

University of Wales Trinity Saint David

Institute of Science



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

Materials Testing and Sustainability in Composites for Motorsport & Automotive Industries

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James Vine

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1 Introduction

Composite materials have become fundamental to the development of high-performance structures in the automotive, motorcycle, and motorsport industries. Their high strength-to-weight ratios, excellent fatigue resistance, and corrosion durability offer significant advantages over traditional metals. However, as environmental concerns and regulatory pressures intensify, material selection must increasingly consider sustainability alongside performance.

This report investigates the mechanical and environmental performance of a range of composite materials through tensile testing and sustainability analysis. Natural fibre composites such as flax and hemp are evaluated alongside synthetic counterparts including carbon and Kevlar, with aluminium used as a baseline reference. Experimental results are validated against manufacturer datasheets and assessed in the context of industry requirements.

In addition to evaluating mechanical behaviour, this study examines each material's lifecycle sustainability, including raw material sourcing, manufacturing processes, recyclability, and end-of-life implications. These findings are then used to develop evidence-based recommendations on the future use of composite materials in motorsport and automotive applications, considering both performance and environmental objectives.

2 Literature Review

Composite materials combine two or more distinct phases, typically a matrix and a reinforcement, to achieve tailored mechanical, thermal, or chemical properties. The matrix binds the structure and transfers load, while the reinforcement, usually in the form of fibres, provides strength and stiffness. In automotive engineering, composites are prized for their high strength-to-weight ratio, fatigue resistance, and corrosion performance, offering clear advantages over traditional metals like steel and aluminium (Simões, 2024; Hull & Clyne, 1996).

Polymer composites are generally classified as thermosets or thermoplastics. Thermosetting polymers, such as epoxy and vinyl ester, form rigid, crosslinked networks once cured, providing high dimensional stability and excellent mechanical performance. These are commonly used in chassis structures, crash protection systems, and suspension arms. In contrast, thermoplastic composites, based on resins like polypropylene or polyether ether ketone (PEEK), can be remelted and reformed, making them more suited to recycling and reshaping in lightweight structural and semi-structural applications (Simões, 2024).

Fibre-reinforced polymer composites vary in performance and cost, with fibre and matrix combinations tailored to meet specific structural or sustainability goals. To bridge the gap between cost and performance, hybrid composites combining fibres such as carbon, glass, aramid, or basalt are gaining attention. These systems allow for optimised mechanical response, balancing stiffness, impact resistance, and durability, making them increasingly attractive for motorsport and high-performance road vehicles (Huang et al., 2023).

2.1 Key Materials Used in Testing

These samples included natural fibres (hemp, flax), synthetic fibres (carbon, Kevlar), and a reference metallic material (aluminium). This section provides an overview of each material group, supported by literature relevant to their use in automotive and motorsport engineering.

2.1.1 Carbon Fibre Composites

Carbon fibre reinforced polymer (CFRP) composites are extensively used in motorsport and high-performance automotive sectors due to their combination of high tensile strength, stiffness, and low weight. These properties deliver excellent specific strength and stiffness, making CFRPs ideal for components such as monocoques, suspension arms, and aerodynamic fairings where performance and mass reduction are critical (Strong, 2008).

CFRPs also offer strong fatigue resistance and corrosion stability, supporting long-term durability in demanding environments. However, they tend to fail in a brittle manner with little plastic deformation and possess limited transverse shear strength. Epoxy matrices, commonly used with CFRPs, can degrade under UV exposure, fire, or chemical attack without proper protection (Vijayan et al., 2023).

Although recycling methods like pyrolysis and mechanical recovery can reclaim fibres, they are often energy-intensive and reduce material quality. Hybrid laminates that combine carbon with aramid or natural fibres further complicate end-of-life separation, limiting recyclability (Rudd, Liu and Balaji, 2020).

2.1.2 Natural Fibre Composites (Flax and Hemp)

Natural fibres such as flax and hemp are increasingly used in non-structural automotive components like door panels and dashboards, offering lightweight, cost-effective, and low-CO₂ alternatives to glass fibre and synthetic composites. Their specific strength-to-weight performance can approach

that of E-glass fibre, a commonly used glass reinforcement material, particularly when combined with bio-resins. They also significantly reduce embodied energy. Flax, especially in woven format, provides good mechanical integrity, while hemp in non-woven form offers high damping and impact absorption (Duplák et al., 2024). Both materials support circular economy goals due to their renewability and low energy inputs, but achieving optimal performance requires careful matrix selection to improve fibre bonding and moisture resistance.

2.1.3 Kevlar Composites

Kevlar composites are renowned for their impact resistance and toughness, though they have lower stiffness compared to carbon. Their use in automotive components such as underbody panels, door reinforcement beams, and hybrid crash structures is well-documented (Kim et al., 2024). Hybrid layups, such as carbon-Kevlar-carbon (CKC) sequences, have shown significantly improved impact force absorption and reduced penetration depth in laminated structures, making them suitable for protective or safety-critical applications in elite motorsport and military applications (Pandian et al., 2024).

While Kevlar offers clear performance benefits, it is less compatible with the growing focus on sustainable and recyclable materials in the automotive industry.

2.2 Motorsport & Industry Context

Composite materials are now integral to high-performance automotive and motorsport engineering, where weight, stiffness, and crash performance must be optimised without compromising safety. In motorsport, especially prototype series, carbon fibre is widely used in chassis, suspension arms, fairings, and aerodynamic parts due to its superior strength-to-weight ratio. MotoGP has recently adopted carbon swingarms and reinforcements over aluminium frames, maximising rigidity and weight savings (Box Repsol, 2021).

Formula Student, which serves as a research and innovation platform for engineering students, has trialled hybrid flax-carbon fibre crash structures. These have been shown to reduce carbon footprint by up to 25% compared to full carbon solutions, while maintaining acceptable crash performance (de Almeida, 2023).

