

University of Wales Trinity Saint David

Wales Institute of Science and Art



Prifysgol Cymru

Y Drindod Dewi Sant

University of Wales

Trinity Saint David

Materials Testing and Sustainability of Composites for Motorsport & Automotive Industries

Nathan Evans

2204179

Motorsport Engineering

April 2026

Automotive Materials & Sustainability – ACHA6012

Word Count: 3264

Contents

1	Introduction	1
1.1	Aims	1
1.2	Objectives	1
2	Literature Review	2
2.1	Material Performance	2
2.2	Fibre Architecture and Failure Behaviour	2
2.3	Manufacturing Processes	3
3	Sustainability Analysis.....	4
3.1	Life Cycle Assessment (LCA)	4
3.2	Environmental Impact of Composites	4
3.3	Recycling and End of Life	4
3.4	Legislation and Industry Pressure.....	5
3.5	Comparative Sustainability – Conclusion	5
4	Experimental Methodology	6
4.1	Materials Tested	6
4.2	Manufacturing Process.....	7
4.3	Testing Procedures	8
5	Results and Analysis.....	9
5.1	Carbon Fibre Composite Response and Effect of Resin System.....	10
5.2	Failure Behaviour and Damage Mechanisms	12
5.3	Repeatability and Material Variability.....	13
5.4	Mass Efficiency and Performance Analysis	15
5.5	Validation.....	16
6	Recommendations for Material Use.....	20
6.1	Kevlar Composites	20
6.2	Flax Fibre Composites.....	20
6.3	Future Research and Development.....	21
7	Conclusion.....	22
8	References	23
9	Appendices.....	25
9.1	Appendix A – Failure Modes of Tested Specimens	25
9.2	Appendix B - Stress Strain Curves.....	25
9.3	Appendix C - Performance Comparisons.....	28

Figure 1 Comparison of continuous, aligned fibre reinforcement and randomly oriented discontinuous fibres, showing how fibre orientation and continuity influence load transfer efficiency, stiffness, and overall composite behaviour (Lichtarowicz, 2013).	2
Figure 2 Comparison of reinforcement architectures: (a) woven flax twill, (b) non-woven flax mat, (c) woven carbon twill, and (d) non-woven recycled carbon mat. Woven structures provide more ordered fibre alignment, influencing load transfer, consistency, and tensile behaviour (Easy Composites Ltd).	3
Figure 3 Recycled carbon fibre material by McLaren Racing, laying up carbon fibre in high-performance motorsport applications (McLaren Racing, 2023).	5
Figure 4 Carbon specimen mounted in the Denison prior to the extensometer being placed on and then tested.	6
The material set was selected to compare the main variables expected to influence composite suitability in automotive and motorsport applications. Full material details are provided in Table 1.	6
Table 1 Full specimen details were available for the aluminium, flax and carbon samples. Equivalent manufacturing details for the Kevlar specimens were unavailable, so these fields are reported as N/A.	6
Figure 5 Vacuum infusion manufacturing set-up used to produce the composite specimens, showing dry fibre lay-up, vacuum bagging, and infusion equipment prior to resin flow (Easy Composites Ltd).	7
Table 2 Summary of specimen cross-sectional areas for each material, including mean area, range, and standard deviation.	8
Figure 6 Comparison of experimental aluminium stress–strain behaviour with literature data, demonstrating consistent elastic–plastic response and ductile deformation trends (Jiang et al., 2024).	9
Figure 7 Showing the two aluminium samples, both showing similar failure modes.	9
Figure 8 Comparison between published stress-strain trends and the present woven carbon results. Flax fibre stress-strain response is shown on the left (Charlet et al., 2009), while resin-system trends for bio-resin and conventional epoxy are shown on the right (Boursier Niutta, Ciardiello et al., 2023).	10
Figure 9 Focused comparison of carbon woven epoxy, carbon woven bio-resin, carbon non-woven bio-resin, and Kevlar, illustrating differences in tensile strength and strain-to-failure.	11
Figure 10 Stress–strain response of bio-resin composite materials, comparing carbon and flax fibre systems in woven and non-woven configurations. Full comparison plots including Kevlar and the remaining materials are provided in Appendix B.	11
Figure 11 Shows all composite specimens tested and their failure modes after testing.	12
Figure 12 Failure modes for carbon non-woven, carbon woven BIO, and flax woven specimens, showing differences in fracture uniformity, fibre exposure, and progressive damage behaviour.	12
Figure 13 Ultimate tensile strength comparison including experimental variability, demonstrating repeatability and uncertainty across tested materials.	13
Table 3 specimen-to-specimen repeatability in ultimate tensile strength, expressed using standard deviation and repeatability percentage.	14
Figure 14 Repeatability of UTS results across all materials, highlighting greater variability in non-woven and natural-fibre systems.	14
Figure 15 Comparison of epoxy and bio-epoxy tensile performance, showing similar repeatability and confirming minimal influence of resin type on mechanical consistency (Boursier Niutta, Ciardiello et al. 2023).	15
Figure 16 Average specimen mass before testing, showing that all composite specimens were substantially lighter than the aluminium baseline, supporting their potential for improved lightweighting and specific performance.	15

Figure 17 Mass-normalised tensile strength comparison, highlighting the superior strength-to-weight efficiency of carbon fibre composites.....	16
Equation 1 Rule-of-mixtures upper bound for composite elastic modulus (isostrain condition), representing maximum stiffness for aligned, continuous reinforcement.....	17
Equation 2 Rule-of-mixtures lower bound for composite elastic modulus (isostress condition), assuming equal stress in fibre and matrix phases.	17
Using these bounds, validation was strongest for the woven carbon systems, with both carbon woven epoxy and carbon woven bio-resin falling within the stiffness and tensile-strength ranges. Flax woven bio-resin and carbon non-woven bio-resin deviated further, although the overall ranking remained consistent. Aluminium matched the tensile-strength range more closely than stiffness, suggesting greater sensitivity of elastic response to specimen geometry and test configuration (Zhao et al., 2019). Kevlar also fell within the tensile-strength window but exceeded the selected stiffness range, which should be treated cautiously because published Kevlar composite properties are strongly influenced by resin system, laminate architecture, and specimen quality (Goud et al., 2022).	17
Table 4 Comparison of experimental values with theoretical bounds and supplier reference ranges used for validation.	17
Figure 18 Experimental stiffness compared with theoretical, datasheet, and literature reference bounds. Agreement was strongest for the woven carbon laminates, while flax woven BIO, carbon non-woven BIO, aluminium, and Kevlar showed varying levels of deviation.....	18
Figure 19 Experimental ultimate tensile strength compared with theoretical, datasheet, and literature reference bounds. Agreement was strongest for the woven carbon laminates, while flax-based and non-woven systems showed larger deviations from reference values.....	18
Figure 20 Bcomp panel made from sustainable materials with integrated reinforcement to improve stiffness and strength (Bcomp).....	20
Figure 21 Bcomp natural-fibre composite applications in lightweight motorsport bodywork (Bcomp).	21

1 Introduction

Composite materials are widely used in automotive and motorsport engineering because they provide high strength-to-weight ratios and can be tailored to structural requirements. However, material selection is now driven not only by performance, but also by sustainability, regulatory pressure, and end-of-life considerations. This report evaluates the mechanical performance and sustainability of selected composite materials through tensile testing, validation against published and manufacturer data, and lifecycle-based assessment in an automotive and motorsport context.

1.1 Aims

To evaluate the mechanical performance and sustainability of composite materials for automotive and motorsport applications through experimental testing and lifecycle analysis.

1.2 Objectives

- Review composite materials used in automotive and motorsport applications, including their structure, properties, manufacturing processes, and uses.
- Experimentally determine key mechanical properties using standard laboratory testing methods.
- Analyse and validate results using appropriate graphs, tables, and comparison with manufacturer and published data.
- Evaluate sustainability using lifecycle assessment principles across raw material extraction, manufacturing, use, and end-of-life.
- Assess the influence of current and future legislation and industry pressures on material selection.
- Compare performance–sustainability trade-offs and provide justified recommendations for future application and development.

2 Literature Review

2.1 Material Performance

Material selection in automotive and motorsport engineering depends on balancing structural performance, failure behaviour, manufacturability, and sustainability. Carbon fibre reinforced polymers (CFRP) remain the benchmark for high-load applications because of their high specific strength and stiffness, making them well suited to chassis structures, aerodynamic components, and other stiffness-critical parts. Kevlar offers lower stiffness than carbon fibre but greater toughness and energy absorption, making it more suitable for damage-tolerant and impact-prone components.

Natural fibre composites such as flax offer lower embodied energy and renewable sourcing, but reduced strength, lower stiffness, and greater variability limit them to lower-load or secondary applications. This reflects the broader direction of automotive material development, where material selection is increasingly driven by structural efficiency, sustainability, and multi-material design rather than mechanical performance alone (Czerwinski, 2021). Hybridisation has therefore been identified as a practical compromise. Dhakal et al. (2019) showed that combining flax with carbon fibre increased tensile strength from approximately 68 MPa to over 500 MPa, demonstrating that hybrid systems can bridge part of the gap between sustainability and structural performance.

2.2 Fibre Architecture and Failure Behaviour

Composite performance is governed not only by fibre type, but also by reinforcement architecture and interface quality. Chen et al. (2021) showed that fibre alignment, fibre volume fraction, and manufacturing quality influence measured properties, while less ordered reinforcement forms reduce stiffness and strength because stress transfer becomes less efficient. This is relevant when comparing woven and non-woven systems.

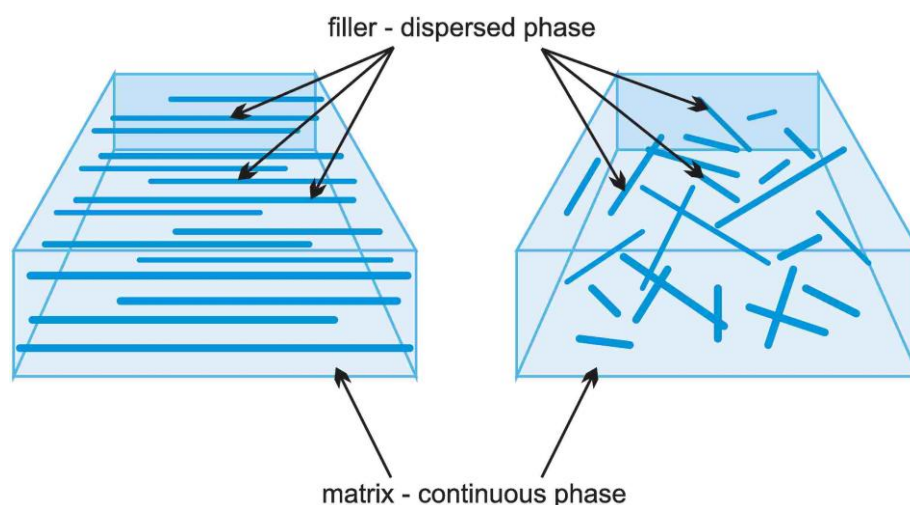


Figure 1 Comparison of continuous, aligned fibre reinforcement and randomly oriented discontinuous fibres, showing how fibre orientation and continuity influence load transfer efficiency, stiffness, and overall composite behaviour (Lichtarowicz, 2013).

