

MATERIALS TESTING AND SUSTAINABILITY OF COMPOSITES FOR MOTORSPORT & AUTOMOTIVE INDUSTRIES

**Automotive Materials &
Sustainability
(ACHA6012)**

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1. Introduction

The demand for lightweight, high-performance materials in industries such as automotive and motorsport has led to the widespread use of fibre-reinforced composites. Carbon fibre composites, in particular, have been widely adopted due to their exceptional strength-to-weight ratio, which offers comparable strength to traditional metals at a much lower density. However, their production is a significant source of emissions, particularly due to energy-intensive manufacturing processes and challenges related to end-of-life disposal.

Therefore, alternatives such as natural fibres and bio-resins have grown in popularity in recent years due to an increasing focus on material sustainability. However, while these materials present environmental benefits, they often exhibit lower mechanical performance, highlighting a key trade-off between performance and sustainability.

This report aims to evaluate this trade-off by analysing the properties and life-cycle impacts of carbon fibre composites compared with flax fibre and bio-resin alternatives. A literature review will be conducted to establish fundamental composite behaviours and applications, followed by a sustainability analysis considering raw materials, manufacturing, and end-of-life challenges. These sections will then be used in collaboration with experimental tensile testing of select metals and composites to suggest recommendations for future development of sustainable composites.

2. Literature Review

2.1 Material Properties

Arguably, the primary advantage of composites is their excellent strength-to-weight ratio, as discussed by Khan, with carbon fibre being stronger and stiffer than both steel and aluminium on a per-unit-weight basis. This is achieved whilst weighing about 25% of steel and 70% of aluminium (Khan, et al., 2024). The key to achieving these properties is carbon fibre's superior modulus-weight ratio and low density, which is another trait of fibre-reinforced polymers (Mallick, 2007).

Composite materials tend to exhibit low fracture toughness as a result of the strong interfacial bond between the fibres and the matrix (Farag, 1979), which opposes the characteristics required for high fracture toughness. Based on these tendencies, fibrous composites would be expected to deflect more rapidly than metals and to exhibit brittle failure behaviour, with limited plastic deformation prior to fracture.

Despite composite materials' strengths in comparison to traditional materials, those benefits are much more direction-dependent than is the case for metals. As Higgins states, the strength measured transversely may be only 2%-5% of that measured longitudinally (Higgins, 1994), meaning the load direction in any application is a critical consideration.

Fibre-reinforced composites also have the benefit of excellent fatigue strength and fatigue damage tolerance, appropriate for usage as structural materials and even consideration for use in weight-critical components in the automotive and aerospace industries (Mallick, 2007). Khan also referred to this, citing it as a reason to use composites for long-term outdoor structures, such as wind turbine blades (Khan, et al., 2024).

2.2 Material Structures

As explained by Ashby, polymers are relatively ductile and have low stiffness, while fibres are strong, stiff, and extremely brittle (Ashby & Jones, 1998). Therefore, fibre-reinforced composites combine a polymer matrix with reinforcing fibres, which allows the exploitation of the fibre's strengths while the polymer matrix mitigates their brittleness. Fibres therefore carry applied loads, while the matrix maintains their alignment and spacing. In addition to this, the matrix also handles the load transition onto the fibres, whilst protecting them from damage inflicted by the external environment (Amran, et al., 2018).

As previously discussed, composites can be sensitive to the direction of applied loads. In continuous-fibre composites, the matrix and fibre strains are parallel, indicating a highly anisotropic material. As explained by Farag, this means that when the composite is loaded perpendicular to the fibre direction, failure occurs at stresses as low as, or even lower than, the matrix strength (Farag, 1979). It is also discussed by Farag that a more isotropic composite can be achieved if the alternating layers are rotated through 45° (Farag, 1979), hence reducing the composite's directional sensitivity to load.

