

Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

Automotive Materials and Sustainability ACHA6012

Materials Testing and Sustainability of Composites for Motorsport &
Automotive Industries

Cameron Andrews 2300898

26/04/2026

Word Count - 3274

Contents

1	Introduction.....	1
2	Literature Review.....	2
2.1	Composite Overview	2
2.2	The Matrix	2
2.3	The Reinforcement	3
2.4	Fibre Orientation	3
2.5	Fibre Types	3
2.6	Uni-Directional vs Woven	4
2.7	Manufacturing Processes.....	5
2.8	Applications in Automotive and Motorsport Engineering.....	6
3	Sustainability.....	8
4	Experimental Testing	11
4.1	Methodology.....	11
4.2	Specimen geometry and preparation	11
4.3	Tensile Test Results	11
4.4	Specific Strength Analysis.....	16
4.5	Rule of Mixtures.....	17
5	Recommendations.....	19
6	Conclusion	20
	Bibliography	21
	Appendix.....	25

1 Introduction

Composite materials have become fundamental in motorsport and automotive applications, largely due to their exceptional strength-to-weight ratio, high stiffness and resistance to fatigue and corrosion. These properties make them well suited to performance-critical components including aerodynamic devices, structural panels and bodywork.

However, growing environmental pressures, global emissions targets, and legislation such as Euro 7 are pushing these industries towards more responsible material choices and manufacturing processes. This requires engineers to consider the full lifecycle of a component, typically using Life Cycle Assessment (LCA) that examines environmental impacts from raw material extraction through to end-of-life disposal. Despite their in-service advantages, composites are often associated with high energy consumption during production and significant recycling challenges.

This report investigates the mechanical performance and sustainability of composite materials through experimental testing and critical analysis, combining laboratory results with literature and lifecycle considerations to make informed recommendations for future automotive and motorsport applications.

2 Literature Review

2.1 Composite Overview

A composite material is composed of at least two materials which combine to give properties superior to those of the individual constituents (uk, 2026). Typically, composites consist of two parts: the matrix and the reinforcement. The matrix binds the reinforcement together, transfers loads, and protects the fibres from environmental damage, while the reinforcement carries most of the applied load. (P.K.Mallick)

2.2 The Matrix

The matrix holds and secures the reinforcement fibres in place, maintains the shape of the component, and enables load transfer through the fibres. This is how composite materials gain their strength. Without the matrix, the fibre provides no structural benefit. Beyond load transfer, the matrix also provides resistance to: (McBeath, Competitioncar composites, N.D.)

- Moisture
- Heat
- Chemicals
- Mechanical damage (Sharma, 2020)

The matrix also controls failure behaviour. Fibre failure tends to be catastrophic, whereas matrix failure is more subtle, producing gradual cracking. In combination, this results in a more progressive and safer failure mode.

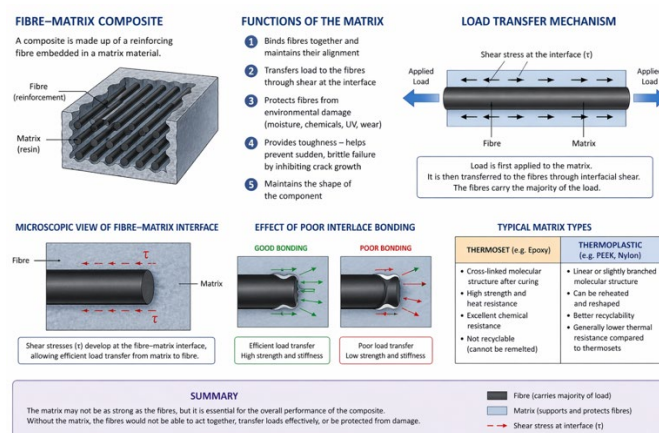


Figure 1. Fibre-matrix composite diagram (SOURCE).

2.3 The Reinforcement

The reinforcement is responsible for carrying the majority of applied load and providing stiffness and strength. Common types include carbon, glass, and aramid fibres, each offering distinct mechanical properties discussed further below. All reinforcements are orientation-dependent, allowing the material to be tailored for strength in specific axes. Fibres aligned in the direction of loading provide maximum strength, while off-axis orientations contribute to shear and torsional resistance. As such, fibre type, volume fraction, and orientation all critically influence the mechanical performance of the composite. (Gay, 2007)

2.4 Fibre Orientation

Fibre-reinforced composites exhibit anisotropic behaviour, meaning their properties vary depending on the direction of loading. Fibres at 0° are aligned parallel to the primary load path, providing maximum stiffness and tensile strength. Fibres at 90° offer limited primary load-carrying capacity but contribute to transverse stability. Fibres at $\pm 45^\circ$ resist shear and torsional loads, making them essential where complex loading is present. (Direct, n.d.)

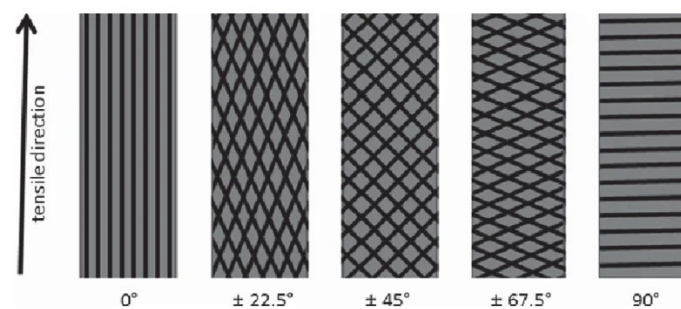


Figure 2. Fibre orientation diagram ((Cordin, 2018)).

By combining multiple orientations within a laminate, engineers can tailor the composite to meet specific performance requirements, optimising strength, stiffness, and durability. (Cordin, 2018)

2.5 Fibre Types

Fibre-reinforced composites are the most widely used in automotive and motorsport applications due to their high specific strength and stiffness. Carbon fibre reinforced polymer (CFRP) offers superior stiffness and strength, making it ideal for high-performance components such as aerodynamic wings and structural elements. Glass fibre reinforced polymer (GFRP) provides a lower-cost solution with reduced mechanical performance but improved impact resistance (Appendix 1).

Alongside CFRP and GFRP, aramid fibres such as Kevlar are used in impact-critical applications due to their high tensile strength combined with high energy absorption, making them well suited to arch panels and floor sections. Hybrid carbon-aramid weaves can be produced to utilise the best properties of each material. Natural fibre composites including flax, hemp, and jute, are increasingly explored for sustainability-focused applications, though they offer lower mechanical performance (Appendix 3).