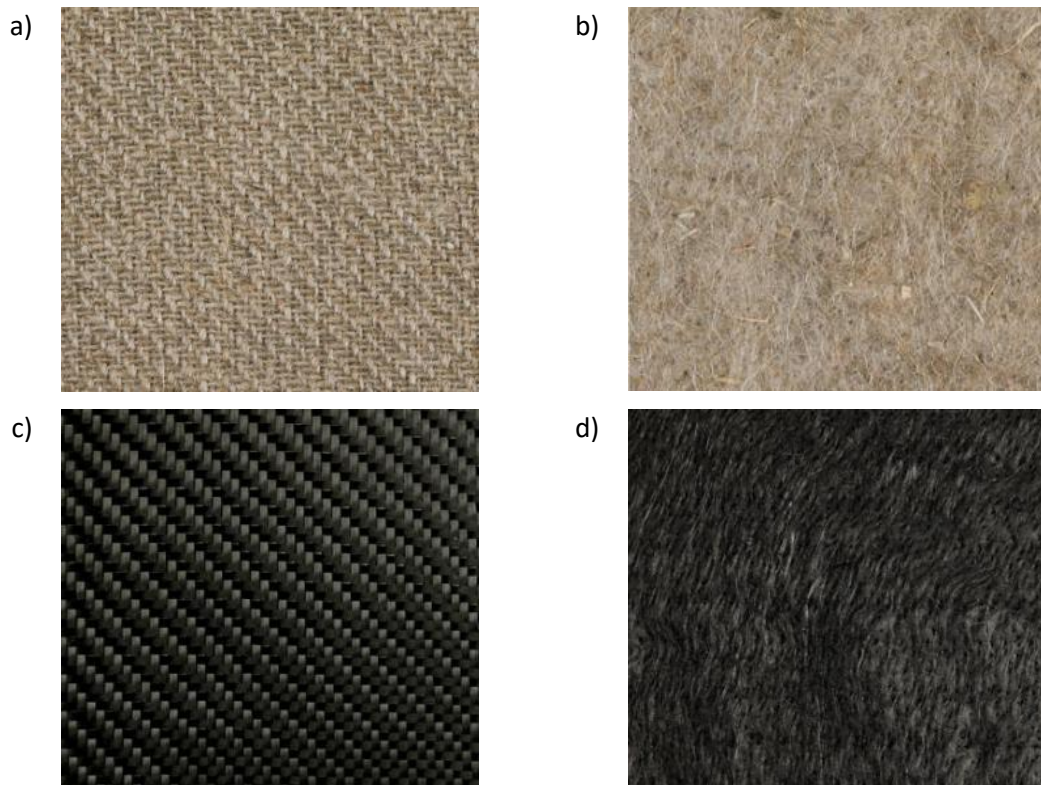


Figure 2 Comparison of reinforcement architectures: (a) woven flax twill, (b) non-woven flax mat, (c) woven carbon twill, and (d) non-woven recycled carbon mat. Woven structures provide more ordered fibre alignment, influencing load transfer, consistency, and tensile behaviour (Easy Composites Ltd).

Woven laminates provide more consistent load paths and better structural stability, whereas non-woven reinforcements contain shorter or less ordered fibres, increasing matrix dependence and variability. Natural fibre systems are especially sensitive to this because fibre heterogeneity, moisture sensitivity, and weaker fibre–matrix adhesion reduce stress transfer efficiency (Elfaleh et al., 2023). Mahboob et al. (2016) found that damage in flax composites often initiates in the fibre or at the fibre–matrix interface, while Charlet et al. (2009) showed that flax fibres display non-linear tensile behaviour due to microstructural effects such as microfibril reorientation, helping explain the greater scatter and progressive failure seen in natural-fibre composites.

2.3 Manufacturing Processes

Composite manufacturing route affects both mechanical performance and process efficiency. Processes such as hand lay-up, vacuum infusion, RTM, compression moulding, and autoclave processing offer different trade-offs in laminate quality, cost, and waste, with higher-control routes generally improving consistency but often increasing tooling, energy input, or consumable use (Bhatt et al., 2018; Chen et al., 2021). Manufacturing impacts therefore extend beyond fibre and resin to include bagging film, peel ply, breather layers, and other process consumables.

3 Sustainability Analysis

Growing environmental pressure in automotive and motorsport engineering requires materials to be assessed beyond mechanical performance alone. Although CFRP offer excellent structural efficiency, their sustainability must also be considered across production, use, and end-of-life.

3.1 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) evaluates environmental impact across the full life of a material, from raw material extraction to disposal. Chandel et al. (2025) show that sustainability conclusions depend strongly on system boundaries, meaning production impact alone is not enough to rank materials. This is important for composites because virgin carbon fibre production is highly energy intensive, with reported embodied energy of 183–286 MJ/kg (Giorgini et al., 2020; Pakdel et al., 2021), giving CFRP a high production-stage burden, whereas flax requires lower processing energy (Elfaleh et al., 2023). Consequently, carbon fibre cannot be judged sustainable purely because it is lightweight, while flax cannot be judged superior purely because it is bio-based.

3.2 Environmental Impact of Composites

The environmental impact of composites is governed by a trade-off between production burden and use-phase benefit. CFRP can reduce vehicle mass by 40–65%, improving in-service efficiency (Spasenović and Blagojević, 2021), but Giorgini et al. (2020) show that this benefit is partly offset by the high energy demand of carbon fibre manufacture. By contrast, Elfaleh et al. (2023) show that natural fibre composites offer lower embodied impact, but their lower strength, stiffness, and moisture resistance restrict high-load use. Dhakal et al. (2019) therefore support hybridisation as the most practical compromise, since it reduces reliance on energy-intensive carbon fibre without the same loss of performance as natural fibres alone.

3.3 Recycling and End of Life

End-of-life remains one of the weakest aspects of composite sustainability because thermoset matrices cannot be remelted, leaving landfill and incineration as common disposal routes (Giorgini et al., 2020). Huang et al. (2020) show that recycled carbon fibres can retain about 95% of original tensile strength, indicating that useful structural value can still be recovered. This suggests recycling can improve the sustainability case for carbon composites, even if it does not remove end-of-life limitations entirely.

A similar trend is seen in motorsport practice, where McLaren Racing (2023) reported up to a 90% reduction in life cycle emissions for recycled carbon fibre compared with virgin material. This is achieved by reclaiming fibres from manufacturing and end-of-life waste and reusing them in secondary or non-critical components, where slightly reduced fibre continuity and performance can

be tolerated. Natural fibre composites appear more favourable in principle, but when combined with thermoset matrices their recovery is still restricted.



Figure 3 Recycled carbon fibre material by McLaren Racing, laying up carbon fibre in high-performance motorsport applications (McLaren Racing, 2023).

3.4 Legislation and Industry Pressure

Automotive and motorsport industries are under increasing pressure to reduce environmental impact, making sustainability a design constraint rather than a secondary consideration. In road vehicles, lightweight materials support decarbonisation by reducing operational emissions (Department for Transport, 2021), while end-of-life legislation promotes reuse, recycling, and recovery of vehicle materials (European Commission, 2023; UK Government, 2003). This creates a challenge for mixed-fibre and thermoset composites, which remain difficult to recycle using conventional methods. Motorsport is moving in the same direction, with the FIA increasing emphasis on sustainability strategy, while McLaren Racing's recycled carbon fibre and flax-fibre trials show that sustainable composite approaches are beginning to move into track-tested use (FIA, 2024; McLaren Racing, 2024).

3.5 Comparative Sustainability – Conclusion

The sustainability analysis shows that no material is inherently sustainable; suitability depends on function. CFRP has the highest production and end-of-life penalty, but this can be justified where its structural efficiency is essential. Natural fibre composites reduce embodied impact, but their lower and less consistent mechanical performance limits them to lower-load applications. The most defensible strategy is therefore selective material use, balancing structural demand against environmental burden and recovery potential.

4 Experimental Methodology

Tensile testing was conducted using a Denison testing machine to determine stiffness, ultimate tensile strength, and strain at failure for the selected materials. This provided a consistent basis for comparing conventional and composite systems and for validating the results against supplier and published reference data (Chen et al., 2021; Dhakal et al., 2019).



Figure 4 Carbon specimen mounted in the Denison prior to the extensometer being placed on and then tested.

4.1 Materials Tested

The material set was selected to compare the main variables expected to influence composite suitability in automotive and motorsport applications. Full material details are provided in Table 1.

Table 1 Full specimen details were available for the aluminium, flax and carbon samples. Equivalent manufacturing details for the Kevlar specimens were unavailable, so these fields are reported as N/A.

Material / Specimen Type	Reinforcement Form	Resin System	Lay-up / Ply Detail	Nominal Reinforcement Weight	Specimen / Analysis Notes
Aluminium baseline	N/A	N/A	Metallic baseline	N/A	Used as the baseline reference material for comparison with the composite systems
Flax twill composite	Woven twill flax	Bio-resin	3 × 200 g flax twill plies	600 g	Multiple plies arranged at 45° to each other

Carbon twill composite	Woven twill carbon	Bio-resin	3 × 200 g carbon twill plies	600 g	Multiple plies arranged at 45° to each other; carbon analysed using assumed 50:50 fibre/epoxy volume fraction
Carbon twill composite	Woven twill carbon	Epoxy	3 × 200 g carbon twill plies	600 g	Multiple plies arranged at 45° to each other; carbon analysed using assumed 50:50 fibre/epoxy volume fraction
Flax non-woven composite	Non-woven flax mat	Bio-resin	1 × 300 g non-woven flax ply	300 g	Single-ply non-woven configuration
Carbon non-woven composite	Non-woven carbon mat	Bio-resin	1 × 300 g non-woven carbon ply	300 g	Single-ply non-woven configuration; carbon analysed using assumed 50:50 fibre/epoxy volume fraction
Kevlar composite	Aramid / Kevlar	N/A	N/A	N/A	Included in the experimental dataset; full manufacturing details unavailable, therefore N/A values are reported where required.

4.2 Manufacturing Process

All composite specimens were manufactured using vacuum infusion. This closed-mould process improves fibre wet-out and reduces void content compared with open-mould methods such as hand lay-up, giving better laminate consistency (Bhatt et al., 2018; Chen et al., 2021). Some variability was still expected, particularly in natural-fibre composites, due to fibre morphology, moisture sensitivity, and fibre–matrix adhesion effects (Elfaleh et al., 2023).



Figure 5 Vacuum infusion manufacturing set-up used to produce the composite specimens, showing dry fibre lay-up, vacuum bagging, and infusion equipment prior to resin flow (Easy Composites Ltd).