In the broader automotive sector, fibre-reinforced polymers (FRPs) are increasingly employed to meet tightening legislative demands on emissions and recyclability. Lightweight structures reduce fuel consumption and associated CO₂ emissions, with studies showing a 10% reduction in vehicle mass can yield up to a 7% improvement in fuel economy (Mohammadi et al., 2023). This has driven the replacement of traditional materials like steel and aluminium in structural and safety-critical applications. Glass fibre-reinforced polymer (GFRP) composites are widely used in bumpers for their ability to absorb impact energy while contributing to overall vehicle weight reduction.

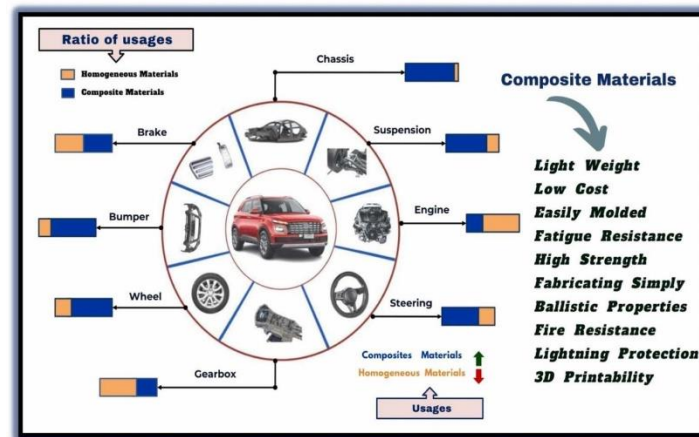


Figure 1 -Composite materials are now applied across nearly all major vehicle systems (Khan et al., 2024)

As shown in Figure 1, composites are now being applied across everything from chassis and suspension to gearbox housings and brake components, driven by their combined benefits of low weight, high strength, and ease of manufacturing.

2.3 Gaps in Research

While composite technologies continue to evolve, several sustainability-related research gaps remain. One key issue is the lack of scalable recycling solutions for thermoset composites, which dominate high-performance applications but cannot be remelted or reshaped. Current recycling methods are either experimental or result in degraded fibre quality, limiting reuse options (De et al., 2024).

Hybrid laminates, such as carbon-Kevlar or carbon-flax structures, also pose challenges at end-of-life due to complex interlayer bonding, making disassembly without fibre damage difficult. Meanwhile, natural fibres, although promising from an environmental perspective, suffer from inconsistent mechanical performance due to variability in crop species, growing conditions, and processing. Their hydrophilic nature also impairs bonding with hydrophobic matrices (Fogorasi and Barbu, 2017).

Additionally, bio-based resins are not yet widely available or fully competitive with epoxy in terms of performance and curing control. There is also a shortage of standardised lifecycle data, particularly for emerging sustainable composites, making it harder for manufacturers to make informed decisions (Simões, 2024).

Addressing these limitations is essential to support wider adoption of sustainable composites in automotive and motorsport sectors.

3 Experimental Testing

To compare the tensile performance of natural and synthetic composite materials, a structured programme of laboratory testing was carried out. The aim was to assess strength characteristics, identify typical failure behaviours, and validate performance using manufacturer data. Results from these tests support later sustainability assessments and material recommendations.



Figure 2 – Setting up of test sample in Denison machine

3.1 Methodology

Tensile testing was conducted using a Denison tensile/compression test machine to evaluate the mechanical performance of natural fibre composites (flax, hemp), synthetic fibre composites (carbon, Kevlar), and aluminium control samples. The materials differed in layup style, resin system, and fibre architecture, as summarised in Table 1.

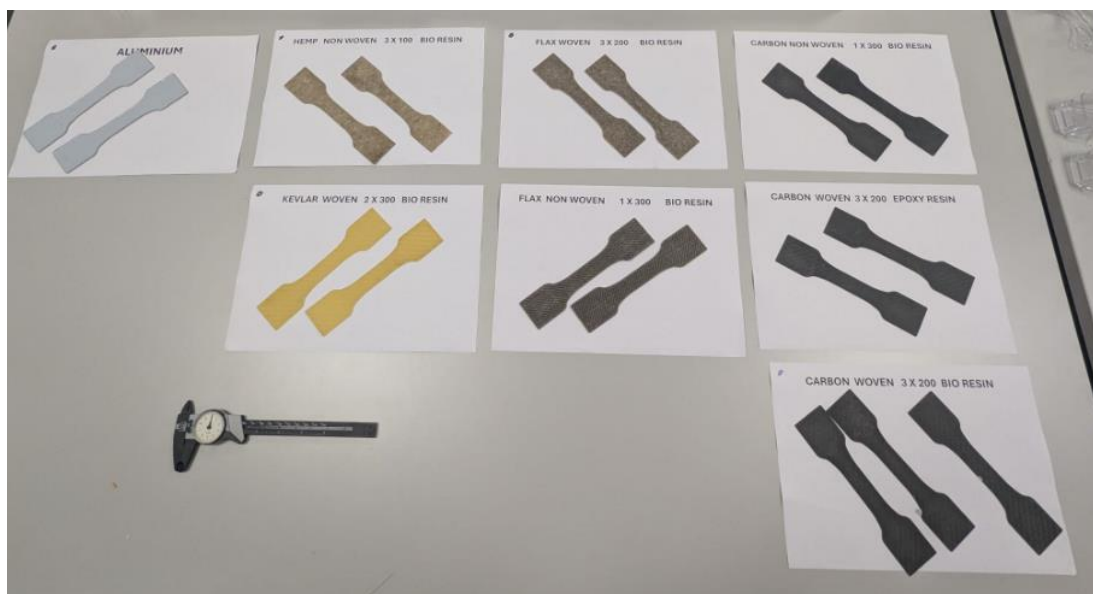


Figure 3 -All samples laid out pre-test, including vernier callipers

All composite samples were manufactured via vacuum infusion using either a bio-based epoxy (IB2) or traditional epoxy (IN2). Twill weave materials used multiple 200–300 g/m² plies arranged at $\pm 45^\circ$

orientations, while non-woven mats were layered to achieve the desired mass per unit area. A mesh was integrated into the tab ends where necessary to improve grip during testing.