2.3 Manufacturing Processes

According to Khan, hand lay-up is one of the earliest and most basic strategies of composite manufacturing. Layers of reinforcement material are manually applied to a mould, with each layer comprising countless fibres already pre-impregnated with resin. These layers are then either woven together or organised unidirectionally before being firmly adhered to the previous layer. This process is frequently used for prototyping and low-volume production (Khan, et al., 2024).

A much more complex manufacturing process is pultrusion, as explained by Mallick, a continuous moulding process for producing long, straight structural members with a constant cross-sectional area. This process outputs products such as solid rods, hollow tubes and flat sheets (Mallick, 2007). However, polyester and vinyl are the matrix materials used, with epoxy omitted due to its longer cure time and a tendency not to release as easily from the pultrusion die (Mallick, 2007).

The autoclave process is especially popular for carbon fibre composites. As explained by Dave', the autoclave process is used to fabricate high-performance structural laminates with the use of a pressure vessel in which pressure and temperature are controlled (Dave', et al., 1988). Individual pre-preg plies are layered in the desired orientation outside the autoclave and covered with a vacuum bag, which is then placed in the autoclave to cure at a set pressure and temperature (Dave', et al., 1988). The final product's quality is dependent on the choice of cure cycle, which affects the autoclave temperature and pressure, as well as the temperature and pressure of the curing resin (Dave', et al., 1988).

2.4 Applications

As noted by Farag, the outstanding strength-weight and modulus-weight of some composite materials, combined with their generally higher costs, mean they should be considered as high-performance materials reserved for cases where their unique properties lead to eventual savings (Farag, 1979). With this in mind, it comes as no surprise that composites are prevalent in the aerospace industry, where they are used in areas such as the wings, body, vertical fin, and horizontal stabiliser (Farag, 1979).

Despite their higher costs, the use of composites within the automotive industry is also increasing. The chassis is one area which benefits from a composite construction, with enhanced handling and fuel economy complementing composites' built-in dampening characteristics that lessen noise and vibration transmission (Khan, et al., 2024).

3. Sustainability Analysis

3.1 Carbon Fibre

3.1.1 Raw Materials

Two raw material streams are used in the production of carbon fibre composites: polymer resins and reinforcing fibres. As explained by Witik, continuous carbon fibres are produced, then wound onto bobbins and transported to resin manufacturing sites for prepregging. Here, the fibres are unwound and combined with a hot-melt epoxy resin before being transported by truck to the site of the panel manufacture (Witik, et al., 2012). Witik found the material production to be responsible for 69% of the total emissions from the panel manufacture, much more than the autoclave process itself (Witik, et al., 2012). This suggests that carbon fibre's environmental impact is predominantly due to the energy-intensive production of the fibres rather than the manufacture of final components via autoclaving.

3.1.2 Manufacturing Processes

Another problem with carbon fibre is its manufacturing, which predominantly uses autoclaves. As discussed by Witik, these are accompanied by high acquisition costs, followed by long process times and energy-intensive operation during the processing (Witik, et al., 2012). As outlined by Witik, when observing the emissions of manufacturing processes in isolation, the curing process contributes the largest proportion of emissions (Witik, et al., 2012). Consequently, more recent out-of-autoclave processes aim to reduce the curing time required for components, thus achieving large reductions in emissions when compared to autoclaving.

3.1.3 Recycling and End-of-Life

Multiple recycling methods are employed for fibre-reinforced polymers; the least favourable is mechanical recycling, which is more akin to downcycling due to degradation of fibre properties. As discussed by Meirbekov, this entails reducing waste to small 10-50mm particles for use as a filler material in applications such as concrete reinforcement. In this process, the environmental impact is reduced by ensuring a high output per unit of recycled carbon fibre (Meirbekov, et al., 2022).

A more established and widely adopted industrial-scale process is pyrolysis, a thermal recycling method. This involves using heat to decompose the polymer matrix (Meirbekov, et al., 2022), recovering the fibres and making them usable for further applications. However, the parameters used, such as the temperature, pressure, and heating rate, are highly important, as they can have a lasting effect on the mechanical properties of reclaimed fibres (Meirbekov, et al., 2022). While this process yields usable fibres, the energy required to reach this point is higher than that of mechanical recycling. This highlights a key sustainability challenge: balancing material recovery with processing energy.