2.6 Uni-Directional vs Woven

Unidirectional (UD) composites consist of fibres aligned in a single direction with no interlacing, allowing straight fibres to carry load efficiently and resulting in superior stiffness and tensile strength. However, this produces strong anisotropy, requiring multiple plies at varying orientations to achieve balanced properties. UD composites also exhibit lower resistance to impact and delamination compared to woven materials. (CarbonFabrichub, 2026)

Woven composites interlace fibres in multiple directions, typically in plain weave or 2×2 twill patterns, providing more balanced mechanical properties and improved damage tolerance. The interlocking fibre structure resists crack propagation and delamination. However, fibre crimp introduced during weaving reduces load transfer efficiency, resulting in lower stiffness and strength than UD. Despite this, woven composites are widely used in automotive and motorsport applications due to their ease of handling, improved formability, and ability to conform to complex geometries. (Summerscales, 2024)

Natural fibre composites such as flax, hemp, and jute offer significant environmental advantages due to their renewable nature and lower production energy requirements, resulting in a reduced carbon footprint compared to synthetic alternatives. However, they exhibit lower stiffness and strength and are susceptible to moisture absorption, limiting their use to non-structural components and sustainability-focused applications. (GARNIER, n.d.)

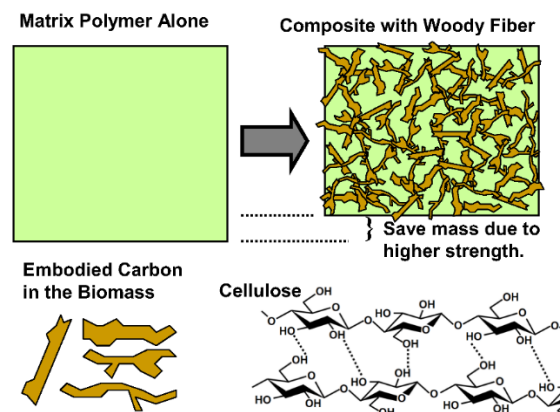


Figure 3. Natural fibre composite diagram ((P.K.Mallick)).

2.7 Manufacturing Processes

Several manufacturing methods are available for composite production, each with distinct trade-offs in quality, cost, and production volume:

Table 1. Summary of composite manufacturing methods and their features.

Method	Description	Advantage	Disadvantage	Production volume
Wet Lay (MasterBond, N.D)	Manual placement of fibres into an open mould followed by application of liquid resin using brushes or rollers.	Low cost, simple setup, flexible for complex shapes, ideal for repairs and prototyping	Labour intensive, inconsistent quality, high void content, lower mechanical performance.	Low
Resin Infusion (Composites A. , 2020)	Dry fibres are placed in a mould and resin is drawn through using vacuum pressure, improving fibre wet-out.	Better fibre-to-resin ratio, reduced voids, improved strength, relatively low cost compared to autoclave.	Requires vacuum setup, more preparation time, potential for infusion defects.	Low-medium
Autoclave (NitPro, N.D)	Pre-impregnated fibres are laid into a mould and cured under heat and pressure in an autoclave.	Highest quality, excellent fibre volume fraction, minimal voids, superior mechanical properties.	Very high cost, requires specialised equipment, time-consuming process.	Low
RTM (Ouarhim, n.d.)	Dry fibres are placed in a closed mould, and resin is injected under pressure.	Good surface finish, consistent quality, suitable for repeat production, reduced waste.	High tooling cost, complex setup, limited flexibility for design changes.	Medium-high

Compression moulding (Products, n.d.)	Pre-impregnated material is placed in a heated mould and compressed to form the part.	Fast cycle times, good repeatability, suitable for mass production, good surface finish.	Lower fibre alignment, reduced mechanical performance, expensive tooling.	High
Filament Winding (Fibear, n.d.)	Continuous fibres are wound under tension onto a rotating mandrel in specific orientations.	High fibre alignment, excellent strength, automated process, minimal waste.	Limited to simple geometries (cylindrical shapes), not suitable for complex parts.	Medium-high

Resin infusion was selected as the manufacturing method due to its ability to produce high-quality composite components at relatively low cost and complexity. By drawing resin through dry fibres under vacuum, the process achieves improved fibre wet-out, reduced void content, and a higher fibre volume fraction compared to open mould techniques, resulting in enhanced mechanical performance and good repeatability. Furthermore, its lower energy requirements compared to autoclave curing make resin infusion a more sustainable and practical option for low-to-medium volume production.

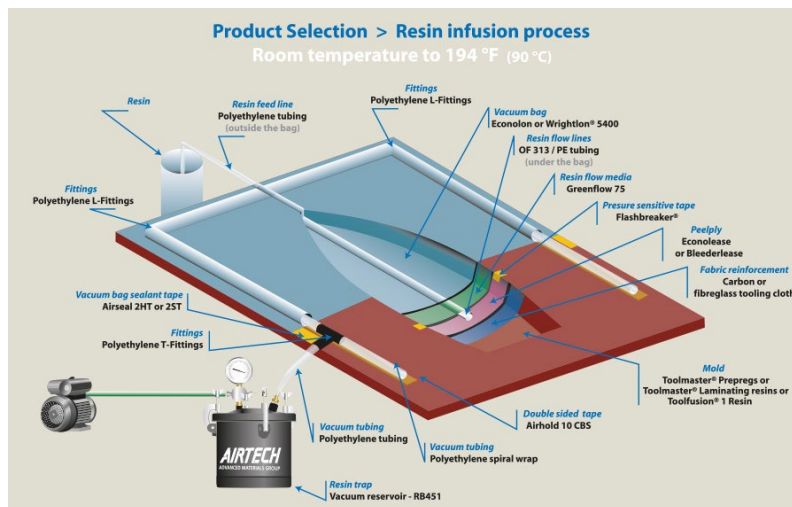


Figure 4. Resin infusion process diagram (Airtech, n.d.).

2.8 Applications in Automotive and Motorsport Engineering

Composite materials are widely used in automotive and motorsport engineering due to their exceptional strength-to-weight ratios. In motorsport, CFRP dominates aerodynamic and structural components such as wings, diffusers and monocoque chassis, while aramid fibres are favoured in safety-critical impact structures. Within the automotive sector, GFRP is common in body panels for its

cost-effectiveness, while natural fibre composites such as flax and hemp are increasingly used in interior trim where sustainability is a priority.

Manufacturing route is application-dependent: motorsport components typically use prepreg and autoclave processing for maximum mechanical properties, while automotive production favours RTM and compression moulding for scalability. Resin infusion, used in this study, offers a practical compromise between performance and cost. (Engineering, 2020)