Gauge widths and thicknesses were measured using vernier callipers to calculate cross-sectional area. Each group tested two specimens per material, producing a dataset of 14 samples per material type. Load–time data was exported and processed in MATLAB. Ultimate tensile strength (UTS) was calculated using:

$$UTS \text{ (MPa)} = \frac{\text{Maximum Load (N)}}{\text{Cross Sectional Area (mm}^2\text{)}}$$

Equation 1 – Ultimate tensile strength in MPa

Strain and elongation outputs were excluded due to the absence of extensometers or displacement tracking systems on the Denison rig. Without accurate strain data, these values were considered unreliable for composites. Mean UTS, standard deviation, and variation were calculated for comparison across materials

Fracture modes were observed during testing and included matrix cracking, delamination, fibre pull-out, and brittle fracture. These findings were qualitatively assessed and considered in Section 5 to support material suitability and sustainability recommendations.

Table 1 -Material sample details and target UTS from datasheets

Material	Layup	Weight (g/m ²)	Estimated UTS (MPa)	Notes/Source
Aluminium	Solid Sheet	N/A	105-145	From Datasheet (Aalco, 2024)
Hemp non-woven	3 x 100	Bio Resin	35-40	From datasheet (EcoTechnilin, 2023a)
Kevlar woven	2 x 300	Bio Resin	1535	From datasheet (50:50 mix (Easy Composites, 2025a, Easy Composites, 2024a)
Flax woven	3 x 200	Bio Resin	58-60	From datasheet (EcoTechnilin, 2023b)
Flax non-woven	1 x 300	Bio Resin	40-48	From datasheet (EcoTechnilin, 2023c)
Carbon woven	3 x 200	Epoxy Resin	585	From datasheets 50:50 ratio (Easy Composites, 2024b, Easy Composites, 2024c)
Carbon woven	3 x 200	Bio Resin	575	From datasheets 50:50 ratio (Easy Composites, 2024b; Easy Composites, 2024a)

Carbon non-woven	1 x 300	Bio Resin	330	From datasheet (Easy Composites,2024d)
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3.2 Data Pre-processing and Filtering

Although a preload was intended to be set during testing, inconsistencies between groups meant that some samples began recording from zero or negative load. To address this, all datasets were trimmed to begin at the first instance where load exceeded 0.1 N, effectively removing slack and ensuring a consistent start point across samples. Time was then zeroed from this point.

Some datasets were excluded due to incomplete or corrupted data, such as invalid area entries or missing load curves. For instance, one Kevlar test was removed due to incorrect machine input.

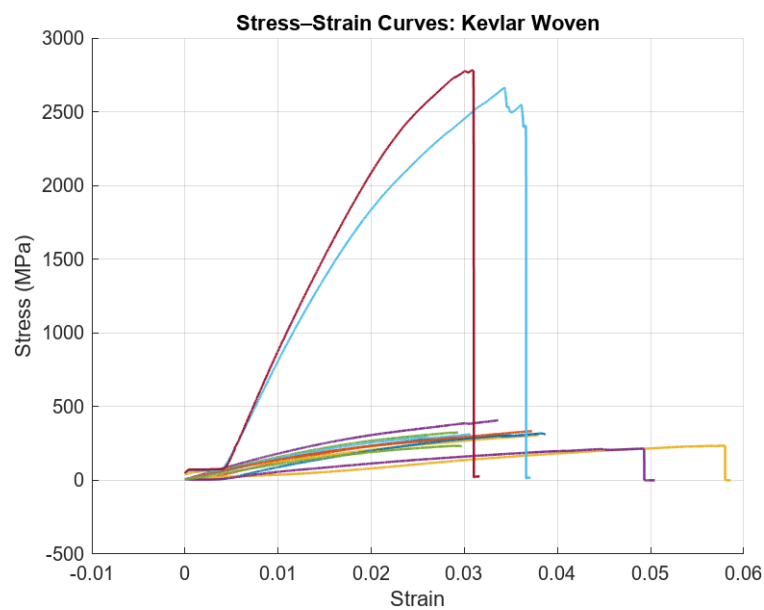


Figure 4 - Kevlar data prior to removal poor samples

3.3 Results

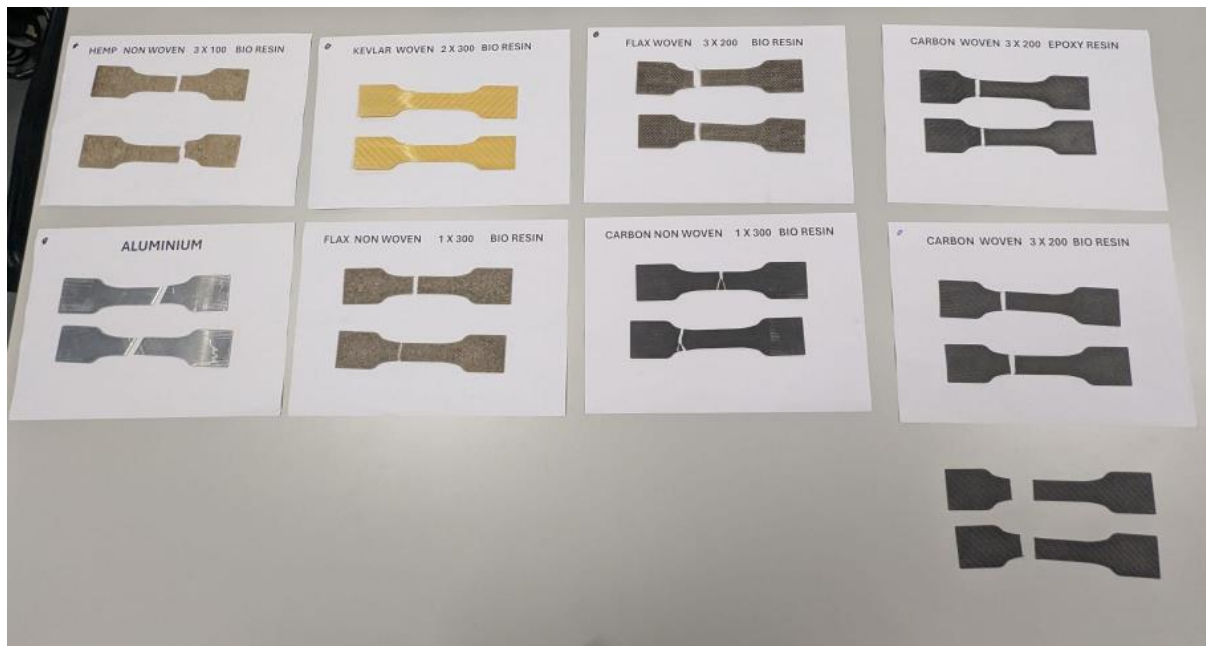


Figure 5 - All samples laid out post testing

Table 2 - Grouped summary table in MATLAB showing the number of samples, mean UTS, standard deviation, reference UTS values, and percentage performance relative to reference data for each tested material.

