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**Materials Testing and Sustainability of Composites for
Motorsport & Automotive Industries**

Automotive Materials & Sustainability

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I – Abbreviations

Abbreviation	Meaning
CSA	Cross-sectional area
D	Density
E	Young's modulus
GPa	Gigapascal
MPa	Megapascal
SW	Surface weight
UTS	Ultimate tensile strength

II - Nomenclature / Symbols

Symbol	Meaning
E_c	Composite modulus
E_f	Fibre modulus
E_m	Matrix modulus
V_f	Fibre volume fraction
V_m	Matrix volume fraction

1 - Introduction

This study evaluates the tensile behaviour and sustainability of flax and carbon fibre composites for automotive and motorsport use. Aluminium was tested as a baseline, while woven and non-woven reinforcements and bio-based and conventional epoxy systems were compared to assess how fibre type, architecture and resin choice affected performance. The results were then considered alongside manufacturer data, end-of-life constraints and current sustainability factors. The aim was to identify the strongest material but also decide which material is most suitable when performance and sustainability are considered together.

2 - Literature review / technical background

2.1 - Composite Materials in Automotive Applications

Composite materials are increasingly important in automotive engineering to address critical challenges affecting consumers and the climate. One of the most difficult tasks is reducing the weight of vehicles to minimise energy consumption. A ten percent decrease in curb weight can result in a six to eight percent reduction in energy consumption (Wazeer et al., 2023). Composite materials offer high specific strength and stiffness, corrosion resistance and design flexibility, allowing vehicle mass to be reduced without loss in performance.

Material selection has usually prioritised lightweight performance over end-of-life considerations. The EU's proposed End-of-Life Vehicles Regulation changes this focus requiring vehicles to be designed for easier dismantling, meeting new reusability and recyclability standards. This is enforced by making producers more responsible for their own materials even after the vehicle has been sold (European Commission, 2023). Therefore, materials cannot be described as sustainable just because they reduce vehicle mass. Their sustainability increasingly depends on whether they also meet End-of-Life regulations.

2.2 - Woven and Non-Woven Reinforcement Architectures

Woven reinforcement is made by interlacing yarns in a regular pattern, whereas non-woven reinforcement is made from fibres arranged without a woven structure. This difference in structure affects fibre orientation, continuity and the way load is transferred through the material (Risteska et al., 2024). Woven materials tend to provide more controlled fibre orientation and a more predictable mechanical response, while non-woven is easier to process, reducing cost. As a result, woven and non-woven composites can show noticeably different tensile behaviour even when similar materials are used (Risteska et al., 2024).

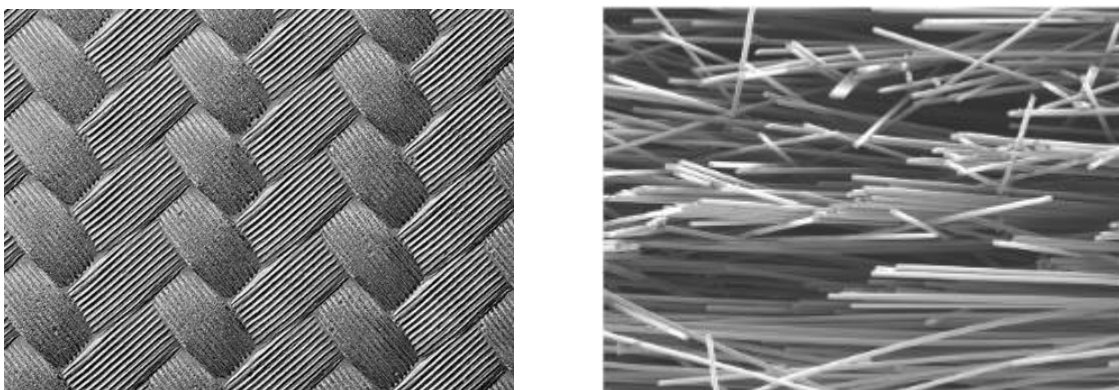


Figure 1: Woven carbon taken from Keyence, 2026 (left), non-woven carbon taken from Goethals et al., 2024 (right)

2.3 - Carbon and Flax Fibre Composites

Carbon fibre composites use carbon fibres as the main reinforcement, whereas flax fibre composites use natural plant fibres. Carbon and flax fibre composites represent a clear trade-off between performance and sustainability. Carbon fibre composites are generally associated with higher strength and stiffness, making them suitable for demanding applications, whereas flax fibre composites are increasingly considered because they offer lower environmental impact (Easy Composites Ltd, 2024a; EcoTechnilin, 2023a).



Figure 2: Carbon fibre taken from CarbonTouch, 2026 (left), Flax taken from EcoTechnilin, 2023a (right)

2.4 - Bio-Epoxy and Conventional Epoxy Resins

Epoxy resins are widely used in fibre composites, and their performance is influenced by factors such as formulation and curing agents (Seid and Adimass, 2024). They form the matrix in many fibre composites and bind the reinforcement together. Conventional epoxy resins are usually produced from fossil-based raw material systems and are still commonly used because of their reliable performance. Bio-epoxy resins replace part of this content with renewable sources (Capretti et al., 2023), giving a more sustainable alternative. This means resin choice is important not only for mechanical performance, but also the environmental benefit (Capretti et al., 2023; Seid and Adimass, 2024).

2.5 - Tensile Performance and Law of Mixtures

Tensile performance describes how a material responds when it is pulled in tension. In fibre composites, this response depends on the combined contribution of the fibre and the matrix, so simple models are often used to estimate overall behaviour (Abdalla, 2025). The rule of mixtures is one of the most common of these models, predicting the effective elastic properties of composite materials. However, its accuracy becomes more limited for woven composites because fabric structure and yarn geometry also affect the result, making them harder to predict (Abdalla, 2025; Zuo et al., 2023).

3 - Materials and methodology

3.1 – Materials

3.1.1 - Materials Investigated

The materials investigated included an aluminium baseline and six composite materials supplied as pre-manufactured tensile specimens. The main composite coupons covered flax and carbon fibre reinforcements in both woven twill and non-woven forms, combined with either a bio-based or conventional epoxy matrix.

Carbon and flax systems were selected to compare performance against sustainability. Woven and non-woven reinforcements show the influence of fibre architecture on load transfer, while bio-based and conventional epoxy matrices were included to assess whether lower-impact resin systems could still provide suitable tensile behaviour.

In addition to the main set of materials, Kevlar coupons were also tested as an extra material. However, unlike the main materials included, no supporting information was available regarding lay-up sequence, resin system or manufacturing conditions. The Kevlar results therefore offer a broader view of tensile performance against the main material set but have limited usability for analysis.



Figure 3: Main material coupons



Figure 4: Kevlar coupon

Table 1: Summary of materials investigated

Test material	Reinforcement type	Architecture	Matrix system	Notes
Aluminium	Metal baseline	N/A	N/A	Baseline
Flax woven bio	Flax fibre	Twill woven	IB2 bio-epoxy	Natural fibre
Carbon woven bio	Carbon fibre	Twill woven	IB2 bio-epoxy	Bio-resin
Carbon woven epoxy	Carbon fibre	Twill woven	IN2 conventional epoxy	Conventional epoxy
Flax non-woven bio	Flax fibre	Non-woven mat	IB2 bio-epoxy	Natural fibre non-woven
Carbon non-woven bio	Recycled carbon fibre	Non-woven mat	IB2 bio-epoxy	Recycled carbon non-woven
Kevlar	Aramid fibre	N/A	N/A	Supplementary material

Table 1 summarises the materials included in the test programme and identifies the reinforcement type, architecture and matrix system for each specimen set.

3.1.2 - Specimen Manufacture and Lay-Up Configuration

Table 2: Specimen manufacture and lay-up configuration

Test material	Manufacturing method	Reinforcement lay-up	Nominal reinforcement weight (g/m ²)	Matrix system	Volume fraction used	Notes
Aluminium	N/A	N/A	N/A	N/A	N/A	Baseline
Flax woven bio	Resin infusion	3 × 200 g twill plies	600	IB2 bio-epoxy	29 ±1% fibre volume fraction	45° ply orientation
Carbon woven bio	Resin infusion	3 × 200 g twill plies	600	IB2 bio-epoxy	50:50 fibre / epoxy assumed	45° ply orientation
Carbon woven epoxy	Resin infusion	3 × 200 g twill plies	600	IN2 conventional epoxy	50:50 fibre / epoxy assumed	45° ply orientation
Flax non-woven bio	Resin infusion	1 × 300 g non-woven layer	300	IB2 bio-epoxy	18 ±1% fibre volume fraction	Single-layer laminate
Carbon non-woven bio	Resin infusion	1 × 300 g non-woven layer	300	IB2 bio-epoxy	50:50 fibre / epoxy assumed	Single-layer laminate
Kevlar	N/A	N/A	N/A	N/A	N/A	Supplementary material

Table 2 summarises the specimen manufacture and lay-up configuration for each test material, including the processing method, reinforcement architecture, matrix system and fibre volume fraction used where applicable.

Table 3: Cross-sectional area used for each tensile test run

Test material	Run 1 area (mm ²)	Run 2 area (mm ²)	Run 3 area (mm ²)	Run 4 area (mm ²)
Aluminium	22.5	22.5	22.5	22.5
Flax woven bio	32.52	32.52	34.56	33.66
Carbon woven bio	13.58	13.65	15.68	15.68
Carbon woven epoxy	15.29	15.29	13.79	13.79
Flax non-woven bio	33.48	33.48	27.86	26.73
Carbon non-woven bio	27.75	27.75	31.97	31.97
Kevlar	19.33	19.33	17.96	17.96

Due to the differences in lay-up and resulting finished thickness, the coupons did not all have the same cross-sectional area (CSA). The woven carbon specimens mainly had thinner finished sections, while the flax and non-woven specimens generally produced larger areas.

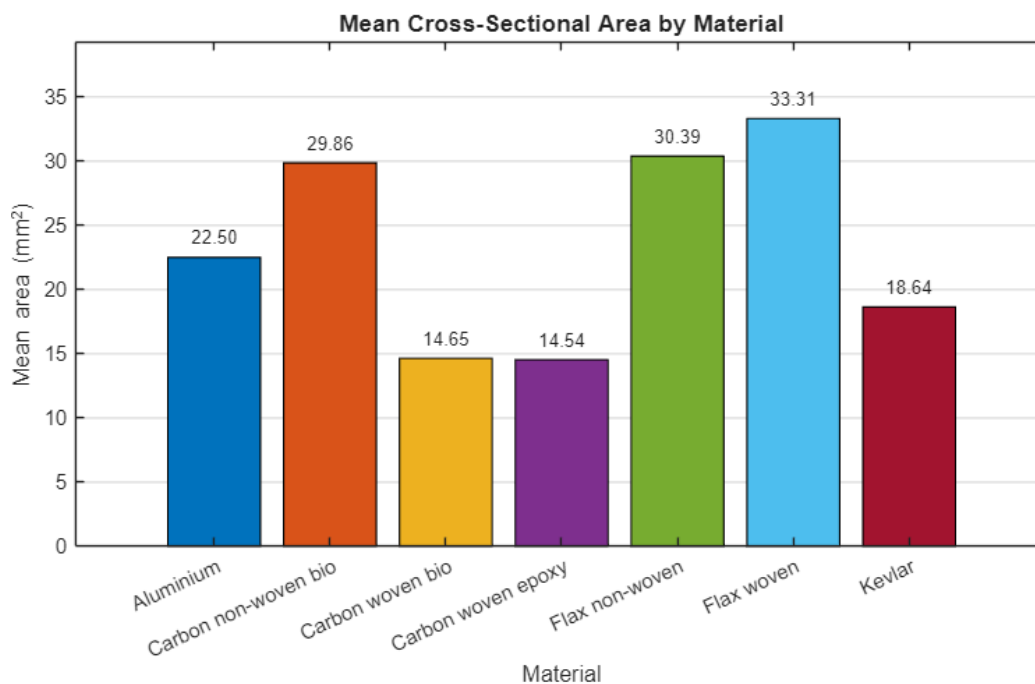


Figure 5: Bar chart showing the different cross-sectional areas of the materials

This is important because CSA directly affects the calculated stress and therefore influences the reported tensile strength and Young's modulus.

3.2 – Methodology

3.2.1 – Equipment

3.2.1.1 – Denison Tensile Tester

The tensile tests were carried out using the Denison tensile tester shown in Figure 6. This machine was used to apply the tensile load to each specimen until failure and to record the load response for later analysis. The tensile tester was calibrated at the time of testing; therefore, calibration drift was considered unlikely.

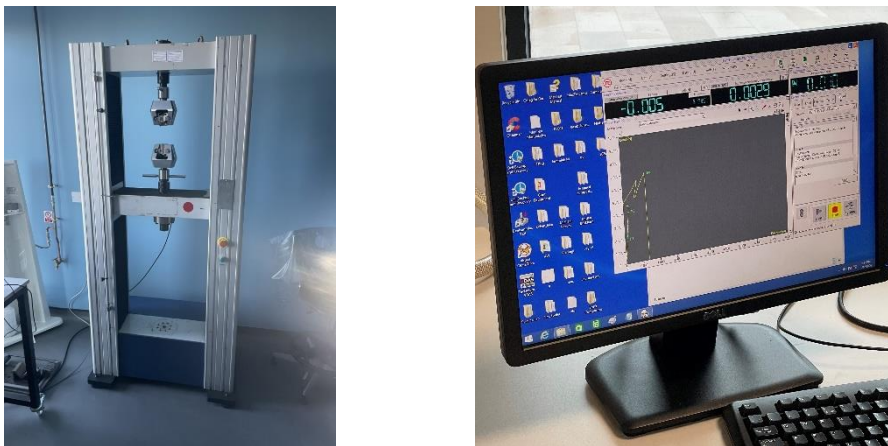


Figure 6: Denison tensile tester (left), operating computer (right)

3.2.1.2 – Epsilon Model 3542 Axial Extensometer

An Epsilon Model 3542 axial extensometer was used to measure axial strain during the initial stage of tensile loading. Its operating range made it suitable for capturing the early strain response needed to determine specimen stiffness accurately (Epsilon, 2026).

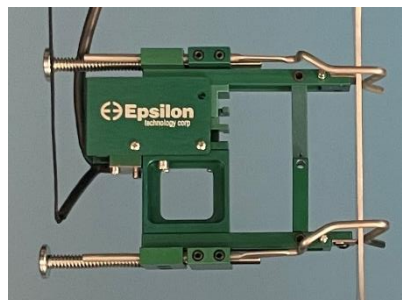


Figure 7: Epsilon model 3542 Axial Extensometer

3.2.2 - Tensile Testing Procedure

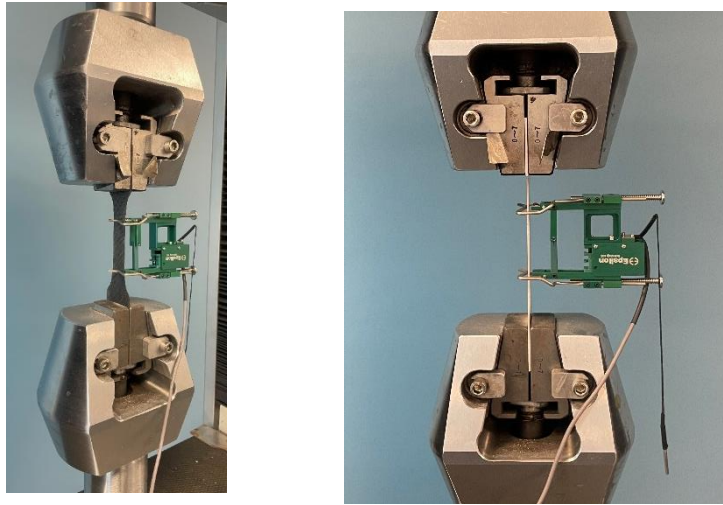


Figure 8: Tensile tester and axial extensometer set up with a coupon

Before each test, the specimen dimensions were entered into the machine software so that load data could be converted into stress and strain. Each coupon was gripped at its ends, and the axial extensometer was attached during the initial stage of loading to record strain before being removed prior to final failure, avoiding damage to the instrument. Testing then continued until fracture.

4 - Experimental Results and Discussion

4.1 - Overview of Experimental Results

Table 4: Processed mean experimental results presented as mean $\pm$ standard deviation using valid runs only

Test material	Valid Runs (n)	Young's Modulus (GPa)	Break Stress (Mpa)	Ultimate Tensile Strength (Mpa)	Failure Load (kN)
Aluminium	3	54.34 $\pm$ 4.43	32.59 $\pm$ 3.71	117.00 $\pm$ 2.65	2.64 $\pm$ 0.06
Flax woven bio	4	1.67 $\pm$ 0.07	57.52 $\pm$ 39.04	91.00 $\pm$ 3.65	3.03 $\pm$ 0.14
Carbon woven bio	4	60.33 $\pm$ 3.65	362.78 $\pm$ 146.71	428.00 $\pm$ 22.42	6.25 $\pm$ 0.23
Carbon woven epoxy	3	58.62 $\pm$ 3.54	387.46 $\pm$ 87.99	416.00 $\pm$ 67.36	5.92 $\pm$ 0.70
Flax non-woven bio	4	5.20 $\pm$ 1.18	22.46 $\pm$ 14.23	34.50 $\pm$ 10.34	1.02 $\pm$ 0.20
Carbon non-woven bio	3	11.37 $\pm$ 6.46	138.66 $\pm$ 32.64	151.00 $\pm$ 43.30	4.45 $\pm$ 1.47
Kevlar	4	14.59 $\pm$ 1.78	208.56 $\pm$ 106.59	300.75 $\pm$ 18.37	5.60 $\pm$ 0.12

A small number of results were identified as outliers and removed where they were considered unrepresentative of the overall material response. These are shown in the raw data graphs provided in Appendix A. The standard deviation shows the variation within the retained results. In general, materials had relatively consistent behaviour, but some displayed greater variation, potentially showing a limitation in repeatability.

