



Wales Institute of Science and Art

Materials Testing and Sustainability of Composites for Motorsport & Automotive Industries

Automotive Materials & Sustainability (ACHA6012)

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1 Introduction

This report evaluates the mechanical performance and sustainability implications of fibre-reinforced composites for automotive, motorcycle and motorsport applications, using aluminium as a baseline alongside carbon-, flax- and aramid-based laminates.

The study investigates the trade-off between structural performance and lifecycle sustainability through three linked stages: literature review, sustainability analysis and experimental tensile testing. Material systems are compared in relation to reinforcement type, laminate architecture, manufacturing route, resource demand, recyclability and end-of-life considerations, with results validated against published or manufacturer data where possible. Based on these findings, recommendations are made for material selection, manufacturing strategy and future development.

The report aims to identify how composite materials can be deployed selectively to balance lightweight structural performance with increasingly important sustainability and circularity requirements in modern vehicle engineering.

2 Literature Review

2.1 Composite materials in automotive, motorcycle and motorsport engineering

Fibre-reinforced polymer composites combine a reinforcement phase with a matrix phase to provide specific stiffness and strength advantages unattainable by either constituent alone. Because behaviour is anisotropic and governed by fibre orientation, stacking sequence and loading mode, composites can be tailored to highly specific structural requirements (ASTM International, 2023; Nettles, 1994).

This has driven widespread adoption in automotive, motorcycle and motorsport engineering, where mass reduction improves acceleration, handling, fuel economy and electric-vehicle efficiency. Their advantages in stiffness-to-weight ratio, corrosion resistance and component integration have made them attractive alternatives to conventional metallic structures, although these benefits must still be balanced against manufacturing complexity, cost and end-of-life limitations, particularly for thermoset systems (Zhang and Xu, 2022; Yan and Xu, 2025).

Composite selection is therefore not simply driven by maximum mechanical performance, but by trade-offs between structural efficiency, manufacturability and sustainability.

2.2 Comparison of major reinforcement systems

Carbon fibre remains the dominant reinforcement for stiffness-critical structures because of its high specific strength and modulus. Toray T700S data illustrates this performance, helping explain continued use in motorsport survival cells and lightweight vehicle structures (Toray Carbon Fibers Europe, 2025; FIA, 2024). Automotive examples such as the BMW i3 and BMW HP4 Race show how this advantage has extended beyond racing into specialist production vehicles (BMW Group, 2013; BMW Group, 2017).

Flax composites represent a lower-impact alternative, offering useful specific properties, low density and good damping, although with lower absolute performance and greater variability than carbon systems. Their application is therefore more credible in semi-structural or secondary components than highly loaded primary structures (Yan, Chouw and Jayaraman, 2014).

Aramid fibres such as Kevlar occupy a more specialised position. Rather than maximising stiffness, they are valued for impact resistance, toughness and damage tolerance, making them suited to protective layers and hybrid reinforcement strategies rather than primary stiffness-driven structures (DuPont, 2019).

Taken together, these materials should not be viewed as direct substitutes but as reinforcements suited to different structural priorities: carbon for stiffness-critical parts, flax for lower-load sustainability-led applications, and aramid for toughness-driven roles.

2.3 Effect of laminate architecture and resin system

Laminate architecture can influence performance as strongly as fibre type. Woven laminates generally provide more effective tensile load paths than discontinuous non-woven systems, although yarn crimp introduces stiffness penalties relative to straight unidirectional fibres (Stig and Hallström, 2013).

Ply orientation also affects response significantly. Classical laminate theory shows 0° plies maximise axial stiffness, whereas $\pm 45^\circ$ laminates carry a greater proportion of load through in-plane shear. This improves shear response and damage tolerance but reduces axial tensile efficiency, which is relevant to interpretation of the present test results (Nettles, 1994; Tamuzs et al., 2004).

The matrix system adds a further trade-off. Conventional epoxies remain dominant due to established structural performance, but bio-based epoxies have shown potential to reduce petrochemical dependence while retaining broadly comparable mechanical properties under suitable formulations (Terry and Taylor, 2021; Boursier Niutta et al., 2023). This suggests bio-resin adoption may represent a viable substitution in some structural applications rather than a purely environmental compromise.

