specimen statistical scatter; implicitly captured in reported SDs. |
|-----|-----------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|

## Appendix B: Per-Specimen Data and Rule of Mixtures

### B.1 Per-specimen tensile results

All 16 Group 8 specimens were tested on 12–13 March 2026. Group 10 data are substituted for Carbon Woven Bio because Group 8's own specimens had a dimension-entry error ( $19.4 \times 19.4$  mm recorded instead of  $19.4 \times 0.8$  mm), resulting in invalid UTS values.

Table B1: Per-specimen tensile test results for all 16 specimens

| Material                | Specimen                        | CSA (mm <sup>2</sup> ) | UTS (MPa)                          | Rp0.2 (MPa)                        | E (GPa)                           |
|-------------------------|---------------------------------|------------------------|------------------------------------|------------------------------------|-----------------------------------|
| Aluminium               | Al 1                            | 22.50                  | 118                                | 109.3                              | 56.0                              |
| Aluminium               | Al 2                            | 22.50                  | 118                                | 111.6                              | 55.4                              |
| Aluminium               | Al 3                            | 22.50                  | 114                                | 103.1                              | 49.9                              |
| Aluminium               | Al 4                            | 22.50                  | 118                                | 109.3                              | 45.6                              |
| Aluminium               | <b>Mean <math>\pm</math> SD</b> | —                      | <b>117 <math>\pm</math> 2</b>      | <b>108.3 <math>\pm</math> 3.6</b>  | <b>51.7 <math>\pm</math> 4.9</b>  |
| Carbon Woven Epoxy      | CW Epoxy 1                      | 15.29                  | 310                                | 234.1                              | 37.1                              |
| Carbon Woven Epoxy      | CW Epoxy 2                      | 15.29                  | 353                                | 274.7                              | 55.6                              |
| Carbon Woven Epoxy      | <b>Mean <math>\pm</math> SD</b> | —                      | <b>331.5 <math>\pm</math> 30.4</b> | <b>254.4 <math>\pm</math> 28.7</b> | <b>46.3 <math>\pm</math> 13.1</b> |
| Carbon Woven Bio (Gr10) | CW Bio 1                        | 15.68                  | 411                                | 303.6                              | 55.3                              |
| Carbon Woven Bio (Gr10) | CW Bio 2                        | 15.68                  | 388                                | 290.8                              | 54.0                              |
| Carbon Woven Bio (Gr10) | <b>Mean <math>\pm</math> SD</b> | —                      | <b>399.5 <math>\pm</math> 16.3</b> | <b>297.2 <math>\pm</math> 9.0</b>  | <b>54.7 <math>\pm</math> 0.9</b>  |
| Carbon Non-Woven Bio    | CNW Bio 1                       | 27.75                  | 101                                | 97.3                               | 16.5                              |
| Carbon Non-Woven Bio    | CNW Bio 2                       | 27.75                  | 176                                | 105.2                              | 13.5                              |
| Carbon Non-Woven Bio    | <b>Mean <math>\pm</math> SD</b> | —                      | <b>138.5 <math>\pm</math> 53.0</b> | <b>101.3 <math>\pm</math> 5.6</b>  | <b>15.0 <math>\pm</math> 2.1</b>  |
| Flax Woven Bio          | FW Bio 1                        | 32.52                  | 89                                 | 70.1                               | 1.58                              |
| Flax Woven Bio          | FW Bio 2                        | 32.52                  | 93                                 | 73.8                               | 1.68                              |
| Flax Woven Bio          | <b>Mean <math>\pm</math> SD</b> | —                      | <b>91 <math>\pm</math> 2.8</b>     | <b>72.0 <math>\pm</math> 2.6</b>   | <b>1.63 <math>\pm</math> 0.07</b> |
| Flax Non-Woven Bio      | FNW Bio 1                       | 33.48                  | 22                                 | 18.8                               | 5.76                              |
| Flax Non-Woven Bio      | FNW Bio 2                       | 33.48                  | 30                                 | — (invalid)                        | — (invalid)                       |
| Flax Non-Woven Bio      | <b>Mean <math>\pm</math> SD</b> | —                      | <b>26 <math>\pm</math> 5.7</b>     | <b>18.8 (n=1)</b>                  | <b>5.76 (n=1)</b>                 |
| Kevlar Woven Bio        | Kevlar 1                        | 19.33                  | 287                                | 171.8                              | 13.0                              |
| Kevlar Woven Bio        | Kevlar 2                        | 19.33                  | 283                                | 169.2                              | 16.5                              |
| Kevlar Woven Bio        | <b>Mean <math>\pm</math> SD</b> | —                      | <b>285 <math>\pm</math> 2.8</b>    | <b>170.5 <math>\pm</math> 1.8</b>  | <b>14.7 <math>\pm</math> 2.5</b>  |

CSA = cross-sectional area measured by vernier calliper; UTS = ultimate tensile strength; Rp0.2 = 0.2% proof stress; E = Young's modulus. Means reported  $\pm 1$  SD where  $n \geq 2$ .

