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Materials Testing and Sustainability of Composites for Motorsport & Automotive Industries

Automotive Materials & Sustainability - ACHA6012

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1. Introduction

Composite materials are increasingly important in automotive and motorsport industries due to their high strength-to-weight ratios and ability to be tailored for specific performance requirements (Singh et al., 2023). Compared to traditional materials such as aluminium, composites including carbon fibre, Kevlar and natural fibre-reinforced polymers offer significant weight reduction while maintaining structural integrity. This contributes to improved fuel efficiency and reduced emissions, making material selection critical in modern engineering design (Hasan et al., 2024). This is further driven by increasing pressure from legislation and sustainability targets aimed at reducing environmental impact within engineering industries (European Commission, 2020).

Despite these advantages, advanced composites present sustainability challenges. The production of synthetic fibres, particularly carbon fibre and Kevlar, is energy intensive and associated with high carbon emissions, while recyclability remains limited. In contrast, natural fibre composites such as flax offer a more sustainable option due to their renewable origin, although with reduced mechanical performance.

This report evaluates the mechanical performance and sustainability of aluminium, carbon fibre, flax and Kevlar composites. Tensile testing was conducted using a universal testing machine, and results were analysed and compared with literature to assess material suitability for automotive and motorsport applications.

2. Literature Review

2.1 Overview of Composite Materials

Composite materials are widely used in automotive applications due to their high strength-to-weight ratio and design flexibility (Singh et al., 2023) . Typically consisting of reinforcing fibres within a matrix, composites allow improved load transfer and enhanced mechanical performance compared to traditional materials. This makes them particularly suitable for performance-critical applications where weight reduction is essential for improving efficiency and dynamic performance.

Unlike traditional metallic materials such as aluminium, which exhibit isotropic behaviour, fibre-reinforced composites are generally anisotropic. This means their mechanical properties vary depending on the direction of loading, making fibre orientation a key factor in determining tensile strength, stiffness and failure behaviour. As a result, the internal structure of composites plays a critical role in their overall performance.

2.2 Aluminium as a Conventional Engineering Material

Aluminium is widely used in the automotive industry due to its low density, corrosion resistance and ease of manufacturing. As an isotropic metal, it exhibits predictable mechanical behaviour, including ductility and the ability to undergo plastic deformation before failure, making it suitable for energy-absorbing applications such as crash structures and chassis components. It is commonly used in body panels, engine parts and lightweight vehicle frames.

However, compared to composite materials, aluminium has a lower strength-to-weight ratio, limiting its use in high-performance applications. Despite this, it remains favourable due to its high recyclability and established processing methods.

2.3 Carbon Fibre Reinforced Polymers (CFRP)

Carbon fibre reinforced polymers (CFRP) are widely used in automotive and aerospace applications due to their high strength-to-weight ratio and stiffness (Singh et al., 2023). These properties arise from the fibre's crystalline structure, enabling efficient load transfer when combined with a polymer matrix. Mechanical behaviour is influenced by fibre orientation, with woven fibres providing more uniform strength compared to non-woven forms. CFRP is commonly used in Formula 1 and high-performance vehicles; however, its production is energy intensive, and recyclability remains limited, raising sustainability concerns (Hasan et al., 2024).

2.4 Natural Fibre Composites (Flax)

Natural fibre composites, such as flax fibre reinforced polymers, are increasingly used as sustainable alternatives to synthetic composites. Flax fibres are renewable, require less energy to produce, and offer improved biodegradability and end-of-life disposal. However, their mechanical performance is generally lower due to variability in fibre properties, weaker fibre–matrix bonding and reduced stiffness. Fibre orientation remains important, with woven flax composites providing better strength than non-woven forms.

These materials are commonly used in automotive interiors and eco-focused designs, where sustainability is prioritised over maximum structural performance.

2.5 Kevlar (Aramid Fibre Composites)

Kevlar, an aramid fibre, is known for its high tensile strength, low density and excellent impact resistance. Its molecular structure allows it to absorb significant energy under load, making it less brittle than carbon fibre and well suited to applications requiring toughness and durability. In automotive and motorsport applications, Kevlar is commonly used in impact-resistant components, crash structures and hybrid composite laminates to improve damage tolerance.

However, despite its mechanical advantages, Kevlar presents sustainability challenges, as its production is energy intensive, and recycling is difficult due to its complex chemical structure.

2.6 Manufacturing Processes of Composite Materials

The manufacturing process plays a critical role in determining the mechanical properties and overall performance of composite materials. Techniques such as prepreg lay-up and resin transfer moulding (RTM) influence both material quality and cost efficiency (Rajak et al., 2021).

Prepreg lay-up is commonly used in high-performance applications, where carbon fibre sheets pre-impregnated with resin are carefully arranged and cured under controlled temperature and pressure. This allows precise control of fibre orientation and reduces defects, producing high-strength components such as Formula 1 chassis structures.

RTM involves injecting resin into a closed mould containing dry fibre reinforcement, enabling faster production rates and improved repeatability, making it suitable for automotive manufacturing. In contrast, hand lay-up is more cost-effective but provides less control over fibre alignment, often resulting in reduced mechanical performance.

Overall, manufacturing processes directly influence fibre alignment, bonding and defect formation, which determine strength, stiffness and failure behaviour.