3.2 Flax Fibre

In recent years, natural fibres have received increasing attention as sustainable alternatives to traditional carbon and glass fibres. One example of these alternatives is flax, derived from fibrous plants that are abundant in agricultural crops and tropical areas (Gholampour & Ozbakkaloglu, 2019). As Mallick discusses, their uses have traditionally been for ropes, carpets, and bags. However, the automotive industry has recently become interested in their use for applications such as the interior door panels, seat backs and inner roof panels (Mallick, 2007).

Natural fibres offer significant environmental advantages. As previously discussed, the largest source of emissions from carbon fibre is material production. Natural fibres significantly reduce this issue, as little energy is required to produce them (Mallick, 2007). Pairing this with their biodegradability, and thus the energy saving at the end of the fibre's life in comparison to carbon, results in an alternative material with clear environmental benefits. As stated by Mallick, these benefits are achieved whilst maintaining the low-density synonymous with composite materials (Mallick, 2007).

However, the advancement of natural fibres in replacing traditional fibres is currently slowed by several limitations. The largest of these is their relatively low tensile strength and susceptibility to moisture absorption (Mallick, 2007). As explained by Mallick, natural fibres start to degrade beyond temperatures of 200°C, leading to odour, discolouration, and deterioration of mechanical properties (Mallick, 2007). In addition, the use of agricultural land to grow the plants needed for flax production may compete with land currently used for food production if it were more widely adopted.

3.3 Epoxy and Bio-Resins

As explained by Capretti, epoxy is derived from fossil feedstocks, many of which present toxicity concerns, and once formed, it has proven difficult to recycle as the components cannot be readily separated once the hardening process is complete due to the strong chemical bonds formed (Capretti, et al., 2023). As previously discussed, epoxy resins can be disposed of through pyrolysis, a high-energy-consuming process, which can only degrade the epoxy (Capretti, et al., 2023) rather than enable true material recycling. Therefore, despite epoxy's strengths as a matrix material for composites, its use comes with some drawbacks.

Bio-resins attempt to replace the key components of epoxy that are harmful, such as the petroleum-based propylene, with renewable sources, such as plant-based glycerol (EasyComposites, 2025). In EasyComposites' case, this results in a hybrid resin with a plant-based content of ~38% once the hardener is applied (EasyComposites, 2025). This results in a resin which is less dependent on fossil and petrochemical resources, whilst also making end-of-life solutions less harmful to the environment.

Despite their environmental benefits, Capretti observed that the use of hybrid composites led to a 25% decrease in mechanical properties compared to traditional equivalents (Capretti, et al., 2023). This indicates that, despite their much-improved manufacturing emissions, further research and development are required to achieve parity with established resins such as epoxy. In their current state, the application of bio-resins for high-load scenarios may be limited.

3.4 Regulations & Legislation

The selection of composite materials in the automotive and motorsport industries is partly influenced by increasing legislative and regulatory requirements. In the automotive industry, the End-of-Life Vehicles directive mandates that all cars and small vans, including the components used within them, must have 95% of their average weight recovered and 85% recycled (Office for Product Safety and Standards & Department for Environment, Food & Rural Affairs, 2021). This presents a challenge for thermoset composites such as epoxy-based carbon fibre, which are inherently difficult to recycle due to their structure.

Within Formula 1, there is no direct regulation mandating the use of sustainable composites. However, the FIA's sustainability strategies targeting net-zero emissions by 2030 are encouraging F1 teams to explore sustainable composite materials in non-critical components, such as McLaren's use of a hybrid sandwich construction of flax and carbon fibre to produce a race seat with an 85% reduction in CO₂ emissions (McLaren Racing, 2021). This highlights the growing viability of hybrid composite solutions for reducing environmental impacts without significantly compromising the mechanical performance of race vehicles.