4.2 - Validation Against Manufacturer Data and Published Literature

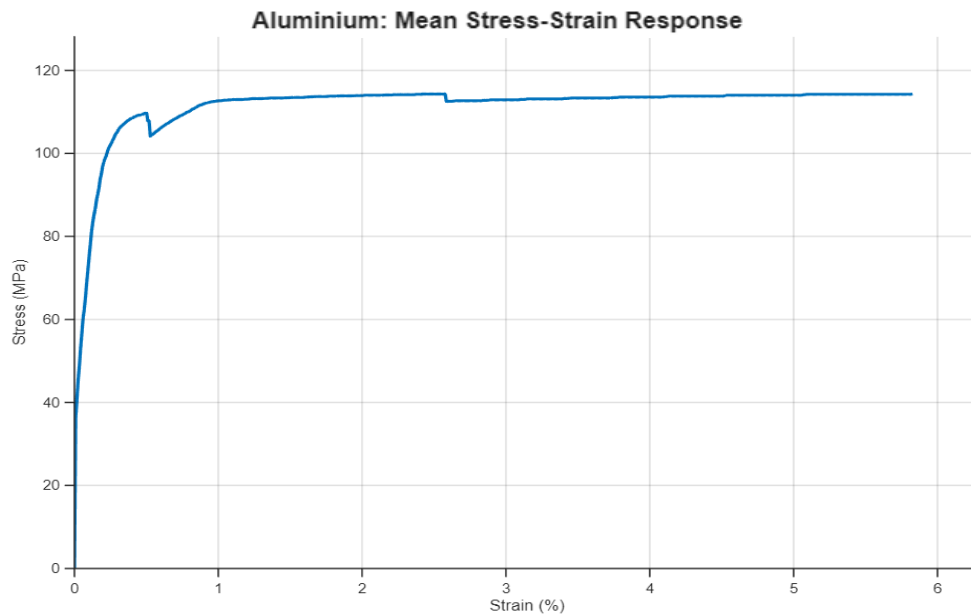


Figure 9: Aluminium mean stress-strain

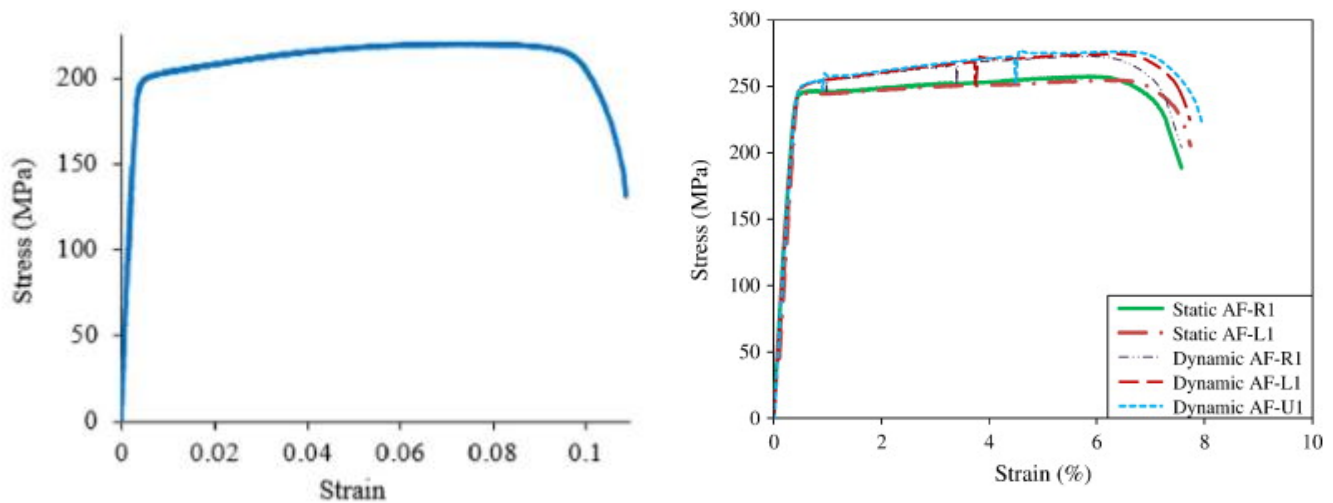


Figure 10: Hussein et al., 2022 (left), Huang and Young, 2014 (right)

Compared with the two published studies, the aluminium baseline in the present study showed a very similar stress-strain trend and a comparable failure strain of around 6%.

Huang and Young reported a modulus of 66.4 GPa, which is reasonably close to the 54.34 GPa obtained in this study. The main difference was in ultimate tensile strength (UTS), with both other studies reporting values of roughly 220-270 MPa compared with 117.34 MPa in the present study.

This is likely due to differences in alloy grade and temper rather than poor testing; aluminium stiffness remains close to 70 GPa across most alloys, but tensile strength depends much more on alloy composition and heat-treatment condition (European Aluminium, 2011a; European Aluminium, 2011b). For example, softer sheet grades such as 1050A-H14 are typically 105-145 MPa (Aalco Metals Ltd, 2009), which is the range recorded during testing. 6061-T6, which was used by both the published studies, is around 260 MPa (The Aluminum Association, 2021). Therefore, the present result is more consistent with a softer sheet aluminium than a stronger T6 alloy.



Figure 11: Coupon after test from present study



Figure 12: Coupon after test taken from Hussein et al., 2022

Both the aluminium coupons tested in the present study and by Hussein et al. failed in the same way, with a diagonal fracture. This similarity between studies suggests that the aluminium baseline testing produced credible results, indicating that the testing method was correct and that the composite results can therefore be interpreted with reasonable confidence.

4.3 - Comparison with Aluminium Baseline

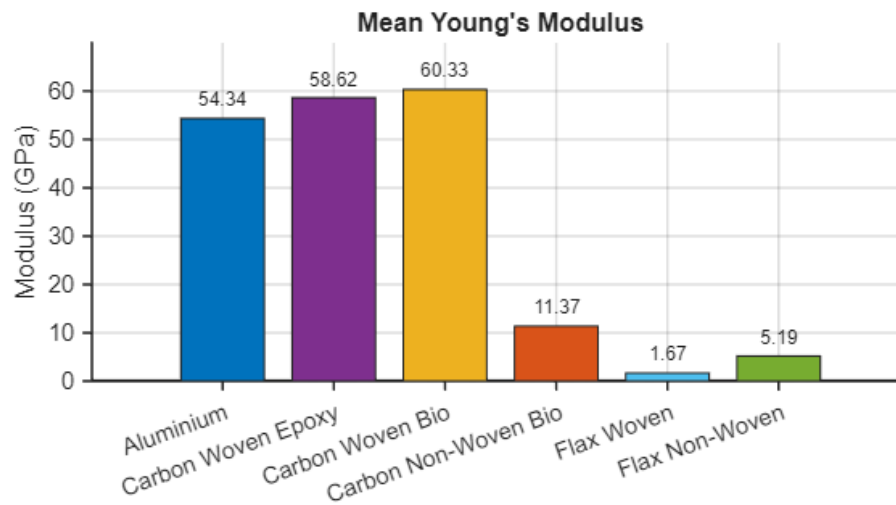


Figure 13: Bar chart comparing baseline material Young's Modulus to tested materials

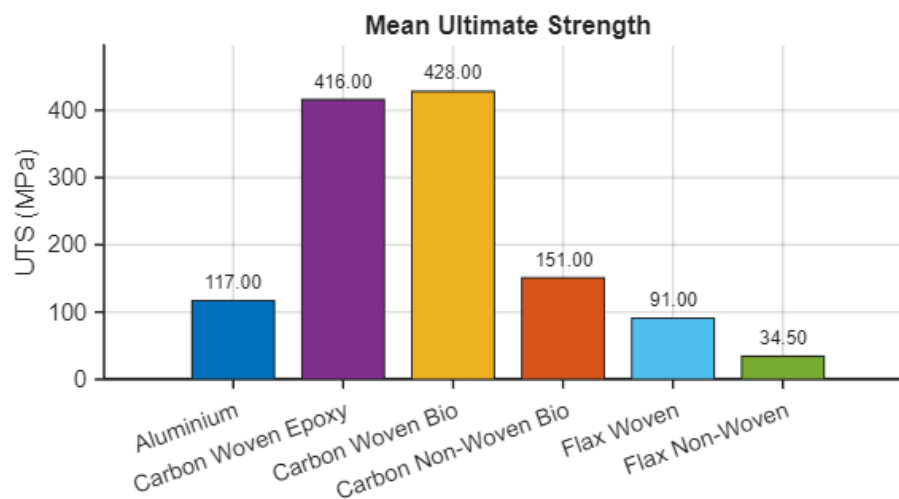


Figure 14: Bar chart comparing baseline material UTS to tested materials

The test results are consistent with normal behaviour of aluminium, which is ductile, because after yielding its crystal structure allows continued plastic deformation before fracture (Clyne and Campbell, 2021). As a result, it can absorb more deformation and reaches a much greater strain before failure. By contrast, the composite materials behaved in a more brittle manner. In tensile loading, the load is carried mainly by the fibres and surrounding matrix, so once damage begins, through matrix cracking or fibre failure, the material has far less ability to continue deforming (Hamzat et al., 2025).

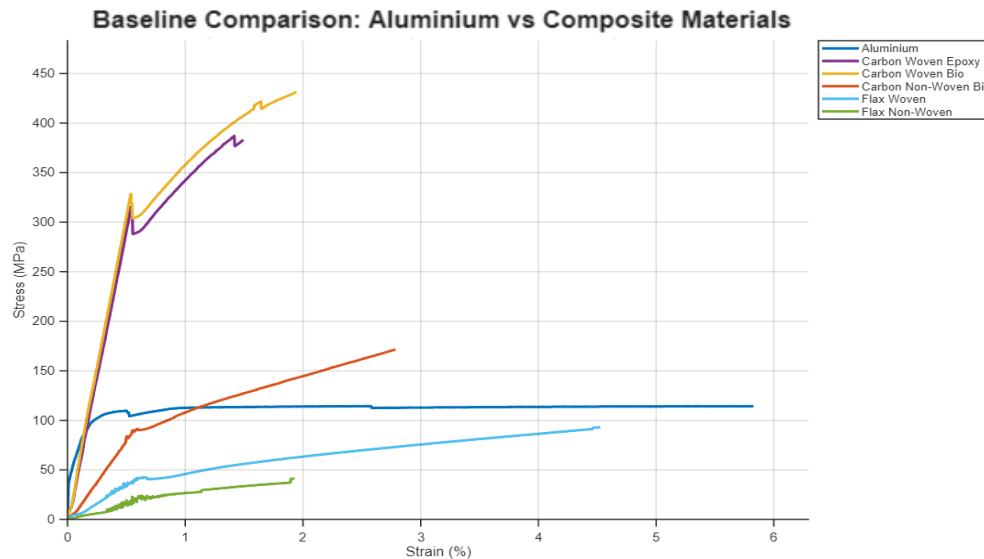


Figure 15: Comparison stress-strain of all materials to baseline

In load-displacement the aluminium stretches without a large increase in load, typical of yielding and continued plastic deformation (Callister and Rethwisch, 2020). The composite traces, however, continue to rise more steadily because they do not have the same ability to keep deforming once damage starts. Overall, this confirms that aluminium was a useful ductile baseline material, whereas the composites showed a distinctly different mechanical response, with lower strain to failure and no clear plastic deformation before fracture.

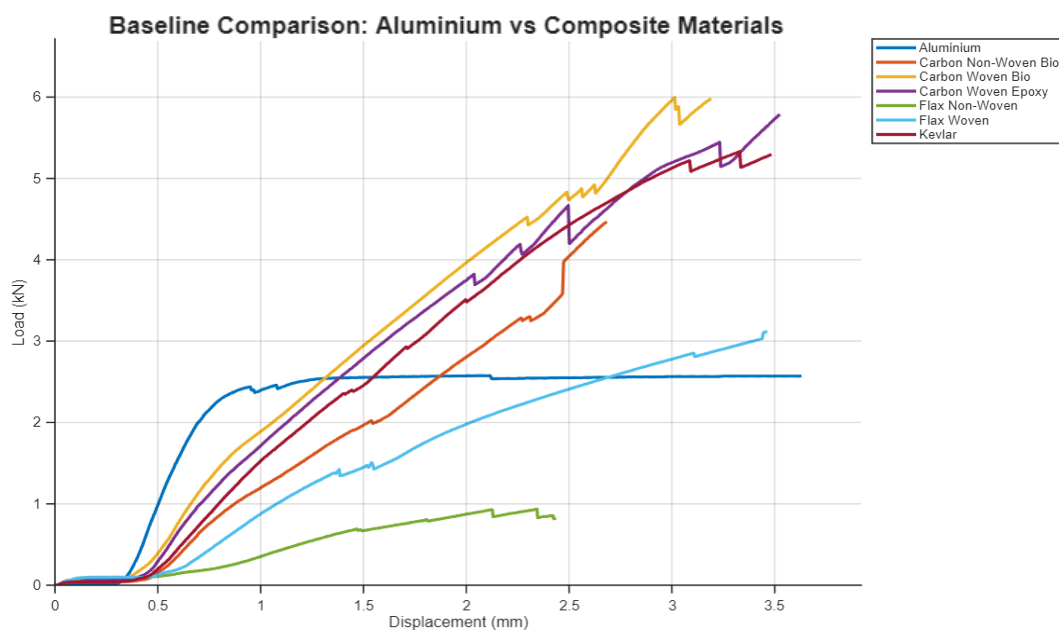


Figure 16: Comparison load-displacement of all materials to baseline

4.4 - Twill and Non-Woven Composite Performance

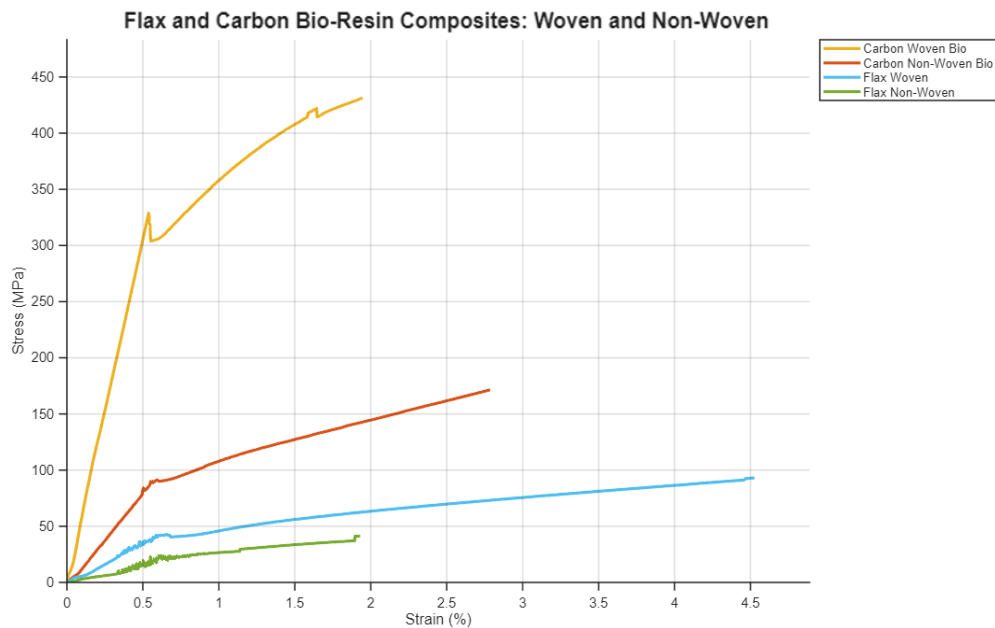


Figure 17: Comparison stress-strain of woven and non-woven

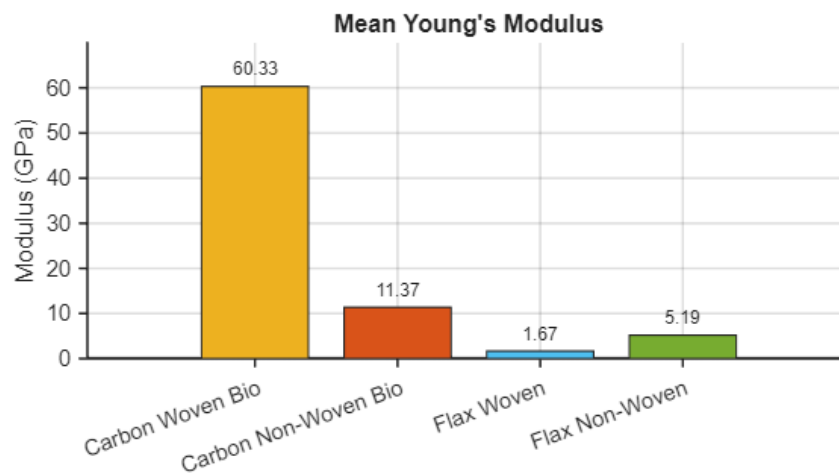


Figure 18: Bar chart comparing Young's Modulus of woven and non-woven

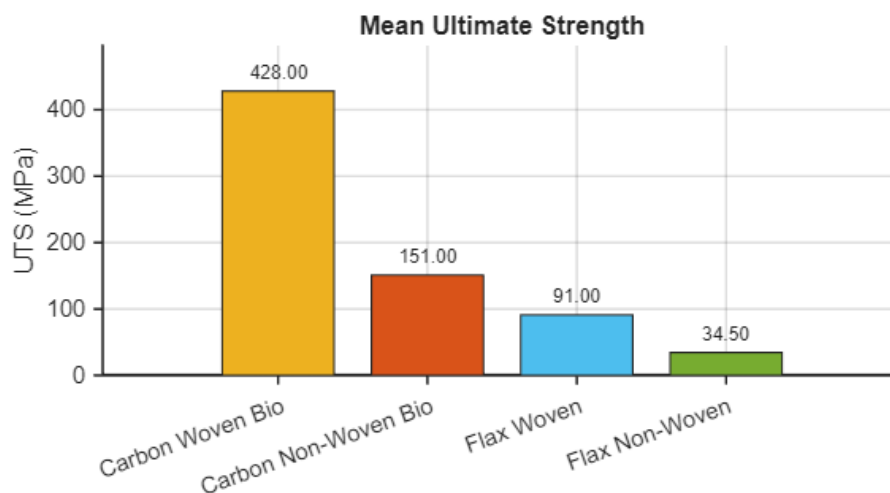


Figure 19: Bar chart comparing UTS of woven and non-woven

The woven laminates generally performed better than the non-woven laminates, transferring load more effectively, which is consistent with the more controlled fibre orientation and more continuous load paths in woven structures. By contrast, the non-woven mats have less ordered fibre alignment, so load is carried less efficiently in tension (Risteska et al., 2024).