2.7 Summary of Material Performance and Applications

The literature highlights a clear distinction between traditional and composite materials in terms of mechanical performance and application. Carbon fibre composites provide the highest strength-to-weight ratio and are therefore dominant in high-performance motorsport applications. Kevlar offers superior impact resistance and is used in safety-critical components, while aluminium provides a reliable and recyclable option for structural applications in the automotive industry.

In contrast, natural fibre composites such as flax offer a more sustainable alternative, although with reduced mechanical performance. This demonstrates a clear trade-off between performance and environmental impact, which must be carefully considered when selecting materials for future automotive and motorsport applications.

3. Sustainability Analysis

3.1 Lifecycle Environmental Impact

The sustainability of materials used in automotive and motorsport applications must be considered across their full lifecycle, including raw material extraction, manufacturing, use and end-of-life disposal. Carbon fibre and Kevlar composites have high environmental impacts due to energy-intensive production processes (Hasan et al., 2024), resulting in significant carbon emissions. Aluminium production is also energy intensive; however, its ability to be efficiently recycled reduces its overall lifecycle impact.

In contrast, natural fibre composites such as flax offer a lower environmental footprint. As a renewable resource requiring less energy to process, flax contributes to reduced emissions during production, making it a more sustainable alternative in appropriate applications.

3.2 Manufacturing Processes and Carbon Footprint

Manufacturing processes play a key role in determining sustainability. High-performance composite production methods, such as prepreg lay-up and autoclave curing, require significant energy input, particularly in motorsport applications. In comparison, processes such as resin transfer moulding (RTM) improve efficiency and reduce waste, making them more suitable for large-scale automotive production.

Natural fibre composites generally require less energy during manufacturing, further reducing their environmental impact. However, achieving consistent quality remains a challenge when compared to synthetic composites.

3.3 Recyclability and End-of-Life Considerations

Recyclability is a major limitation of composite materials. Carbon fibre and Kevlar composites typically use thermoset resins, which cannot be easily reprocessed, leading to disposal challenges. In contrast, aluminium is highly recyclable and retains its properties through repeated recycling, making it a more sustainable option.

Flax-based composites offer improved end-of-life potential due to their natural origin, although full biodegradability is often limited by the polymer matrix. This highlights the need for further development of recyclable composite systems.

3.3 Performance vs Sustainability Trade-Off

While composites improve fuel efficiency through weight reduction, their lifecycle environmental impact remains a significant concern (Singh et al., 2023; Hasan et al., 2024). Carbon fibre provides superior mechanical performance but at a high environmental cost. In contrast, flax composites offer improved sustainability but reduced strength and durability.

This trade-off demonstrates that material selection must balance performance requirements with environmental impact, particularly as sustainability becomes an increasingly important factor in engineering design.

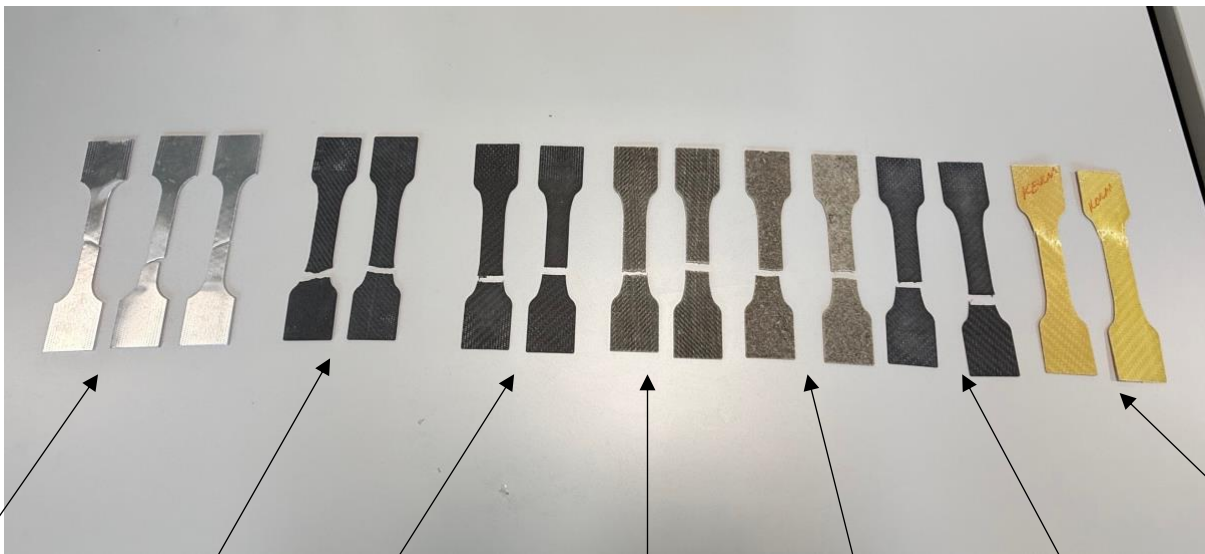
3.4 Legislation and Future Developments

Increasing environmental regulations and industry initiatives are driving the development of more sustainable materials. Both the automotive and motorsport industries are under pressure to reduce emissions and improve recyclability, encouraging the adoption of bio-based composites and recyclable materials.

Future developments are likely to focus on thermoplastic composites, improved recycling methods and hybrid materials, which aim to balance performance with sustainability.

4 Experimental Testing

Tensile testing was conducted in accordance with the laboratory testing plan using a Denison universal testing machine. Two tests were performed for each material, and the second test was selected for detailed analysis. To improve reliability, results were also compared with the wider class dataset, consisting of multiple test results per material. Composite samples were tested with fibres oriented at 45°, influencing the observed deformation behaviour.