=== Grouped Summary by Material ===					
Material	n	MeanUTS	StdUTS	RefUTS	%Ref
Aluminium	14	116.32	2.75	110.00	105.7%
Carbon Woven Epoxy	14	395.42	52.13	585.00	67.6%
Carbon Non-Woven	14	180.08	44.71	290.00	62.1%
Carbon Woven Bio	14	342.38	82.77	575.00	59.5%
Flax Non-Woven	13	44.56	8.40	44.00	101.3%
Flax Woven	14	84.75	5.71	58.00	146.1%
Hemp Non-Woven	14	23.90	9.40	38.00	62.9%
Kevlar Woven	13	303.61	50.67	1500.00	20.2%

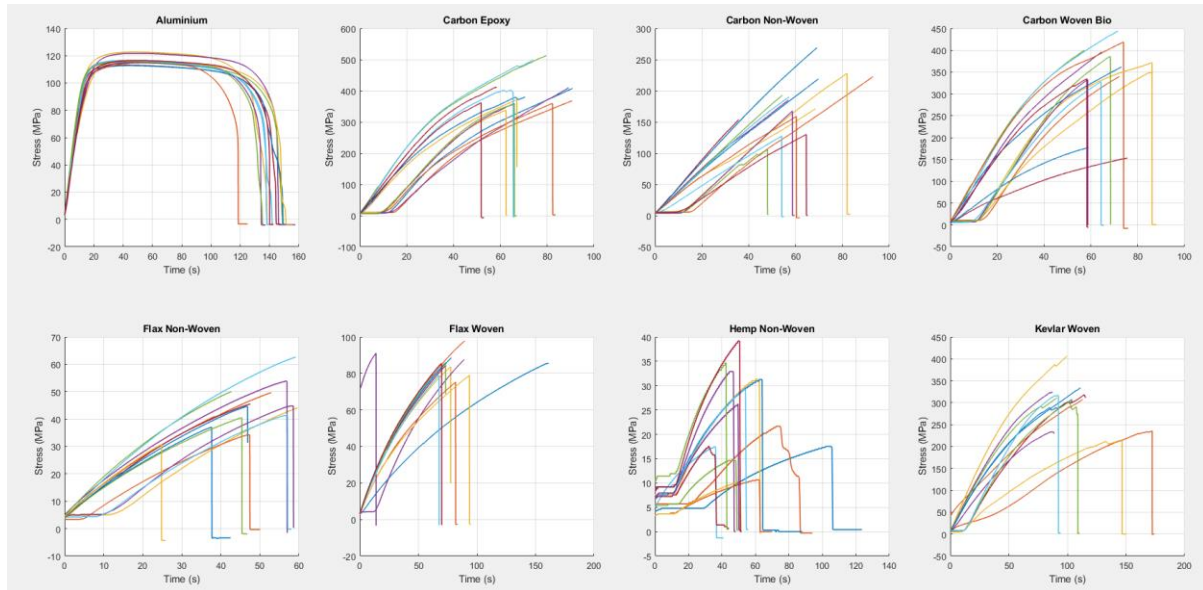


Figure 6 - Stress against time for all datasets in MATLAB

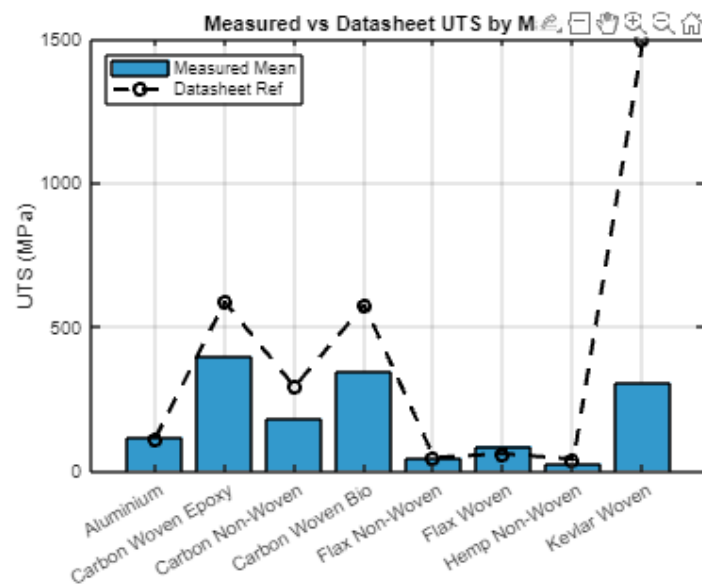


Figure 7 - Measured versus datasheet ultimate tensile strength (UTS) for all tested materials. Dashed line represents datasheet reference values; solid bars indicate mean measured UTS.

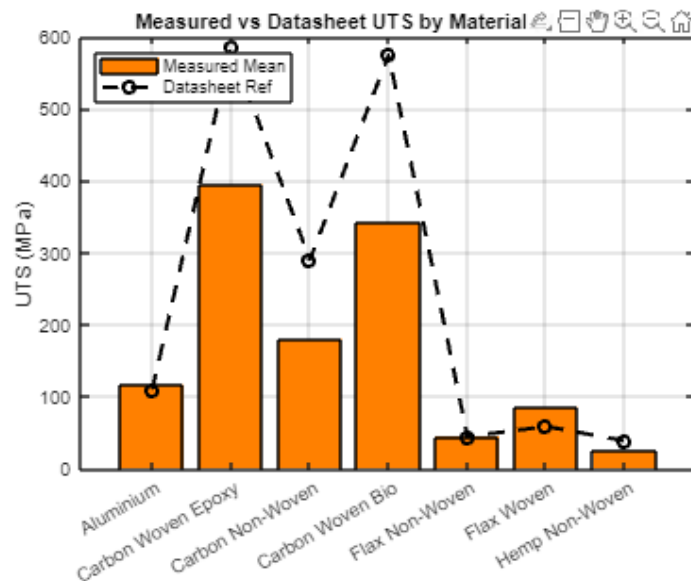


Figure 8 - Measured versus datasheet ultimate tensile strength (UTS) for tested materials excluding Kevlar.