Overall, fibre type, architecture and matrix choice should be treated as interacting design variables rather than independent material selections.

2.4 Manufacturing routes and application suitability

Manufacturing route strongly affects final composite performance through its influence on fibre volume fraction, void content and defect formation. Resin infusion offers relatively low tooling cost and flexibility for low-volume structures, although performance can vary significantly with process conditions (Van Oosterom et al., 2019).

For higher-volume automotive production, routes such as resin transfer moulding, compression moulding and thermoplastic overmoulding offer greater repeatability and scalability. These processes may sacrifice some flexibility compared with labour-intensive motorsport manufacture but provide stronger industrial and sustainability cases for large-series production (Bank et al., 2018; Akkerman, Bouwman and Wijskamp, 2020).

This distinction is important because the most mechanically effective composite is not always the most manufacturable or sustainable choice. Motorsport may justify labour-intensive routes

for ultimate performance, whereas mainstream vehicle production requires solutions compatible with industrial scale.

3 Sustainability Analysis

The sustainability of the tested materials is governed by a fundamental trade-off between structural performance and lifecycle burden. Carbon-based laminates provide the highest structural efficiency but carry high resource and processing impacts with weak end-of-life circularity. Flax composites offer lower-impact potential but reduced mechanical capability, while Kevlar provides useful toughness without resolving broader recyclability limitations. Sustainability therefore depends less on material identity alone than on matching material burden to functional requirement.

3.1 Resource Extraction

Carbon fibre remains the most resource-intensive reinforcement considered, due to fossil-derived precursor materials and energy-intensive production. Combined with conventional epoxy matrices, this gives carbon/thermoset laminates high embodied impact, meaning their use is most defensible only where major structural or mass-reduction benefits are required (Zabihi et al., 2025).

Flax offers lower fossil-resource dependence and lower embodied impact potential, although cultivation, processing and variability mean its advantage is comparative rather than absolute (Yan, Chouw and Jayaraman, 2014). Its greatest sustainability value therefore lies in replacing higher-burden materials only where reduced mechanical performance is acceptable.

Bio-based epoxy systems offer incremental rather than complete improvement but can reduce petrochemical dependence while remaining structurally viable (Terry and Taylor, 2021; Boursier Niutta et al., 2023). Overall, the lowest-burden material should be selected only where it still satisfies performance requirements.

3.2 Manufacturing Process

Manufacturing route strongly affects sustainability because process energy, waste and repeatability can outweigh raw material advantages. Resin infusion used in this study offers lower energy demand than autoclave processing but still generates consumable waste and variability-related inefficiencies.

This creates a sector-specific distinction: infusion may remain appropriate for low-volume motorsport manufacture, while higher-volume automotive production aligns more closely with RTM, compression moulding and thermoplastic over moulding, which offer stronger scalability and lower waste potential (Bank et al., 2018; Akkerman, Bouwman and Wijskamp, 2020).

As a result, manufacturing sustainability depends not only on material selection but on whether the process route is appropriate to production context.

3.3 Recyclability

The main recyclability limitation of the tested laminates is their thermoset matrix. Because cured thermosets cannot be remelted, recovery typically depends on destructive processes such as pyrolysis or solvolysis, often resulting in downcycled rather than closed-loop reuse.

Carbon-fibre recovery has growing technical potential, but practical circularity remains limited. For flax- and Kevlar-based thermoset laminates, the economic case is weaker still. By comparison, aluminium benefits from established high-value recycling infrastructure, highlighting that lightweighting alone does not guarantee sustainability advantage.

This comparison strengthens the case for recyclable thermoplastic composites and greater emphasis on recoverability during material selection.

3.4 End-of-Life Disposal

End-of-life remains a major weakness of thermoset composites. Where recycling is impractical, disposal often relies on landfill or energy recovery, neither of which retains significant material value.

This increases the importance of design-for-disassembly. Composite sustainability improves when components are designed as separable subassemblies with recovery considered at design stage rather than after disposal. Without this, gains achieved through lower-impact reinforcement or bio-based matrices may be lost at end of life.