Aluminium	Carbon Non-woven BIO	Carbon Woven BIO	Carbon Woven Epoxy	Flax Non-woven BIO	Flax Woven BIO	Kevlar
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Figure 1 – Display of testing samples after test conducted.

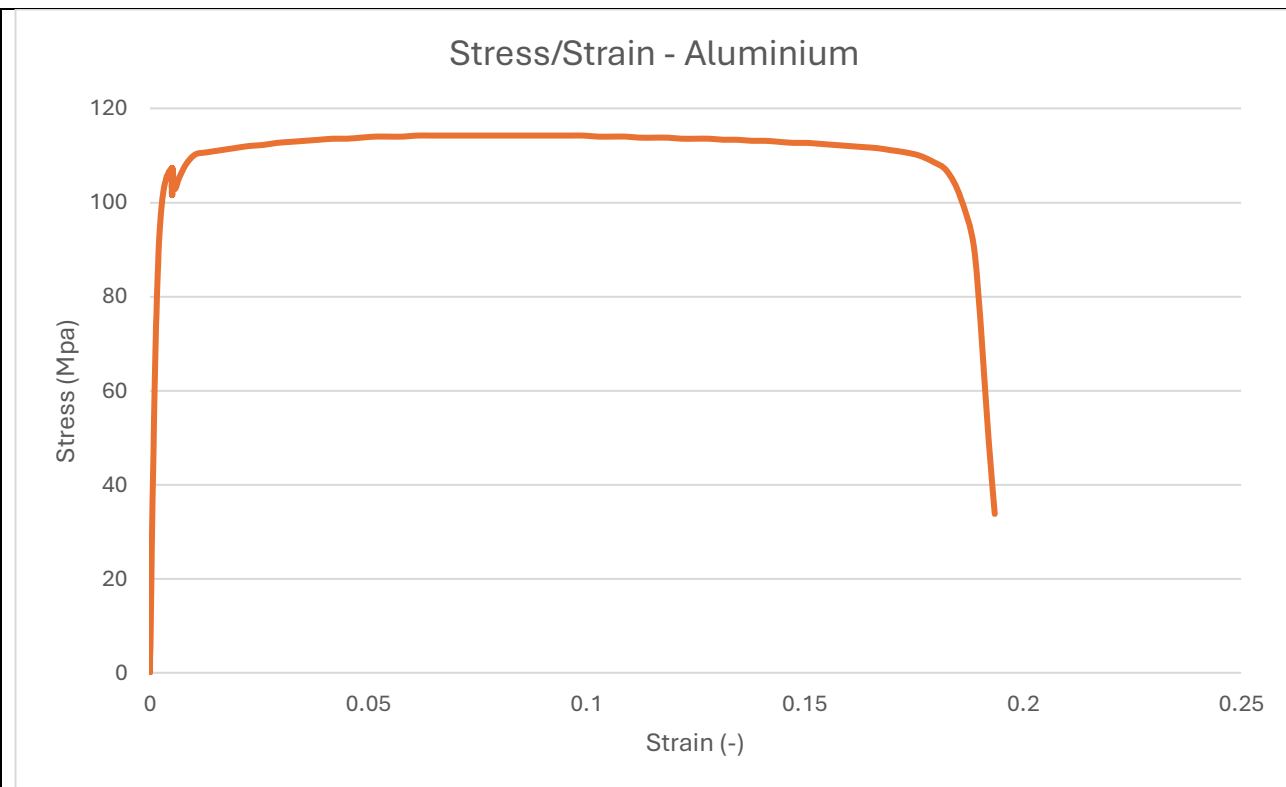


Figure 2:
Stress–
strain
curve for
Aluminium

Figure 2 shows the stress–strain behaviour of the aluminium sample, exhibiting a typical ductile response. The curve is characterised by an initial linear elastic region followed by yielding and an extended plastic deformation region. This behaviour indicates high ductility, as the material undergoes significant plastic deformation before fracture. A relatively constant stress level is observed after yielding, indicating strain hardening, before a sharp reduction in stress occurs due to necking and eventual fracture. The maximum stress achieved is approximately 110–120 MPa, suggesting the use of a relatively low-strength or annealed aluminium alloy.

A small irregular region is observed immediately after yielding, which may be associated with localised yielding behaviour similar to the yield point phenomenon described by Callister and Rethwisch (2019). This behaviour is linked to the initiation of plastic deformation and the movement of dislocations within the material, resulting in slight fluctuations in stress before stable plastic flow is established.

Further, as shown in Figure 2, the initial region of the stress–strain curve is approximately linear, indicating elastic behaviour. In this region, stress is directly proportional to strain and follows Hooke’s Law ($\sigma=E\varepsilon$), where E represents the Young’s modulus of the material. This relationship is characteristic of metallic materials under low levels of applied stress (Callister and Rethwisch, 2019). Beyond this linear region, the material begins to yield and no longer obeys Hooke’s Law.