4. Experimental Testing

4.1 Testing Methodology

In addition to material research, experimental tensile testing was conducted on a variety of composites and metals. These were performed using a universal testing machine, which applies an increasing tensile load to a sample of known cross-sectional area. The tensile testing machine is designed to continuously monitor the applied load, and an extensometer was used to accurately measure the resulting elongations (Callister Jr. & Rethwisch, 2018), as shown in Figure 1. These measurements allowed for the generation of stress-strain curves for all materials, as well as the calculation of their Young's modulus and ultimate tensile strength.



Figure 1 - Universal testing machine with a material sample clamped in place and an extensometer attached

As described by Callister Jr., the tensile test is destructive, meaning the test specimen is permanently deformed and often fractured (Callister Jr. & Rethwisch, 2018). This provided an opportunity to observe the tested materials' failure behaviour in addition to their tensile strength.

To ensure the safety of all participants, safety goggles and steel-toed boots were worn at all times. A safe distance from the machine was maintained throughout its operation, and checks were conducted prior to testing of all materials to ensure they were adequately fastened.

4.2 Results Validation

The experimental results shown in Table 1 exhibit a reasonable agreement with literature values, with all materials following the expected trends in mechanical performance. However, most measured values are lower than those reported in the literature, particularly for UTS, likely due to manufacturing variations and differing testing methodologies. The Young's modulus of the woven carbon samples shows the strongest agreement, with differences of 5%-8% relative to the literature values, indicating that the testing methodology can provide accurate results under appropriate conditions.

Table 1 - Experimental Young's modulus and UTS values compared to literature (Cavallo, 2020), (EasyComposites, 2024), (Niutta, et al., 2023), (EcoTechnilin, 2023), (EcoTechnilin, 2023)

Material	Tested Young's Modulus (Gpa)	Young's Modulus Target (Gpa)	Difference	Tested UTS (Mpa)	UTS Target (Mpa)	Difference
Aluminium	44.737	68.9	42.53%	114.889	241	70.87%
Non-Woven Carbon	16.947	25	38.40%	149.418	290	63.99%
Woven Carbon (Bio)	57.508	54.8	4.82%	352.025	650	59.47%
Woven Carbon (Epoxy)	62.435	57.8	7.71%	333.022	716	73.02%
Non-Woven Flax	3.628	5	31.80%	49.005	44	10.76%
Woven Flax	4.933	7	34.64%	78.127	61	24.62%
Kevlar	31.003			286.012		

4.3 Results Discussion

4.3.1 Twill against Non-Woven

The first comparison of interest to make is the effect of implementing a twill structure on composite materials. Both carbon and flax were tested in twill and nonwoven structures for this comparison.