3.5 Legislation and Policy Context

Policy trends reinforce this direction. UK end-of-life vehicle recovery targets and emerging EU circularity legislation increasingly favour recoverable material systems and recycled content, creating pressure on conventional thermoset composites despite their performance advantages (European Commission, 2023; GOV.UK, 2021).

Motorsport policy follows a similar trajectory. FIA sustainability strategy and Formula One carbon-reduction commitments do not remove the role of carbon composites, but they narrow where high-burden materials can be justified (FIA, 2020; Formula One, 2025).

The implication is not replacement of carbon composites, but more selective use: high-performance composites retained where function demands them, lower-impact alternatives adopted where feasible, and greater emphasis placed on recoverability from design stage onward.

4 Experimental Testing

4.1 Testing Procedure

Uniaxial tensile testing was undertaken to compare the mechanical behaviour of the selected composite systems with each other and with an aluminium baseline.

The materials assessed comprised an aluminium baseline, carbon non-woven bio resin, carbon woven bio resin, carbon woven epoxy resin, flax non-woven bio resin, flax woven bio resin, and Kevlar woven bio resin. The composite specimens were manufactured using a resin infusion process and included both woven/twill and non-woven reinforcement architectures, with both bio-based and conventional epoxy infusion resin systems represented.

Twill laminates were produced using a multi-ply arrangement, whereas the non-woven materials used a single-layer mat construction. Where multiple plies were used, the layers were oriented at 45° relative to each other. All specimens were measured prior to testing so that cross-sectional area could be determined for subsequent stress calculations.

Testing was carried out using a tensile/compression test machine in accordance with the laboratory procedure. Load was recorded continuously during each test, while material displacement was measured using an extensometer, with the machine software calculating stress and strain throughout the test. Approximately 20 tests were available for each material, providing a sufficient dataset for comparison. Stress values were obtained from the measured load and specimen area, while strain was determined from extensometer displacement, allowing stress-strain curves to be generated for each material. From these curves, elastic modulus, yield stress, yield strain, ultimate tensile strength, and the relevant corresponding strain values were extracted.

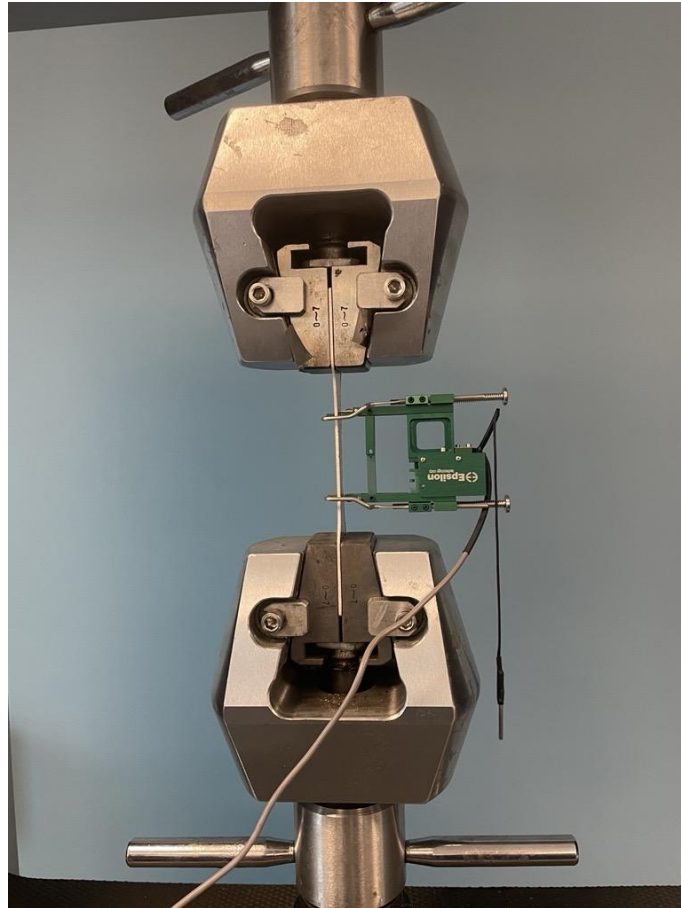


Figure 1: The Denison tensile testing setup, with the aluminium specimen and extensometer attached.