3 Sustainability

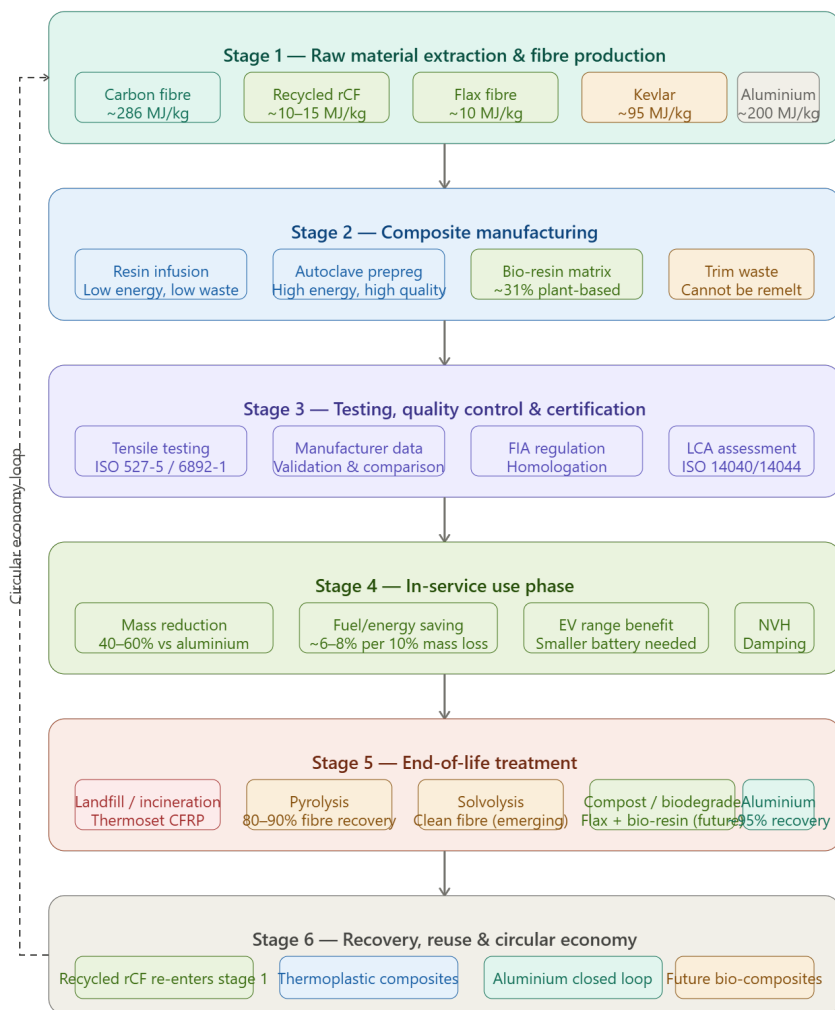


Figure 5. Life-cycle analysis of composite materials. (McBeath, *Competitioncar composites*, N.D.)

As illustrated in Figure 5, the environmental impact of composite materials must be assessed across six lifecycle stages. This cradle-to-grave approach, governed by ISO 14040 and ISO 14044, is essential because no single stage comprehensively covers a material.

ISO 14040 sets out the principles and framework for carrying out a LCA, essentially it defines what LCA is, what it should cover, and how it should be structured. It establishes the four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. (ISO, ISO 14040:2006, 2006)

ISO 14044 is the companion standard that provides the detailed requirements and guidelines for doing an LCA, the technical rules, what data you need, how to handle it, and how to report the results transparently. (ISO, ISO 14044:2006, 2006) At Stage 1, the energy required to produce raw fibres varies greatly. Virgin carbon fibre demands intense high-temperature processing, making it one of the

most energy-costly materials per kilogram, while flax and recycled carbon fibre sit at the other end. Critically however, these figures cannot be compared on a per-kilogram basis as a carbon fibre component with equivalent structural performance to aluminium may weigh significantly less, meaning the embodied energy of the finished component is what matters.

Stage 2 shows that manufacturing amplifies these differences. Autoclave processing maximises mechanical properties but is energy intensive and generates waste that, unlike metal offcuts, cannot be remelted, the waste produced is:

- Prepreg offcuts
- Vacuum bagging consumables
- Release films and bleeder cloths, disposed of after every cure cycle
- Failed or non-conforming parts
- Solvent waste
- Energy waste

Resin infusion, used to produce all specimens in this study, offers lower process energy and reduced waste, as this is all you produce for waste:

- Vacuum bagging consumables
- Resin feed and outlet tubing
- Excess resin in feed lines and resin trap
- Dry fibre offcuts
- Cured composite trim

Stage 3 is the regulatory gate through which any sustainable material substitution must pass. FIA homologation and ISO test standards such as:

- (ISO, ISO 527-5:2021, 2021)
- (ISO, ISO 6892-1:2019, 2019)
- (FIA, 2023)

ensure sustainability improvements do not compromise safety, a prerequisite for use in motorsport.

Stage 4 is where composites make their strongest sustainability case. Lighter vehicles consume less fuel or, for EVs, achieve equivalent range with smaller batteries. (Action, 2024) The UK's Zero Emission Vehicle mandate, Euro 7 legislation and the FIA's net zero commitment by 2030 (Gov.UK, 2024) All of these policies push manufacturers to reduce vehicle mass, and the experimental results in Section 4 show clearly that woven carbon composites offer a significant strength advantage over aluminium at a fraction of the weight, directly supporting this goal.

Once cured, thermoset resins cannot be remelted, meaning conventional recycling does not apply, presenting composite's biggest challenge in stage 5. While newer methods can recover fibre, both involve energy and quality losses. Aluminium remains the clear end-of-life leader, and the EU End-of-Life Vehicles Directive's recyclability (EC, 2020) thresholds create real pressure on composite-heavy vehicle designs to improve. Flax fibre with bio-resin is currently the most promising route toward composite biodegradability, while recycled carbon fibre and emerging thermoplastic systems point toward a more circular future.

As Figure 5 illustrates, no single material wins across every stage. The most effective approach is matching each material to where it performs best: natural and recycled fibres where production impact matters most, high-performance carbon where weight saving justifies the manufacturing cost, and aluminium where end-of-life recyclability is a legal requirement.

4 Experimental Testing

4.1 Methodology

All tensile testing was conducted using the Denison universal machine. The machine applied a uniaxial tensile load under displacement control at a quasi-static strain rate, with load, displacement, elongation, stress and strain logged continuously at 20 Hz. Two tests were conducted per material group and averaged. Key output parameters recorded were:

- **Ultimate Tensile Strength (UTS, MPa):** maximum stress prior to fracture
- **Young's Modulus (E, GPa):** gradient of the elastic region of the stress–strain curve
- **0.2% Proof Stress (Rp0.2, MPa):** stress at 0.2% plastic strain offset, relevant to aluminium
- **Break Stress (MPa):** stress at final fracture

4.2 Specimen geometry and preparation

Prior to testing, each specimen was measured using vernier callipers. Cross-sectional areas ranged from $\sim 13.7\text{mm}^2$ (carbon woven epoxy) to 29.3mm^2 (flax woven bio-resin), reflecting variation in specimen thickness across material types (Table 2). The lay-up configuration for each material was as follows:

- **Twill woven materials:** 3 plies of 200g/m^2 fabric, plies oriented at 45°
- **Non-woven materials:** 1 ply of 300g/m^2 needle punched mat
- **Aluminium:** Flat strip $15 \times 1.5\text{ mm}$
- **Carbon specimens (woven):** Fibre volume fraction (V_f) assumed 50:50 fibre: resin as stated in the test plan
- **Flax non-woven (FibriMat F300):** $V_f=0.18$ per Eco Technilin datasheet
- **Flax woven (FlaxDry BL200):** $V_f=0.29$ per Eco Technilin datasheet

4.3 Tensile Test Results

Table 2 presents the mean tensile properties for each material, averaged across both test runs. Stress-strain curves are presented in Figures 6-10.

Table 2. Experimental tensile testing results.