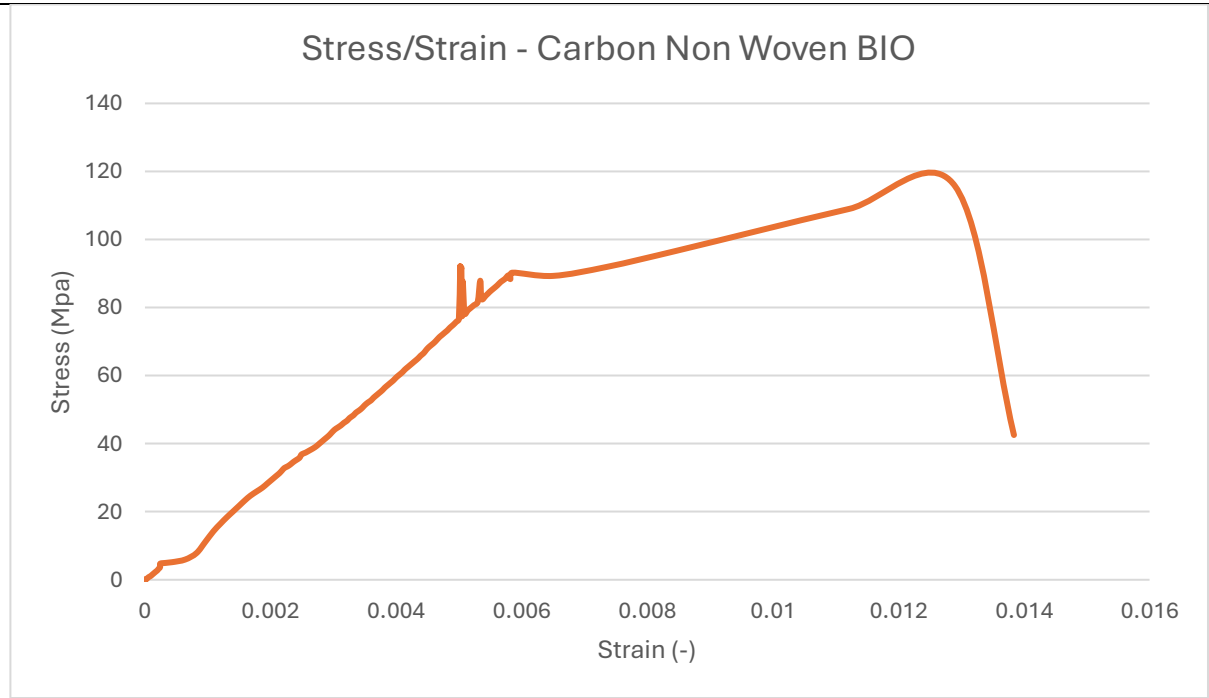


Figure 3:
Stress–
strain
curve for
carbon
non-
woven
BIO
composite

Figure 3 above illustrates the stress–strain curve for the carbon non-woven bio composite. The material demonstrates a gradual increase in stress with increasing strain, with a noticeably lower stiffness compared to woven carbon composites. The absence of a clearly defined linear elastic region indicates matrix-dominated behaviour, resulting from the random fibre orientation. Fluctuations in the mid-region of the curve suggest progressive fibre breakage and load redistribution. The composite exhibits a pseudo-ductile response, reaching a maximum stress of approximately 120 MPa prior to failure.