Testing was carried out in accordance with the relevant laboratory health and safety requirements, including the use of appropriate PPE.

4.2 Results

The processed tensile-test results are presented in Figure 2 as a combined stress-strain overlay and in Table 1 as a summary of the extracted mechanical properties for each material. Full details of the data-processing methodology are provided in Appendix A, including the treatment of non-representative traces, generation of representative material curves, and extraction of the final characteristic values. Only the final processed results are presented in this section to maintain a clear basis for comparison between materials.

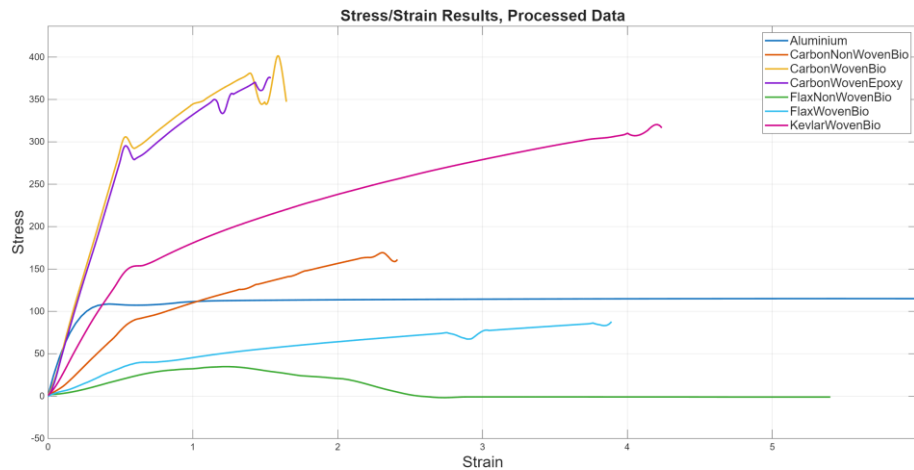


Figure 2: Processed stress/strain curve for each material.

Table 1: Numeric results for each material.

Material	Elastic Modulus (GPa)	Yield Stress (MPa)	Yield Strain (-)	UTS (MPa)
Aluminium	10.94	110.31	0.88	115.05
Carbon, Non-Woven, Bio Resin	11.06	114.62	1.09	169.24
Carbon, Woven, Bio Resin	61.44	303.48	0.55	401.45
Carbon, Woven, Epoxy Resin	58.72	288.28	0.56	376.18
Flax, Non-Woven, Bio Resin	3.97	31.95	0.96	34.78
Flax, Woven, Bio Resin	6.77	39.52	0.69	87.78
Kevlar, Woven, Bio Resin	30.42	152.43	0.60	320.36

4.3 Validation

The processed tensile properties were compared with available supplier laminate data to assess whether the measured values were of a realistic magnitude for the tested material systems. Validation was possible only where the uploaded datasheets gave broadly comparable composite-laminate tensile properties, rather than resin-only properties.

Table 2: Comparison between test results and material datasheets.

Material	Measured Modulus (GPa)	Specified Modulus (GPa)	Diff (%)	Measured UTS (MPa)	Specified UTS (MPa)	Diff (%)
Flax, Non-Woven, Bio Resin	3.97	5.0	-20.6%	34.78	37 to 44	-6.0% to -21.0%
Flax, Woven, Bio Resin	6.77	6.0 to 7.0	Within Range	87.78	58 to 61	43.9% to 51.3%
Carbon, Non-Woven, Bio Resin	11.06	25 to 35	-55.8% to -68.4%	169.24	290 to 330	-41.6% to -48.7%

Table 2 compares measured modulus and ultimate tensile strength with the available supplier values for flax woven bio resin, flax non-woven bio resin, and carbon non-woven bio resin, including percentage difference and a short validation comment for each row. The flax non-woven material showed the closest overall agreement, with modulus and tensile strength remaining in the same general range as the supplier data. Flax woven bio resin showed good agreement in modulus, but a substantially higher tensile strength than the datasheet values. Carbon non-woven bio resin showed the weakest agreement, with both modulus and tensile strength considerably lower than the supplier values, so this comparison should be treated as indicative only.