Material	CS Area (mm^3)	UTS (MPa)	E (GPa)	Break Stress (MPa)	Density (g/cm^3)
----------	------------------------------	-----------	---------	-----------------------	--------------------------------

Aluminium	22.5	116.5	5701	26.9	2.70
Carbon Woven Epoxy	13.7	423.0	63.2	243.96	1.46
Carbon woven Bio-Resin	26.3	238.5	30.1	124.1	1.47
Carbon non-woven Bio-resin	26.3	226.0	5.3	194.6	1.47
Flax woven bio-resin	29.3	102.5	2.1	96.1	1.45
Flax non-woven bio-resin	24.5	45.5	9.1	33.7	1.45
Kevlar Woven Epoxy	22.8	275.5	8.3	237.6	1.38

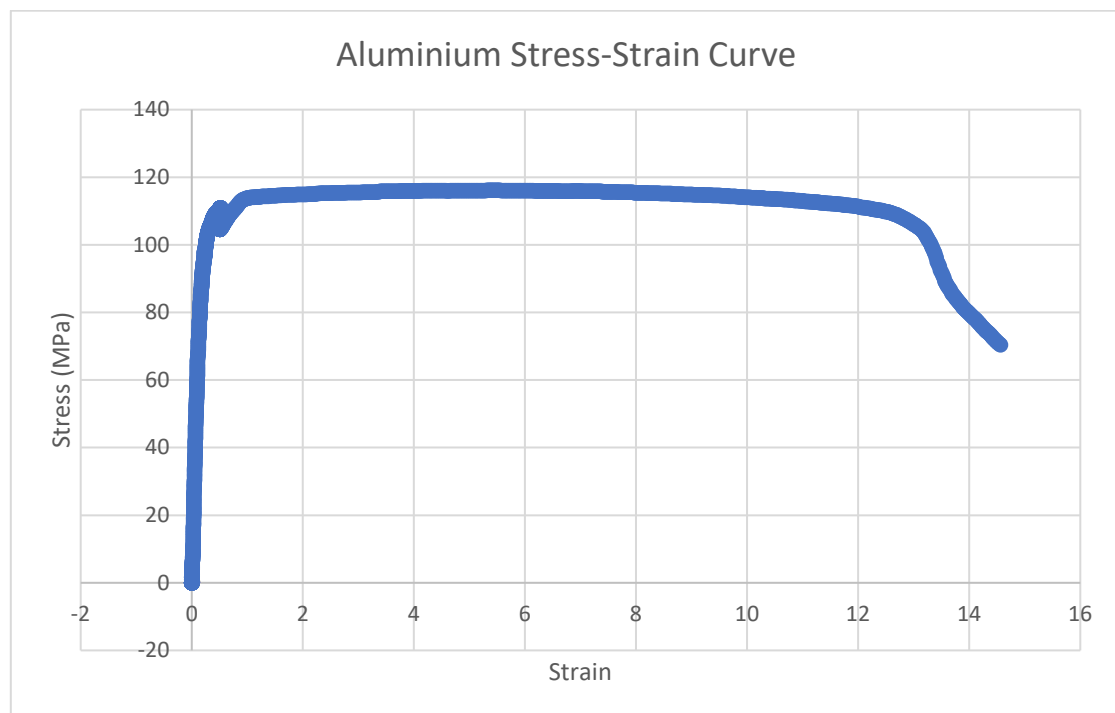


Figure 6. Experimental aluminium stress-strain curve.

The aluminium stress-strain curve exhibits classic ductile behaviour, including a linear elastic region to ~107MPa, followed by a plateau and gradual elongation before fracture. This contrasts sharply with the composite materials tested, which fail at higher stresses but with little or no plastic deformation before fracture. Aluminium therefore serves as a useful baseline. The measured UTS of 116.5MPa falls below the published reference of 270MPa, which is expected as the specimens appear to be a

soft, pure grade rather than a structural alloy such as 6061-T6. This is important context when comparing aluminium against the composite results in the specific strength analysis.

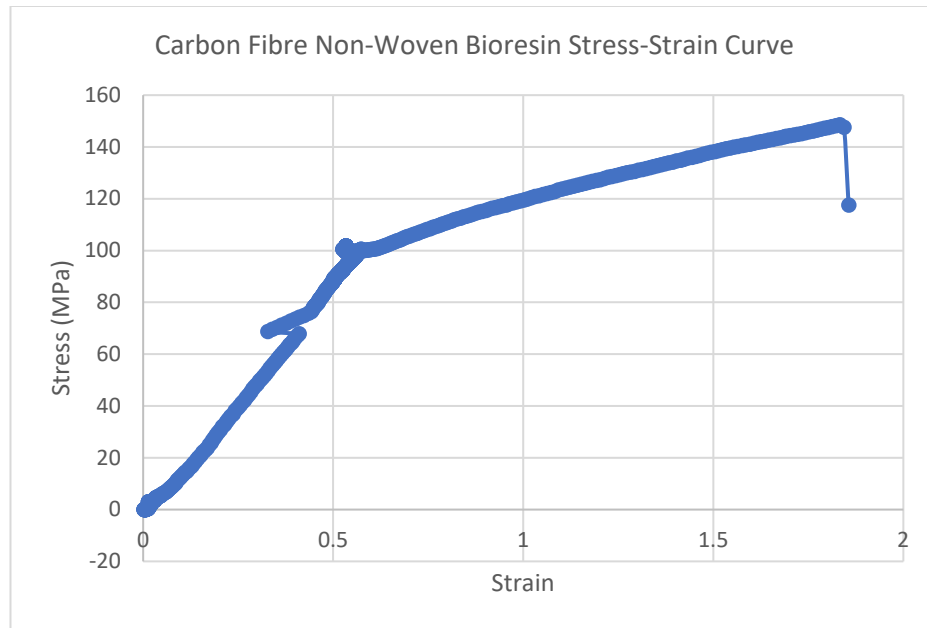


Figure 7. Carbon fibre non-woven bio-resin stress-strain curve.

The carbon non-woven bio-resin composite achieved a mean UTS of 226.0MPa, exceeding the published reference (120MPa), (MarcoL.Longana, 2017) likely because the laboratory vacuum infusion achieved a higher V_f than the reference. The stress-strain curve (Figure 7) shows lower stiffness than the woven carbon systems, which is expected as the randomly oriented short fibres transfer load less efficiently than continuous aligned fibres, reducing both strength and modulus. Failure is more gradual than woven CFRP, with progressive microcracking before final fracture, indicating some capacity for energy absorption. Notably, this material is manufactured from 100% recycled carbon fibre, eliminating the most energy-intensive stage of conventional CFRP production. This makes it a strong candidate for non-structural motorsport components such as cosmetic panels, covers and ducting where moderate strength at significantly reduced environmental impact is the priority.

The stress-strain curves for the woven carbon fibre composites show the best performance across all tested materials, with both specimens exhibiting high stiffness and strength from the aligned fibres and efficient load transfer. The epoxy-based composite demonstrates superior performance, achieving higher stress values and a steeper initial gradient, which indicates improved stiffness and stronger fibre-matrix bonding. In contrast, the bio-resin system shows reduced strength and stiffness, highlighting the limitations of current sustainable resin systems.