3.4 Analysing Results

The experimental data reveals several key trends and discrepancies compared to manufacturer datasheets. Aluminium samples behaved predictably, with an average UTS of 116.32 MPa, just 5.7% above the reference value of 110 MP, suggesting consistent test conditions and accurate baseline results

3.5 Natural Fibres Analysis

Among natural fibres, flax woven composites performed exceptionally well, exceeding reference UTS by 146.1%. This likely reflects effective fibre alignment and resin penetration, and possibly a conservative estimate on the reference sheet. In contrast, hemp non-woven samples underperformed, achieving just 62.9% of expected UTS. This discrepancy may stem from fibre orientation limitations in chopped mats or inconsistent compaction during layup.

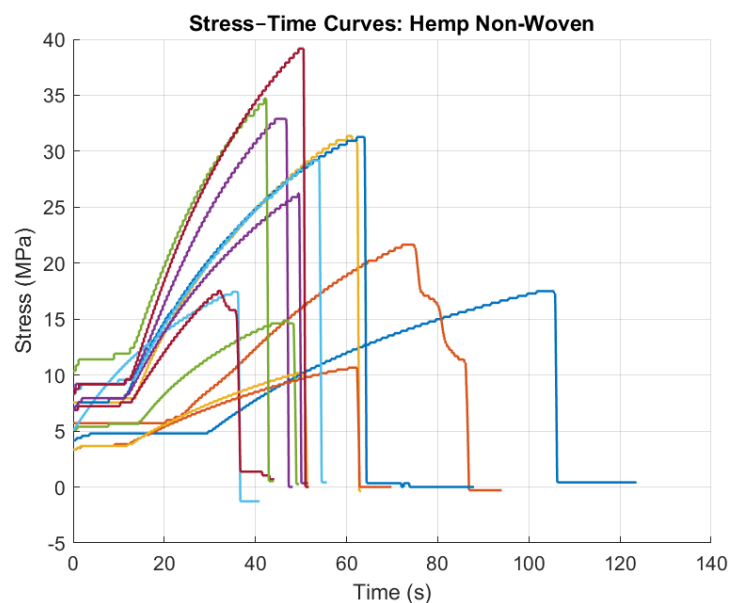
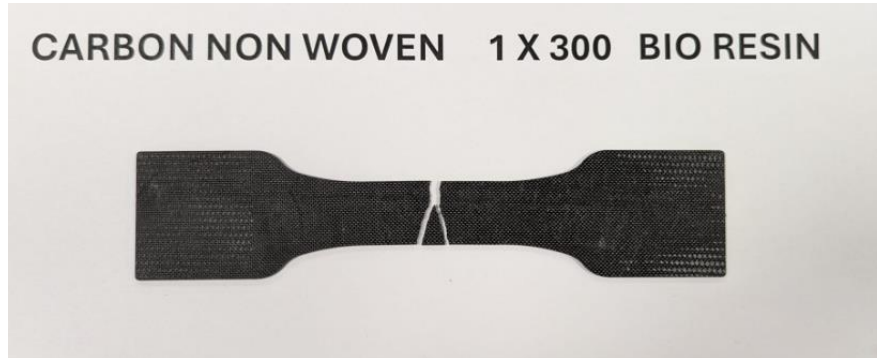


Figure 9 - Stepped data from hemp testing

Hemp specimens (figure 9) displayed gradual, stepped failures rather than sharp breaks, suggesting fibres were pulled out progressively rather than fracturing simultaneously

3.5.1 Carbon Analysis

Synthetic composites exhibited greater variability. Carbon woven with epoxy reached 395.42 MPa, 67.6% of the datasheet estimate, while the bio-resin variant performed slightly lower at 342.38 MPa (59.5%). These values may reflect layup inconsistencies or minor deviations in fibre-to-resin volume fraction, especially if 50:50 ratios were not precisely maintained.



Uniquely, carbon non-woven was the only composite that did not fracture cleanly into two pieces; instead, partial tearing and irregular failure occurred, suggesting poor stress distribution across the sample.

3.5.2 Kevlar Analysis



Figure 10 - Kevlar sample after test

Kevlar woven specimens recorded a mean UTS of 303.61 MPa, significantly below the datasheet estimate of 1500 MPa, just 20.2% of the expected value. While still high relative to most other samples, this underperformance likely reflects challenges in processing Kevlar, including difficulty achieving full fibre wet-out and consistent fibre-resin bonding.