The modulus results were less consistent, suggesting that stiffness was influenced not only by whether the reinforcement was woven or non-woven, but also by the lay-up. The twill specimens were made from three plies placed at 45° to each other, so the tensile response was not measured purely in the main fibre direction.

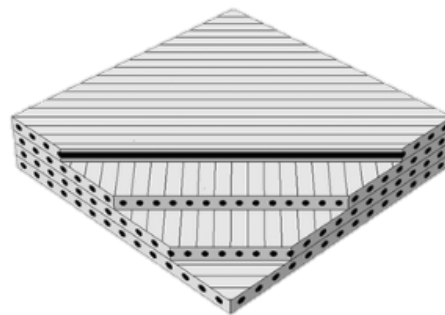


Figure 20: Example of plies layered at 45° taken from Moncada et al. (2012)

This 45° lay-up is likely to have increased yarn rotation and shear deformation, which can reduce apparent stiffness and make the response more non-linear (Risteska et al., 2024).

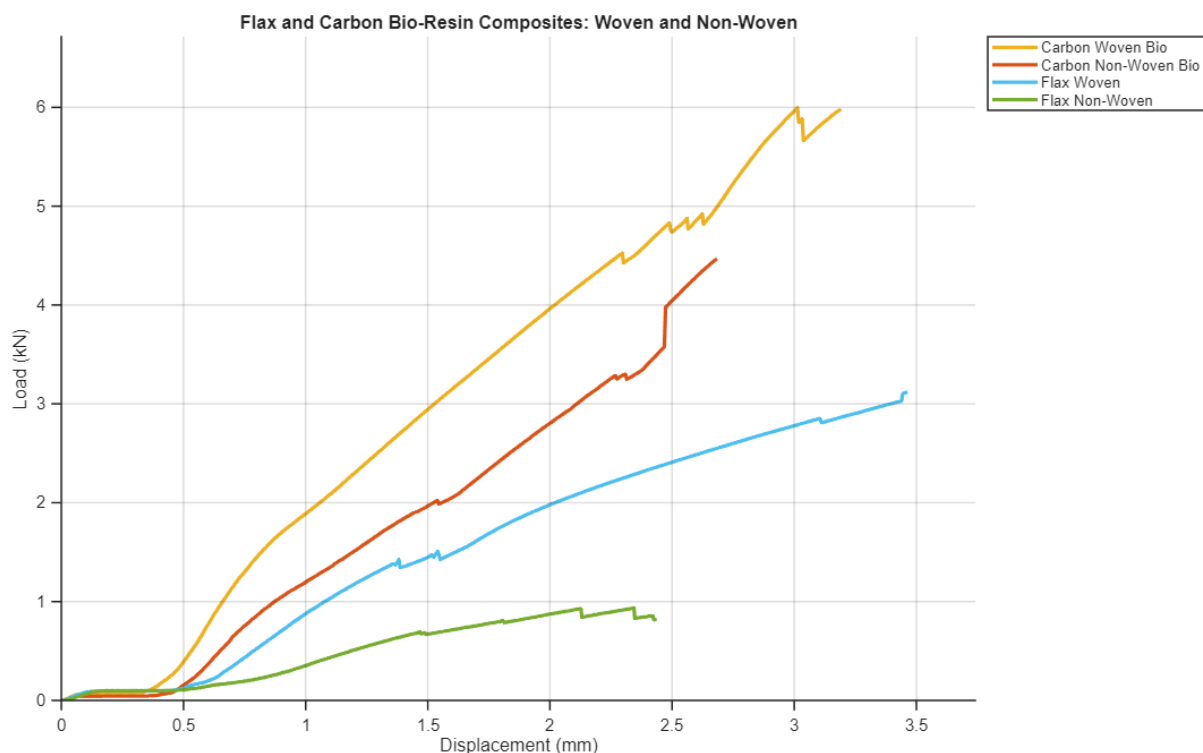


Figure 21: Comparison load-displacement of woven and non-woven

Figure 21 further supports this, showing that both woven laminates sustained higher loads before failure. Overall, this indicates that woven reinforcement provided a more effective tensile architecture than the non-woven form in the present study, although the 45° ply arrangement also influenced the measured behaviour.

4.5 - Flax and Carbon Performance

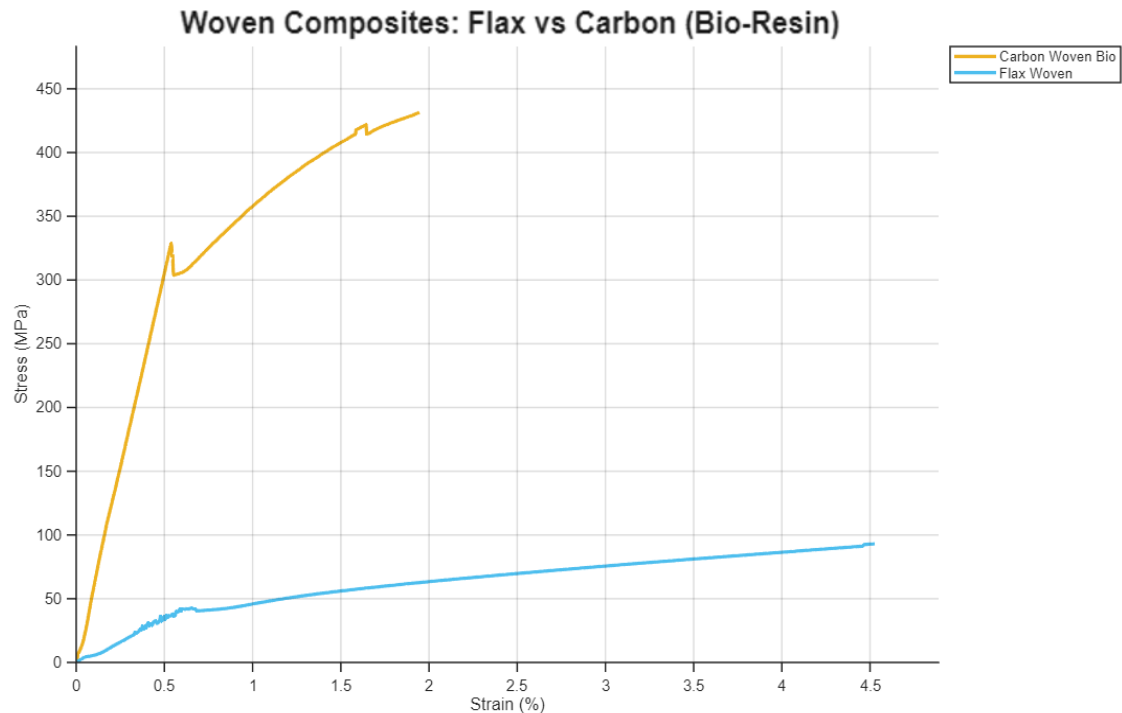


Figure 22: Comparison stress-strain of flax and carbon

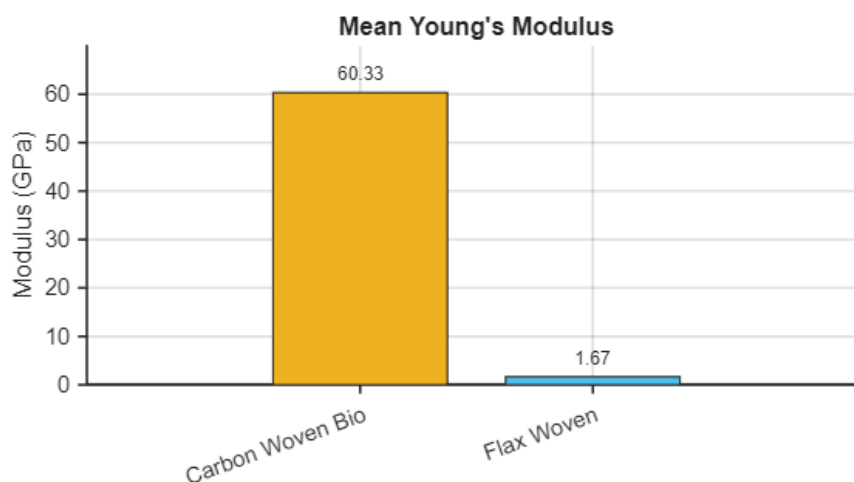


Figure 23: Bar chart comparing Young's Modulus of flax and carbon

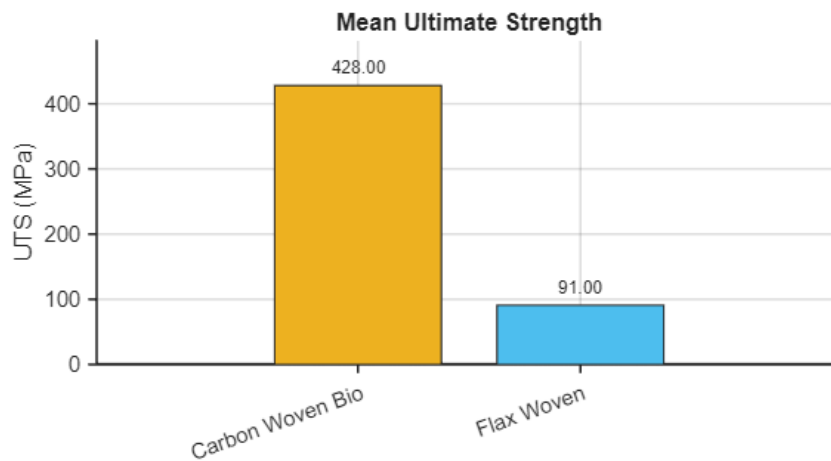


Figure 24: Bar chart comparing UTS of flax and carbon

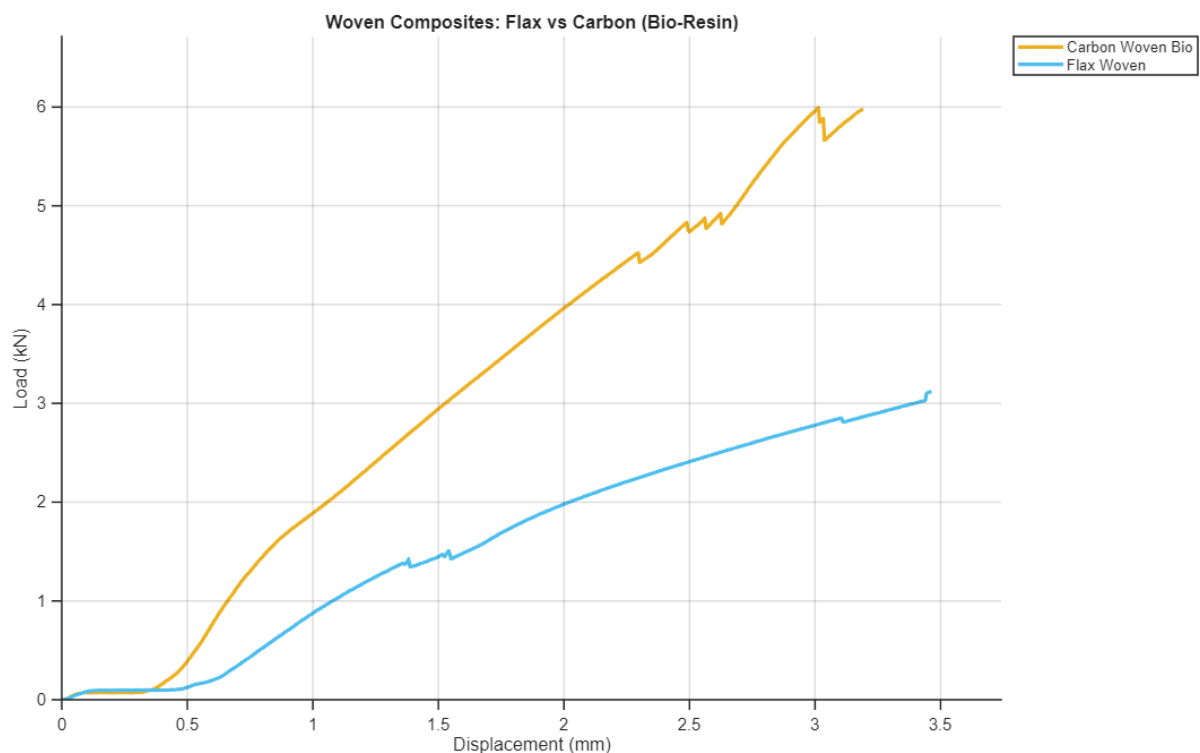


Figure 25: Comparison load-displacement of flax and carbon

The woven carbon showed much higher stiffness due to its steeper stress-strain curve. It also had higher strength and load-carrying capacity, while the woven flax reached a greater strain before failure. Carbon fibre is a synthetic reinforcement made mainly of aligned carbon atoms, giving it much higher stiffness and strength at the fibre level (Encyclopedia.com, 2026). Flax tends to deform more due to the non-linear tensile behaviour where cellulose microfibrils progressively align during loading (Charlet et al., 2009), as shown by the results. Because flax is a natural plant-based fibre, its properties also vary more and are influenced by factors such as growth conditions and fibre sampling (Baley et al., 2020).

4.6 - Bio-Resin and Conventional Epoxy Performance

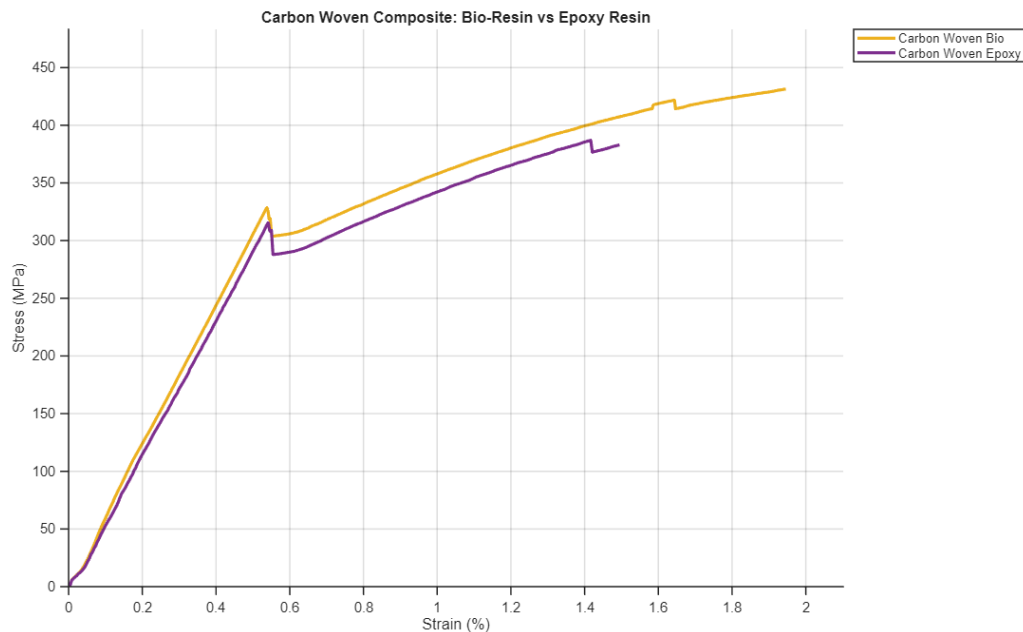


Figure 26: Comparison stress-strain of bio-resin and epoxy-resin

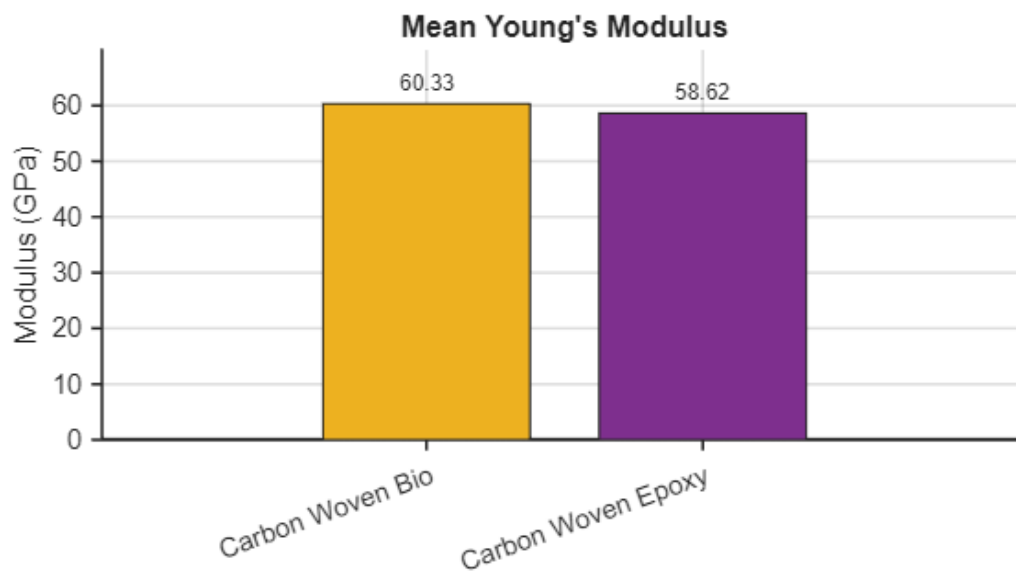


Figure 27: Bar chart comparing Young's Modulus of bio-resin and epoxy-resin

Changing from conventional epoxy to bio-resin made only a small difference to the tensile behaviour of the woven carbon. The bio-resin was able to retain its performance without reducing deformation capacity. This suggests that the carbon reinforcement remained the main factor affecting the tensile response, resin only had a minor effect.