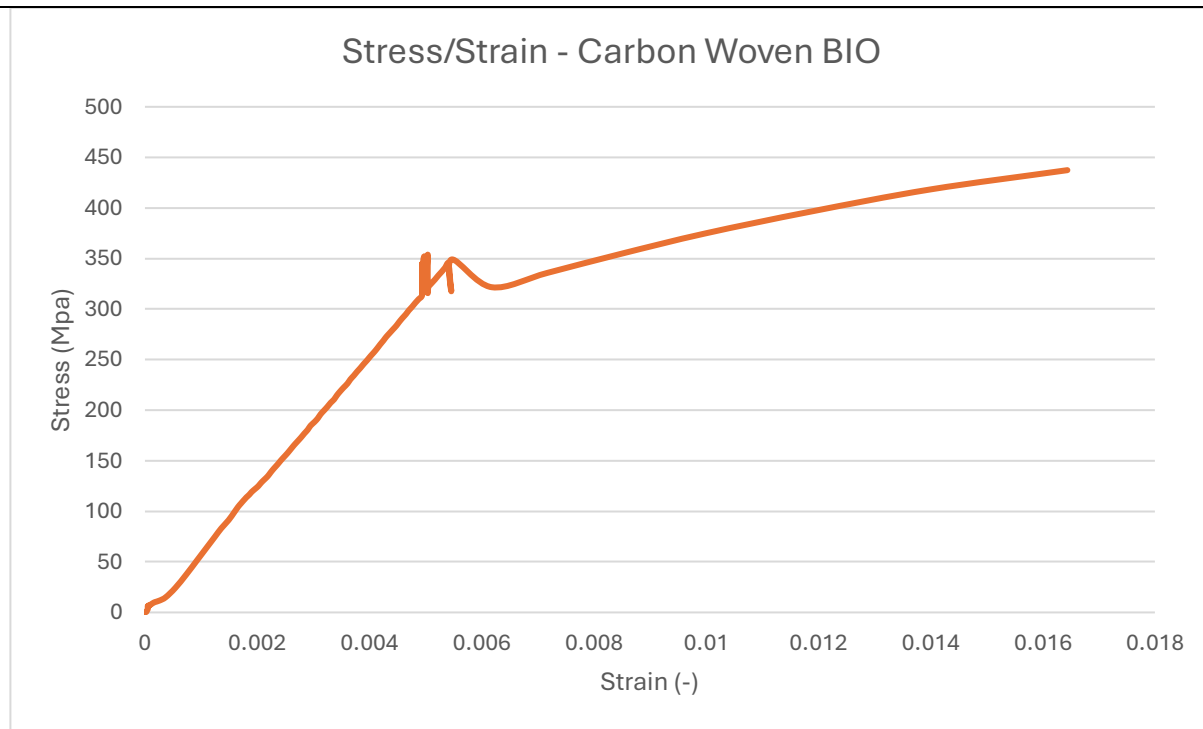


Figure 4:
Stress–
strain
curve for
carbon
woven
BIO
composite

Figure 4 above presents the stress–strain response of the carbon woven bio-resin composite. Compared to the non-woven material, the curve shows a steeper initial slope, indicating increased stiffness and improved load transfer due to fibre alignment. The material demonstrates a gradual increase in stress rather than purely brittle behaviour, which can be attributed to the influence of the bio-resin matrix and the 45° fibre orientation, introducing shear deformation. This results in a slightly reduced performance compared to more optimised composite configurations.

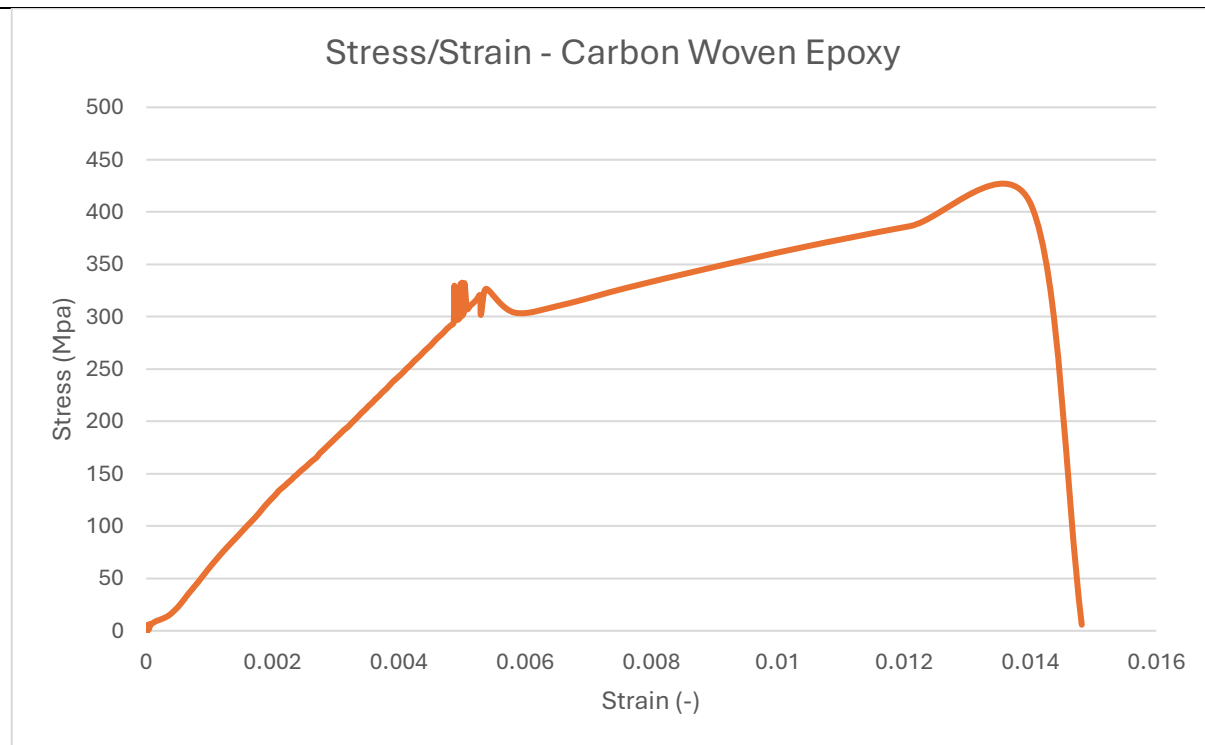


Figure 5:
Stress–
strain
curve for
carbon
woven
epoxy
composite

Figure 5 above shows the stress–strain behaviour of the carbon woven epoxy composite, which exhibits the highest mechanical performance among the tested materials. The curve displays a steep initial slope, indicating high stiffness, followed by a steady increase in stress up to a peak of approximately 420–440 MPa before sudden failure. Compared to the bio-resin equivalent, the epoxy matrix provides stronger fibre-matrix bonding and more efficient load transfer, resulting in higher overall tensile strength. Minor irregularities observed in the curve are likely due to localised fibre fracture or interfacial effects during loading.