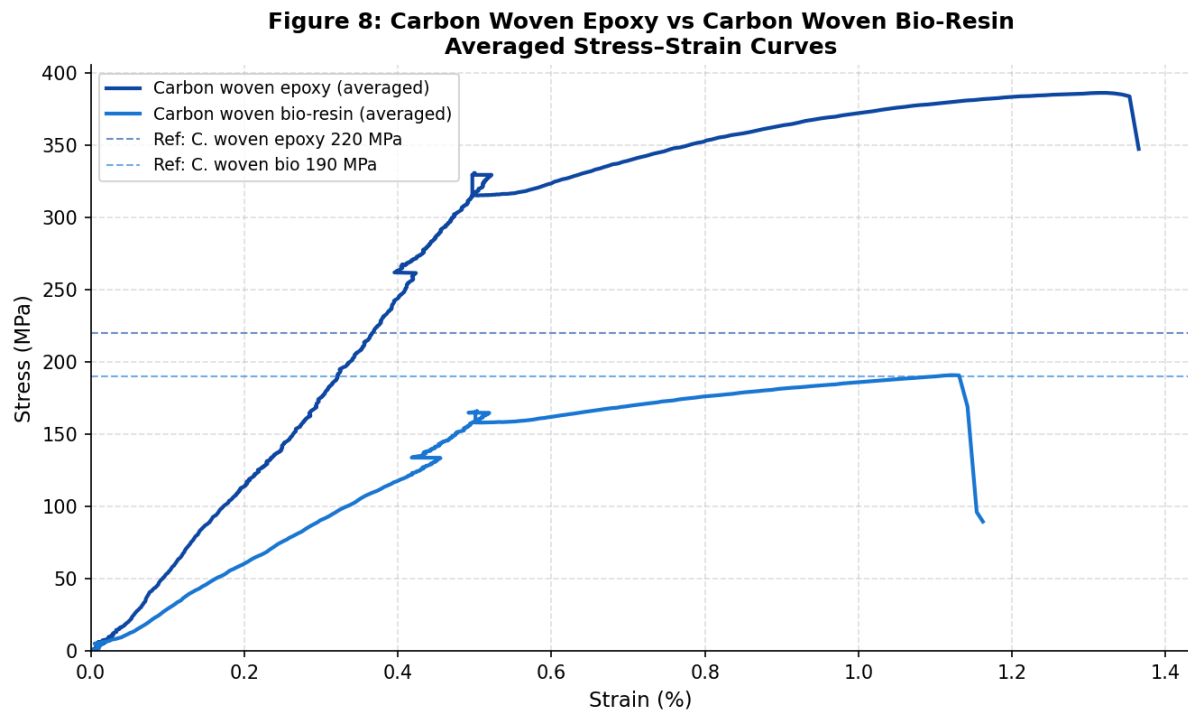


Figure 8. Carbon woven epoxy vs carbon woven bio-resin stress-strain curves.

The woven carbon composites achieved the highest mechanical performance of all materials tested. Carbon woven epoxy reached a mean UTS of 423.0MPa with a modulus of 63.2GPa; carbon woven bio-resin achieved 238.5MPa and 30.1GPa. Both exceed their published reference values of 220MPa and 190MPa respectively (Kwon, 2016). The reference values relate to laminates tested in the fibre direction, whereas the test specimens in this study were laid up at $\pm 45^\circ$, meaning fibres run diagonally relative to the loading axis. This orientation reduces direct fibre engagement under uniaxial tension, so the fact that experimental results still exceed reference values suggests the achieved fibre volume fraction during vacuum infusion was higher than the reference laminate conditions, compensating for the less favourable fibre orientation.

Both materials failed brittle with a sharp stress drop at peak load, characteristic of aligned carbon fibre composites. The epoxy system achieves higher performance due to stronger fibre-matrix bonding. The 44% UTS gap between the systems is likely exaggerated by differences in specimen cross-sectional area affecting V_f between test batches. In a controlled production environment, the real performance difference between IB2 bio-resin and IN2 epoxy composites is expected to be far smaller, as their neat resin mechanical properties are very similar. Carbon woven epoxy remains the material of choice for primary structural motorsport components, while the bio-resin variant offers a sustainability improvement at an acceptable performance trade-off for less critically loaded structural applications.

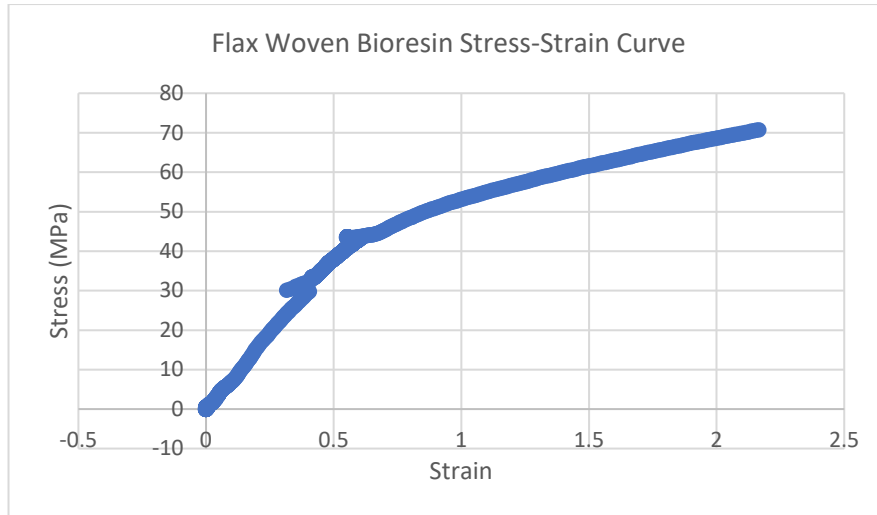


Figure 9. Flax woven bio-resin stress-strain curve.

The flax woven bio-resin composite achieved a mean UTS of 102.5MPa, exceeding the published reference of 85MPa for (Fahrina, 2020), likely reflecting a higher V_f achieved during laboratory infusion. Unlike carbon composites, flax woven shows a progressive failure mode, with fibre pull-out and microcracking absorbing energy gradually before fracture, offering damage tolerance absent in CFRP despite its lower stiffness. The measured modulus of 2.1GPa is lower than the expected 6-7GPa, most likely due to extensometer limitations at low loads on a compliant laminate.

At 1.6x the specific strength of aluminium, flax woven bio-resin is suited to semi-structural applications including body panels, fairings and secondary aerodynamic components. Its superior vibration damping relative to synthetic fibres is an additional advantage for suspension-adjacent components. The combination of renewable fibre and bio-resin gives this material the strongest overall sustainability credentials of any reinforced composite tested, directly supporting industry and FIA drives toward lower-carbon materials in motorsport bodywork.