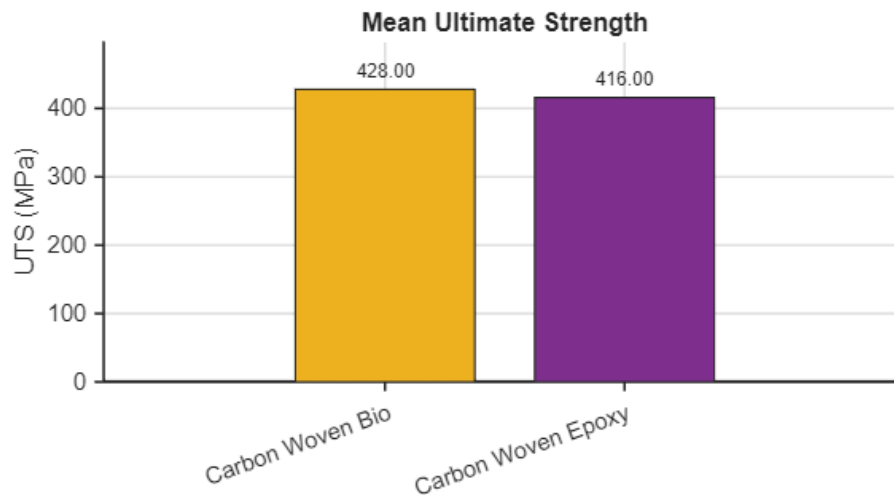


Figure 28: Bar chart comparing UTS of bio-resin and epoxy-resin

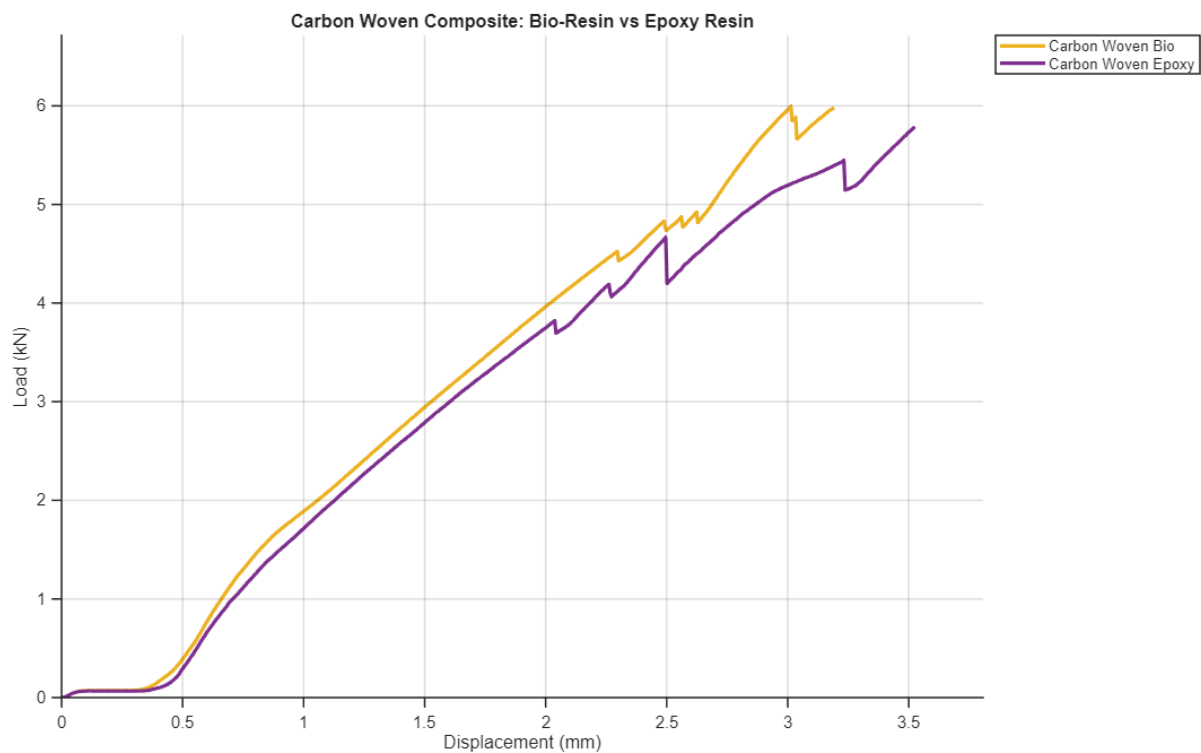


Figure 29: Comparison load-displacement of bio-resin and epoxy-resin

Although epoxy-resin reached a slightly greater displacement, the bio-resin generally carried a slightly higher load during the test. The epoxy-resin trace also showed more variation than the bio-resin, which may suggest a less smooth damage progression, possibly involving matrix cracking or small fibre-bundle failures (Wu et al., 2021). Overall, there is no clear mechanical advantage shown by the conventional epoxy, and bio-resin was able to provide very similar structural performance.

4.7 - Comparison with Kevlar

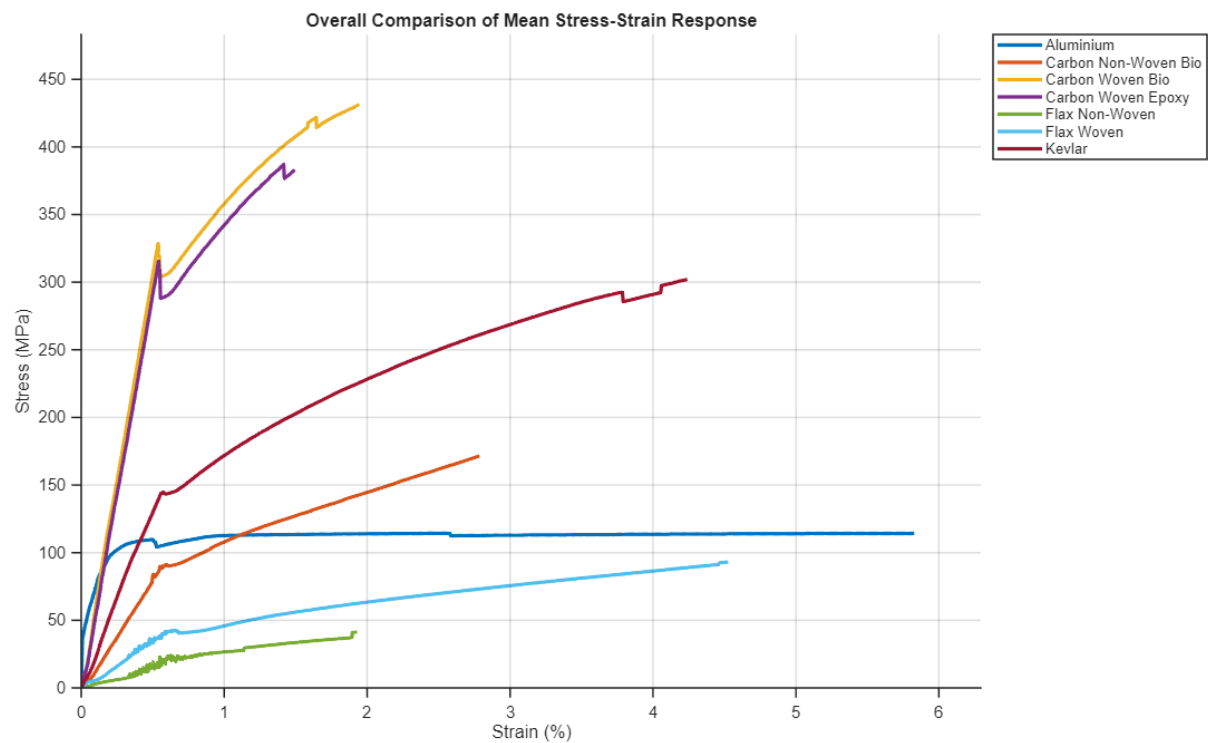


Figure 30: Comparison stress-strain of Kevlar and other materials

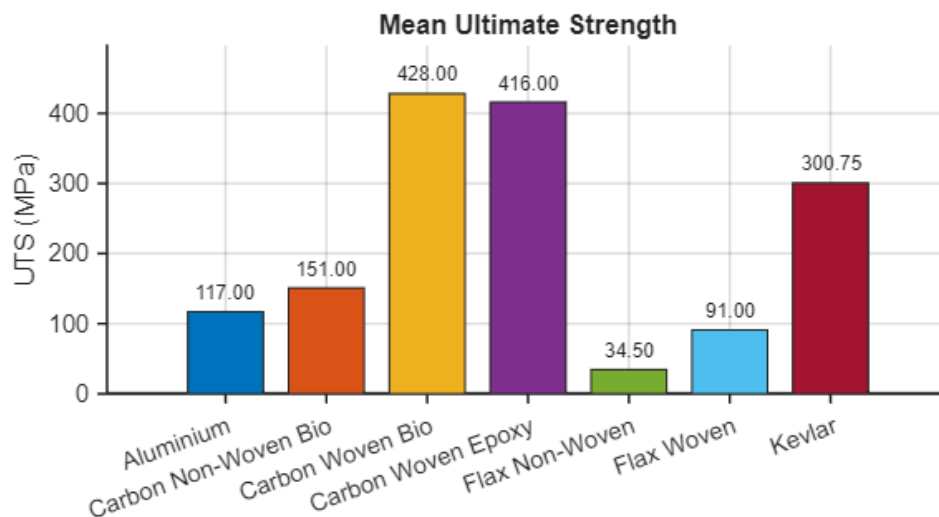


Figure 31: Bar chart comparing Young's Modulus of Kevlar and other materials

Kevlar is a tough aramid fibre that is typically valued for impact resistance and damage tolerance rather than maximum stiffness (Ursache, Cerbu and Hadăr, 2024), which helps explain its results compared to the carbon composites. In this study, Kevlar showed intermediate tensile performance, with a mean UTS above aluminium and flax, but below the woven carbon materials.

4.8 - Failure Behaviour and Key Observations

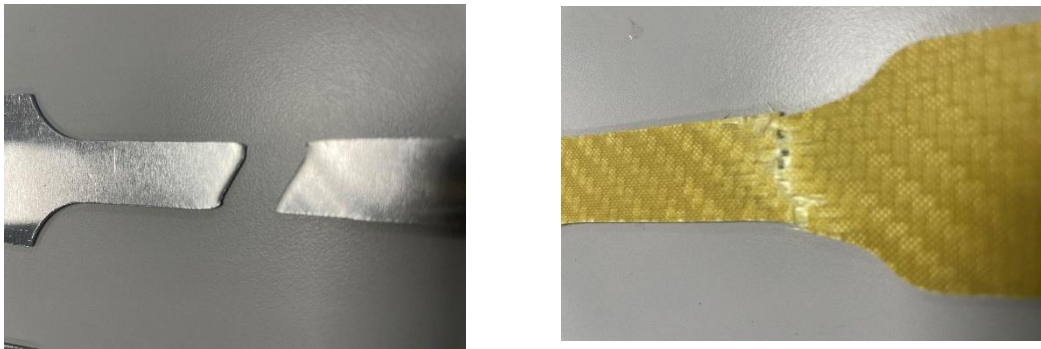


Figure 32: Aluminium (left), Kevlar (right)

The aluminium specimen showed ductile behaviour failing with a clear diagonal fracture through the coupon. The Kevlar specimen did not separate fully like the other materials, suggesting more progressive damage. This is consistent with Kevlar's tougher, more energy-absorbing behaviour, which helps explain why it was able to sustain relatively high stress and strain without a completely clean fracture.



Figure 33: Flax non-woven (left), Flax woven (right)

Both flax specimens failed in a relatively brittle manner, but the non-woven flax showed a noticeably rougher fracture surface than the woven flax. This is likely because the non-woven structure has a less organised fibre arrangement, so failure did not follow one clean path through the specimen. The woven flax failed more cleanly, suggesting a more controlled fracture path.



Figure 34: Carbon non-woven bio (left), Carbon woven bio (middle), Carbon woven epoxy (right)

All three carbon specimens showed clean, brittle fracture. The non-woven sample had an angled break, while both woven carbon specimens failed almost flat, suggesting a more uniform failure path in the woven laminates. Epoxy-resin had the cleanest fracture, which is consistent with its slightly more abrupt final failure. The non-woven bio may also have shown a less uniform fracture because of its less organised fibre arrangement like non-woven flax.

4.9 - Law of Mixtures

The law of mixtures was used as a simplified theoretical comparison to assess whether the measured composite modulus values were consistent with expected upper and lower stiffness bounds. The equations used can be found in Appendix DA.

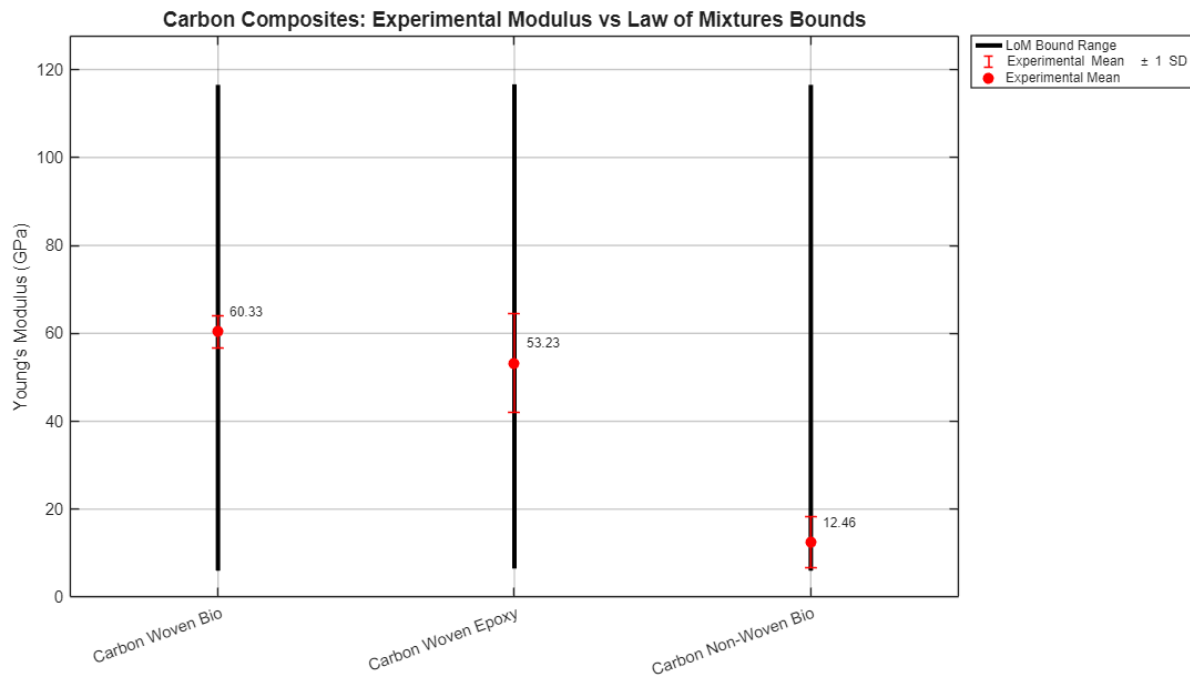


Figure 35: Law of mixtures for carbon composites

For the carbon composites, the experimental modulus values all fell within the theoretical bounds, indicating that the measured stiffness values were reasonable. However, they remained well below the upper bound, meaning the laminates did not behave perfectly where all fibres are aligned with the loading direction. This is consistent with the earlier discussion, where the woven and non-woven carbon specimens showed clear differences in tensile response and were affected by reinforcement architecture.

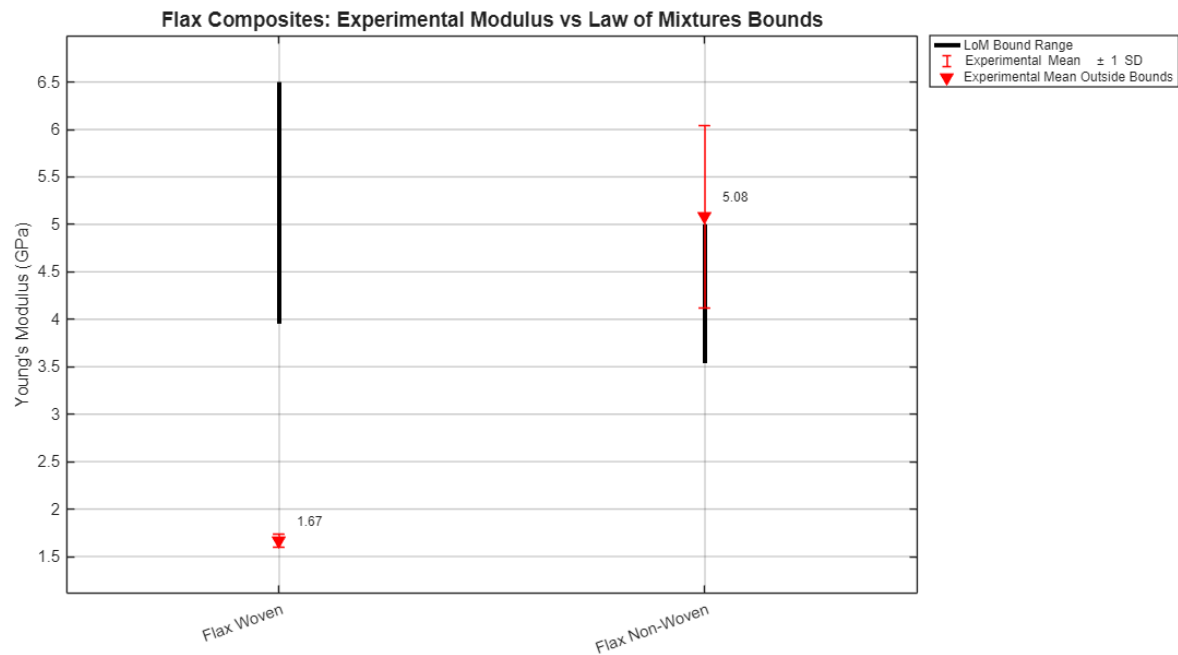


Figure 36: Law of Mixtures for flax composites

The flax results showed less similarity. This might be because the simple law of mixtures assumptions were less suitable for the flax laminates, rather than that the test results were invalid. This is likely because the fibres did not align directly with the tensile load as well as the carbon samples did. Overall, the law of mixtures gives a useful comparison, but the experimental results confirm that laminate architecture and fibre arrangement had a strong influence on the measured stiffness.