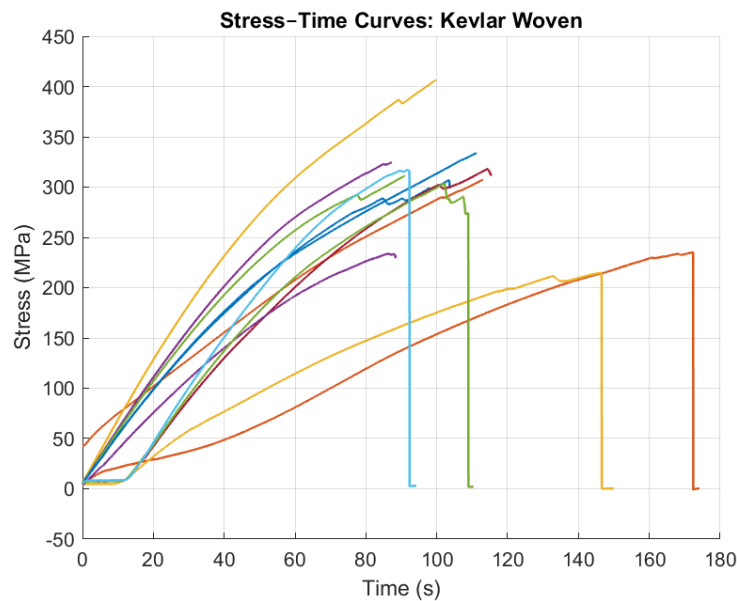


Figure 11 - Kevlar stress against time plot in MATLAB

The stress–time plots show a wide-spread in peak values and inconsistent failure behaviour, indicating variability in the mechanical response of Kevlar samples. Physical inspection (Figure 9) reveals localised tearing and fibre pull-out rather than clean fracture, suggesting that energy was absorbed through plastic deformation and delamination before failure. This aligns with Kevlar’s known toughness and resistance to brittle breakage, distinguishing it from the cleaner, more brittle fractures observed in other composite samples.

3.6 Experimental Errors

Several limitations may have affected the accuracy and comparability of results. Samples were manufactured smaller than recommended, reducing the effective test area. In addition, some materials had fewer useable test runs than planned. Preload was not consistently applied, and several test files had incorrect time stamps or were corrupted. These required manual correction or removal during data cleanup. No extensometers were used, so strain and elongation data were excluded. Finally, panels were not heat-cured, which may have limited resin cross-linking and ultimate performance, particularly in epoxy-based composites.

4 Sustainability Analysis

The sustainability of composite materials is increasingly under scrutiny as the automotive and motorsport industries work toward decarbonisation, circular economy goals, and compliance with legislation such as the EU End-of-Life Vehicle Directive (European Commission, 2024) and the UK Net Zero Strategy (HM Government, 2021). This section evaluates the environmental impact of the materials tested during this project by examining their performance across key lifecycle stages: resource extraction, manufacturing, recyclability, and end-of-life (EoL) disposal.

4.1 Sustainability of Carbon Composites

Carbon fibre composites offer unmatched strength-to-weight performance, making them a staple in motorsport and high-end automotive engineering. However, they pose significant sustainability challenges throughout their lifecycle. The production of carbon fibre begins with polyacrylonitrile (PAN), a petroleum-based precursor that undergoes energy-intensive stabilisation and carbonisation processes at temperatures exceeding 1000°C. This results in a very high embodied energy, estimated at around 286 MJ/kg of fibre, far greater than that of metals such as aluminium. When converted into composites using thermoset epoxy resins, the environmental impact is further increased. Epoxies are derived from fossil resources, requiring heat and pressure to cure, and emit volatile organic compounds during processing. While CFRPs contribute to reduced emissions in service through lightweighting benefits, their environmental cost is heavily front-loaded (Borjan et al., 2021).

Recyclability remains a major concern. Thermoset matrices cannot be remelted, making conventional recycling of CFRPs difficult. Most waste is still landfilled or incinerated, increasingly incompatible with current environmental regulations. Mechanical recycling typically produces short, damaged fibres with limited reuse potential. Pyrolysis and steam thermolysis are more promising alternatives, capable of recovering up to 80–95% of the original fibre strength. However, these processes are energy-intensive and not yet widely scalable (Oliveira Nunes et al., 2018). Chemical recycling using supercritical fluids can achieve high-quality fibre recovery, but the technology is still in its infancy, complex, costly, and largely restricted to laboratory settings (Borjan et al., 2021).

At end-of-life, the lack of efficient, lack of commercially viable disposal pathways continues to limit the sustainability of CFRPs. Hybrid layups present additional barriers, introducing incompatible fibre types and resin chemistries that are difficult to separate and recycle, further complicating circularity.

4.2 Sustainability of Natural Fibre Composites (Flax and Hemp)

Natural fibre composites, particularly those reinforced with flax and hemp, are increasingly recognised as viable alternatives to synthetic fibre systems due to their low environmental footprint and renewable origins. These fibres are derived from agricultural crops and require minimal processing, resulting in significantly lower embodied energy compared to carbon or glass fibres. Cultivation also contributes to carbon sequestration, enhancing their sustainability profile during the resource extraction phase (Puttegowda, 2025). Manufacturing processes for flax and hemp composites are relatively low-energy and compatible with established techniques such as hand lay-up, compression moulding, and vacuum infusion. When paired with bio-based resins, these systems avoid the high-temperature curing and Volatile organic compound (VOC) emissions associated with epoxy-based composites (Duplák et al., 2024).

Recyclability is one of the strongest sustainability advantages of natural fibre composites, especially when combined with biodegradable or thermoplastic matrices. These combinations support composting, low-emission incineration, or mechanical recycling without the fibre degradation

commonly seen in synthetic systems. However, most natural fibres are hydrophilic, and this moisture sensitivity can impair long-term durability and limit reuse, particularly in humid or fluctuating environments. At end-of-life, flax and hemp composites offer disposal routes unavailable to thermoset CFRPs, namely biodegradation or low-toxicity thermal processing, but the feasibility of these routes is dependent on the matrix. Fully biodegradable systems are still under development, and the compatibility between fibre and matrix is critical to both mechanical performance and end-of-life breakdown (Puttegowda, 2025; Duplák et al., 2024).

Despite these limitations, natural fibre composites have already been adopted by several automotive OEMs for vehicle interiors, including dashboards, panels, and seat structures. Their use is driven by growing industry goals to reduce embodied carbon, improve material safety, and enhance recyclability. With continued advances in fibre surface treatments and resin formulations, flax and hemp composites offer strong potential as lower-impact alternatives for non-structural components in the automotive and motorsport sectors.

4.3 Kevlar Sustainability

Kevlar is derived from petroleum-based monomers and involves complex multi-step synthesis and fibre spinning processes that contribute to its high embodied energy and environmental impact (Algahtani, 2006).