These differences are reasonable because the comparison is not strictly like-for-like. The test laminates were produced by resin infusion, the twill specimens used three plies arranged at 45° to each other, and the carbon material was treated using an assumed 50:50 fibre-resin volume fraction. By contrast, the flax datasheets report properties for specific infused flax/bio-epoxy laminates at defined fibre volume fractions, while the carbon non-woven datasheet gives only indicative values for a typical epoxy laminate with 30% fibre fraction and explicitly notes that these values are approximate. The main effect of this mismatch is reduced confidence in absolute numerical agreement, particularly for tensile strength, although the comparison remains useful for confirming that the measured responses are broadly credible and of the correct order of magnitude.

Uncertainty could be reduced by validating only against datasheets with matching fibre architecture, resin system, fibre volume fraction and loading direction, and by improving

control of specimen geometry and laminate characterisation prior to testing. More consistent thickness measurement within the gauge section, together with confirmation of the actual fibre volume fraction and cure condition, would reduce uncertainty in calculated stress and improve the reliability of the comparison.

No directly comparable laminate datasheets were available in the uploaded material set for aluminium, carbon woven bio resin, carbon woven epoxy resin, or Kevlar woven bio resin, so robust manufacturer-based validation was not achievable for these materials within the present study. The uploaded IB2 and IN2 documents provide resin processing and cured resin properties, but not directly equivalent laminate tensile data for the tested coupons.

4.4 Analysis

The processed stress-strain responses show a clear separation between the woven and non-woven laminates, and between the metallic baseline and the composite systems. In general, the woven carbon laminates gave the strongest combined tensile response, Kevlar occupied an intermediate position, and the flax systems remained the weakest, particularly in non-woven form. This pattern is consistent with the differences in reinforcement type, fibre continuity and laminate architecture identified in the literature review and testing plan.

Relative to the aluminium baseline, the composites behaved in a fundamentally different manner. Aluminium showed pronounced necking before fracture, indicating substantial plastic deformation and a more ductile failure mode. By contrast, the composite laminates failed abruptly with little warning after the onset of non-linear behaviour, indicating a more brittle tensile response. Within the composite group, the woven materials consistently outperformed the non-woven equivalents, suggesting that the more ordered fibre architecture provided a more effective load path under tensile loading. The comparison between woven carbon with bio-resin and woven carbon with conventional epoxy showed only limited separation, indicating that the bio-resin system did not introduce a major tensile-performance penalty under the present test conditions.

The laminate lay-up is also important in interpreting these results. The twill laminates were manufactured from three plies arranged at 45° to each other, whereas the non-woven materials used a single-layer mat construction. Consequently, the measured axial response of the woven laminates should not be expected to reach the ideal longitudinal fibre-direction upper bound, but instead to fall between the longitudinal and transverse limits. This helps explain why the woven laminates still showed strong tensile behaviour, while remaining below the level that might be expected from a purely aligned fibre system. A simple law-of-mixtures interpretation supports this trend: carbon-based laminates would be expected to retain a

higher effective modulus than flax-based laminates, but off-axis ply orientation reduces the direct axial contribution of the fibres.



Figure 3: Two specimens of each material after testing to failure. Note that aluminium split in the centre whereas the composite materials broke at the end of a radius, which acts as a stress concentrator.

Observed failure behaviour from Figure 3 supported the mechanical data. Most of the composite specimens fractured harshly and with little visible warning, which was consistent with their comparatively limited plastic deformation. The Kevlar laminate appeared to behave slightly differently, with evidence of ply separation and fibre pull-out before final rupture rather than a single clean break. This suggests that, although Kevlar retained comparatively strong tensile behaviour, its failure mechanism may have involved more progressive interlaminar damage than the carbon and flax systems. Overall, the results show that tensile response was governed not only by material type, but also by reinforcement architecture and ply orientation, and this distinction is central to the recommendations made in the following section.