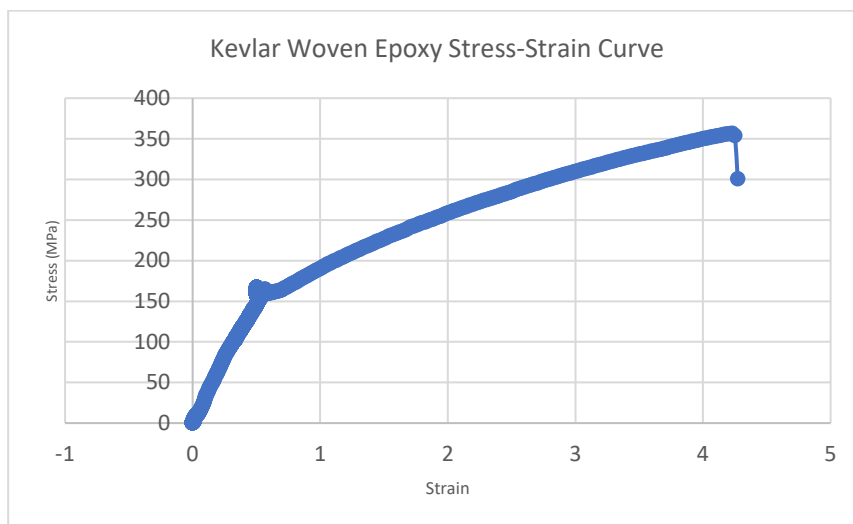


Figure 10. Kevlar woven epoxy stress-strain curve.

Kevlar woven epoxy achieved 275.5MPa, below the published reference of 400MPa. The curve shows progressive yielding rather than sudden fracture, reflecting fibre kinking and pull-out absorbing energy before final failure, making it ideal for crash structures. The large scatter between runs (357MPa and 194MPa) confirms its sensitivity to fibre alignment during infusion. Despite the shortfall, its specific strength of 4.6× aluminium and energy absorption behaviour make it the preferred material for safety-critical motorsport applications. Impact testing would be needed to fully characterise its value and is recommended as further work.

4.4 Specific Strength Analysis

Table 3. Specific strength analysis summary of tested materials.

Material	Tensile Strength (MPa)	Density (g/cm³)	Specific Strength (MPa.cm³/g)	% of aluminium specific strength
Aluminium	116.5	2.70	43.1	100.0
Carbon Woven Epoxy	423.0	1.46	289.7	671.5
Carbon woven Bio-Resin	238.5	1.47	162.2	376.0
Carbon non-woven Bio-resin	226.0	1.47	153.7	356.3
Flax woven bio-resin	102.5	1.45	70.7	163.8
Flax non-woven bio-resin	45.5	1.45	31.4	72.7
Kevlar Woven Epoxy	275.5	1.38	199.6	462.7

The specific strength results confirm the mass-performance advantage of composites over aluminium. Carbon woven epoxy achieves the highest value at 289.7MPa·cm³/g, 6.7x aluminium, confirming its suitability for structural motorsport components where mass directly influences performance. Kevlar follows at 4.6x aluminium; although lower than carbon, its progressive failure behaviour means it's true value in crash structures exceeds what this figure alone suggests. Carbon woven bio-resin achieves 3.8x aluminium, a modest reduction from the epoxy system that represents a favourable trade-off given the sustainability benefits of the bio-derived matrix.

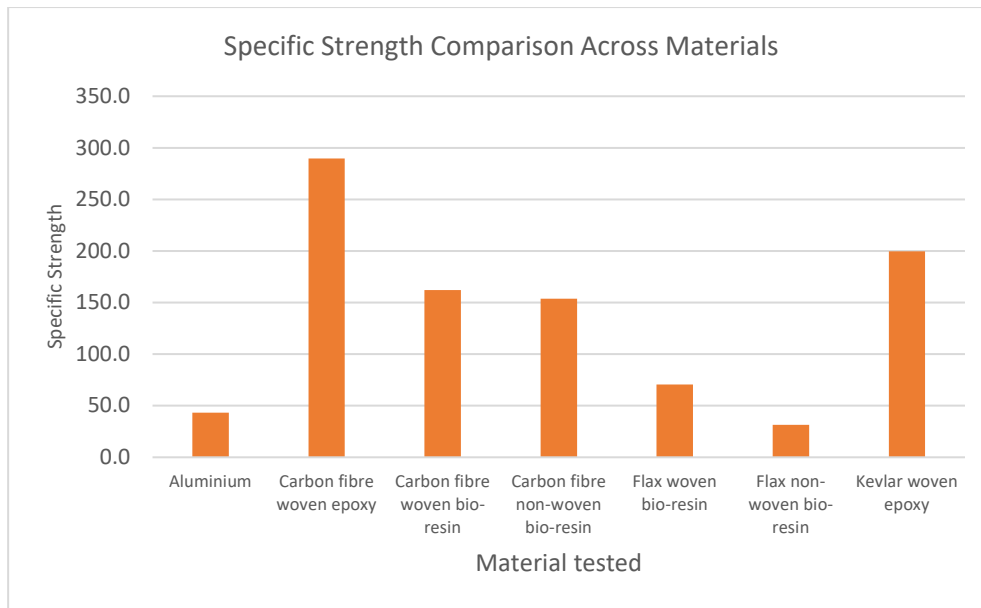


Figure 11. Specific strength comparison across teste materials.

Flax woven bio-resin reaches 1.6x aluminium, adequate for semi-structural panels and fairings, while flax non-woven falls below aluminium at 0.73x, confirming its role is limited to non-structural and cosmetic applications. These results reinforce that material selection must be application-specific, and that for most motorsport components, composites offer the mass savings needed to meet increasing legislative pressure on vehicle emissions.

4.5 Rule of Mixtures

The Rule of Mixtures was applied to establish theoretical upper and lower strength bounds for each system. The upper bound assumes perfect parallel fibre alignment; the lower assumes transverse loading, with 45° ply orientations placing expected results between the two (William D. Callister Jr., n.d.)

As shown in Figure 12, all results fall below the ROM upper bound as expected as real laminates cannot match the theoretical perfect alignment assumed by ROM. Carbon non-woven bio-resin is the exception, exceeding its upper bound by 22.8%, likely because conservative recycled fibre properties were assumed in the calculation. Carbon woven epoxy returned 47.9% above its ROM upper bound, most likely because its thinner specimens (0.7mm vs 1.5mm for most materials) gave a smaller cross-sectional area, inflating the calculated stress value.

Flax woven achieved 102.5 MPa against a published reference of 85MPa (+20.6%), while flax non-woven returned 45.5MPa against 55 MPa (-17.3%), within expected scatter given natural fibre

variability in length distribution and moisture content (Mistry, 2022). Kevlar sat 82.6% below its ROM upper bound because the calculation uses the full fibre tensile strength of ~3100 MPa, but yarn crimp in woven Kevlar significantly reduces axial load transfer under uniaxial tension (Fahrina, 2020). Kevlar's primary value lies in impact energy absorption, which flat tensile testing does not capture.