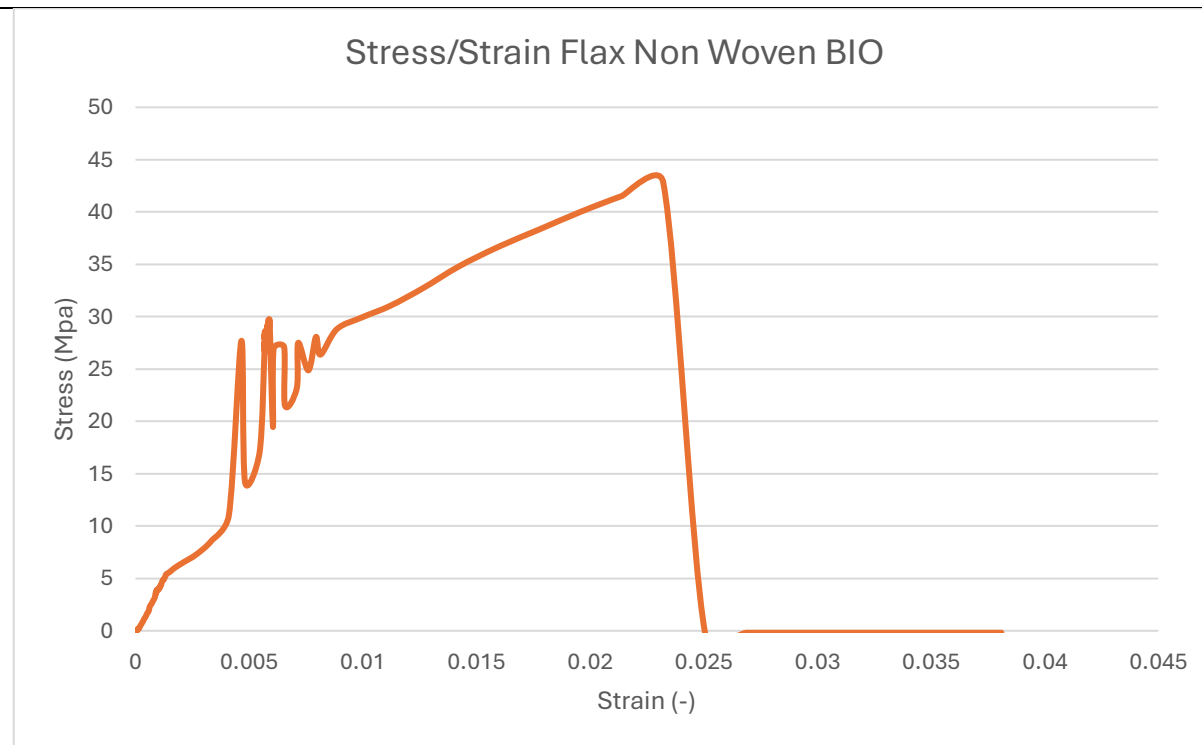


Figure 6:
Stress–
strain
curve for
flax non-
woven
BIO
composite

Figure 6 above illustrates the stress–strain response of the flax non-woven bio composite, which exhibits the lowest mechanical performance among the tested materials. The curve shows a low initial slope, indicating poor stiffness, along with significant fluctuations during early loading. These variations can be attributed to fibre pull-out, weak fibre-matrix bonding and the inherent variability of natural fibres. The material demonstrates progressive failure behaviour, with a maximum stress of approximately 40–45 MPa.