5 – Sustainability analysis

5.1 - Environmental Comparison of Carbon and Flax Composites

Table 5: Sustainability strengths and limitations of the tested composite systems

Material	Sustainability strengths	Sustainability limitations	Source
Flax woven bio	Renewable reinforcement with lower environmental impact, renewable fibre	Natural fibre variability	EcoTechnilin (2023a), Composite Testing Plan (2026)
Carbon woven bio	Bio-based resin, ~31% plant-based resin	Carbon fibre still energy intensive	Easy Composites Ltd (2026), Composite Testing Plan (2026)
Carbon woven epoxy	Can be combined with natural flax reinforcements	Higher fossil-based material dependence	Easy Composites Ltd (2024b), Composite Testing Plan (2026)
Flax non-woven bio	Economical, renewable reinforcement with lower environmental impact, renewable fibre	Natural fibre variability	EcoTechnilin (2023b), Composite Testing Plan (2026)
Carbon non-woven bio	100% recycled carbon fibre / cost savings / mat binding readily breaks down with resin and can be easily conformed to complex, compound forms	Unknown origin of the feed stock	Easy Composites Ltd (2024a), Composite Testing Plan (2026)

The main sustainability difference between the composites is the origin and production of the reinforcement feedstock. Ramachandran et al. (2023) compared flax-based biocomposites with carbon fibre composites and found that carbon fibre production had an energy use of 1100 MJ, compared with 203 MJ for flax. Its global warming potential was also much higher, at 54.3 kgCO₂eq compared with 12.5 kgCO₂eq. This difference is mainly linked to the energy-intensive processes like carbonisation and graphitisation. However, certain areas like toxicity showed higher values in biocomposites which is likely due to the use of fertilisers containing nitrogen and phosphorus for growth of crops (Ramachandran et al., 2023).

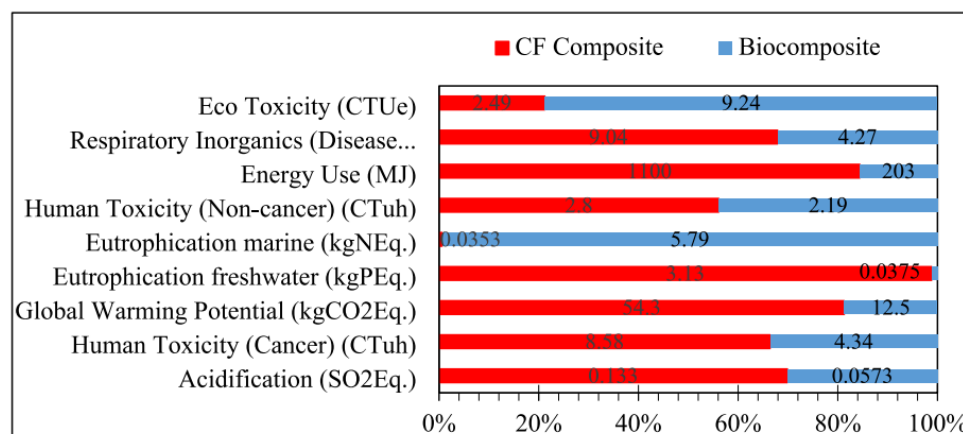


Figure 37: Environmental analysis taken from Ramachandran et al. (2023)

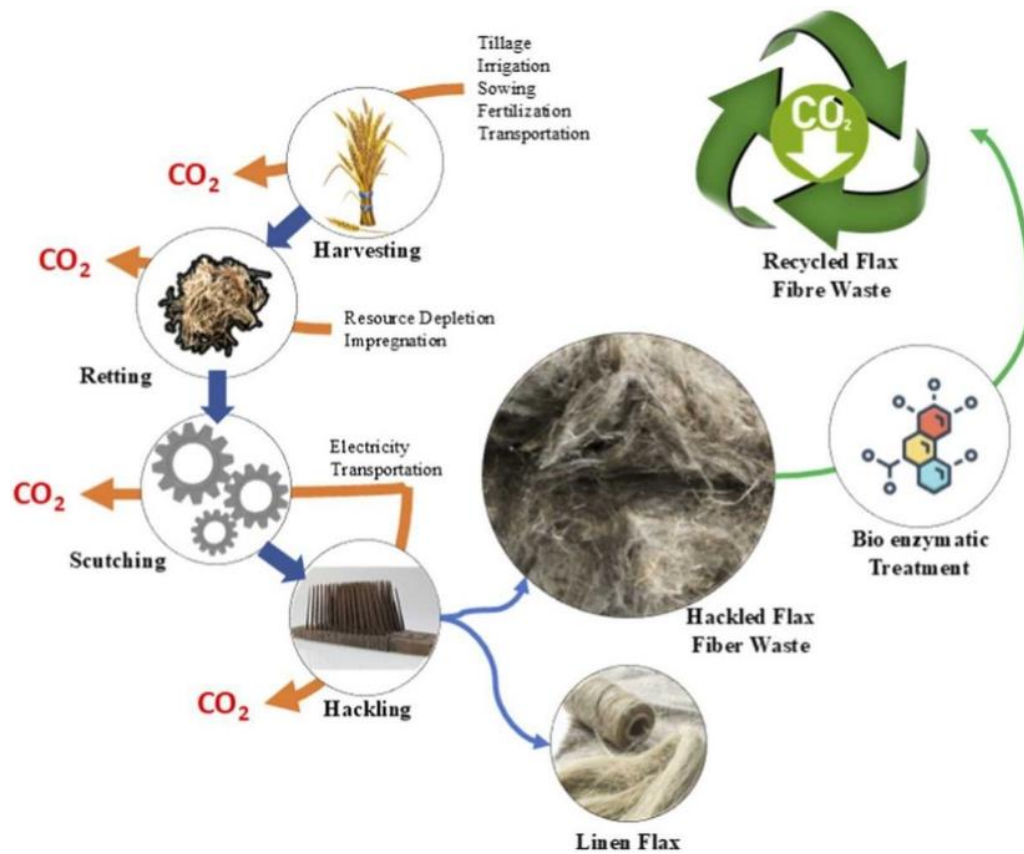


Figure 38: Flax manufacturing process taken from Chowdhury et al. (2025)

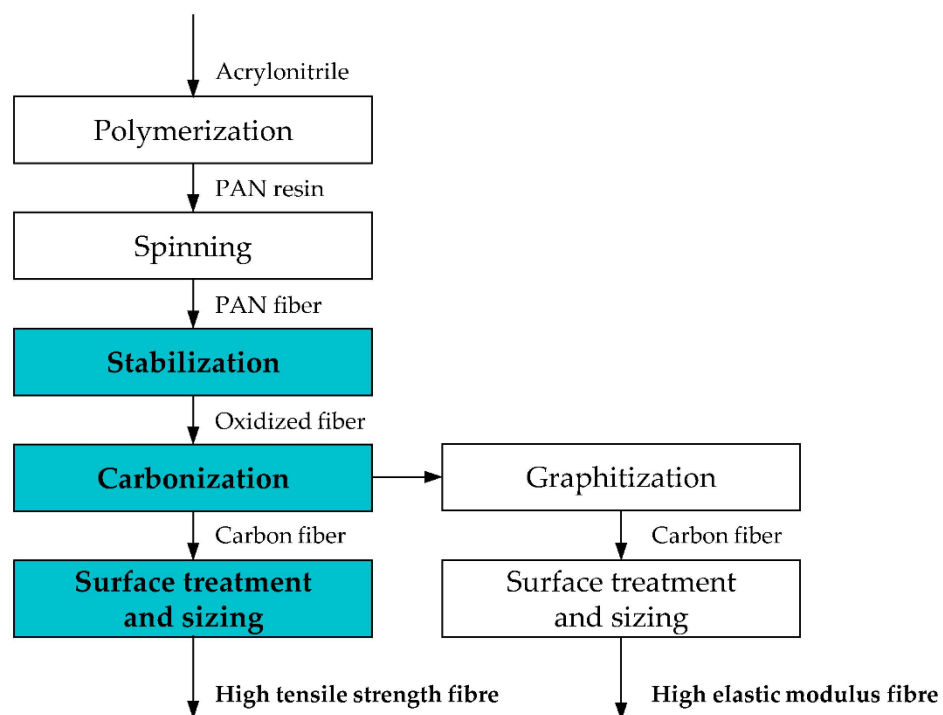


Figure 39: Carbon fibre manufacturing process taken from Prenzel et al. (2023)

5.2 - Recyclability, End-of-Life and Practical Constraints

Table 6: End-of-life constraints and recommended applications of the tested composite systems

Material	Processing	End-of-life / practical constraints	Recommended application	Source
Flax woven bio	Infusion / RTM / thermocompression / hand lay up	Moisture / fire / less usability / must be stored in dry area and avoid direct sunlight	Semi-structural panels / Interior / trim / non-critical panels	EcoTechnilin (2023a), Composite Testing Plan (2026)
Carbon woven bio	3-ply 200 g carbon twill / resin infusion / 45° lay-up / bio-epoxy	Recycling is difficult because the matrix is a thermoset	High-performance structural panels	Easy Composites Ltd (2026), Composite Testing Plan (2026)
Carbon woven epoxy	3-ply 200 g carbon twill / resin infusion / 45° lay-up / conventional epoxy	Recycling is difficult because the epoxy matrix is a thermoset	Performance-first applications	Easy Composites Ltd (2024b), Composite Testing Plan (2026)
Flax non-woven bio	Needlepunching / infusion / RTM / thermocompression / hand lay up	Moisture / fire / less usability / must be stored in dry area and avoid direct sunlight	Interior / trim / non-critical panels	EcoTechnilin (2023b), Composite Testing Plan (2026)
Carbon non-woven bio	Most composite processes and resin systems, like hand layup and resin infusion using epoxy, vinylester or polyester resin systems.	Matrix is a thermoset but recycling is possible, but the recycled output is lower grade	Compression moulding processes / vacuum infusion to consolidate and bulk out laminates / excellent surface finish	Easy Composites Ltd (2024a), Composite Testing Plan (2026)

As a thermoset, epoxy cannot simply be melted and reused, so recycling options are limited and generally lower value than normal material recovery. The lower manufacturing impact of flax does not remove the end-of-life issue once the fibre is inside a cured resin system. Biocomposites can still have environmental impacts in categories such as eutrophication (Ramachandran et al., 2023), meaning their sustainability depends on the full lifecycle rather than fibre origin alone.

The flax composites also have practical limits due to moisture and storage conditions, which significantly reduce what they can be used for. Recycled carbon non-woven improves the carbon option by avoiding virgin fibre production, but it is better suited for bulking, cosmetic or secondary laminate use than primary structural parts.

5.3 - Sustainability of Bio-Resin and Conventional Epoxy

Table 7: IB2 and IN2 processing and service comparison

Property	IB2 bio-resin	IN2 conventional epoxy
Sustainability basis	~31% plant-based content	Conventional infusion epoxy
Pot life	1 h 25 min @ 20°C	120-150 min slow / 10-14 min fast @ 25°C
Demould time	35 h 30 min @ 20°C	18-24 h slow / 6-8 h fast @ 25°C
Initial cure schedule	No separate short full-cure value stated	7 days @ 25°C
Time to full mechanical performance	At least 14 days @ 25°C	At least 14 days @ 25°C
Suggested post-cure	16 h ambient + 24 h at 40°C	24 h ambient + 6 h at 60°C
Cured resin tensile strength	60-68 MPa	68.5-80.0 MPa
Heat resistance indicator	Tg onset 71-85°C	Maximum Tg 82-98°C
Storage conditions	10-25°C, sealed	10-25°C, sealed
Shelf life	24 months	12 months
Source	Easy Composites Ltd (2026)	Easy Composites Ltd (2024b)

The difference between IB2 and IN2 is not just their sustainability once made, but also how they must be processed and brought to full performance. Although IN2 offers greater flexibility through its fast and slow hardener options, both resins still require controlled storage, post-curing and time to reach full mechanical performance.

Table 8: IB2 and IN2 sustainability and application comparison

Property	IB2 bio-resin	IN2 conventional epoxy
Sustainability / practical strength	~31% plant-based content; lower fossil-based raw material dependence, usable cured-resin strength and heat resistance	High-performance infusion epoxy; strong processing and structural-part suitability
Sustainability limitation	Thermoset epoxy at end of life	Higher fossil-based raw material dependence / thermoset epoxy at end of life
Mechanical outcome in present tests	Comparable tensile performance in the present tests	Comparable tensile performance in the present tests
Typical applications	Motorsport panels / aerodynamic elements / structural members	Panels, aerodynamic elements, structural members
Recommended use	Laminating unpainted carbon fibre composites / structural parts / resin infusion composites production	High performance resin infusion applications / for use in combination with natural flax reinforcements
Source	Easy Composites Ltd (2026)	Easy Composites Ltd (2024b)

The sustainability advantage of IB2 lies mainly in its partly plant-based feedstock, rather than in removing the broader limitations associated with epoxy composites. Both systems are cured thermoset epoxies in use, so the overall change represents a modest improvement in sustainability rather than a complete shift in lifecycle outcome. This supports what's stated in Section 2.4, sustainability depends not only on feedstock origin but also on how the resin performs and is managed in service (Capretti et al., 2023; Seid and Adimass, 2024).

5.4 - Suitability for Automotive and Motorsport Applications

All tested composites have potential automotive or motorsport applications. But suitability is no longer based only on reducing weight or improving performance because of the proposed EU End-of-Life Vehicles regulation mentioned in Section 2.1. However, this regulation is primarily aimed at automotive applications rather than track-only motorsport. Motorsport is instead influenced more by governing-body sustainability strategies and championship-specific requirements (FIA, 2021).

Materials that use renewable or recycled feedstocks like flax align more naturally with the direction of regulation, especially where lower material impact is more important than maximum structural performance. By contrast, conventional virgin-carbon systems remain easier to justify only where their higher performance is necessary enough to outweigh their weaker end-of-life recovery.

5.5 - Material Selection Recommendations

Table 9: Performance validation and physical-property comparison of the tested composite systems

Material	Experimental performance	Supplier reference performance	Density (g/cm ³) / Surface weight (gm ²)	Source
Flax woven bio	E = 1.67 GPa / UTS = 91.00 MPa	E = 6-7 GPa / UTS = 58-61 MPa	D = 1.45 / SW = 220	EcoTechnilin (2023a) / Composite Testing Plan (2026)
Carbon woven bio	E = 60.33 GPa / UTS = 428.00 MPa	3k PYROFIL fibre: E = 234 GPa / UTS = 4120 MPa	D = 1.79 / SW = 200	Mitsubishi Rayon Co., Ltd. (2013) / Easy Composites Ltd (2026) / Composite Testing Plan (2026)
Carbon woven epoxy	E = 58.62 GPa / UTS = 416.00 MPa	3k PYROFIL fibre: E = 234 GPa / UTS = 4120 MPa	D = 1.79 / SW = 200	Mitsubishi Rayon Co., Ltd. (2013) / Easy Composites Ltd (2024b) / Composite Testing Plan (2026)
Flax non-woven bio	E = 5.20 GPa / UTS = 34.50 MPa	E = 5 GPa / UTS = 37-44 MPa	D = 1.45 / SW = 300	EcoTechnilin (2023b) / Composite Testing Plan (2026)
Carbon non-woven bio	E = 11.37 GPa / UTS = 151.00 MPa	E = 25-35 GPa / UTS = 290-330 MPa	D = 1.51	Easy Composites Ltd (2024a) / Composite Testing Plan (2026)

Compared to the supplied data sheets, only flax non-woven bio produced similar results, the PYROFIL values especially were much higher. This is because they represent raw fibre properties, whereas the experimental values are finished laminates, whose stiffness and strength are reduced by matrix content and laminate architecture.

The other published higher UTS and modulus values were obtained for a specific vacuum-infused reference laminate tested in the warp and weft directions. The woven coupons in this study used a simple lay-up, which likely affected the measured response. Despite this, carbon consistently had higher stiffness and strength, making it more suitable for structural or exterior components.

Because flax is typically lighter than carbon, it is the better choice for non-structural interior parts on vehicles, reducing weight, which in turn reduces fuel use improving its carbon footprint. Section 4.6 and 5.3 showed that bio-resin was more sustainable without large performance losses. Material selection therefore must consider manufacturing impact, practical service requirements and end-of-life recovery together or potentially prioritise one depending on the intended function.

Companies may also consider added coatings or finishes to increase durability, surface quality or heat resistance, improving service performance, but this could add further material and end-of-life complexity (Atalie and Gideon, 2025).

6 - Recommendations

Further work should compare flat and curved composite coupons, as specimen geometry can influence the measured tensile response and load-deformation characteristics depend on the specimen size (Callister and Rethwisch, 2020).

Coupon testing procedures need to account for both the type and size of coupons, highlighting the importance of specimen form in mechanical testing (Huang and Young, 2014). In the present study, this would be particularly relevant because laminate thickness and architecture were not identical across the supplied material set.

7 - Conclusion

Overall, the results showed a clear trade-off between tensile performance and sustainability. Woven carbon bio gave the strongest tensile performance, with a Young's modulus of 60.33 GPa and an ultimate tensile strength of 428 MPa, while woven flax bio returned 1.67 GPa and 91 MPa. This confirms that carbon is more suitable where high stiffness, strength and load-carrying capacity are required. Flax offers a clear sustainability advantage over virgin carbon, but its benefit still depends on responsible cultivation and processing. The difference between bio-resin and conventional epoxy was small, so the bio-resin offered a better sustainability compromise without a major tensile penalty.

However, the automotive and motorsport industries do not have the same material requirements. In automotive, material choice is increasingly influenced by end-of-life considerations, lower environmental impact and suitability for mass production, which makes flax and other lower-impact materials better for non-structural parts. In motorsport, the priority is still maximum performance, meaning woven carbon is still the more defensible option for demanding components. Overall, the environmental benefit was driven mainly by whether the reinforcement was renewable, virgin synthetic or recycled synthetic.