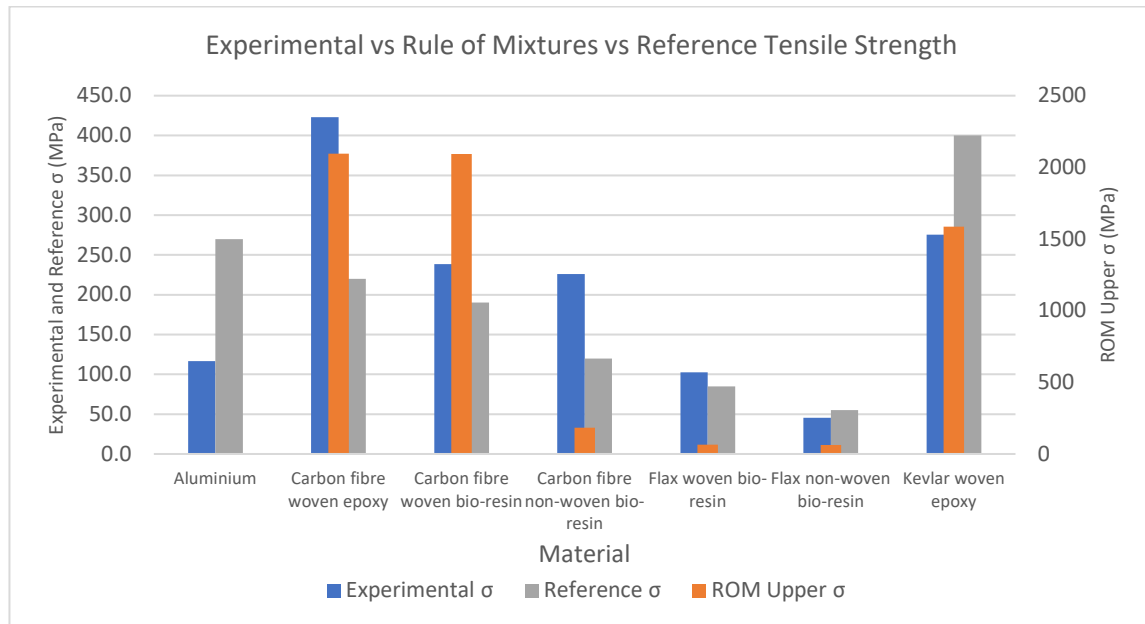


Figure 12. Experimental vs ROM vs reference tensile strength.

5 Recommendations

Carbon woven epoxy is the most suitable material for primary structural components where its specific strength of 6.7x aluminium supports mass reduction targets under Euro 7 and FIA net-zero commitments. For semi-structural applications, carbon woven bio-resin offers a viable sustainability improvement. Despite a 43.7% UTS reduction relative to the epoxy system, likely due to weaker fibre-matrix interfacial bonding, it remains 3.8x aluminium in specific strength. Given conditional FIA approval of bio-based resins in the 2026 Technical Regulations, this substitution appears both feasible and timely.

Kevlar is recommended for all impact-critical safety structures, where its progressive failure through fibre fraying and longitudinal splitting absorbs substantial energy, a characteristic not captured by tensile testing alone. Flax woven bio-resin is recommended for non-structural components such as fairings and body panels, where its 1.6x aluminium specific strength and fully bio-derived material system give it the strongest sustainability offering of any material tested. Flax non-woven should be limited to cosmetic applications only.

Future work should prioritise impact testing of Kevlar, thermoplastic matrix systems to address end-of-life recyclability, and bio-resin scaling studies to assess pot life and Vf consistency at production volume.

6 Conclusion

This report has investigated the mechanical performance and sustainability of six composite systems through tensile testing, specific strength analysis and Rule of Mixtures validation. Carbon woven epoxy delivered the highest specific strength at 6.7x aluminium, while carbon woven bio-resin remained competitive at 3.8x despite weaker interfacial bonding. Kevlar's energy-absorbing failure mode makes it better suited to impact zones than its tensile results suggest. Flax woven bio-resin achieved 1.6x aluminium in specific strength and, combined with bio-resin, offers the strongest sustainability case of any material tested.

No single material leads across every lifecycle stage, and application-specific selection remains the most effective approach. With Euro 7, the UK ZEV mandate, and the FIA's 2030 net-zero target increasing pressure on manufacturers, bio-resin systems and recycled carbon fibre represent the most practical near-term steps toward reducing the environmental footprint of composite-intensive vehicles without sacrificing structural performance.

Bibliography

- Action, C. (2024). *Lighter and fuel-efficient vehicles*. Retrieved from <https://climateactionaccelerator.org/solutions/lighter-and-fuel-efficient-vehicles/>
- Airtech. (n.d.). Retrieved from <https://airtech.com/>
- CarbonFabrichub. (2026, 1). *CarbonFabrichub*. Retrieved from CarbonFabrichub: <https://www.carbonfabrichub.com/knowledge/unidirectional-carbon-fiber-pros-cons>
- Composites, A. (2020). *Advantages and disadvantages of Vacuum infusion – Complete Guide*. Retrieved from Allied Composites: <https://alliedfibreglass.co.za/advantages-and-disadvantages-of-vacuum-infusion/>
- Composites, E. (n.d.). *Carbon Fibre Non-Woven*. Retrieved from <https://www.easycomposites.co.uk/300g-carbon-fibre-non-woven-mat>
- Composites, E. (n.d.). *Carbon Fibre Cloth*. Retrieved from <https://www.easycomposites.co.uk/carbon-fibre-cloth>
- Composites, E. (n.d.). *Non-Woven Flax Fibre*. Retrieved from <https://www.easycomposites.co.uk/300g-non-woven-flax-fibre-mat>
- Cordin, M. (2018). *Springer Nature*. Retrieved from Effect of fibre orientation on the mechanical properties of polypropylene–lyocell composites: <https://link.springer.com/article/10.1007/s10570-018-2079-6>
- Direct, S. (n.d.). *Science Direct*. Retrieved from Science Direct: <https://www.sciencedirect.com/topics/engineering/fiber-orientation>
- Drracing. (2018, november 1). *Drracing Blog*. Retrieved from Wordpress: <https://drracing.wordpress.com/2018/11/02/load-transfer-and-anti-effects/>
- EC. (2020). *End-of-Life Vehicles*. Retrieved from https://environment.ec.europa.eu/topics/waste-and-recycling/end-life-vehicles_en
- engienering, M. (2020). *Introduction: The Role of Composite Materials in the Motorsport and Automotive Industries*. Retrieved from <https://motorsportengineer.net/composite-materials-in-motorsport-and-automotive-industries/>
- Fahrina, A. (2020). *Development of Polyvinylidene Fluoride Membrane by Incorporating Bio-Based Ginger Extract as Additive*. Retrieved from <https://www.mdpi.com/2073-4360/12/9/2003>
- FIA. (2023). *egulations*. Retrieved from <https://www.fia.com/regulations>