5 Recommendations

Material selection should follow a selective deployment strategy rather than treating one composite system as universally preferable.

For stiffness- and mass-critical structures, woven carbon-fibre laminates remain the preferred material. Experimental results confirmed their superior tensile performance, while the small difference between bio-resin and conventional epoxy systems suggests partial bio-based substitution may be adopted without significant tensile penalty. However, because carbon/thermoset systems carry high embodied impacts and weak circularity, their use should be concentrated only in components where this performance is necessary.

For lower-load applications, woven flax/bio-resin laminates offer the more sustainable near-term option. Although mechanically inferior to carbon systems, they are suitable for semi-structural panels and secondary components where lower environmental burden may outweigh reduced performance. Kevlar is best reserved for localised impact-sensitive regions rather than broad structural substitution.

Manufacturing strategy should also become more selective. Resin infusion remains appropriate for low-volume motorsport or specialist applications, but tighter process control is needed to minimise variability and material waste. For higher-volume automotive production, more scalable routes such as resin transfer moulding, compression moulding and thermoplastic over moulding should be prioritised due to improved repeatability, reduced waste and stronger long-term sustainability potential.

End-of-life considerations should be addressed at design stage rather than after manufacture. Composite parts should be designed for disassembly, material separation and recovery wherever possible. For carbon-fibre systems, reclamation routes should be used where economically viable, while greater emphasis should be placed on recyclable matrix systems in future applications.

Future development should prioritise improving the sustainability-performance balance rather than simply maximising strength. Three areas are recommended: recyclable matrix systems, hybrid laminates combining high- and low-impact reinforcements, and broader experimental validation including fatigue, impact and compression testing to better represent real service conditions.

Overall, the preferred strategy is targeted use of carbon composites in genuinely critical structures, wider adoption of lower-impact alternatives where feasible, and progressive movement toward manufacturing and material systems compatible with circular design principles.

6 Conclusion

This study shows that material selection for automotive and motorsport composites cannot be based on mechanical performance alone but must balance structural efficiency with lifecycle sustainability and practical manufacturability.

The literature review showed carbon-fibre composites remain the strongest solution for stiffness-critical structural applications, while flax-based composites and bio-resin systems offer potential sustainability benefits where lower structural demand permits their use. The sustainability analysis found that the major limitation of conventional thermoset composites is not only resource intensity but weak recyclability and end-of-life circularity, increasing the importance of selective deployment and design-for-recovery strategies. Experimental testing supported the superior tensile performance of woven carbon laminates, demonstrated competitive behaviour from Kevlar in toughness-oriented applications, and confirmed that bio-resin carbon systems can provide comparable tensile behaviour to conventional epoxy systems under the present test conditions.

Overall, the findings support a selective material strategy rather than wholesale substitution: carbon composites retained for genuinely critical structural applications, lower-impact materials such as flax adopted in suitable secondary structures, and future development focused on improved manufacturing efficiency, recyclable matrix systems and hybrid composite solutions. This represents the most credible route to balancing performance and sustainability in future vehicle composite design.

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8 Appendices

8.1 Appendix A: Data Processing Methodology

The raw tensile-test data showed scatter between repeated specimens, local noise, and occasional anomalous traces that did not represent the main material response. To produce consistent and comparable results, the data were processed in several stages before extracting the final mechanical properties.

8.1.1 Removal of Anomalous Traces

Because some specimens showed stress levels that were clearly outside the main cluster, the first step was to identify and remove non-representative traces. This was done by comparing all repeat tests for each material over a common strain range and retaining the group of traces that clustered most closely together. Traces that deviated substantially from the main response were excluded from further analysis.

This approach reduced the influence of unusually high or low specimens and ensured that the final material response was based on the repeat tests most representative of the dataset.