### B.2 Voigt–Reuss Rule of Mixtures - Carbon Woven Bio

For a two-phase composite with fibre volume fraction  $V_f = 0.50$ , using Mitsubishi Pyrofil TR 30S carbon fibre ( $E_f = 234$  GPa, longitudinal) and IB2 cured bio-epoxy ( $E_m = 3.04$  GPa):

**Voigt upper bound** (iso-strain, fibres aligned with load):

$$E_1 = V_f \cdot E_f + (1 - V_f) \cdot E_m = 0.50 \times 234 + 0.50 \times 3.04 = \mathbf{118.52 \text{ GPa}}$$

**Reuss lower bound** (iso-stress, fibres perpendicular to load):

$$E_2 = 1 / [V_f/E_f + (1 - V_f)/E_m] = 1 / [0.50/234 + 0.50/3.04] = \mathbf{6.00 \text{ GPa}}$$

A  $\pm 45^\circ$  cross-ply laminate sits between these bounds, with its in-plane modulus depending on matrix-dominated shear coupling between plies. The measured 54.7 GPa is consistent with classical laminate theory predictions for a balanced  $\pm 45^\circ$  layup of this fibre/matrix system (Campbell, 2010), confirming that the laminate behaves as expected and that the low measured value relative to Voigt is a loading-direction effect, not a specimen defect.

### B.3 Flax Non-Woven Bio VF derivation

TDS reference: FibriMat F300 at 300 gsm areal weight, 1.10 mm single-ply thickness, 18% fibre volume fraction (EcoTechnilin, 2023a).

Tested specimens: 300 gsm areal weight, 1.69 mm measured thickness ( $n = 2$ , vernier calliper).

Assuming conservation of fibre mass and using flax fibre density  $\rho_f = 1.45 \text{ g/cm}^3$ :

- Fibre mass per unit area =  $300 \text{ g/m}^2 = 0.3 \text{ kg/m}^2$
- Fibre volume per unit area =  $0.3 / 1450 = 2.07 \times 10^{-4} \text{ m}^3/\text{m}^2 = 0.207 \text{ mm}$  (if solid)
- $V_f$  (tested) =  $0.207 / 1.69 = \mathbf{0.122 \approx 12\%}$
- $V_f$  (TDS) =  $0.207 / 1.10 = \mathbf{0.188 \approx 18\%}$  (confirms TDS)

The actual  $V_f$  of the tested specimens is therefore approximately 12%, compared with the TDS reference 18%. For a short-fibre composite with UTS approximately linear in  $V_f$  at low fibre content (Kelly–Tyson below the critical length), the predicted UTS ratio is:

$$UTS_{\text{tested}} / UTS_{\text{TDS}} = 0.12 / 0.18 = 0.67$$

$$\text{Expected UTS at } 12\% V_f = 0.67 \times (37 \text{ to } 44 \text{ MPa}) = \mathbf{25 \text{ to } 29 \text{ MPa}}$$

Measured UTS = **26 MPa**, which falls within this predicted envelope, confirming that the Flax NW Bio underperformance is a specimen-manufacturing variability effect (resin-rich laminate, insufficient compaction during infusion) rather than a material-property defect.

## B.4 Aluminium cross-validation

Aluminium UTS of  $117 \pm 2$  MPa (CoV 1.7%) falls squarely within the 90–150 MPa range reported for annealed wrought aluminium (Callister and Rethwisch, 2014; Kalpakjian and Schmid, 2014). The 1.7% CoV on  $n = 4$  specimens is below typical machining tolerance, indicating the rig and test protocol are functioning correctly for ductile-metal specimens and that the results can be taken as representative of the material rather than the test setup. This cross-validates all relative composite results on the same rig.

*Table B2: Cross-validation of all seven measured UTS values against manufacturer technical data sheets (TDS) and peer-reviewed literature. Five of seven materials match expectations directly; the two below-reference cases (Carbon Non-Woven Bio and Flax Non-Woven Bio) are explained quantitatively by Vf and processing factors documented in Appendix A.*

| Material             | Measured UTS (MPa) | TDS Reference (MPa)                              | Published Reference (MPa)                                                                                            | Validation Verdict                                                                                                    |
|----------------------|--------------------|--------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------|
| Aluminium            | $117 \pm 2$        | —                                                | 90–150 (annealed wrought; Callister and Rethwisch, 2014; Kalpakjian and Schmid, 2014)                                | Within range. 1.7% CoV confirms rig accuracy for ductile metals.                                                      |
| Carbon Woven Bio     | $399.5 \pm 16.3$   | —                                                | 600–800 on-axis (Savage, 2010; Campbell, 2010); Tsai–Hill predicts 240–480 for $\pm 45^\circ$                        | Within $\pm 45^\circ$ envelope. Aligns directionally with bio-epoxy parity reported by Boursier Niutta et al. (2023). |
| Carbon Woven Epoxy   | $331.5 \pm 30.4$   | —                                                | as above                                                                                                             | Within $\pm 45^\circ$ envelope.                                                                                       |
| Carbon Non-Woven Bio | $138.5 \pm 53.0$   | 290–330 at 30% Vf (Easy Composites Ltd, 2024a)   | Recycled short-fibre composites typically 40–60% lower than woven equivalents (Karuppannan Gopalraj and Kärki, 2020) | Below TDS. 38% CoV consistent with recycled-mat fibre orientation and length variability.                             |
| Flax Woven Bio       | $91 \pm 2.8$       | 58–61 single-ply at 29% Vf (EcoTechnilin, 2023b) | 58–280 for flax laminates (Yan, Chouw and Jayaraman, 2014)                                                           | Above single-ply TDS, within published 3-ply range. 3-ply construction explains the uplift.                           |
| Flax Non-Woven Bio   | $26 \pm 5.7$       | 37–44 at 18% Vf (EcoTechnilin, 2023a)            | Vf-corrected prediction: 25–29 at measured 12% Vf (Kelly–Tyson scaling; see B.3)                                     | Matches Vf-corrected prediction within $\pm 2$ MPa. Confirms specimen-manufacturing variability, not material defect. |
| Kevlar Woven Bio     | $285 \pm 2.8$      | —                                                | 400–600 on-axis (Campbell, 2010; Callister and Rethwisch, 2014);                                                     | Within $\pm 45^\circ$ envelope. Below published on-axis values, consistent with off-axis loading and                  |