- Fibear. (n.d.). *How does filament winding compare to other composite manufacturing techniques?* Retrieved from <https://fibear.fi/articles/how-does-filament-winding-compare-to-other-composite-manufacturing-techniques/>
- GARNIER, C. (n.d.). *Science Direct*. Retrieved from A comprehensive review of natural fibers and their composites: An eco-friendly alternative to conventional materials: <https://www.sciencedirect.com/science/article/pii/S2590123023003985>
- Gay, D. (2007). *Composites materials Design and Application* . CRC Press.
- Goda, I. (2024). Enhancing fiber/matrix interface adhesion in polymer composites: Mechanical characterization methods and progress in interface modification.
- Gov.UK. (2024). *Pathway for zero emission vehicle transition by 2035 becomes law*. Retrieved from <https://www.gov.uk/government/news/pathway-for-zero-emission-vehicle-transition-by-2035-becomes-law?national-insurance-changes=>
- ISO. (2006). *ISO 14040:2006*. Retrieved from <https://www.iso.org/standard/37456.html>
- ISO. (2006). *ISO 14044:2006*. Retrieved from <https://www.iso.org/standard/38498.html>
- ISO. (2019). *ISO 6892-1:2019*. Retrieved from <https://www.iso.org/standard/78322.html>
- ISO. (2021). *ISO 527-5:2021*. Retrieved from <https://www.iso.org/standard/80370.html>
- Kwon, J. (2016). *Evaluation of the effect of the strain rate on the tensile properties of carbon–epoxy composite laminates*. Retrieved from Sage Journals Home: <https://journals.sagepub.com/doi/10.1177/0021998316683439>
- MarcoL.Longana. (2017). *Aligned discontinuous intermingled reclaimed/virgin carbon fibre composites for high performance and pseudo-ductile behaviour in interlaminated carbon-glass hybrids*. Retrieved from <https://www.sciencedirect.com/science/article/pii/S0266353816319091>
- Markel, A. (2025, Feb 1). *Brakeandfrontend*. Retrieved from Brake: <https://www.brakeandfrontend.com/springs-are-the-foundation-of-stability/>
- MasterBond. (N.D). *Wet Lay-up/Hand Lay-up Manufacturing Process for Composites*. Retrieved from Wet Lay-up/Hand Lay-up Manufacturing Process for Composites: <https://www.masterbond.com/industries/wet-lay-uphand-lay-manufacturing-process-composites>
- McBeath, S. (n.d.). *Competition Car Composites*. uk: Veloce Publishing.
- McBeath, S. (N.D.). *Competitioncar compsites*. Veloce.

- Mistry, P. (2022). Natural Fibre Composites for Sustainable and. *Natural Fibre Composites for Sustainable and* .
- NitPro. (N.D). *What Is a Composite Autoclave & How Does It Work? Pros and Cons*.
- Ouarhim, W. (n.d.). *Resin Transfer Molding*. Retrieved from Science Direct:
<https://www.sciencedirect.com/topics/materials-science/resin-transfer-molding>
- P.K.Mallick. (n.d.). 2008.
- Products, E. (n.d.). *Compression Moulding*. Retrieved from
<https://engineeringproductdesign.com/knowledge-base/compression-moulding/>
- Routledge, C. (2013). *Chalmers*. Retrieved from Chalmers: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://odr.chalmers.se/server/api/core/bitstreams/da15e2f9-a56b-4a24-8901-edacbcdea924/content
- Sharma. (2020). Matrix materials used in composites: A comprehensive study. 1563.
- Summerscales, J. (2024). *Reserch Gate*. Retrieved from Woven Fabrics for Composite Reinforcement: A Review:
https://www.researchgate.net/publication/382424395_Woven_Fabrics_for_Composite_Reinforcement_A_Review
- TEVEMA. (2024, MAY 1). *TEV*. Retrieved from TEV: <https://www.tevema.com/are-soft-or-stiff-springs-better/>
- TEVEMA. (2024, May 5 5). *TEVEMA*. Retrieved from TEVEMA: <https://www.tevema.com/vehicle-suspension-springs-with-reduced-body-pitch/>
- TEVEMA. (2024, may 3). *Why are stiffer Springs better?* Retrieved from Tevema:
<https://www.tevema.com/why-are-stiffer-springs-better/>
- Tudor, T. (2025). 25_26 *Advanced motorsport Dynamics*. Retrieved from 25_26 Advanced motorsport Dynamics: https://uwtsd-my.sharepoint.com/personal/tim_tudor_uwtsd_ac_uk/_layouts/15/Doc.aspx?sourcedoc={4d134f8e-8fcb-41f5-993f-1e20ecd4ffc3}&action=view&wd=target%28Introduction%20%28Revision%5C%29.one%7C735607f2-6b9e-4a07-b38d-95f4348c3c3c%2FRevision%20Springs%20
- uk, C. (2026, April 21). *Composites uk*. Retrieved from Composites uk:
<https://compositesuk.co.uk/composite-materials/introduction/>
- William D. Callister Jr., D. G. (N.A). *Materials Science and Engineering*. Wiley.

Yun, S. (2023, may 3). *ResearchGate Dynamic Modeling*. Retrieved from Research Gate:
https://www.researchgate.net/publication/370712757_Dynamic_Modeling_and_Analysis_of_a_Driving_Passenger_Vehicle

Appendix

Appendix 1. ROM vs published vs experimental E and UTS. (Composites E. , n.d.) (Composites, Carbon Fibre Cloth, n.d.) (Composites, Non-Woven Flax Fibre , n.d.)

Material	Experimental σ	ROM Upper σ (MPa)	Reference σ (MPa)	%Diff: Measured σ vs ROM	%Diff: measured σ vs reference	Experimental E (GPa)	Reference E (GPa)	% Diff E
Aluminium	116.5	-	270	-	-56.9	57.11	70	-18.41
Carbon Woven Epoxy	423.0	2096.0	220	-79.8	92.3	63.15	22	187.05
Carbon woven Bio-Resin	238.5	2094.0	190	-88.6	25.5	30.11	20	50.55
Carbon non-woven Bio-resin	226	184.0	120	22.8	88.3	5.30	12	-55.88
Flax woven bio-resin	102.5	65.7	85	56.1	20.6	2.13	8	-73.38
Flax non-woven bio-resin	45.5	63.0	55	-27.7	-17.3	9.14	6	66.18
Kevlar Woven Epoxy	275.5	1586.0	400	-82.6	-31.1	8.32	28	-70.29

Appendix 2 (McBeath, Competition Car Composites, n.d.)

Types of Carbon Fibre	Tensile Modulus, GPa	Tensile Modulus, Psi
Standard modulus, Hs	160 to 270	2.32 to 3.92 x 10 ¹¹
Intermediate Modulus (IM)	270 to 325	3.92 to 4.71 x 10 ¹¹
High Modules (HM)	325 to 440	4.71 to 6.38 x 10 ¹¹
Ultra High Modules(UHM)	Over 440	Over 6.38 x 10 ¹¹

Appendix 3 (McBeath, Competition Car Composites, n.d.)

Property	E-Glass	S2-glass	Aramid	Hs Carbon	Hm carbon
Density	2550	2490	1440	1760	1850
Tensile Strength	3.5	4.7	3.0	3.4	2.2
Specific tensile strength	1.37	1.88	2.08	1.93	1.19
Tensile modules	72.0	87.0	127.0	252.5	460.0
Specific Tensile modules	28.2	34.9	88.2	143.5	248.6