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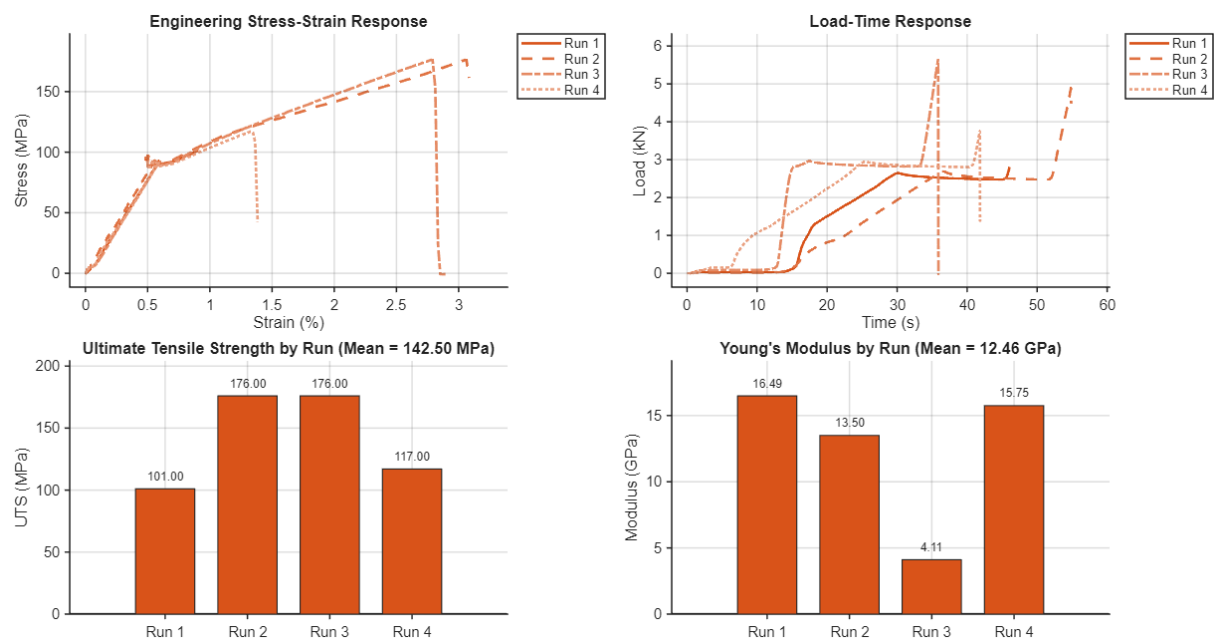
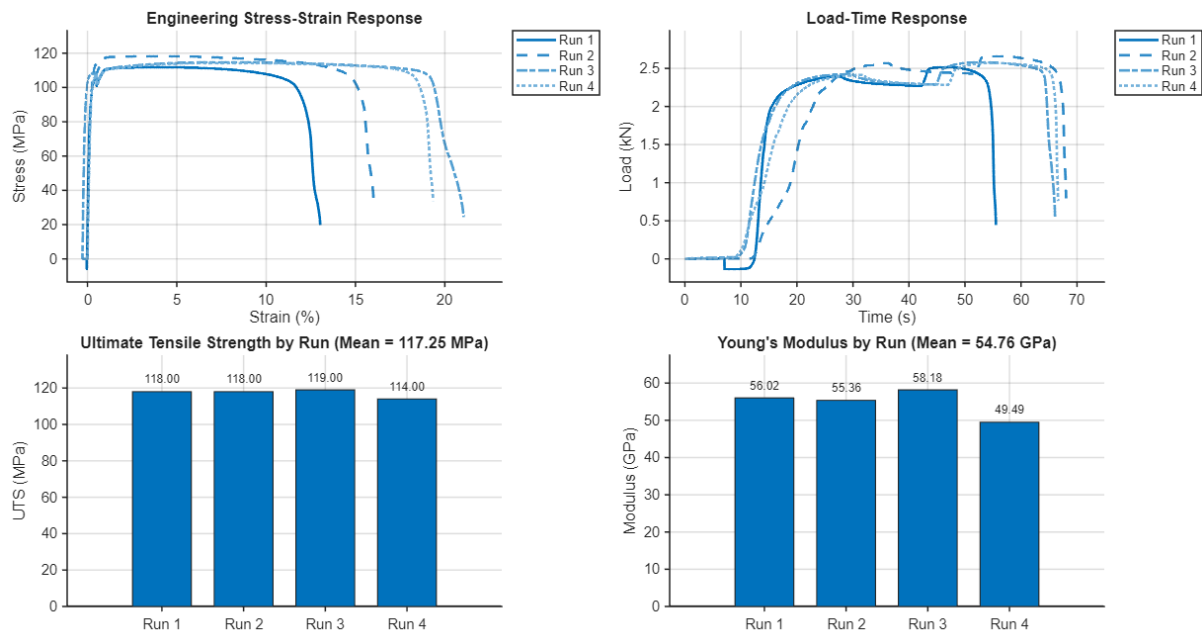
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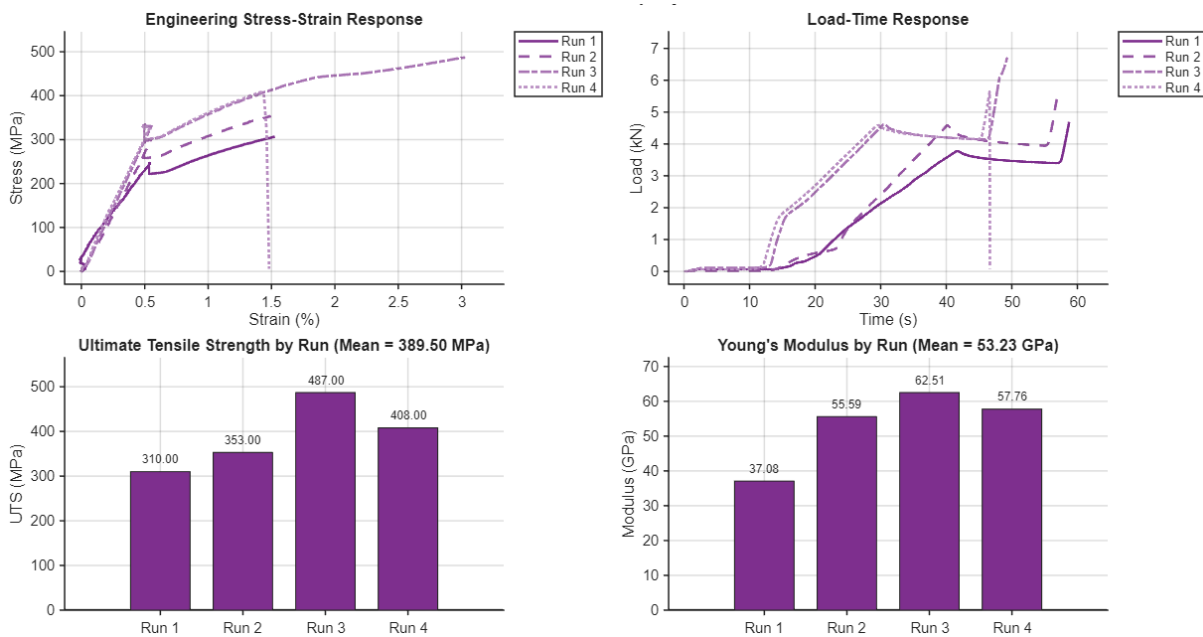
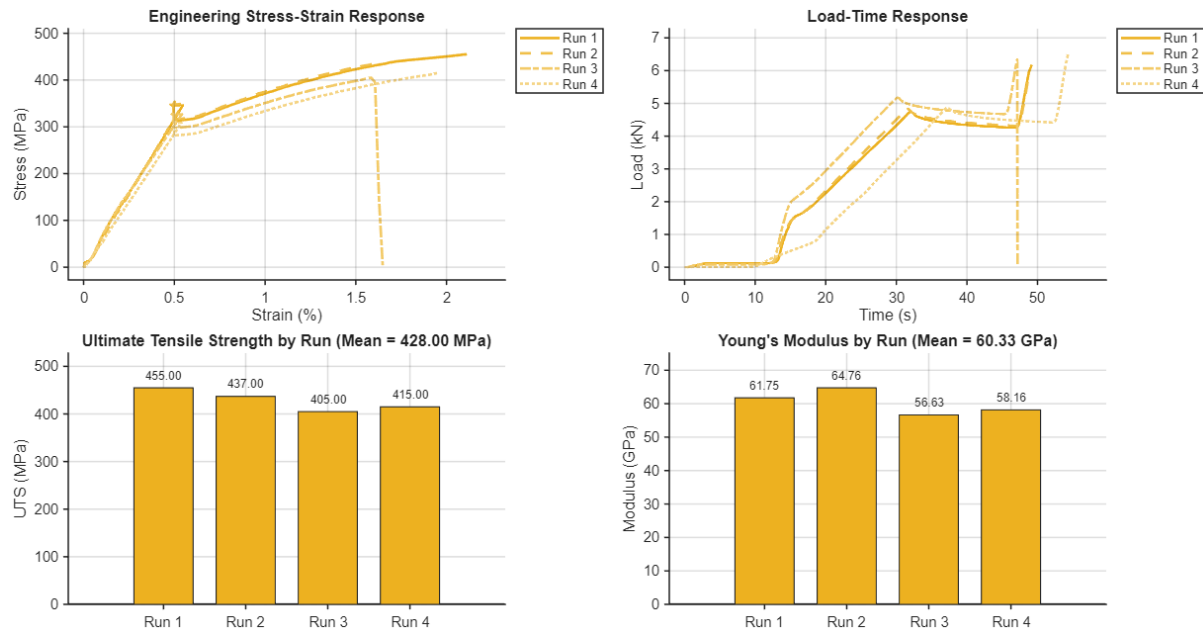
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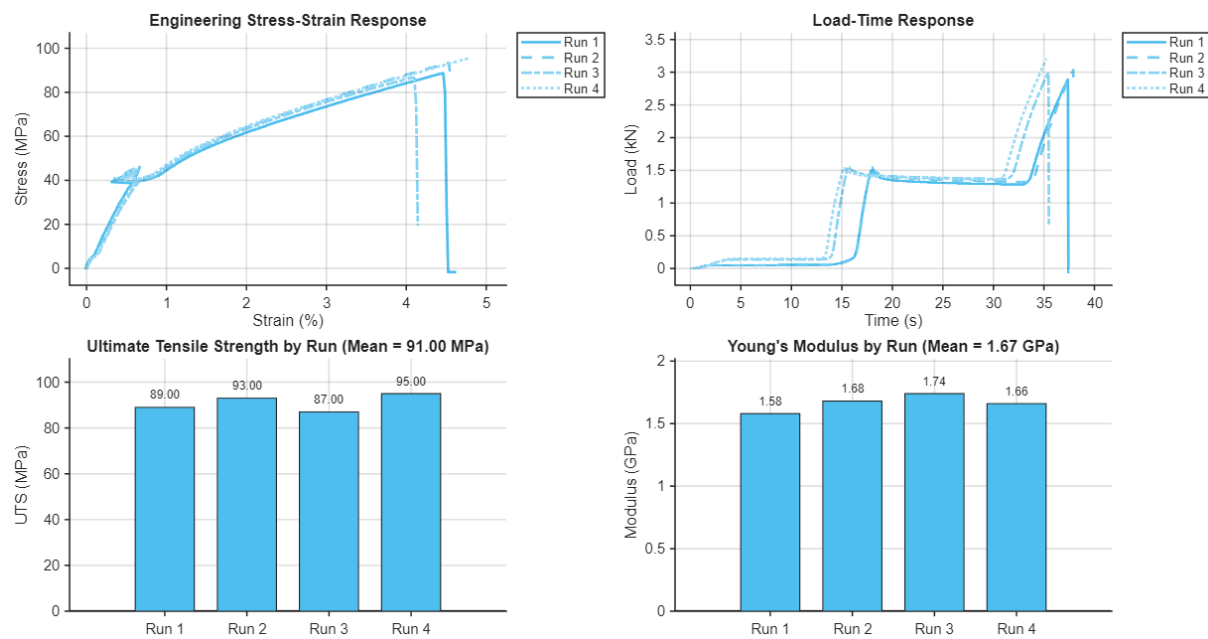
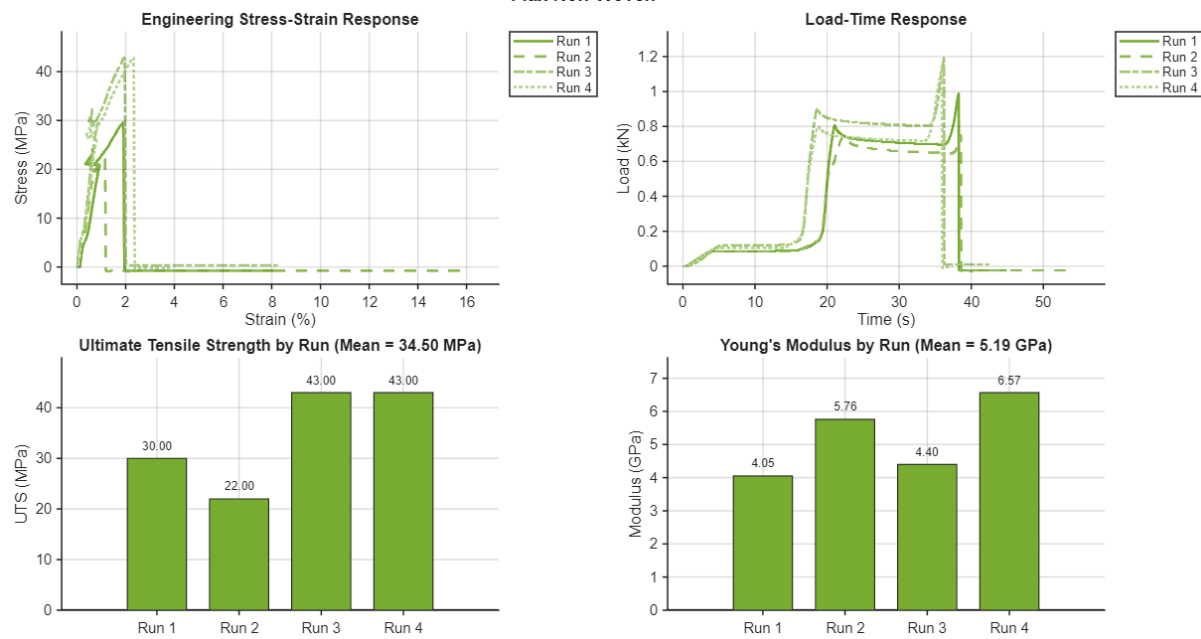
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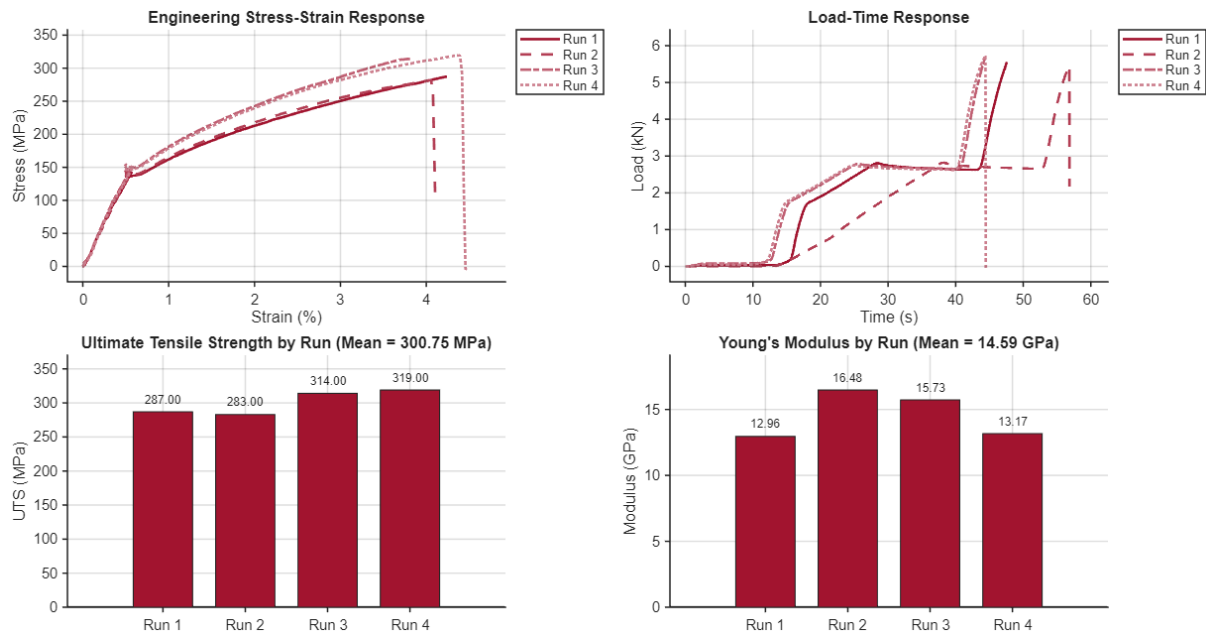
9 – Appendices