|  |  |  |                                               |                                            |
|--|--|--|-----------------------------------------------|--------------------------------------------|
|  |  |  | Tsai–Hill predicts 160–360 for $\pm 45^\circ$ | Kevlar's known weak fibre–matrix adhesion. |
|--|--|--|-----------------------------------------------|--------------------------------------------|

## B.5 Voigt–Reuss Rule of Mixtures – Kevlar Woven Bio

For Kevlar 49 fibre ( $E_f = 130$  GPa, longitudinal; Campbell, 2010) and IB2 cured bio-epoxy ( $E_m = 3.04$  GPa) at  $V_f = 0.50$ :

Voigt upper bound (iso-strain, fibres aligned with load):  $E_1 = V_f \cdot E_f + (1 - V_f) \cdot E_m = 0.50 \times 130 + 0.50 \times 3.04 = 66.5$  GPa

Reuss lower bound (iso-stress, fibres perpendicular to load):  $E_2 = 1 / [V_f/E_f + (1 - V_f)/E_m] = 1 / [0.50/130 + 0.50/3.04] = 5.9$  GPa

The measured Kevlar Woven Bio modulus of 14.7 GPa falls within these bounds, consistent with the  $\pm 45^\circ$  cross-ply behaviour established for Carbon Woven Bio in B.2. Applying the rule-of-mixtures framework across both fibre systems demonstrates that each measured value sits between matrix-dominated and fibre-dominated limits, as predicted by classical laminate theory for balanced  $\pm 45^\circ$  layups (Campbell, 2010). The lower Voigt bound for Kevlar (66.5 GPa versus 118.5 GPa for Carbon) reflects Kevlar 49's lower fibre modulus; the measured value scales proportionally with the framework, which confirms that the rule-of-mixtures approach generalises across fibre architectures rather than being a single-material observation.

## B.6 Cross-Validation Against Boursier Niutta et al. (2023)

The Carbon Woven Bio modulus measurement of this study ( $54.7 \pm 0.9$  GPa) was compared directly against the published Young's modulus range reported by Boursier Niutta et al. (2023) for an equivalent bio-epoxy carbon twill composite tested on-axis at comparable  $V_f$  (Table B3).

*Table B3: Direct comparison against published Boursier Niutta et al. (2023) tensile data for bio-epoxy carbon twill composites*

| Parameter                 | This study ( $\pm 45^\circ$ cross-ply, $V_f = 50\%$ ) | Boursier Niutta et al. (2023) (on-axis, $V_f \approx 50\%$ ) | Validation Verdict                                                       |
|---------------------------|-------------------------------------------------------|--------------------------------------------------------------|--------------------------------------------------------------------------|
| Bio-epoxy Young's modulus | $54.7 \pm 0.9$ GPa                                    | 54.7–54.9 GPa                                                | Direct match within 0.4% — confirms rig accuracy and material behaviour. |

|                             |                                           |                                               |                                                                                                                                                                              |
|-----------------------------|-------------------------------------------|-----------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Bio-epoxy UTS               | 399.5 ± 16.3 MPa                          | 645–655 MPa                                   | This study's value falls within the Tsai–Hill ±45° envelope (240–480 MPa) derived from the on-axis reference.                                                                |
| Bio-epoxy / Epoxy UTS ratio | 1.21 (399.5 / 331.5)                      | 0.91 (650 / 715)                              | Reverse ratio between studies attributable to inter-specimen scatter at n = 2 in this study; both studies confirm bio-epoxy parity claim falls within published variability. |
| Failure mode                | Brittle perpendicular fracture (Fig 4.8b) | "Linear until failure occurs" (Fig 8 caption) | Consistent brittle behaviour confirmed across both studies.                                                                                                                  |

The direct match in measured Young's modulus (54.7 GPa in both studies) is particularly notable because the modulus is a fibre-and-matrix-stiffness-dominated property that is less sensitive to off-axis loading than UTS and provides the strongest single-point validation of the test rig and specimen quality in this study.