4.3 Testing Procedures

Specimen dimensions were measured before testing so that recorded load could be converted into engineering stress and strain. An extensometer was used during the initial loading stage to obtain accurate strain measurements in the elastic region before removal prior to failure. The full stress–strain response was then used to determine stiffness, ultimate tensile strength, strain at failure, and failure behaviour. For composites, this included progressive damage mechanisms such as interfacial debonding, matrix cracking, and fibre fracture, whereas aluminium showed yielding and plastic deformation before fracture (Budiman et al., 2017). Two specimens per material were tested in the primary programme, with one additional dataset included for each material to provide three data points per material for mean-property and repeatability calculations.

Table 2 Summary of specimen cross-sectional areas for each material, including mean area, range, and standard deviation.

Material	Sample 1 (mm ²)	Sample 2 (mm ²)	Sample 3 (mm ²)	Average (mm ²)	Difference (mm ²)	Std. Dev. (mm ²)
Aluminium	22.50	22.50	22.50	22.50	0.00	0.00
Carbon Non-Woven BIO	31.97	31.97	29.96	31.30	2.01	1.16
Carbon Woven BIO	13.58	13.65	10.22	12.48	3.43	1.97
Carbon Woven Epoxy	13.79	13.79	13.65	13.74	0.14	0.08
Flax Non-Woven BIO	27.86	26.73	23.76	26.12	4.10	2.11
Flax Woven BIO	33.66	34.56	33.32	33.85	1.24	0.64
Kevlar	15.68	15.68	17.64	16.33	1.96	1.13

5 Results and Analysis

The aluminium specimens exhibited the expected ductile tensile response, with an initial linear elastic region followed by yielding, strain hardening, and plastic deformation prior to fracture. All three samples showed near-identical elastic gradients and peak stresses of approximately 113–115 MPa, indicating good repeatability and a consistent metallic baseline. This behaviour is consistent with published aluminium stress–strain data, which show a smooth elastic–plastic transition and progressive post-yield deformation (Zhao et al., 2019). Published testing on 6061-T6 aluminium also reports that the alloy does not exhibit a distinct yield plateau, with yielding instead defined using the 0.2% proof stress criterion, supporting the interpretation that the present results remain representative (Jiang et al., 2024).

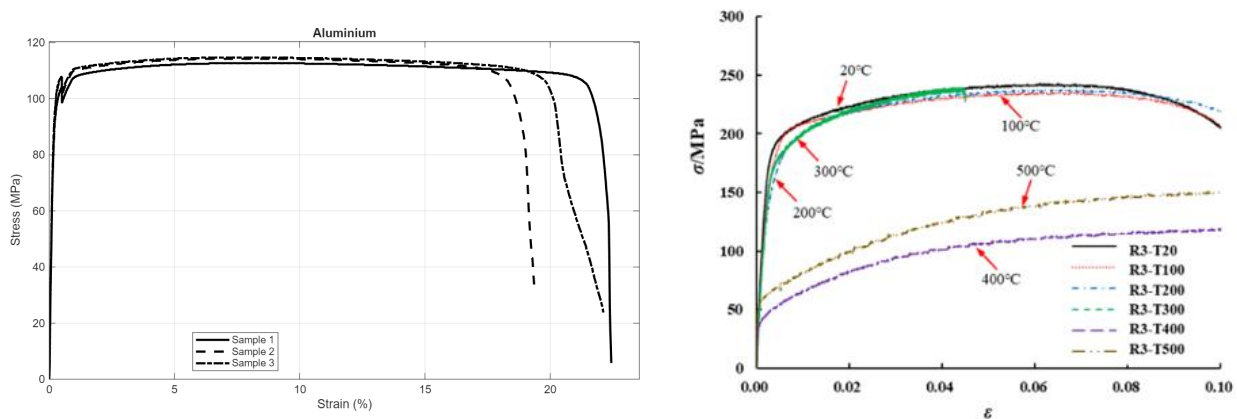


Figure 6 Comparison of experimental aluminium stress–strain behaviour with literature data, demonstrating consistent elastic–plastic response and ductile deformation trends (Jiang et al., 2024).

Compared with published aluminium data, the experimental curves showed strong agreement in overall shape, including the elastic–plastic transition, strain hardening behaviour, and extended ductility (Jiang et al., 2024). A more distinct yield point was observed in the present results, this is due to differences in specimen geometry, material condition, or testing configuration. Minor variation in failure strain between specimens was also evident, but this remained within the expected range for ductile metallic behaviour.



Figure 7 Showing the two aluminium samples, both showing similar failure modes.

Fracture observations supported this response, with both specimens showing similar shear-dominated failure at approximately 45° to the loading direction, characteristic of ductile metallic fracture under tensile loading (Zhao et al., 2019). Overall, the close agreement between the experimental stress–strain response, failure mode, and published behaviour confirms that the testing methodology captured representative aluminium deformation, providing a reliable metallic baseline for comparison with the composite systems.

5.1 Carbon Fibre Composite Response and Effect of Resin System

The carbon fibre results show that tensile performance was governed primarily by fibre architecture rather than resin type. Carbon woven epoxy (~ 433 MPa) and carbon woven bio-resin (~ 450 MPa) produced near-identical peak stresses and similar elastic gradients, indicating that load was predominantly carried by the carbon fibres. This trend agrees with Boursier Niutta et al. (2023), who reported comparable quasi-static properties between bio-based and conventional epoxy matrices when fibre architecture is maintained. As shown in Figure 8, the experimental woven carbon responses follow the same overall trend as the published comparison data, supporting the view that the present results are representative despite differences in absolute strain response.

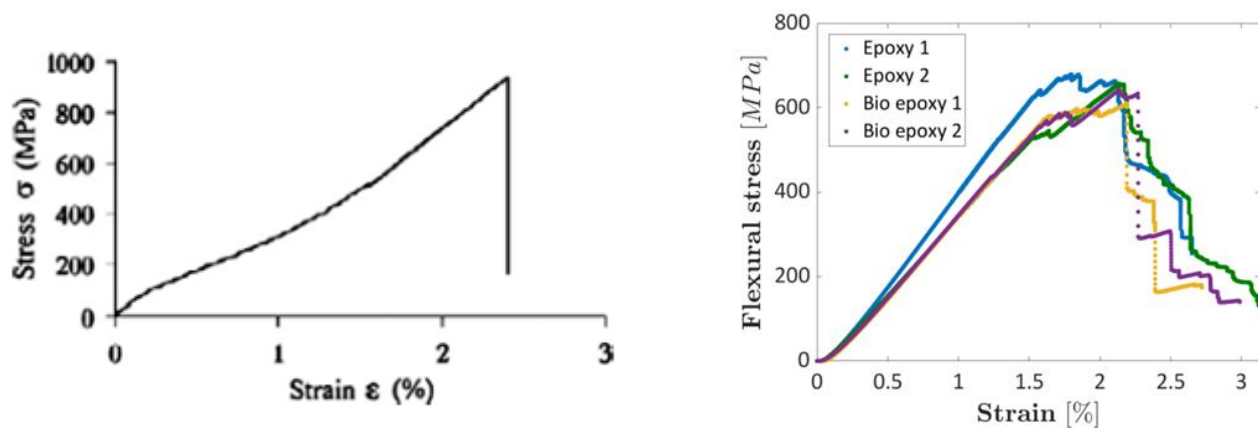


Figure 8 Comparison between published stress-strain trends and the present woven carbon results. Flax fibre stress-strain response is shown on the left (Charlet et al., 2009), while resin-system trends for bio-resin and conventional epoxy are shown on the right (Boursier Niutta, Ciardiello et al., 2023).

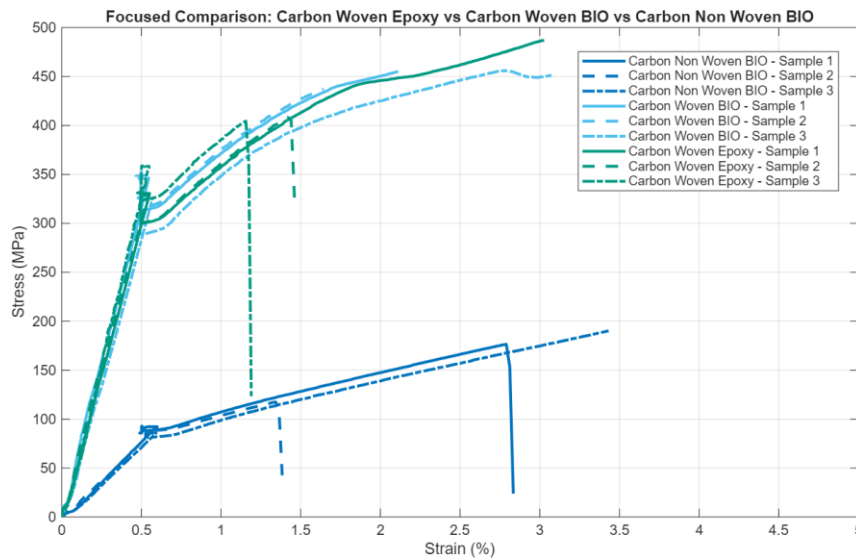


Figure 9 Focused comparison of carbon woven epoxy, carbon woven bio-resin, carbon non-woven bio-resin, and Kevlar, illustrating differences in tensile strength and strain-to-failure.

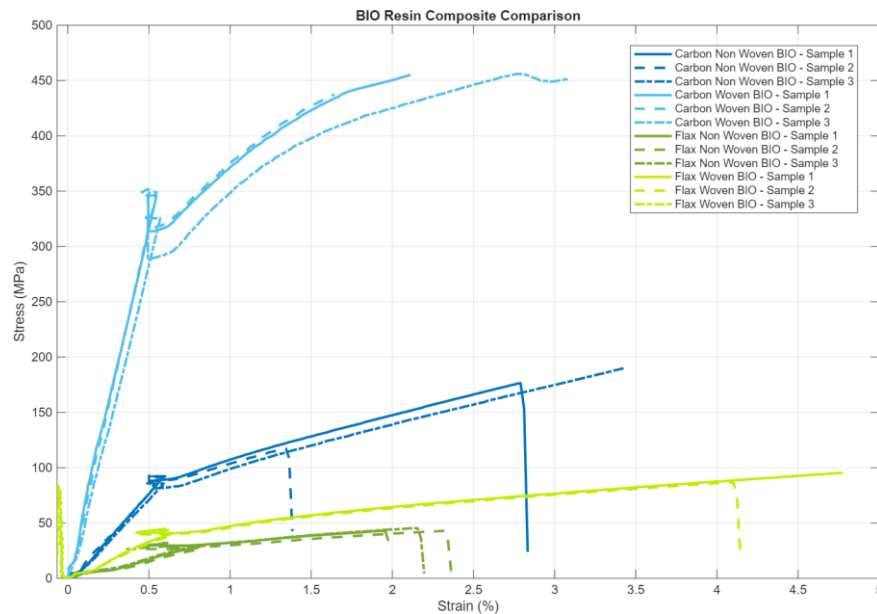


Figure 10 Stress–strain response of bio-resin composite materials, comparing carbon and flax fibre systems in woven and non-woven configurations. Full comparison plots including Kevlar and the remaining materials are provided in Appendix B.