Appendix A - Raw Data Tables

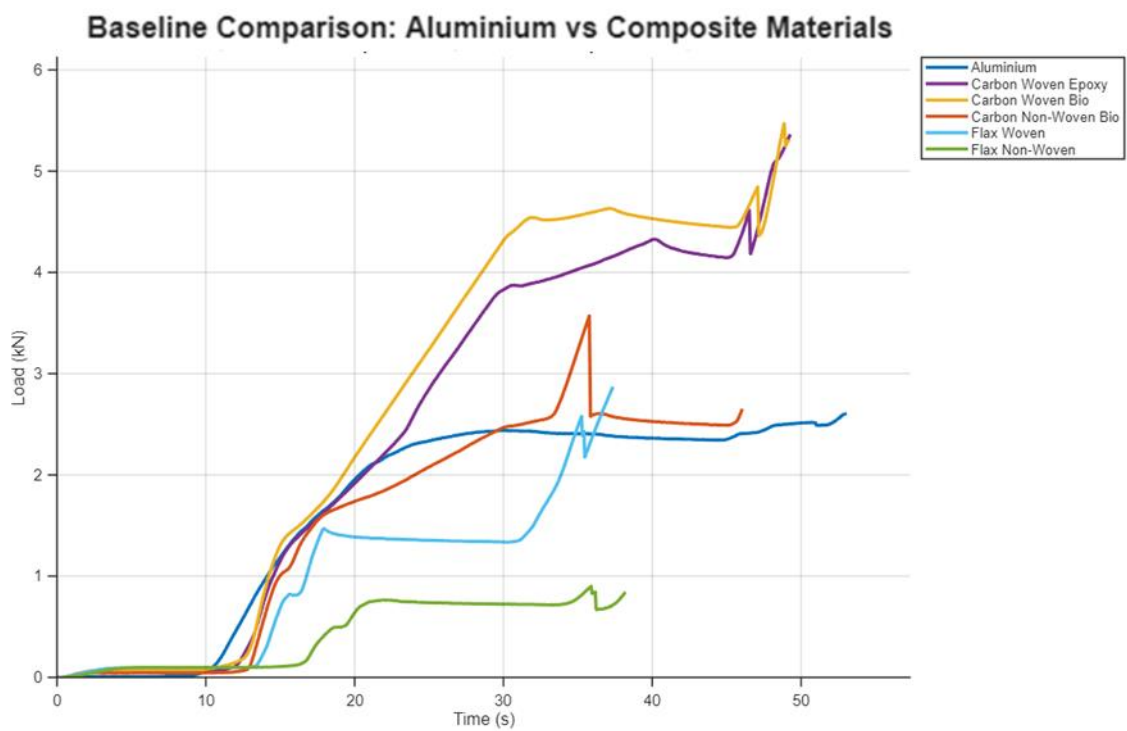


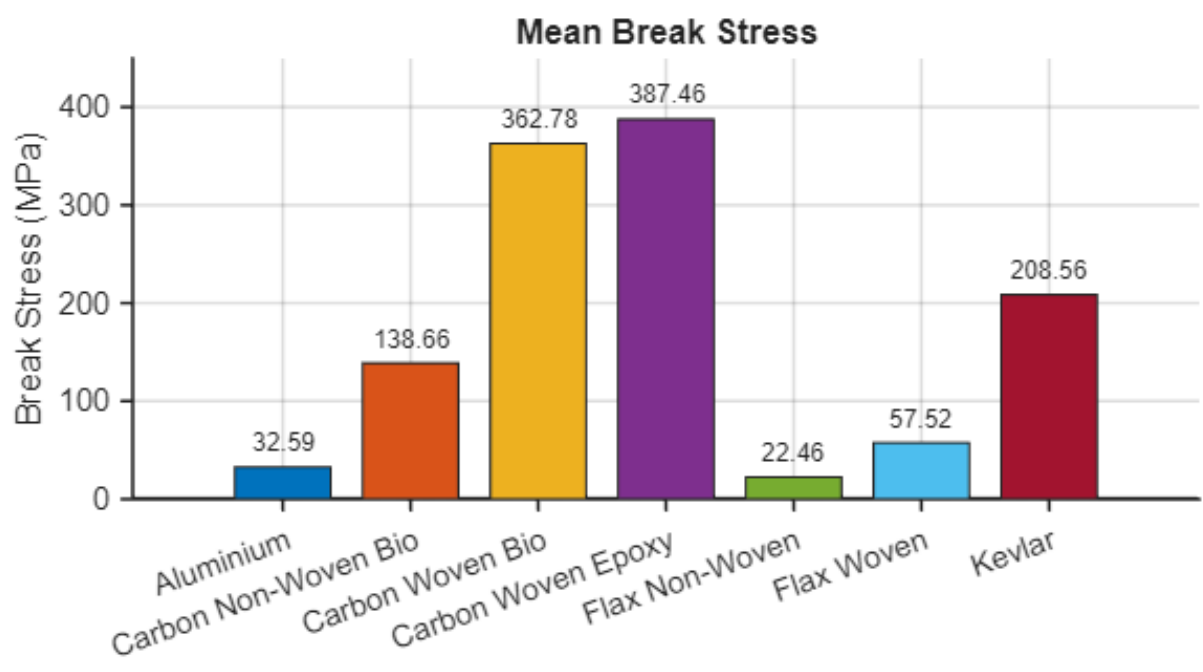
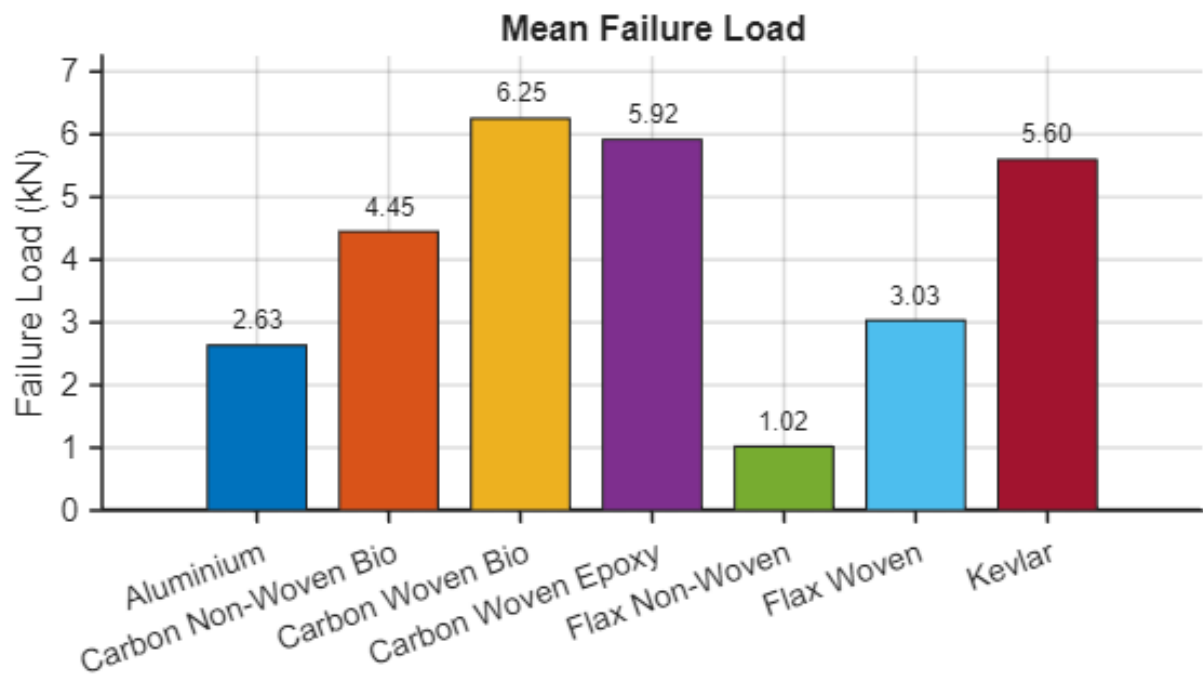


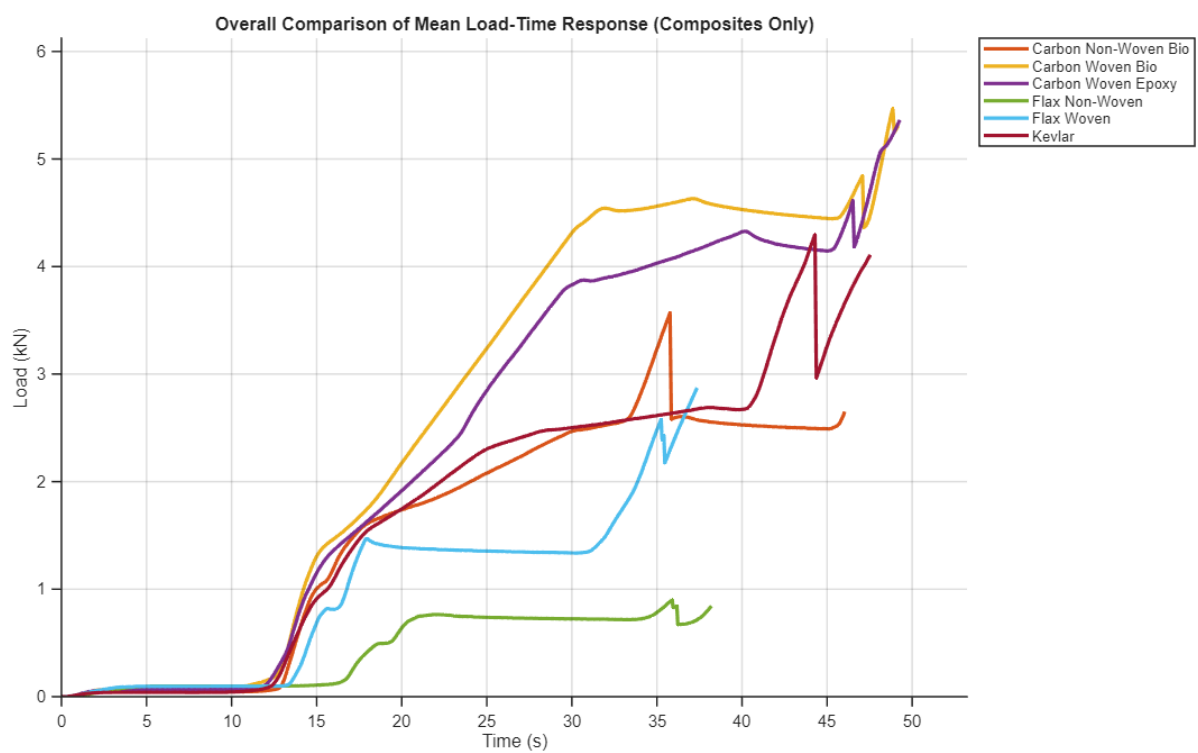
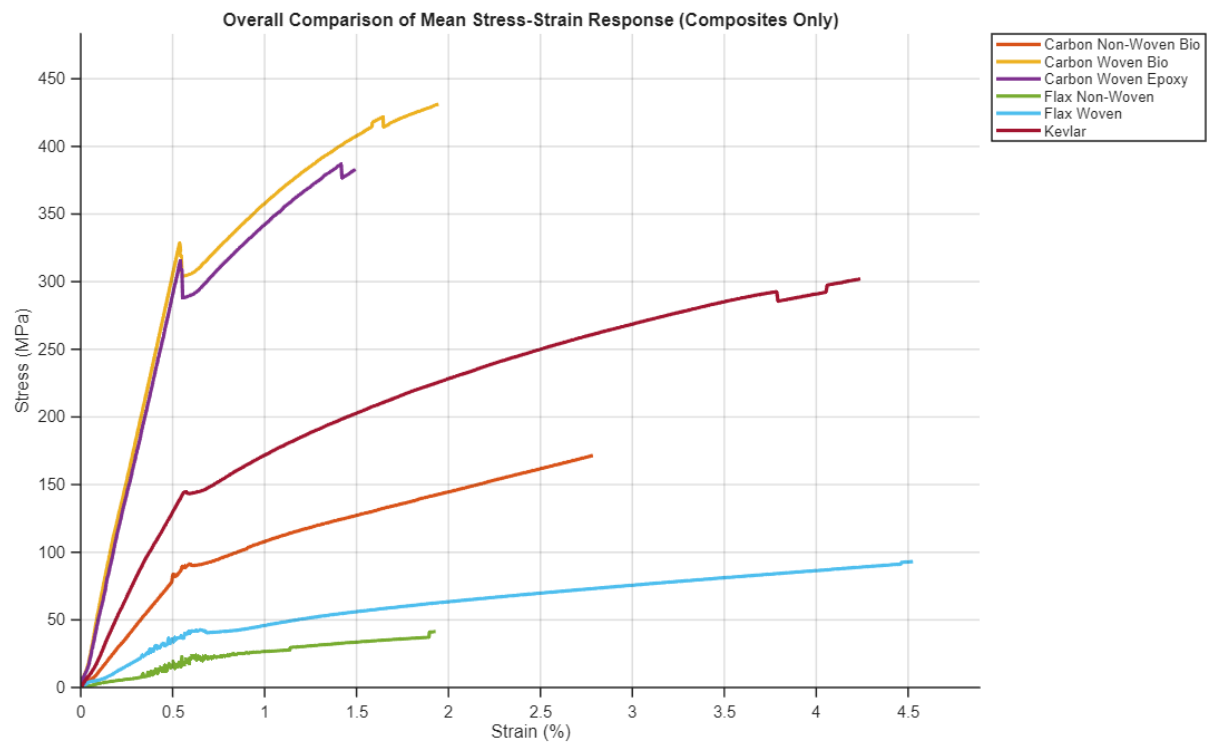




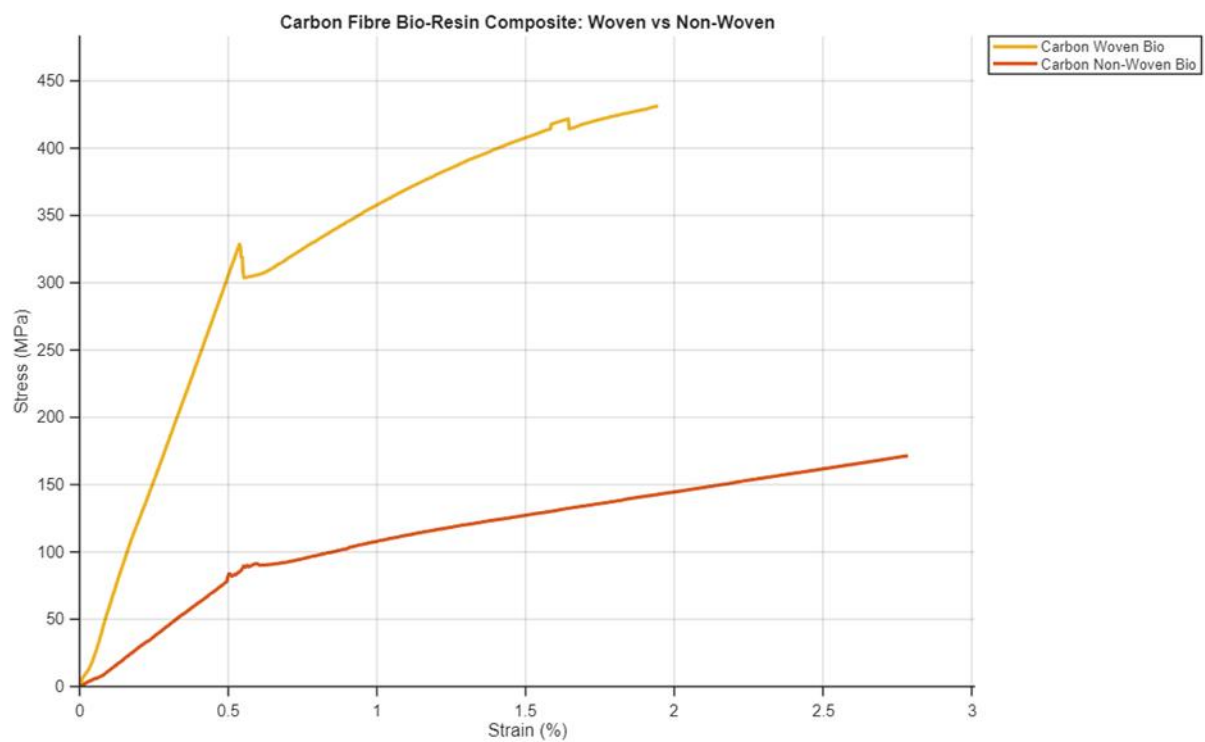
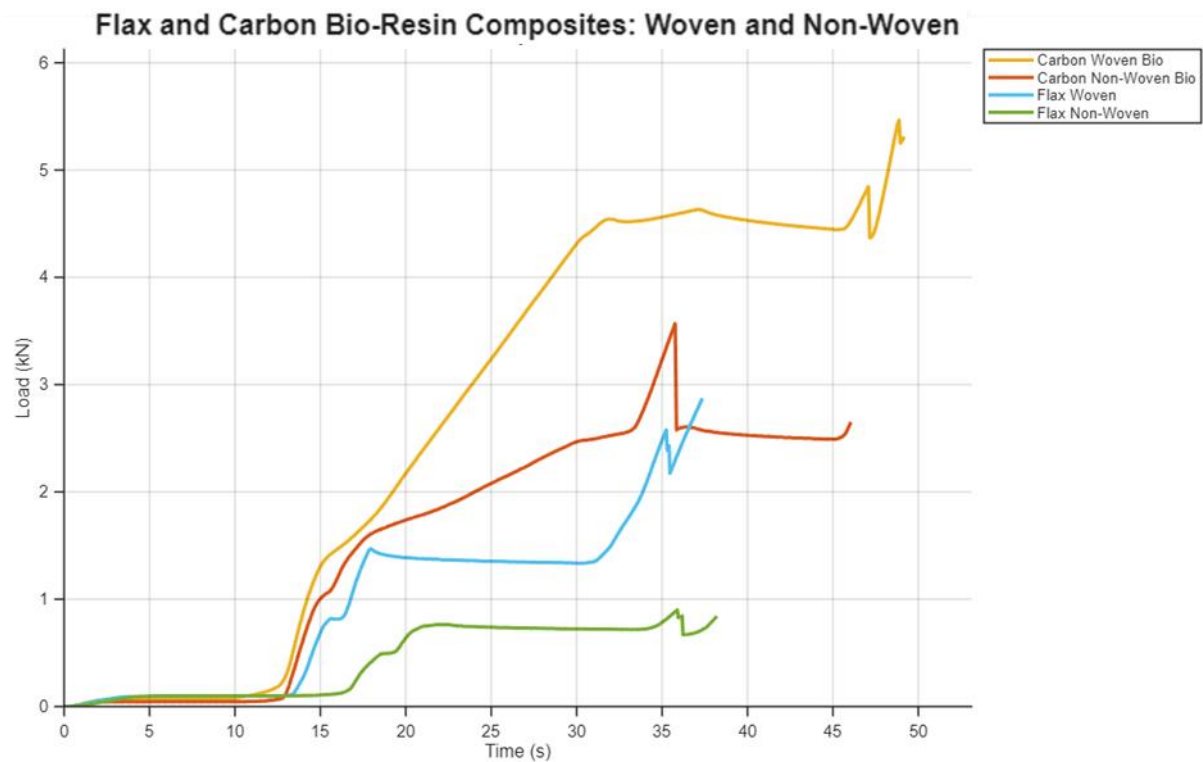
Appendix B - Additional Graphs