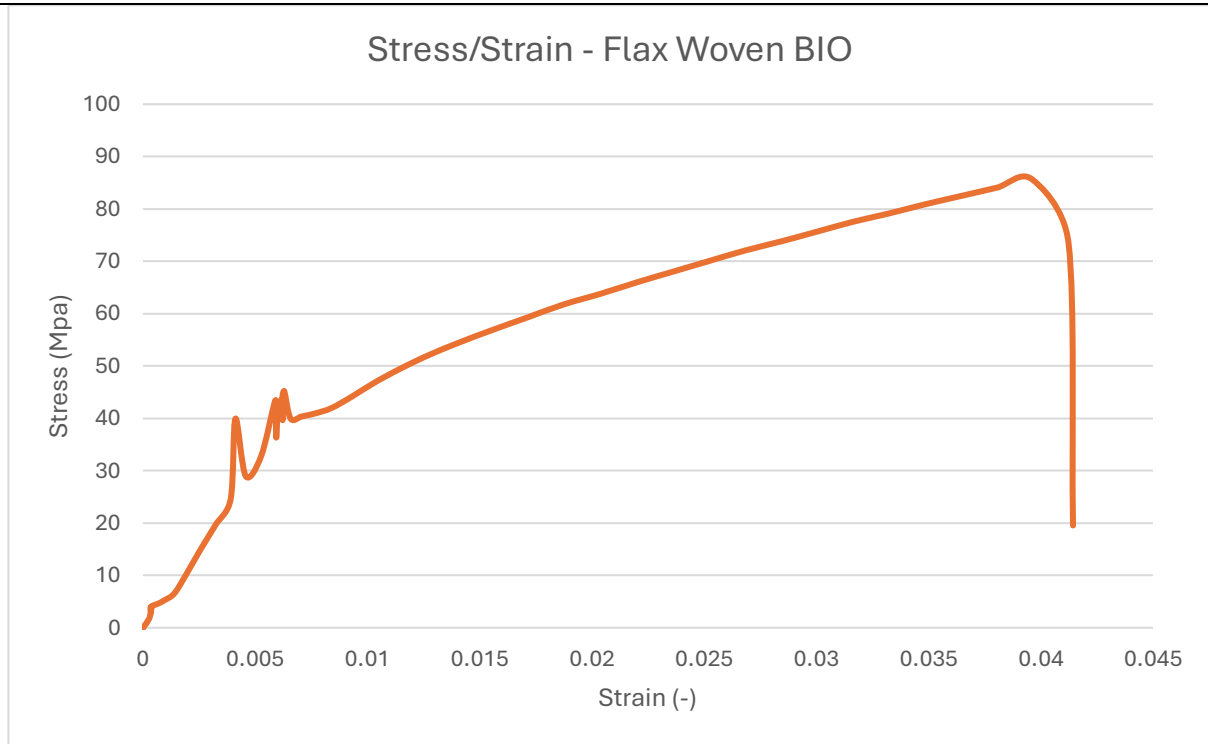
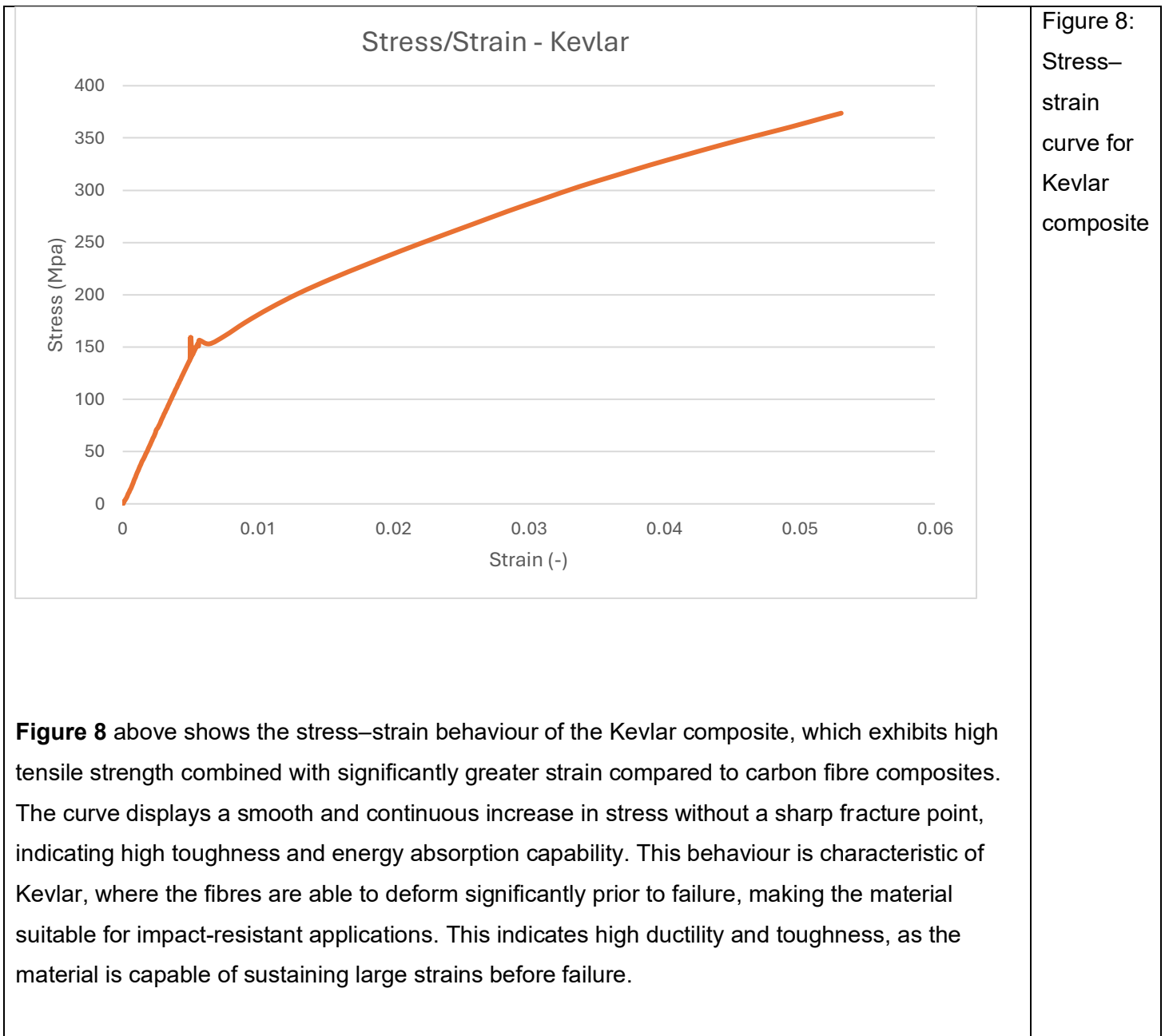


Figure 7:
Stress–
strain
curve for
flax
woven
BIO
composite

Figure 7 above presents the stress–strain behaviour of the flax woven bio composite. Compared to the non-woven flax material, the curve is smoother and exhibits fewer fluctuations, indicating improved load transfer due to better fibre alignment within the woven structure. The material reaches a higher maximum stress of approximately 85–90 MPa, demonstrating improved mechanical performance. However, it still exhibits lower strength and more gradual deformation compared to synthetic composites.

In contrast to aluminium at the start, the composite materials do not exhibit a clearly defined linear elastic region, and therefore Hooke’s Law is only valid over a limited strain range.



As shown across **Figures 2–8**, significant differences in mechanical behaviour are observed between the tested materials. Unlike the aluminium sample, which exhibits behaviour similar to the yield point phenomenon described by Callister and Rethwisch (2019), the composite materials do not display a distinct yielding region. Instead, the minor fluctuations in the stress–strain curves are attributed to progressive fibre failure, matrix cracking and interfacial debonding, which are well-established damage mechanisms in fibre-reinforced composites (Hull and Clyne, 1996; AZoM, 2023).

Carbon fibre composites, particularly the woven epoxy variant, exhibit the highest strength and stiffness, while natural fibre composites such as flax demonstrate lower strength but increased variability and deformation. Kevlar provides a balance between strength and high strain capacity, indicating superior toughness. Aluminium displays a ductile response with extensive plastic deformation, but lower strength compared to composite materials. Aluminium and Kevlar exhibit higher ductility, whereas carbon fibre composites demonstrate low ductility and more brittle behaviour. These results highlight the influence of fibre type, orientation and matrix material on overall mechanical performance.