The influence of architecture became clearer when the woven and non-woven systems were compared. Carbon non-woven BIO showed substantially lower tensile strength (~161 MPa) and more gradual stress development, indicating less efficient load transfer than the woven laminates. This is consistent with published work showing that discontinuous or randomly oriented reinforcement reduces stiffness and strength through inefficient stress transfer and limited fibre alignment (Chen et al., 2021; Elfaleh et al., 2023). Flax systems followed the same woven-versus-non-woven trend, but at substantially lower stress levels overall, confirming the importance of both fibre type and reinforcement architecture.

5.2 Failure Behaviour and Damage Mechanisms

Failure behaviour across the material systems supported the mechanical results. Woven carbon composites showed abrupt fracture after peak stress, consistent with brittle, fibre-dominated failure. Carbon non-woven specimens exhibited irregular fracture surfaces and less distinct separation, indicating increased matrix deformation, fibre discontinuity, and interfacial debonding, consistent with progressive damage mechanisms reported by Dhakal et al. (2019).

Flax systems demonstrated lower mechanical performance and more distributed failure, with woven flax BIO outperforming the non-woven variant due to improved fibre continuity and load transfer. Increased scatter and reduced strength are attributed to natural fibre variability, weaker fibre–matrix adhesion, and moisture sensitivity (Elfaleh et al., 2023). The gradual failure behaviour observed aligns with the non-linear deformation and microstructural variability of flax fibres (Charlet et al., 2009).

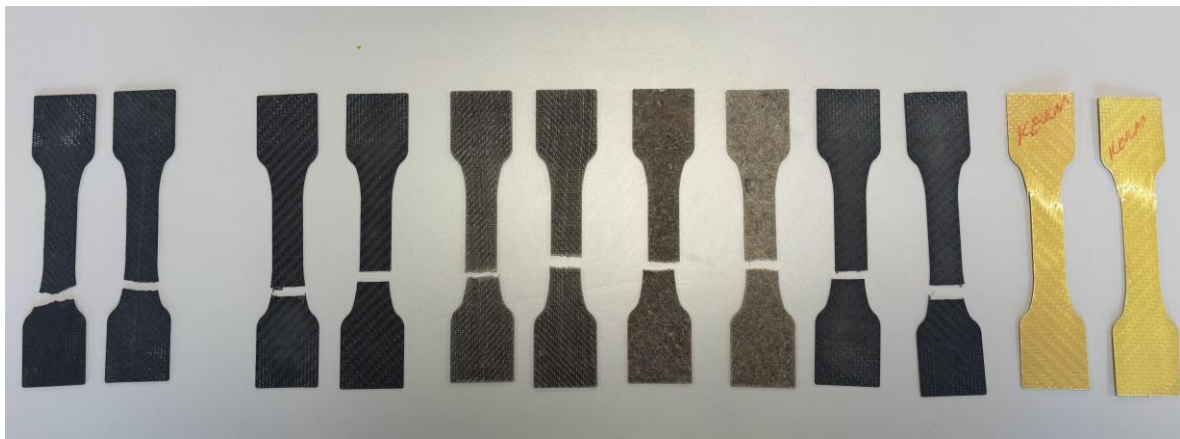


Figure 11 Shows all composite specimens tested and their failure modes after testing.

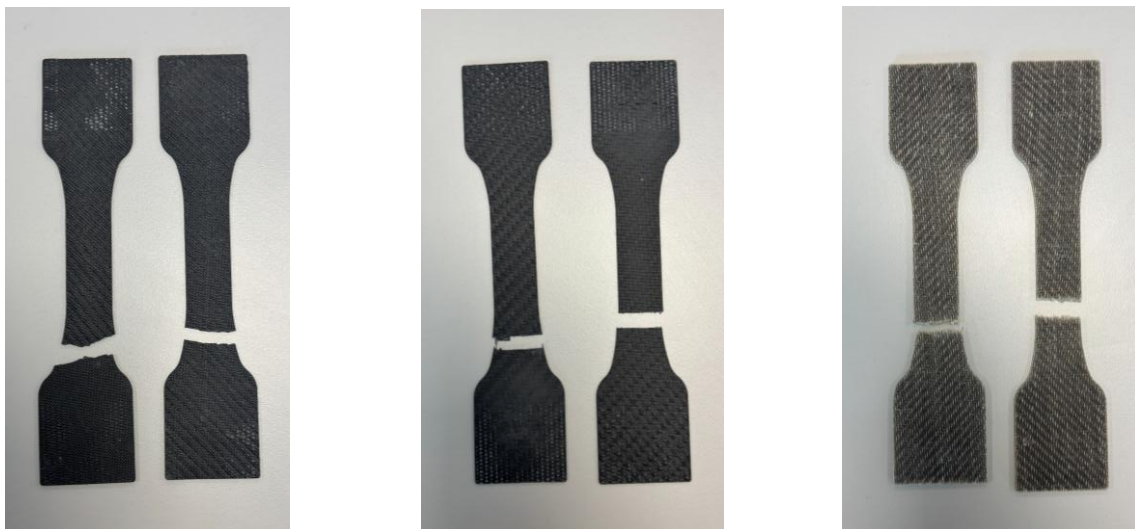


Figure 12 Failure modes for carbon non-woven, carbon woven BIO, and flax woven specimens, showing differences in fracture uniformity, fibre exposure, and progressive damage behaviour.

Visual inspection confirmed aluminium failed via yielding and plastic deformation, while composites exhibited matrix cracking, fibre pull-out, and interfacial debonding, most pronounced in non-woven and natural-fibre systems.

5.3 Repeatability and Material Variability

Repeatability provides insight into manufacturing consistency and load-transfer reliability within each material system. Figure 13 presents the ultimate tensile strength (UTS) results with associated variability, while Table 3 summarises specimen-to-specimen variation through standard deviation and repeatability percentage.

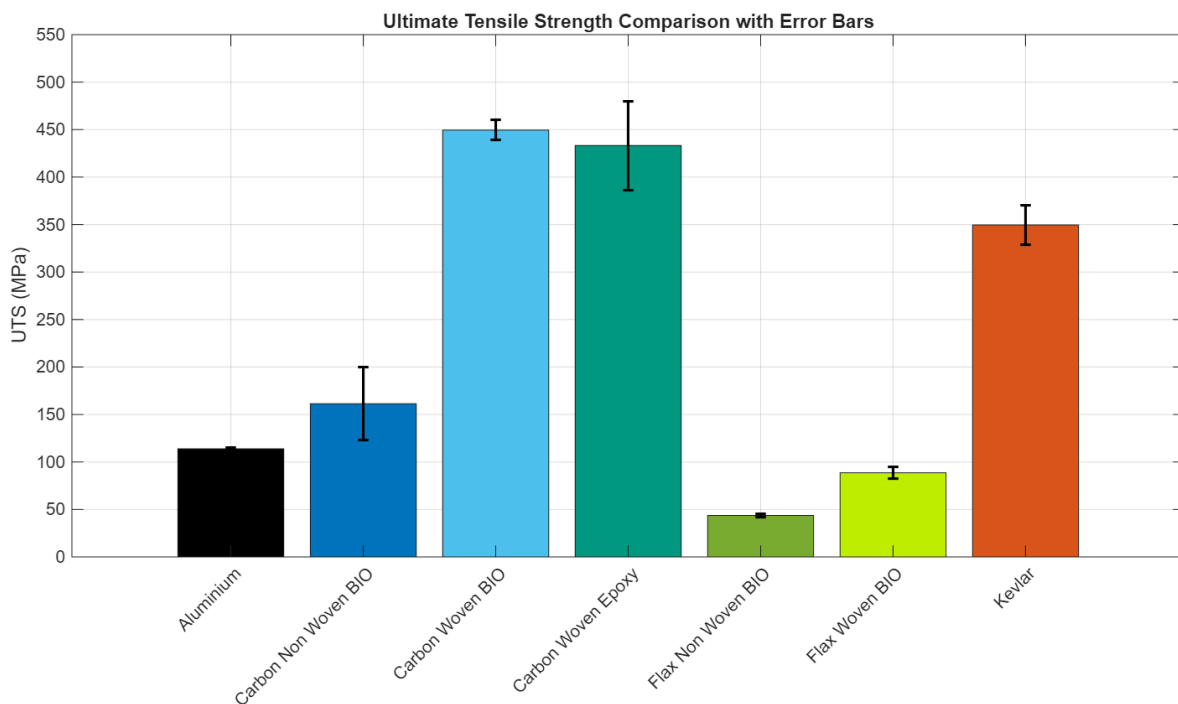


Figure 13 Ultimate tensile strength comparison including experimental variability, demonstrating repeatability and uncertainty across tested materials.

The results show clear differences in repeatability between materials. Aluminium and carbon woven BIO exhibited the lowest scatter, with repeatability values of 0.92% and 2.34% respectively, indicating stable and predictable behaviour. In contrast, carbon woven epoxy and especially carbon non-woven BIO showed much higher variability, with repeatability values of 10.75% and 23.95%. This is consistent with published work showing that discontinuous reinforcement and poorer fibre alignment reduce the consistency of stress transfer and increase specimen-to-specimen variation (Chen et al., 2021).

Table 3 specimen-to-specimen repeatability in ultimate tensile strength, expressed using standard deviation and repeatability percentage.

Material	Sample 1 UTS (MPa)	Sample 2 UTS (MPa)	Sample 3 UTS (MPa)	Mean UTS (MPa)	Standard Deviation UTS	Repeatability (%)
Aluminium	112.67	114.22	114.67	113.85	1.05	0.92
Carbon Non-Woven BIO	176.41	117.45	190.25	161.37	38.66	23.95
Carbon Woven BIO	455.08	437.36	455.97	449.47	10.5	2.34
Carbon Woven Epoxy	486.95	408.27	404.40	433.20	46.58	10.75
Flax Non-Woven BIO	42.893	42.836	45.455	43.728	1.49	3.42
Flax Woven BIO	95.365	86.806	83.583	88.585	6.09	6.87
Kevlar	338.97	373.72	336.17	349.62	20.92	5.98