Recyclability remains a key challenge. Conventional Kevlar composites are typically reinforced with thermoset matrices such as epoxy, which cannot be remelted or reshaped, severely limiting material recovery. Mechanical recycling can recover some fibre fragments but with significant loss of performance. Recent advances in nanostructured Kevlar composites, particularly Kevlar nanofibers (KNF) aerogels, offer promising alternatives. These aerogels can undergo reversible sol–gel transitions triggered by chemical triggers, enabling the recovery, reprocessing, and reshaping of both wet gels and dried aerogels multiple times without significant loss in mechanical strength or thermal insulation properties (Li et al., 2023).

Despite of this, recycling strategies for Kevlar composites remain limited to lab-scale applications and require highly controlled conditions. Most automotive-grade Kevlar, particularly in thermoset or hybrid layups, remains difficult to recover due to inseparable material layers. This creates challenges for meeting circular economy objectives and emerging end-of-life recovery expectations. While Kevlar's durability may extend component lifespan, its high manufacturing energy and poor recyclability currently limit its potential for reducing carbon footprint in automotive and motorsport applications

5 Recommendations

This section presents practical suggestions for applying composite materials in motorsport and automotive contexts, followed by areas for further research to support long-term sustainability.

5.1 Racing Motorcycle Fairings

Based on the experimental findings and sustainability analysis, woven flax fibre composites are recommended for non-structural motorcycle components such as race fairings. While carbon fibre and Kevlar demonstrated superior ultimate tensile strength (UTS), both materials present notable environmental limitations, including high embodied energy, low recyclability, and energy-intensive processing. Carbon fibre bodywork is also typically confined to elite-level racing due to its cost and vulnerability to brittle failure.

As shown in Table 3, woven flax fibre achieved a mean UTS of 84.75 MPa, surpassing the manufacturer's reference value of 58 MPa (EcoTechnilin, 2023b) by approximately 46%. It outperformed non-woven flax and hemp alternatives and presents a credible substitute for fibreglass in applications where fairing failure is expected and cosmetic damage is acceptable. In racing contexts, primary impact absorption is handled by engine covers, crash bars, and bar ends, making flax composites a suitable solution. Observed failure behaviour suggested gradual delamination and fibre pull-out, which may offer advantages in terms of safety and post-crash inspection.

From a sustainability perspective, flax composites align more closely with circular economy principles. Flax is a renewable resource with low embodied energy, and it is compatible with bio-based epoxy systems that enable lower-emission processing and more favourable end-of-life outcomes. Unlike CFRPs and Kevlar laminates, which remain difficult to recycle, especially in hybrid layups, flax composites offer potential for composting or low-energy disposal. The material is also amenable to hand lay-up and vacuum infusion techniques, making it well-suited to low-volume or custom-built motorsport components.

Future development should focus on improving the durability of flax composites, particularly through enhanced fibre–matrix bonding to minimise moisture absorption. Research into UV-stable bio-resins and compatible surface coatings may help improve outdoor lifespan without compromising recyclability. Trials of flax-based bodywork in real motorsport environments could provide valuable insight into repairability, cost implications, and long-term mechanical performance under repeated loading or impact scenarios.

In conclusion, flax fibre composites present a feasible, well-supported alternative for use in motorcycle race fairings. They offer a compelling balance of performance and environmental responsibility, with strong alignment to future sustainability goals in motorsport and beyond.

6 Conclusion

This report has explored the mechanical performance and sustainability of a range of composite materials relevant to the automotive, motorsport, and motorcycle sectors. Experimental testing using UTS analysis revealed that woven flax composites outperformed expectations, suggesting potential for sustainable fairing and bodywork applications. In contrast, Kevlar samples underperformed against datasheet values, likely due to manufacturing challenges, while carbon fibre composites showed variable but generally high strength.

Sustainability analysis highlighted that natural fibres such as flax and hemp offer clear environmental benefits, including low embodied energy and improved recyclability, though they come with trade-offs in consistency and moisture resistance. Thermoset carbon and Kevlar systems, while mechanically superior, remain difficult to recycle and energy-intensive to produce.

Overall, the findings support the strategic use of natural fibre composites in non-structural applications where sustainability is a priority and suggest that further development of bio-resins and scalable recycling technologies is essential to enhance the lifecycle performance of composite systems in high-performance vehicles.