Further, comparing woven and non-woven composites, woven structures consistently demonstrated improved stiffness and strength due to enhanced fibre alignment and load transfer efficiency. This confirms that fibre alignment in woven composites enables more efficient load transfer, resulting in improved tensile strength compared to non-woven materials. Additionally, epoxy-based composites outperformed bio-resin equivalents, indicating improved fibre–matrix bonding. The 45° ply orientation likely introduced shear deformation effects, reducing stiffness compared to purely longitudinal alignment.

Overall, testing implied Aluminium exhibited the highest strain to failure, followed by Kevlar, while carbon fibre composites failed at significantly lower strain values.

During testing, brittle fracture was observed in carbon composites, whereas aluminium showed noticeable necking prior to failure.

Overall limitations include potential variation in fibre distribution, grip alignment in the testing machine, and inconsistencies in natural fibre composites, which may influence the accuracy of results.

4.1 Dataset comparison from other groups

To assess the reliability of the experimental results, the maximum stress values obtained from this study were compared with the averaged values calculated across all group datasets.

Material	Your Result (MPa)	Class Average (MPa)	Difference (%)
Aluminium	118.9	116.6	+2.0
Carbon Woven Bio	437.4	390.7	+11.9
Carbon Non-Woven Bio	117.5	179.4	-34.5
Carbon Woven Epoxy	408.3	401.6	+1.7
Flax Non-Woven Bio	42.8	47.5	-9.9
Flax Woven Bio	86.8	83.0	+4.5
Kevlar Woven Bio	373.7	274.0	+36.4

Table 1: Comparison of maximum stress values obtained in this study with averaged results from all groups.

The results show generally good agreement with the class average, with most materials exhibiting relatively small deviations. However, larger differences were observed for carbon non-woven and Kevlar composites. The lower value for carbon non-woven bio may be attributed to variations in fibre distribution or matrix bonding, while the higher Kevlar result may reflect improved fibre alignment or reduced defects in the tested specimen. Overall, the trends remain consistent with expected material behaviour, supporting the validity of the experimental results.

The experimental results are also consistent with published material data. Carbon fibre composites typically exhibit tensile strengths in the range of 300–600 MPa, while aluminium alloys commonly range between 100–300 MPa depending on condition (Callister and Rethwisch, 2019). Natural fibre composites such as flax generally demonstrate significantly lower strength, which aligns with the results obtained in this study.

Table 2 below summarises the key mechanical properties obtained from the tensile testing of all materials, including maximum stress, strain and observed failure behaviour.

Material	Maximum Stress (MPa)	Maximum Strain (–)	Behaviour Type	Key Characteristics
Aluminium	~120	~0.20	Ductile	Large plastic deformation, necking observed
Carbon Woven (Epoxy)	~420–440	~0.015	High strength, semi-brittle	High stiffness, efficient load transfer
Carbon Woven (Bio)	~340–360	~0.015	Semi-brittle	Slightly reduced performance vs epoxy
Carbon Non-Woven (Bio)	~110–130	~0.010–0.015	Pseudo-ductile	Matrix-dominated, fibre misalignment
Flax Woven (Bio)	~85–90	~0.035–0.045	Moderate, semi-ductile	Improved over non-woven, better alignment
Flax Non-Woven (Bio)	~40–45	~0.020–0.025	Low strength, progressive	Fibre pull-out, high variability
Kevlar	~350–370	~0.045–0.055	Tough (high energy absorption)	High strain, gradual failure behaviour

Table 2: Summary of mechanical properties obtained from tensile testing.

The results highlight significant variation in mechanical performance between materials, with carbon fibre composites exhibiting the highest strength, while natural fibre composites demonstrate lower strength but increased deformation and variability.

5 Recommendations

Based on the experimental results and sustainability analysis, material selection should be application-specific, balancing mechanical performance with environmental impact.

Carbon woven epoxy composites showed the highest tensile strength (~420–440 MPa) and stiffness, making them suitable for high-performance motorsport applications. However, their energy-intensive production and limited recyclability restrict use to critical components. Carbon woven bio-resin composites exhibited slightly lower strength (~340–360 MPa) but offer a more sustainable alternative where reduced environmental impact is required.

Flax fibre composites, particularly woven flax (~85–90 MPa), showed significantly lower strength but improved sustainability due to their renewable origin. These are suitable for non-structural automotive components with lower load requirements.

Kevlar composites demonstrated high tensile strength (~350–370 MPa) and strain capacity, making them suitable for impact-resistant and safety-critical applications, although recyclability remains limited.

Aluminium showed lower strength (~120 MPa) but high ductility and recyclability, making it suitable for energy-absorbing structures.

Future development should focus on improving bio-resin performance, optimising fibre orientation, and developing scalable recycling methods for composite materials.

6 Conclusion

This study evaluated the mechanical performance and sustainability of aluminium and composite materials used in automotive and motorsport applications. Carbon fibre composites, particularly woven epoxy systems, exhibited the highest strength and stiffness, while Kevlar demonstrated superior toughness and energy absorption. In contrast, flax composites showed significantly lower strength but improved sustainability due to their renewable origin. Aluminium provided good ductility and recyclability, but lower strength compared to composites.

Overall, the results highlight the importance of balancing mechanical performance with environmental impact when selecting materials for future engineering applications.

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