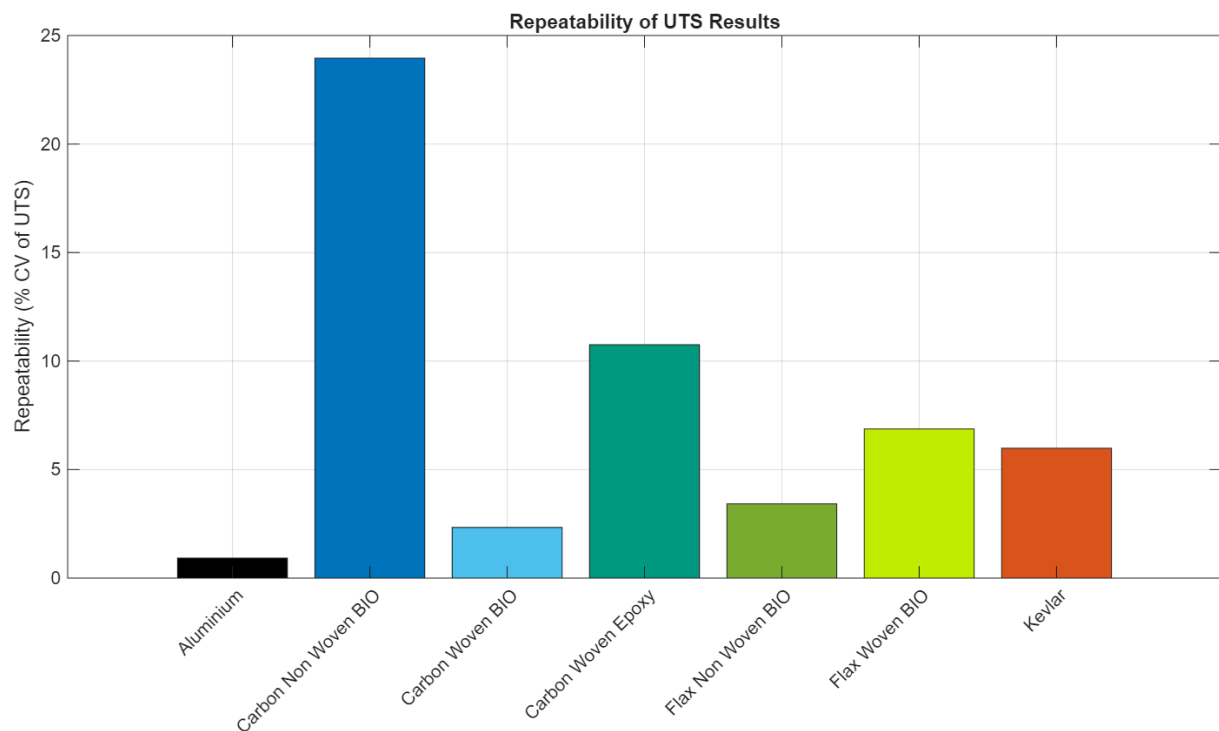


Figure 14 Repeatability of UTS results across all materials, highlighting greater variability in non-woven and natural-fibre systems.

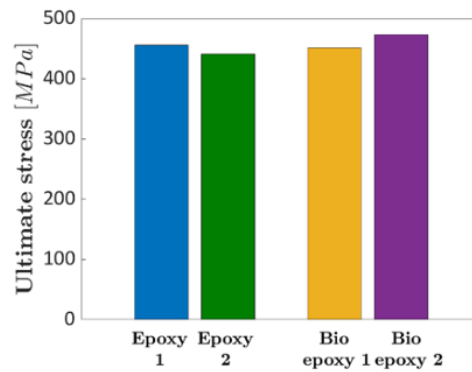


Figure 15 Comparison of epoxy and bio-epoxy tensile performance, showing similar repeatability and confirming minimal influence of resin type on mechanical consistency (Boursier Niutta, Ciardiello et al. 2023).

Natural fibre systems showed lower strength and moderate variability, while Kevlar exhibited intermediate repeatability ($\sim 5.98\%$), consistent with its more progressive failure behaviour. Figure 15 further shows that the epoxy and bio-resin woven carbon systems exhibited comparable repeatability, indicating that resin substitution had little influence on consistency when fibre architecture remained unchanged, in agreement with Boursier Niutta et al. (2023).

Overall, woven carbon systems combined high strength with the most reliable structural response, whereas non-woven and natural-fibre systems showed greater scatter due to fibre discontinuity, heterogeneity, and interface sensitivity.

5.4 Mass Efficiency and Performance Analysis

In addition to absolute mechanical properties, material performance was evaluated in relation to specimen mass, which is particularly important in automotive and motorsport applications where reducing weight improves efficiency, handling, and overall structural performance.

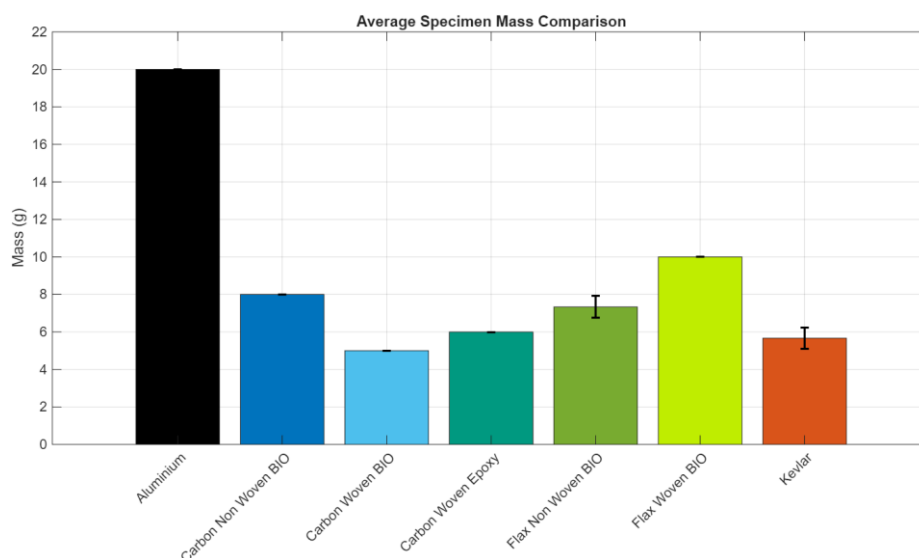


Figure 16 Average specimen mass before testing, showing that all composite specimens were substantially lighter than the aluminium baseline, supporting their potential for improved lightweighting and specific performance.

When tensile strength was normalised by specimen mass, carbon fibre composites showed the highest mass-normalised strength, with both carbon woven epoxy and carbon woven BIO clearly outperforming the other materials. This confirms that carbon fibre composites offer superior efficiency in load-bearing applications, combining high strength with low weight.

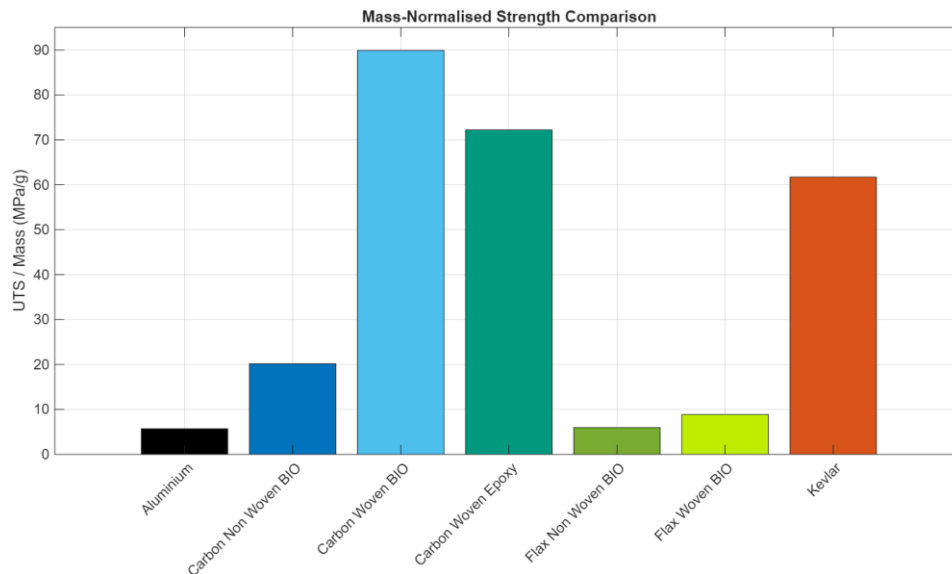


Figure 17 Mass-normalised tensile strength comparison, highlighting the superior strength-to-weight efficiency of carbon fibre composites.

Overall, the mass-efficiency results showed that carbon fibre composites delivered the strongest balance of low mass and high tensile strength, making them the most structurally efficient materials tested. The strong performance of both woven carbon systems also showed that improved sustainability can be achieved without a major mechanical penalty when fibre architecture is maintained. Kevlar provided a useful compromise between strength and deformation capacity, while flax composites were better suited to lower-load, sustainability-led applications.

5.5 Validation

Experimental results were validated against supplier reference values and literature, with interpretation adjusted to reflect the tested laminate architecture rather than fully longitudinal fibre loading. The testing plan specified woven laminates with plies arranged at 45° to each other, with longitudinal and transverse behaviour treated as upper and lower bounds. This $\pm 45^\circ$ orientation reduces direct fibre alignment with the loading axis, increasing the influence of matrix deformation, interfacial stress transfer, and shear-dominated load sharing, so the woven carbon specimens would be expected to fall below a purely longitudinal rule-of-mixtures prediction.

The expected stiffness range was defined using rule-of-mixtures upper and lower bounds, with the Voigt model taken as the isostrain upper limit and the Reuss model as the isostress lower limit (Kim et al., 2001).

$$E_c^{(u)} = E_m V_m + E_f V_f$$

Equation 1 Rule-of-mixtures upper bound for composite elastic modulus (isostrain condition), representing maximum stiffness for aligned, continuous reinforcement.

$$E_c^{(l)} = \frac{E_m E_f}{V_m E_f + V_f E_m}$$

Equation 2 Rule-of-mixtures lower bound for composite elastic modulus (isostress condition), assuming equal stress in fibre and matrix phases.

where E_c is composite modulus, E_m matrix modulus, E_f fibre modulus, and V_m and V_f are the matrix and fibre volume fractions.

Using these bounds, validation was strongest for the woven carbon systems, with both carbon woven epoxy and carbon woven bio-resin falling within the stiffness and tensile-strength ranges. Flax woven bio-resin and carbon non-woven bio-resin deviated further, although the overall ranking remained consistent. Aluminium matched the tensile-strength range more closely than stiffness, suggesting greater sensitivity of elastic response to specimen geometry and test configuration (Zhao et al., 2019). Kevlar also fell within the tensile-strength window but exceeded the selected stiffness range, which should be treated cautiously because published Kevlar composite properties are strongly influenced by resin system, laminate architecture, and specimen quality (Goud et al., 2022).

Table 4 Comparison of experimental values with theoretical bounds and supplier reference ranges used for validation.