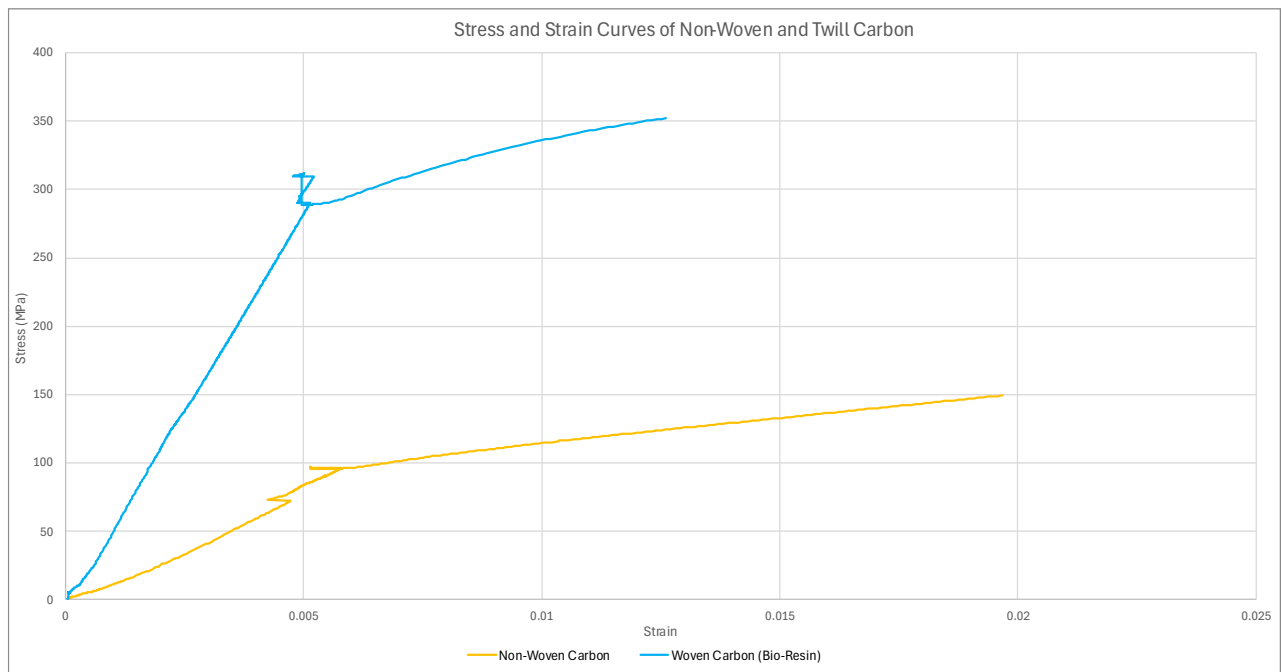


Figure 2 - Stress-strain curves of non-woven and twill carbon

Observing the carbon stress-strain curves in Figure 2, the twill (woven) structure exhibits a significantly steeper initial slope, supporting the increased Young's modulus seen in Table 1, and indicating a greater stiffness than the non-woven carbon. While both materials show the onset of damage occurring at a strain of around 0.005, the twill reaches a much higher stress at this point (approximately 280 MPa compared to 85 MPa).

Beyond this region, the twill carbon continues to exhibit higher stress but with a lower increase in strain, indicating brittle failure behaviour. In contrast, the non-woven carbon continues to exhibit a stress increase over a larger strain region, suggesting greater deformation before failure, but a significantly lower overall strength.



Figure 3 - Stress-strain curves of non-woven and twill flax

Comparing these trends to twill and non-woven flax in Figure 3, the first difference is the clearly lower stresses achieved, demonstrating the gulf between synthetic and natural fibres. Considering the flax structures, a reduced benefit is observed when implementing a twill structure compared to the non-woven flax, suggesting a lower performance ceiling than carbon, likely due to the reduced bond strength between matrix and fibre in natural fibre materials. Interestingly, failure behaviour is the inverse of the carbon materials. A twill structure has allowed the flax to deform further before failure, and the failure itself is less catastrophic than the non-woven equivalent.

4.3.2 Bio-Resin against Epoxy Resin

As previously discussed by Capretti, the use of hybrid composites led to a 25% reduction in mechanical performance compared to traditional equivalents (Capretti, et al., 2023). However, when the epoxy and bio-resins were experimentally tested, a small performance advantage in the bio-resin's favour was observed, as seen in Figure 4. A comparable initial slope validates the similar Young's modulus seen in Table 1. This suggests that the material stiffness is largely governed by the fibres rather than by the matrix. However, the bio-resin exhibits an increased ultimate tensile strength and marginally greater strain to failure. This may be due to variability in manufacturing conditions, such as fibre alignment or void content, which can influence material performance. Regardless, these results suggest that modern bio-resins can offer comparable mechanical performance to epoxy, supporting their use as more sustainable alternatives.