Word Count: 3256

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8 Appendix

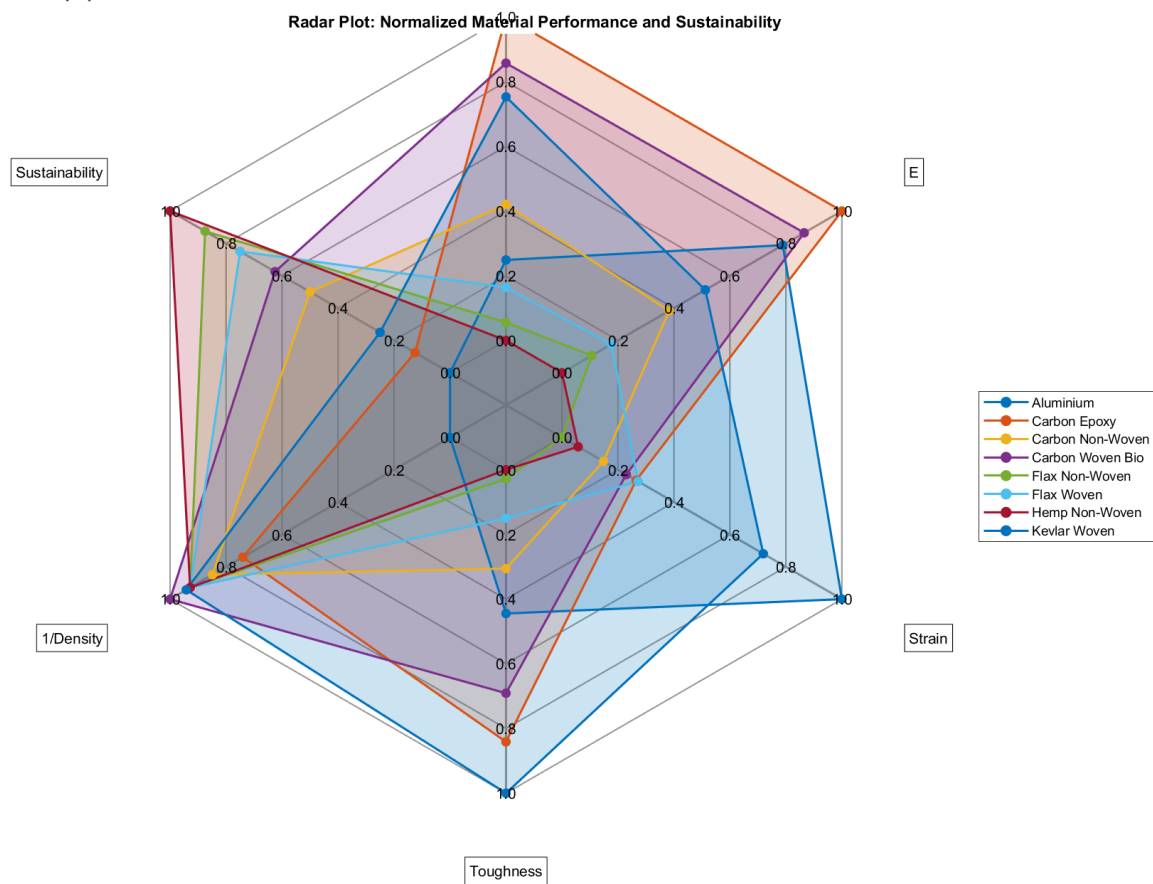


Figure 12 - With more information comparisons between materials could be made in more depth, spider plot in MATLAB

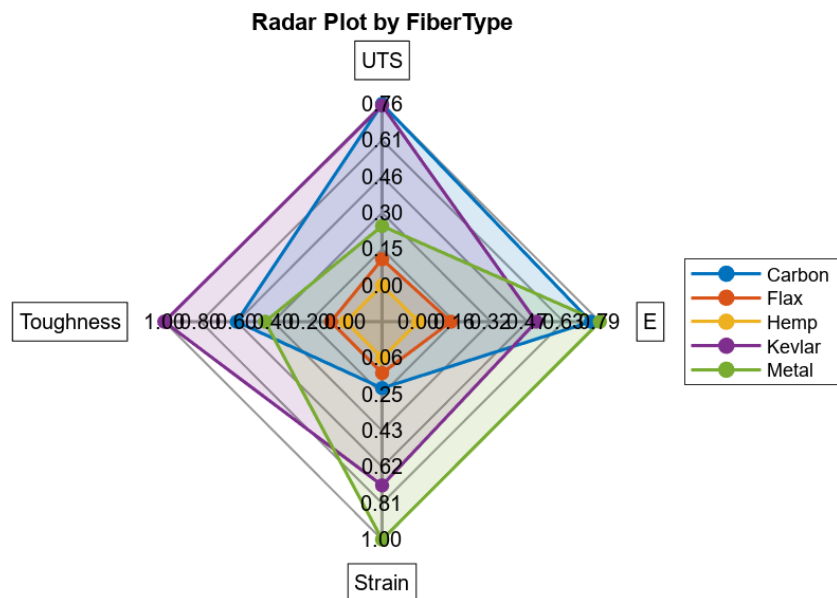


Figure 13 - Large datasets could be easily looked at by type, such as fibre type, other examples could be resin type or layup

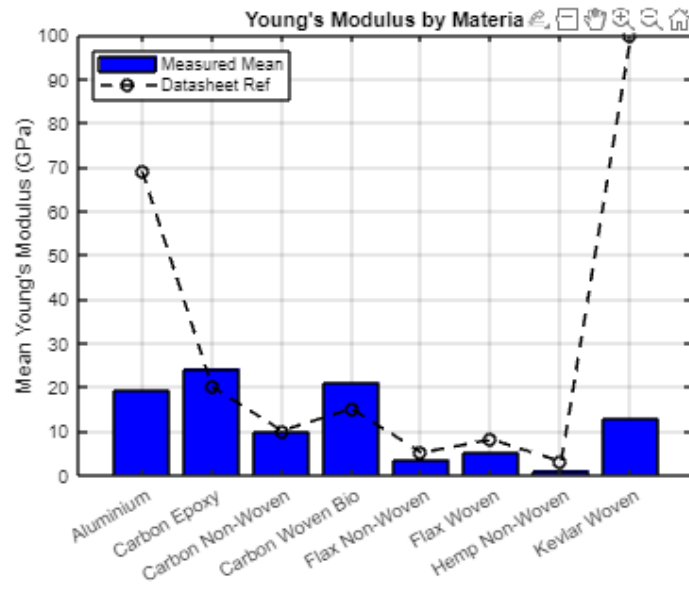


Figure 14 - If appropriate data, Young's modulus could be calculated

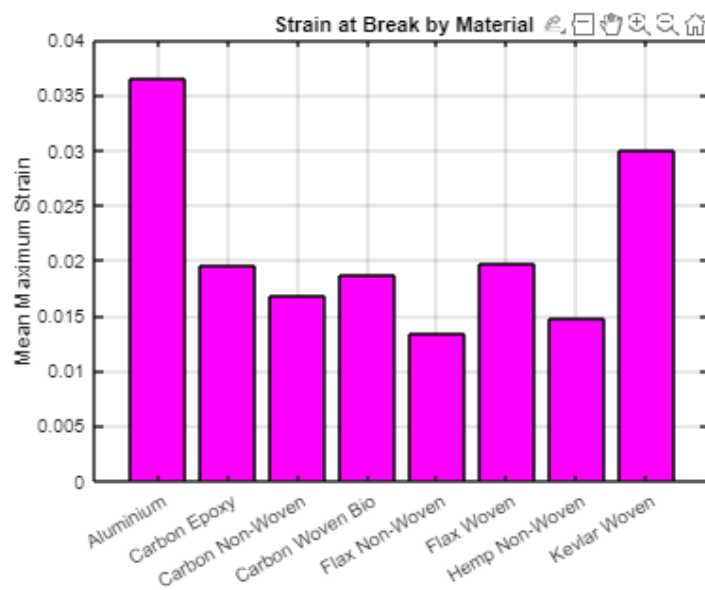


Figure 15 - Compare strain at breaking point for each material