Material	Stiffness Experimental (GPa)	Stiffness Reference (GPa)	UTS Experimental (MPa)	UTS Reference (MPa)
Carbon Woven Epoxy	65.97	65.1–72.59	433.2	145.4–637.9
Carbon Woven BIO	64.62	60–72.31	449.5	133.4–628.6
Flax Woven BIO	4.83	6–7	88.6	58–61
Carbon Non-Woven BIO	15.34	25–35	161.4	290–330
Flax Non-Woven BIO	2.89	4–6	43.72	37–44
Aluminium	32.34	68–72	113.9	110–130
Kevlar	33.33	18–30	349.6	300–450

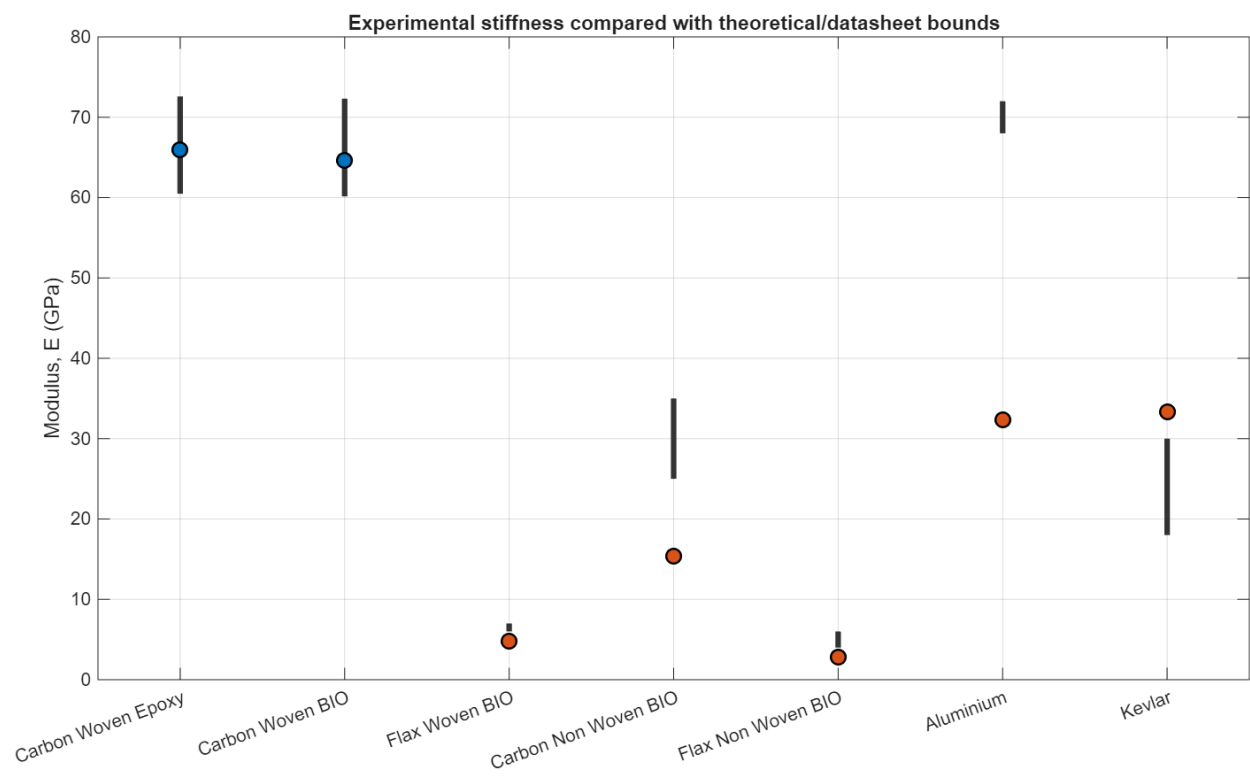


Figure 18 Experimental stiffness compared with theoretical, datasheet, and literature reference bounds. Agreement was strongest for the woven carbon laminates, while flax woven BIO, carbon non-woven BIO, aluminium, and Kevlar showed varying levels of deviation.

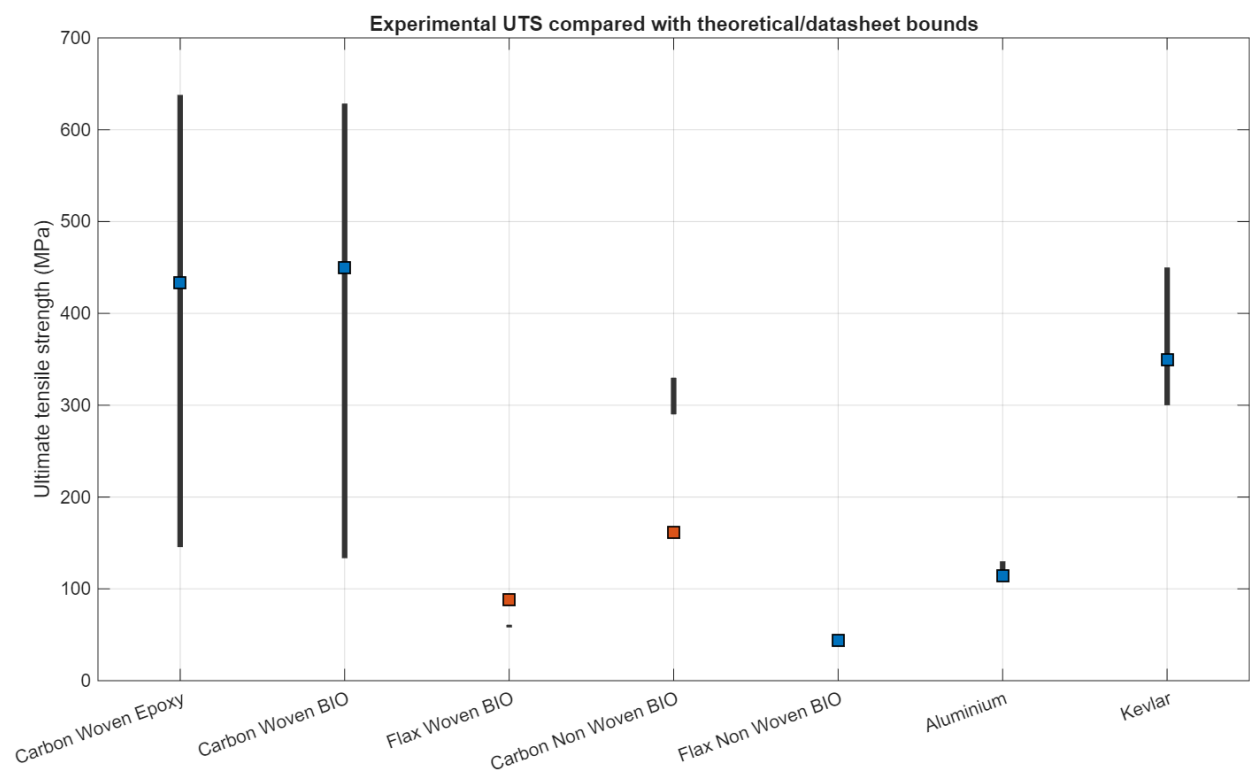


Figure 19 Experimental ultimate tensile strength compared with theoretical, datasheet, and literature reference bounds. Agreement was strongest for the woven carbon laminates, while flax-based and non-woven systems showed larger deviations from reference values.

The woven carbon laminates showed the closest agreement with the selected validation bounds, which is expected because continuous, well-aligned fibres provide efficient load transfer and allow rule-of-mixtures assumptions to be more closely satisfied. By contrast, the flax-based and non-woven materials, particularly carbon non-woven BIO, deviated further from the reference ranges because discontinuous or less ordered reinforcement reduces load transfer efficiency and increases reliance on the matrix. In the flax systems, this effect is compounded by fibre heterogeneity, moisture sensitivity, and weaker fibre–matrix adhesion, all of which reduce consistency and structural efficiency.

Aluminium matched the tensile-strength range more closely than stiffness because elastic modulus is more sensitive to specimen geometry, strain measurement, and boundary conditions than ultimate failure. Kevlar also aligned more closely with the tensile-strength range than with stiffness, reflecting its lower modulus and more compliant behaviour relative to carbon fibre systems.

Overall, the results support the observed material ranking even where exact agreement with reference values was not achieved, which is consistent with Zhao et al. (2020), who show that rule-of-mixtures predictions are better treated as idealised bounds than exact values when fibre architecture departs from the aligned case.

6 Recommendations for Material Use

Carbon woven composites are recommended for stiffness- and strength-critical automotive and motorsport components where minimum mass and maximum structural efficiency are required. The similar behaviour of woven carbon bio-resin and epoxy systems indicates that reduced environmental impact can be achieved without a significant loss in quasi-static performance when fibre architecture is maintained. However, bio-resin systems may exhibit lower thermal resistance, increased moisture sensitivity, and greater variability than conventional epoxies, meaning their use is better suited to controlled environments or applications where long-term durability requirements are less severe.

6.1 Kevlar Composites

Kevlar composites are recommended where toughness, damage tolerance, and progressive failure are more important than maximum stiffness. Compared with the carbon systems, Kevlar showed lower stiffness and strength but greater strain-to-failure, making it better suited to protective or impact-tolerant applications than primary stiffness-critical members.

6.2 Flax Fibre Composites

Flax fibre composites are recommended only for lower-load, non-critical, or sustainability-led applications where reduced embodied impact is prioritised over structural performance (Elfaleh et al., 2023). Although woven flax performed better than non-woven flax, both flax systems showed lower stiffness and strength than the synthetic-fibre composites. Their main value therefore lies in secondary structures, trim, and non-safety-critical bodywork rather than primary structural use.



Figure 20 Bcomp panel made from sustainable materials with integrated reinforcement to improve stiffness and strength (Bcomp).

6.3 Future Research and Development



Figure 21 Bcomp natural-fibre composite applications in lightweight motorsport bodywork (Bcomp).

Hybrid composite studies also suggest that combining natural and carbon-based reinforcement can improve mechanical performance while retaining part of the sustainability benefit. Overall, material selection should remain application-specific: carbon fibre is preferred for primary structural efficiency, Kevlar for protective or energy-absorbing roles, and flax composites for lower-load components where environmental benefit is prioritised.

Future work should focus on hybrid carbon–natural fibre laminates, improved end-of-life recovery, and durability testing under fatigue, impact, moisture ageing, and thermal cycling. This is particularly important for flax-based and bio-resin systems, where repeatability, environmental resistance, and long-term suitability for demanding motorsport applications remain key limitations.

7 Conclusion

This study showed that composite selection for automotive and motorsport applications cannot be based on performance alone. Carbon fibre composites delivered the highest tensile strength, stiffness, and mass efficiency, making them the most suitable for stiffness- and strength-critical structures.

The similar response of woven carbon epoxy and woven carbon bio-resin showed that lower-impact resin substitution can be achieved without a significant quasi-static performance penalty when fibre architecture is maintained. Kevlar provided a useful compromise through greater strain-to-failure and more progressive failure, while flax composites were restricted by lower and less consistent structural performance.

Overall, the results confirm that material choice should be function-led: carbon fibre for primary structural efficiency, Kevlar for protective or energy-absorbing roles, and flax-based composites for lower-load components where environmental benefit can justifiably outweigh reduced mechanical capability.