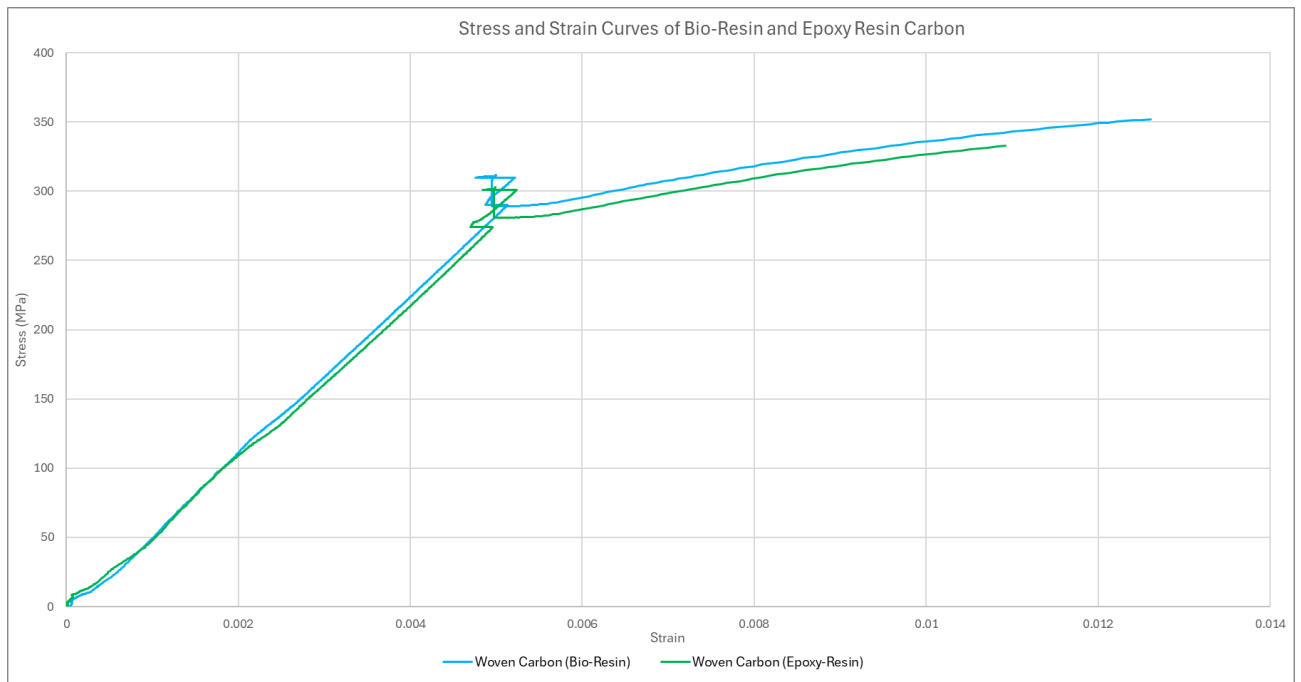


Figure 4 - Stress-strain comparison of carbon fibre with epoxy and bio-resins

4.3.3 Comparison of All Tested Materials

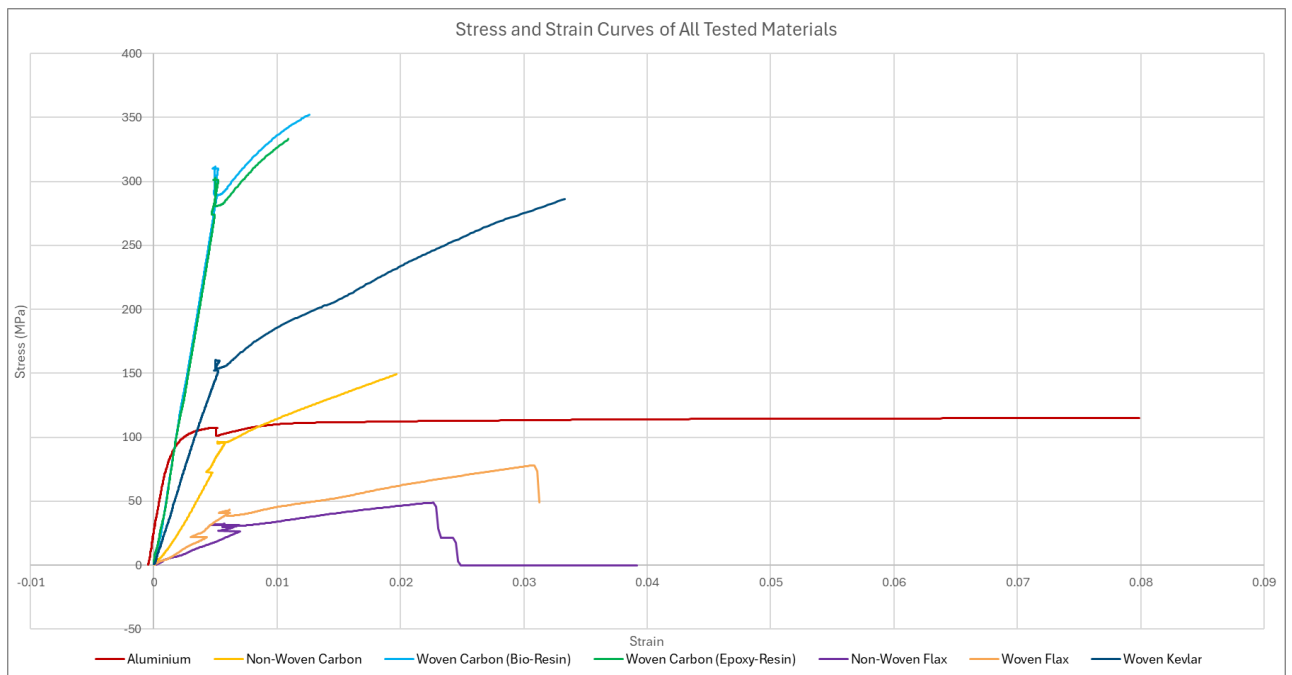


Figure 5 - Stress-strain curve comparison of all tested materials

Figure 5 presents a comparison of all tested materials, highlighting the variation in mechanical performance. Carbon fibre composites exhibit the highest stiffness and strength, with the twill configurations significantly outperforming the non-woven samples. Kevlar also demonstrates high strength compared to aluminium; however, its more gradual failure behaviour, as evidenced by the failed sample in Figure 6 showing partially attached fibres, indicates improved

toughness. Aluminium exhibits lower strength than the composites, but undergoes extensive plastic deformation, as shown by the necking observed in Figure 6, demonstrating its high ductility. In contrast, flax composites achieve considerably lower stresses in both configurations, reflecting the limitations of natural fibres in load-bearing applications.

This comparison highlights the trade-offs among stiffness, strength, and ductility across the tested materials, suggesting that hybrid composites may offer a more effective balance of mechanical performance and sustainability than fully natural fibre composites.