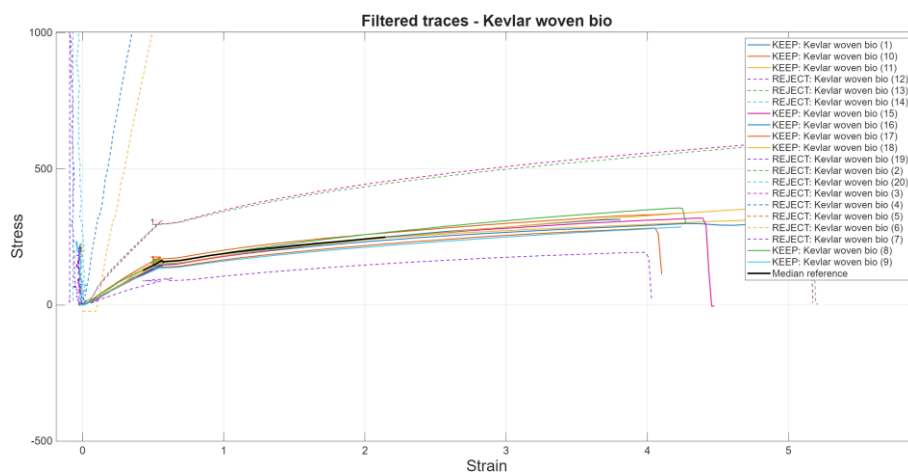


Figure 4: Test result filtering process, with a median reference used to identify anomalous traces.

8.1.2 Generation of a Representative Material Trace

After filtering, the remaining traces for each material were combined to form one representative stress-strain curve. This was done by aligning the accepted traces onto a common strain basis and averaging them point-by-point. A light smoothing step was then applied so that the final curve was not excessively jagged, allowing gradients and fitted lines to be extracted without being dominated by local noise.

The representative trace was therefore intended to describe a generic material response rather than any single specimen.

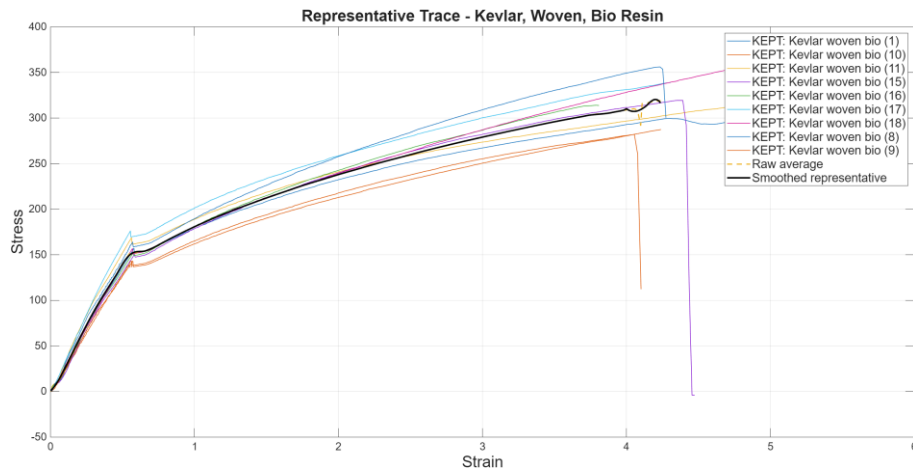


Figure 5: Representative trace compared to input traces.

8.1.3 Elastic Modulus & Yield Point Determination

The early part of the representative stress-strain curve was used to estimate elastic modulus. Because the initial region of some materials did not show a perfectly constant gradient, modulus was not taken directly from the raw derivative. Instead, a straight line was fitted to the earliest suitable approximately linear part of the curve. The fit was constrained so that it remained close to the start of the test and did not drift into later non-linear behaviour.

Where required, the fit was adjusted interactively so that the selected line matched the intended elastic region of the material more accurately.

Yield was identified from the same representative curve and the same fitted elastic line. The fitted modulus line was extended beyond the elastic region, and the yield point was taken as the first sustained point where the measured curve deviated significantly below this extension. This method was used so that yield reflected the onset of measurable departure from the elastic response, rather than a single noisy point.