8 References

- Bcomp (2026) *Bcomp – Sustainable lightweighting to decarbonise the world*. Available at: <https://www.bcomp.com/> (Accessed: 17 April 2026).
- BHATT, A.T., GOHIL, P.P. and CHAUDHARY, V. (2018) *Primary manufacturing processes for fibre reinforced composites: history, development and future research trends*. IOP Publishing.
- BOURSIER NIUTTA, C., CIARDIELLO, R., TRIDELLO, A. and PAOLINO, D.S. (2023) *Epoxy and bio-based epoxy carbon fibre twill composites: comparison of the quasi-static properties*. MDPI AG.
- BUDIMAN, B.A., TRIAWAN, F., ADZIMAN, F. and NURPRASETIO, I.P. (2016) *Modelling of stress transfer behaviour in fibre-matrix composite under axial and transverse loadings*. Informa UK Limited.
- CHARLET, K., EVE, S., JERNOT, J.P., GOMINA, M. and BREARD, J. (2009) *Tensile deformation of a flax fibre*. Elsevier BV.
- CHANDEL, S., et al. (2025) *Life cycle assessment of bio composites: environmental impacts and sustainability perspectives*.
- CHEN, A.Y., BAEHR, S., TURNER, A., ZHANG, Z. and GU, G.X. (2021) *Carbon-fibre reinforced polymer composites: a comparison of manufacturing methods on mechanical properties*. Elsevier BV.
- CZERWINSKI, F. (2021) *Current trends in automotive lightweighting strategies and materials*. MDPI AG.
- Department for Transport (2021) *Decarbonising transport: a better, greener Britain*. London: Department for Transport. Available at: <https://assets.publishing.service.gov.uk/media/610d63ffe90e0706d92fa282/decarbonising-transport-a-better-greener-britain.pdf> (Accessed: 16 April 2026).
- DHAKAL, H.N. and SAIN, M. (2019) *Enhancement of mechanical properties of flax-epoxy composite with carbon fibre hybridisation for lightweight applications*. MDPI AG.
- Easy Composites Ltd *Easy Composites*. Available at: <https://www.easycomposites.co.uk/> (Accessed: 17 April 2026).
- Easy Composites Ltd (2024) *Carbon Fibre Non-Woven Mat: Technical Datasheet*. Version 1.0 revised 11 October 2024. Stoke-on-Trent: Easy Composites Ltd.
- Easy Composites Ltd (2024) *IB2 Epoxy Infusion Bio Resin: Technical Datasheet*. Stoke-on-Trent: Easy Composites Ltd.
- Easy Composites Ltd (2024) *IN2 Infusion Resin: Technical Datasheet*. 28 March 2024. Stoke-on-Trent: Easy Composites Ltd.
- EcoTechnilin (2023) *FibriMat F300: Technical Data Sheet*. Updated 17 January 2023. Valliquerville: EcoTechnilin.
- EcoTechnilin (2023) *FlaxDry BL200: Technical Data Sheet*. Updated 17 January 2023. Valliquerville: EcoTechnilin.
- ELFALEH, I., ABBASSI, F., HABIBI, M., AHMAD, F., GUEDRI, M., NASRI, M. and GARNIER, C. (2023) *A comprehensive review of natural fibers and their composites: an eco-friendly alternative to conventional materials*. Elsevier BV.
- European Commission (2023) *End-of-life vehicles*. Available at: <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=legissum:l21225> (Accessed: 16 April 2026).

European Parliament and Council (2000) *Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles*. Available at: <https://eur-lex.europa.eu/eli/dir/2000/53/2023-03-30/eng> (Accessed: 16 April 2026).

FIA (2024) *FIA Sustainability and D&I Report 2023*. Available at: <https://sustainabilityreport.fia.com/wp-content/uploads/2024/07/FIA-Sustainability-and-D-I-Report-2023.pdf> (Accessed: 16 April 2026).

GIORGINI, L., BENELLI, T., BRANCOLINI, G. and MAZZOCCHETTI, L. (2020) *Recycling of carbon fibre reinforced composite waste to close their life cycle in a cradle-to-cradle approach*. Elsevier BV.

HUANG, H., LIU, W. and LIU, Z. (2020) *An additive manufacturing-based approach for carbon fibre reinforced polymer recycling*. Elsevier BV.

JIANG, M., SHU, Q., YUAN, G., WU, J. and WANG, F., 2024. *Compressive testing and numerical modelling of concrete-filled aluminium tubular stub columns after exposure to high temperatures*. Elsevier BV.

KUMAR, J., PANCHORE, V., RAJAK, D.K. and JOSHI, T. (2025) *Dynamic properties and vibration response of polymer matrix composites: mechanisms, influences, and applications in engineering*. Wiley.

LICHTAROWICZ, M., 18th March, 2013-last update, Composites. Available: <https://www.essentialchemicalindustry.org/materials-and-applications/composites.html> [Apr 22, 2026].

McLaren Racing (2023) *McLaren Racing pioneers use of sustainable materials with innovative recycled carbon fibre trial*. Available at: <https://www.mclaren.com/racing/formula-1/2023/mclaren-racing-pioneers-use-of-sustainable-materials-with-innovative-recycled-carbon-fibre-trial/> (Accessed: 21 April 2026).

MAHBOOB, Z., EL SAWI, I., ZDERO, R., FAWAZ, Z. and BOUGHERARA, H. (2016) *Tensile and compressive damaged response in flax fibre reinforced epoxy composites*. Elsevier BV.

NAGARAJ GOUD, B., SURA, S., ARAVIND, P., JAWAHAR LAL, B., SANSKRUTI, K. and PAVAN, C.H., 2022. *An experimental study on mechanical properties of Kevlar composite for aircraft structural applications*. Elsevier BV.

PAKDEL, E., KASHI, S., VARLEY, R. and WANG, X. (2021) 'Recent progress in recycling carbon fibre reinforced composites and dry carbon fibre wastes', *Resources, Conservation and Recycling*, 166, 105340.

Pyrofil (2013) *Pyrofil / Gafil carbon fibre data sheet*. November.

SAPIAI, N., JUMAHAT, A. and HAKIM, R.N. (2014) *Advances in Environmental Biology*.

SPASENOVIĆ, J. and BLAGOJEVIĆ, I. (2021) *Composite materials in automotive industry: a review*. Centre for Evaluation in Education and Science (CEON/CEES).

UK Government (2003) *The End-of-Life Vehicles Regulations 2003*. Available at: <https://www.legislation.gov.uk/ukxi/2003/2635/contents/made> (Accessed: 16 April 2026).

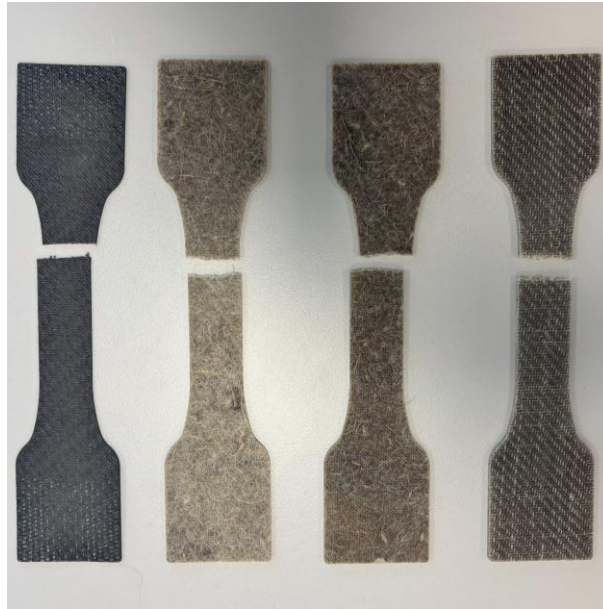
ZHAO, X., LI, H., CHEN, T., CAO, B. and LI, X. (2019) *Mechanical properties of aluminium alloys under low-cycle fatigue loading*. MDPI AG.

ZHAO, S., ZHAO, Z., YANG, Z., KE, L., KITIPORNCHAI, S. and YANG, J., 2020. *Functionally graded graphene reinforced composite structures: A review*. Elsevier BV.

9 Appendices

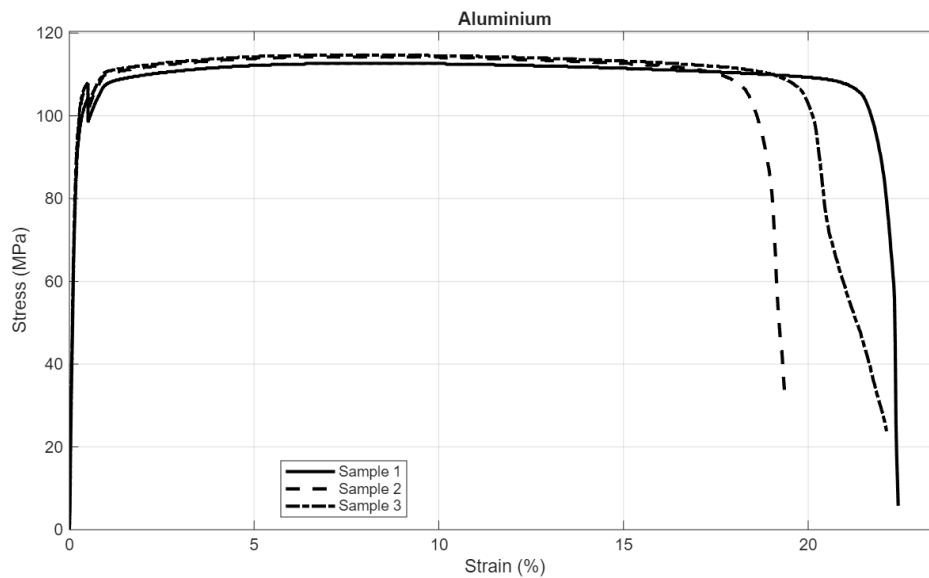
9.1 Appendix A – Failure Modes of Tested Specimens