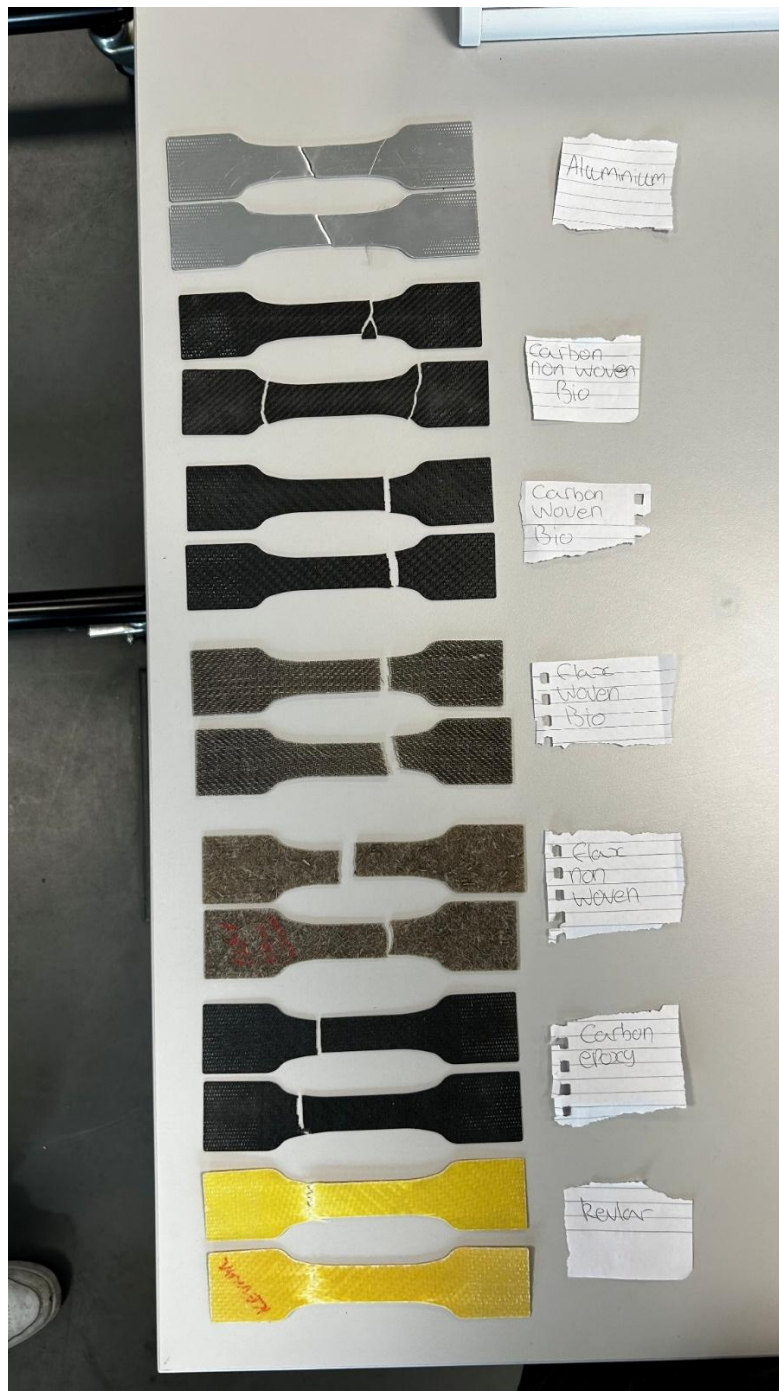


Figure 6 - Post-failure samples of all materials

5. Recommendations and Future Development

5.1 Current Recommendations

Based on the findings of this report, carbon fibre composites should remain the primary material for high-performance and high-load applications, given the superior mechanical performance observed in the material testing. However, their use should be minimised wherever possible due to the large environmental impact of their production and disposal, as found in the sustainability analysis.

Due to their reduced mechanical performance, flax fibre composites are currently best suited for non-structural applications that prioritise sustainability over performance, such as the previously noted automotive interiors.

On a more positive note for sustainable materials, bio-resins should be considered a viable alternative to petroleum-based resins, as experimental results indicate comparable mechanical performance, complementing their reduced dependence on fossil-based resources.

5.2 Areas for Future Development

Natural fibres require further research to improve their mechanical performance and align their significant emissions reductions with comparable performance to traditional composites, which, as seen in the experimental testing, is currently not the case.

As noted in the sustainability review, current bio-resins contain approximately 38% plant-based content (EasyComposites, 2025). However, further development should be conducted to increase this ratio whilst ensuring that the promising mechanical performance observed in the experimental testing is maintained.

The dependency on the autoclave manufacturing process in carbon fibre production should be reduced despite its current prominence. Alternative out-of-autoclave processes have significantly reduced energy consumption in the manufacturing of carbon fibre panels and should be further refined to promote broader adoption.

6. Conclusion

To conclude, carbon fibre composites have demonstrated superior mechanical performance, while flax fibres show significantly lower performance, but with the benefit of improved sustainability. Therefore, a clear trade-off exists between mechanical performance and environmental impact, with no single material providing an optimal solution. With this in mind, hybrid composites, which combine the performance benefits of synthetic fibres with the sustainability advantages of bio-resins, represent a promising current solution for composite materials.

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