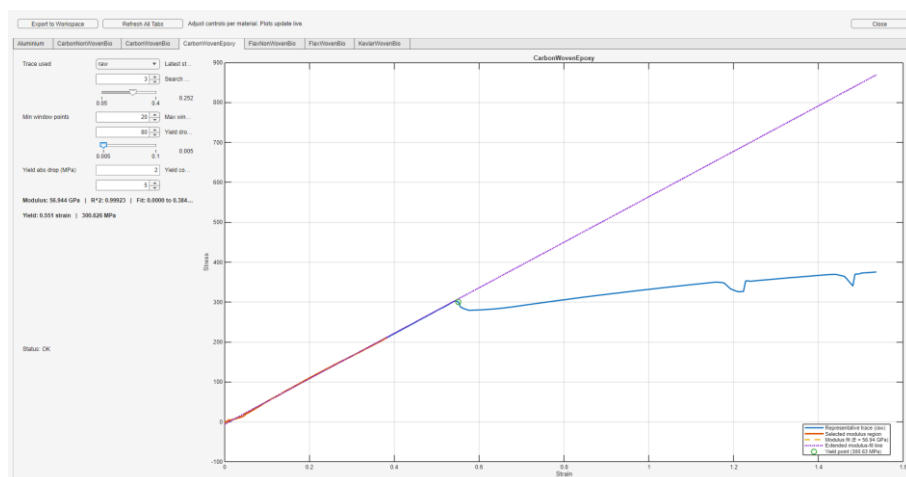


Figure 6: User interface to curve fit for elastic modulus and identify a yield point.

8.1.4 UTS and Strain Measures

Ultimate tensile strength was taken as the maximum stress reached on the final representative curve. The corresponding strain was recorded as the strain at UTS. The final strain of the representative trace was also retained as a measure of the usable strain range captured after filtering and averaging.

This allowed each material to be compared in terms of stiffness, yield behaviour, peak stress and strain capacity.

8.1.5 Final Comparison Between Materials

Once each material had been reduced to a representative trace and key properties had been extracted, the final curves were overlaid on a single comparison plot. A summary table was then produced containing the main results for all materials. These outputs were used in the main body of the report to compare mechanical behaviour between the tested materials.

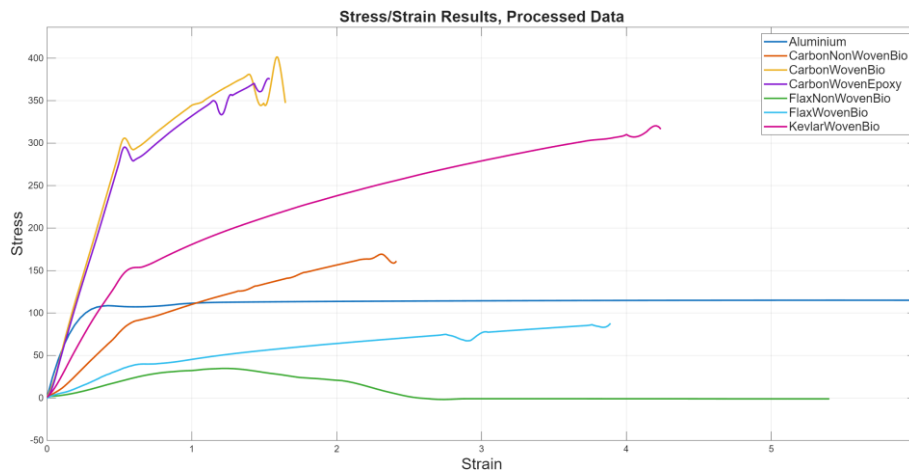


Figure 7: Final material stress/strain curves.

Table 3: Numeric results from the stress/strain curves.

Material	Elastic Modulus	Yield Stress	Yield Strain	UTS
	GPa	MPa	(-)	MPa
Aluminium	10.94	110.31	0.88	115.05
Carbon, Non-Woven, Bio Resin	11.06	114.62	1.09	169.24
Carbon, Woven, Bio Resin	61.44	303.48	0.55	401.45
Carbon, Woven, Epoxy Resin	58.72	288.28	0.56	376.18
Flax, Non-Woven, Bio Resin	3.97	31.95	0.96	34.78
Flax, Woven, Bio Resin	6.77	39.52	0.69	87.78
Kevlar, Woven, Bio Resin	30.42	152.43	0.60	320.36