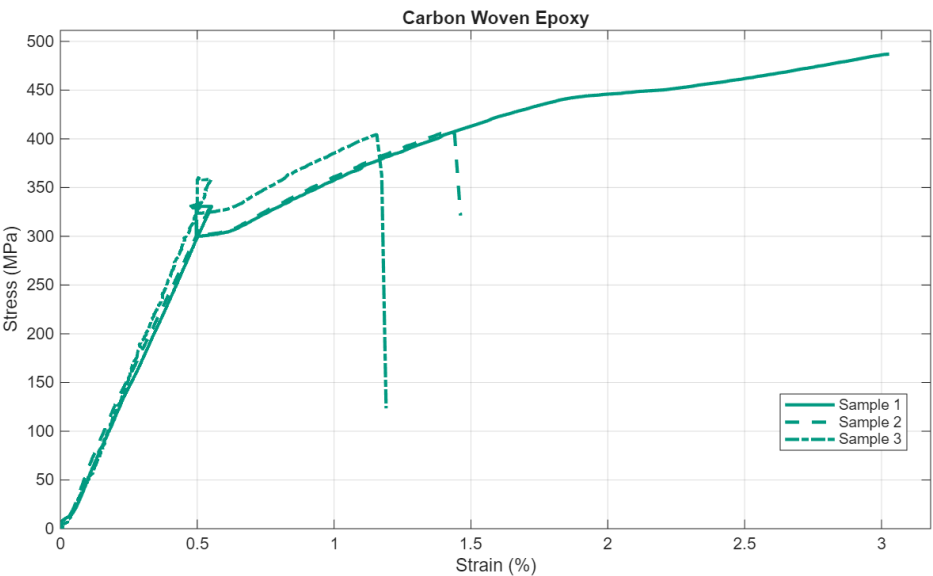
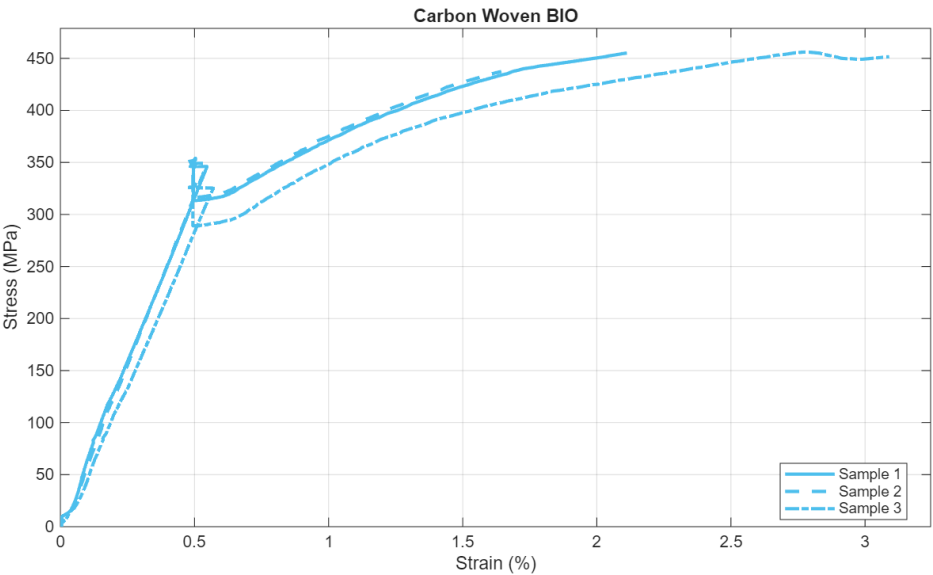
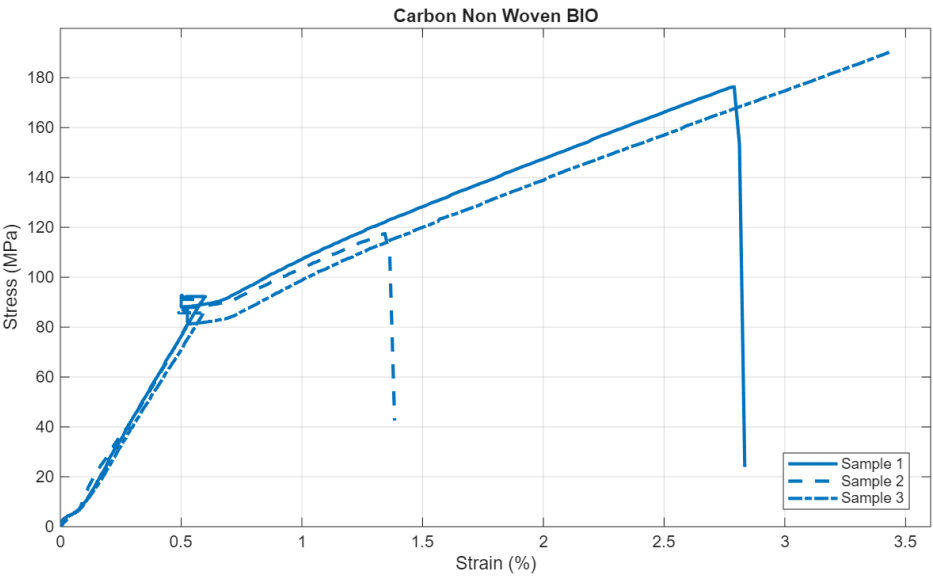
Failure modes of carbon woven epoxy, woven flax BIO, and non-woven flax specimens after tensile testing.

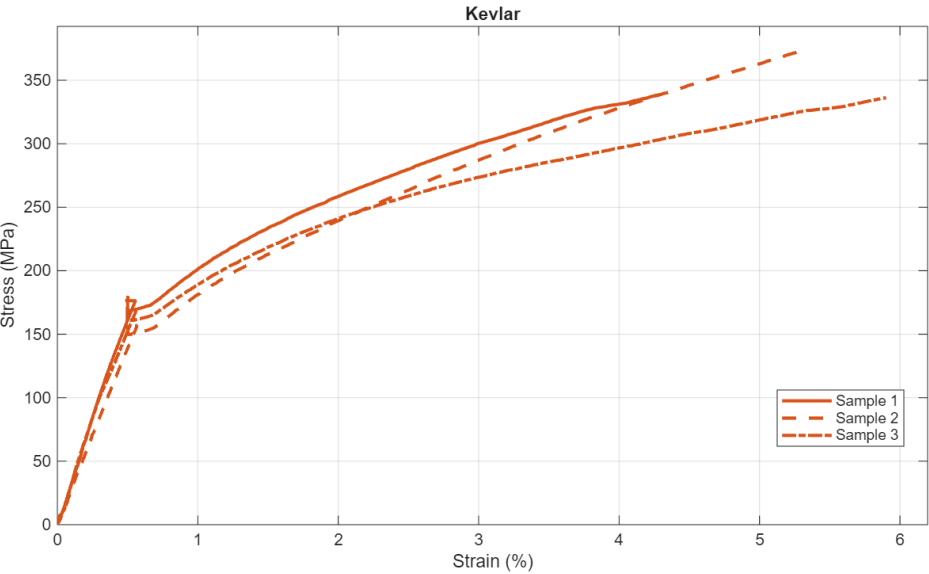
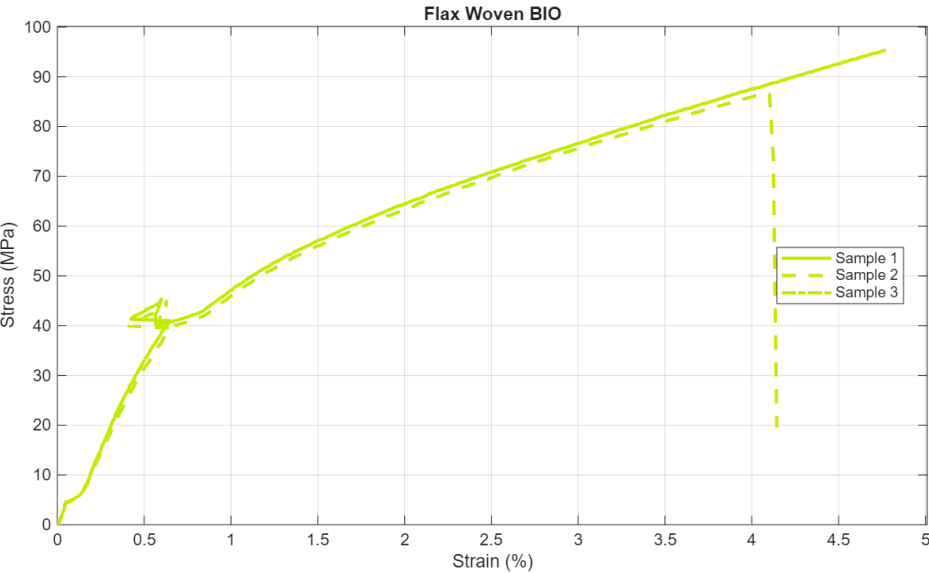
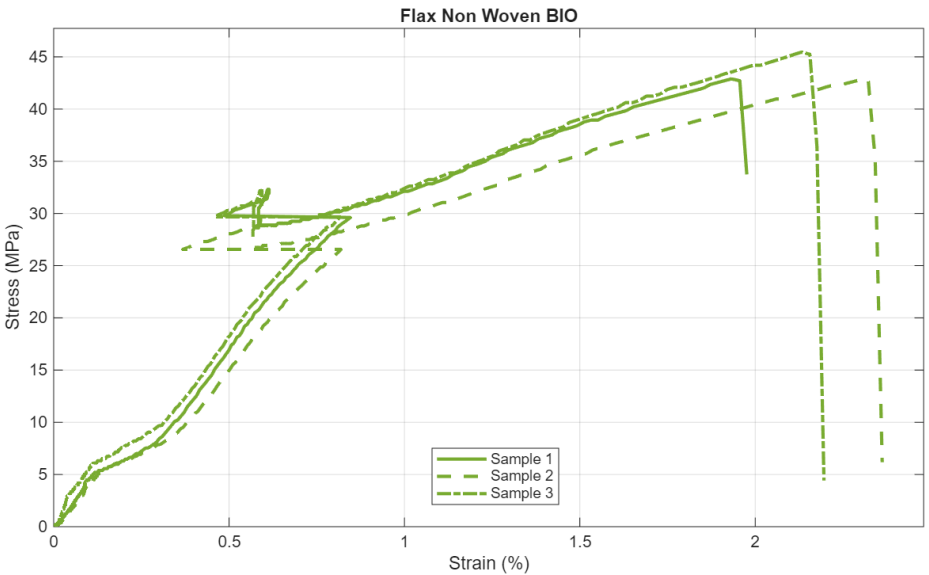


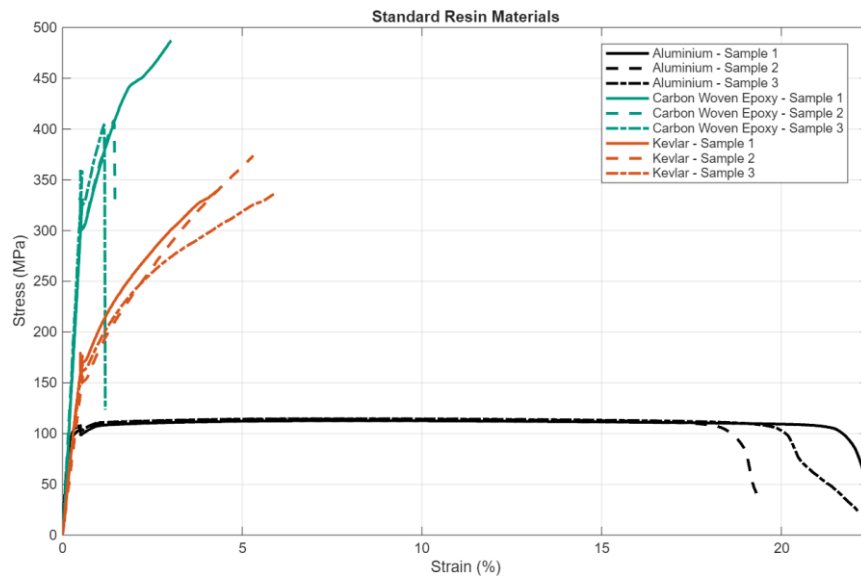
9.2 Appendix B - Stress Strain Curves

This appendix provides the full specimen-level stress–strain curves used to assess stiffness, ultimate tensile strength, failure strain, and repeatability across the tested materials.









9.3 Appendix C - Performance Comparisons

These plots reinforce the main trends discussed in Section 5. Carbon fibre composites occupy the high-strength, low-ductility region and provide the best strength-to-mass performance. Aluminium shows lower strength but greater ductility, while Kevlar offers an intermediate balance of strength and deformation capacity. Flax-based composites remain the least structurally efficient materials tested, but their lower embodied impact supports their use in sustainability-led, non-critical applications.