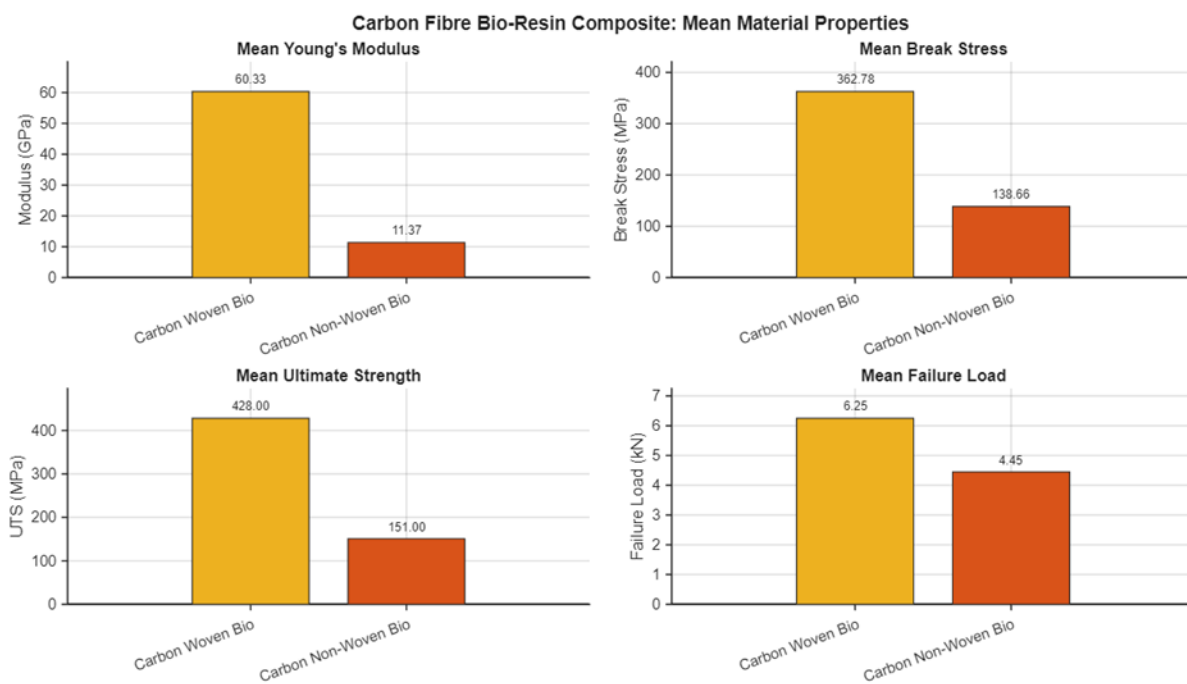
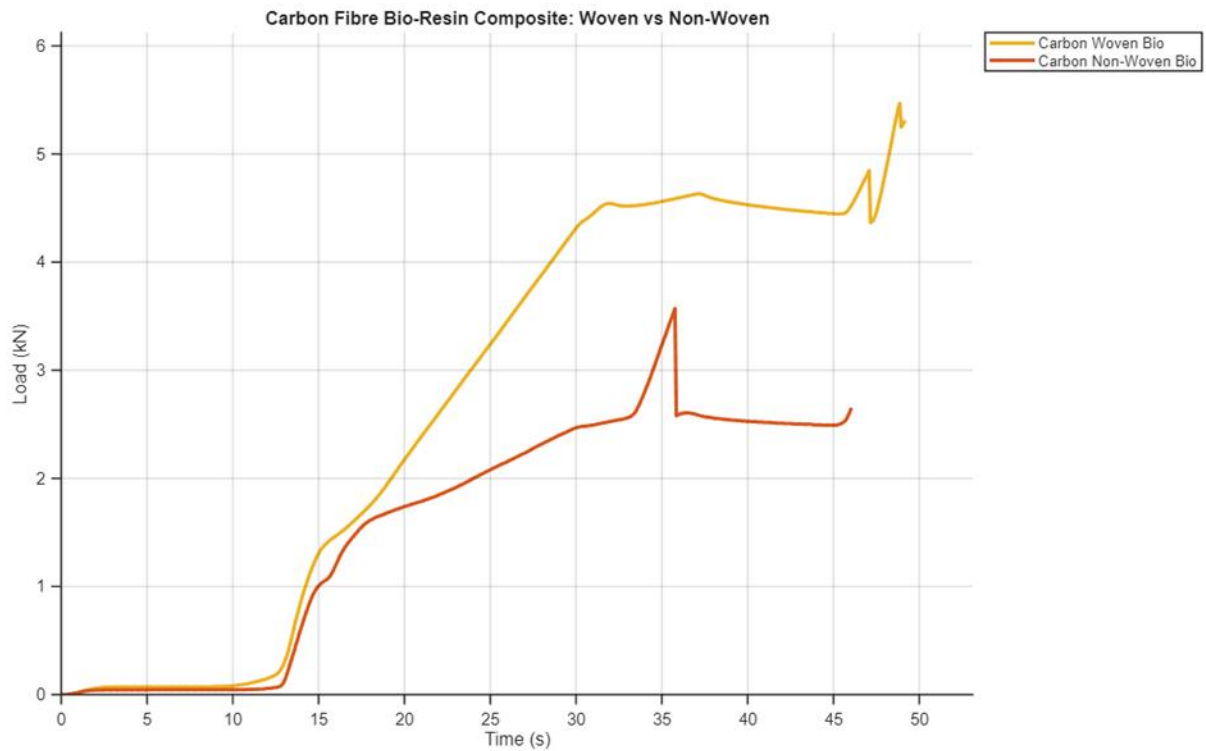


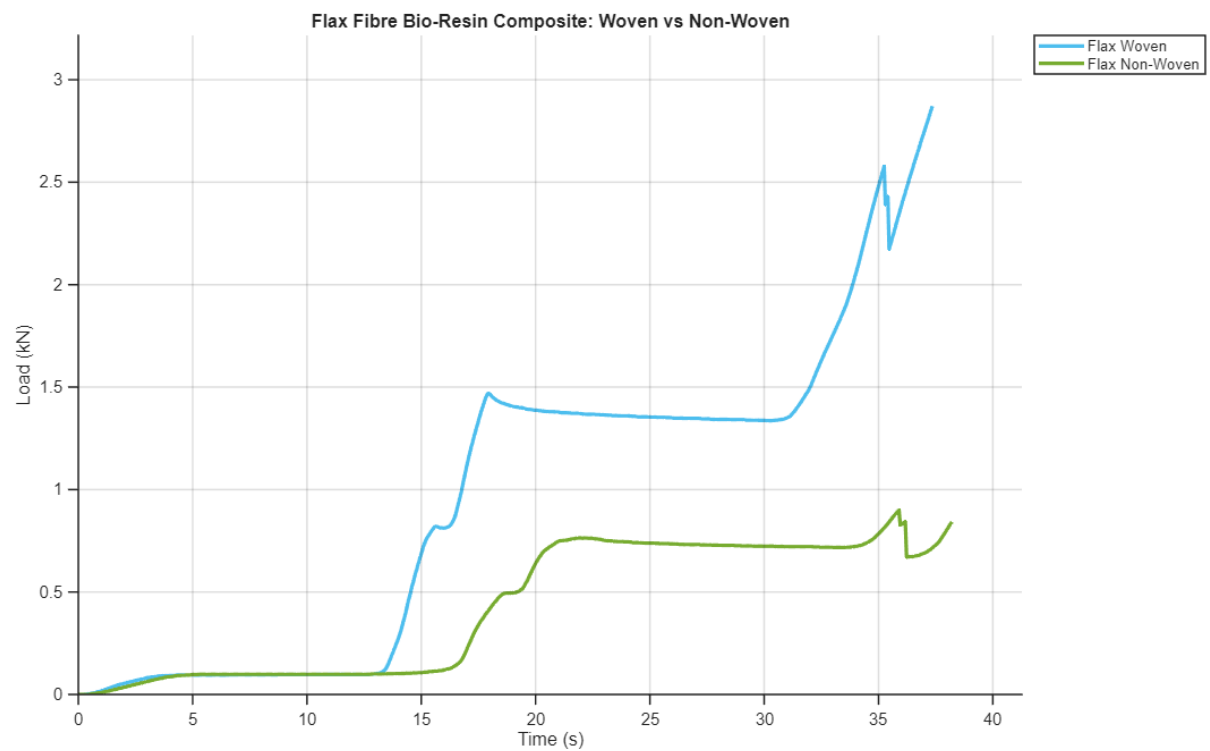
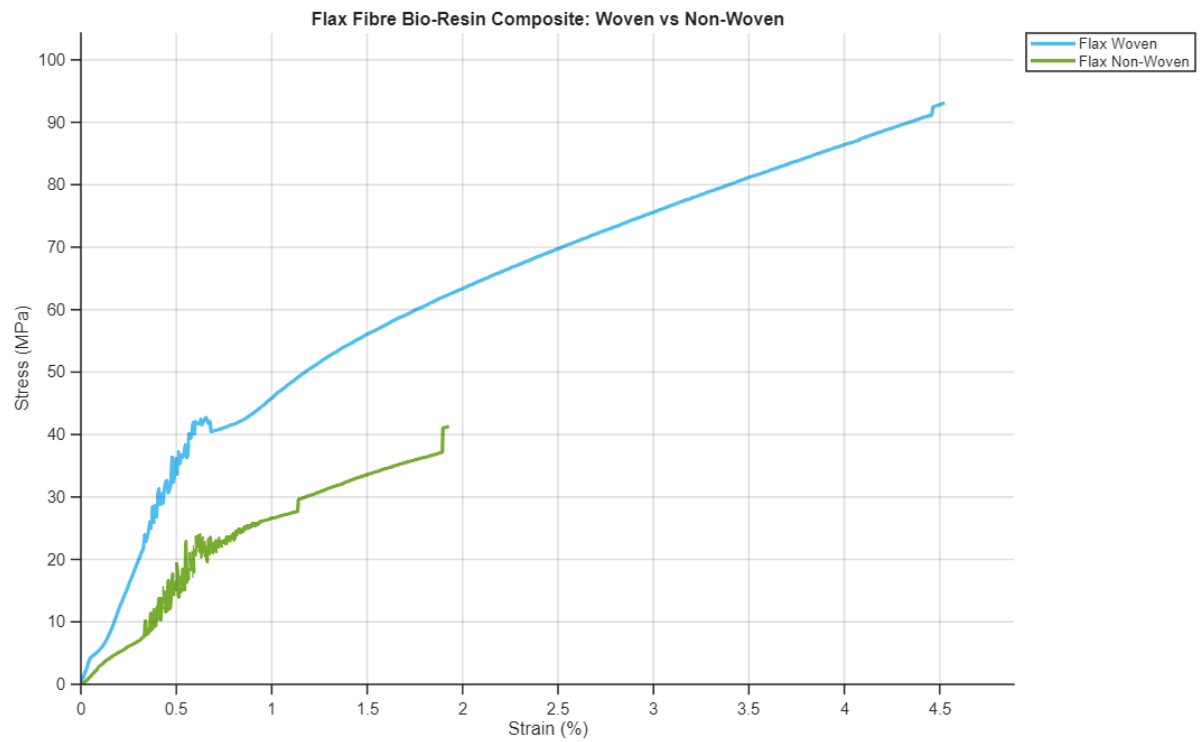


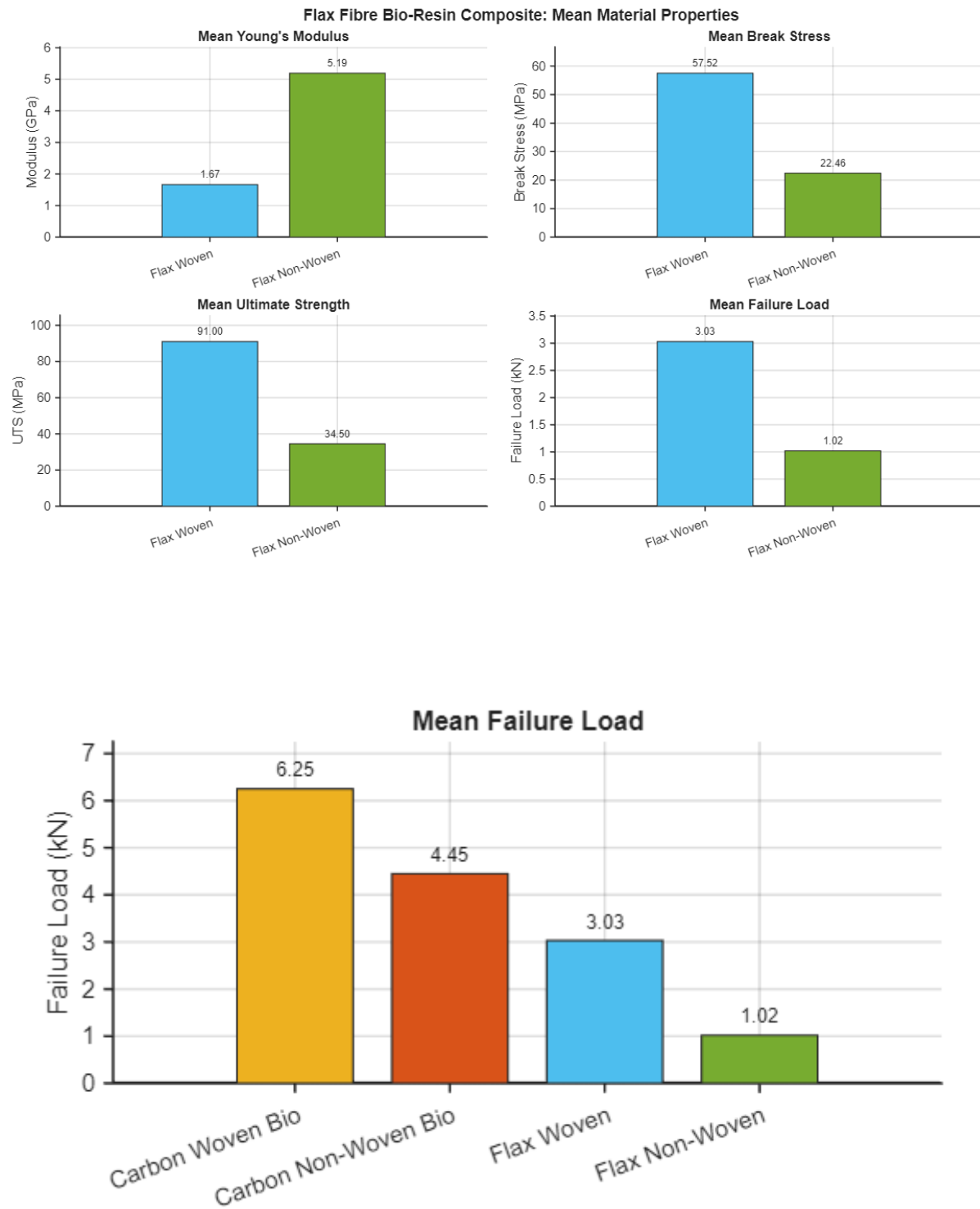


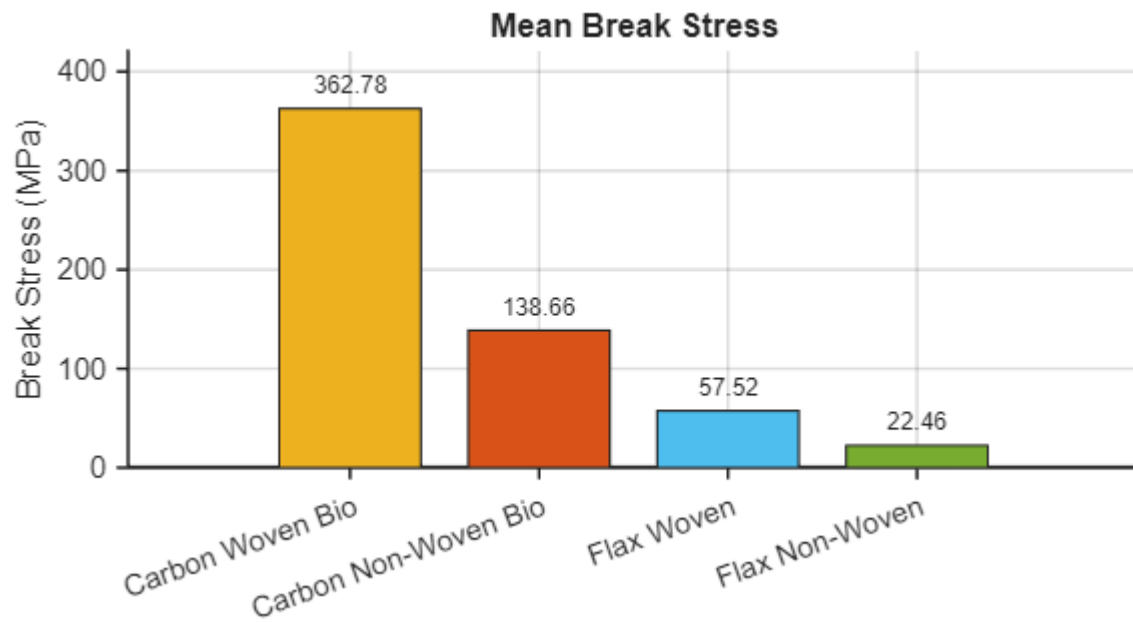
Appendix BA – Additional Twill and Non-Woven graphs



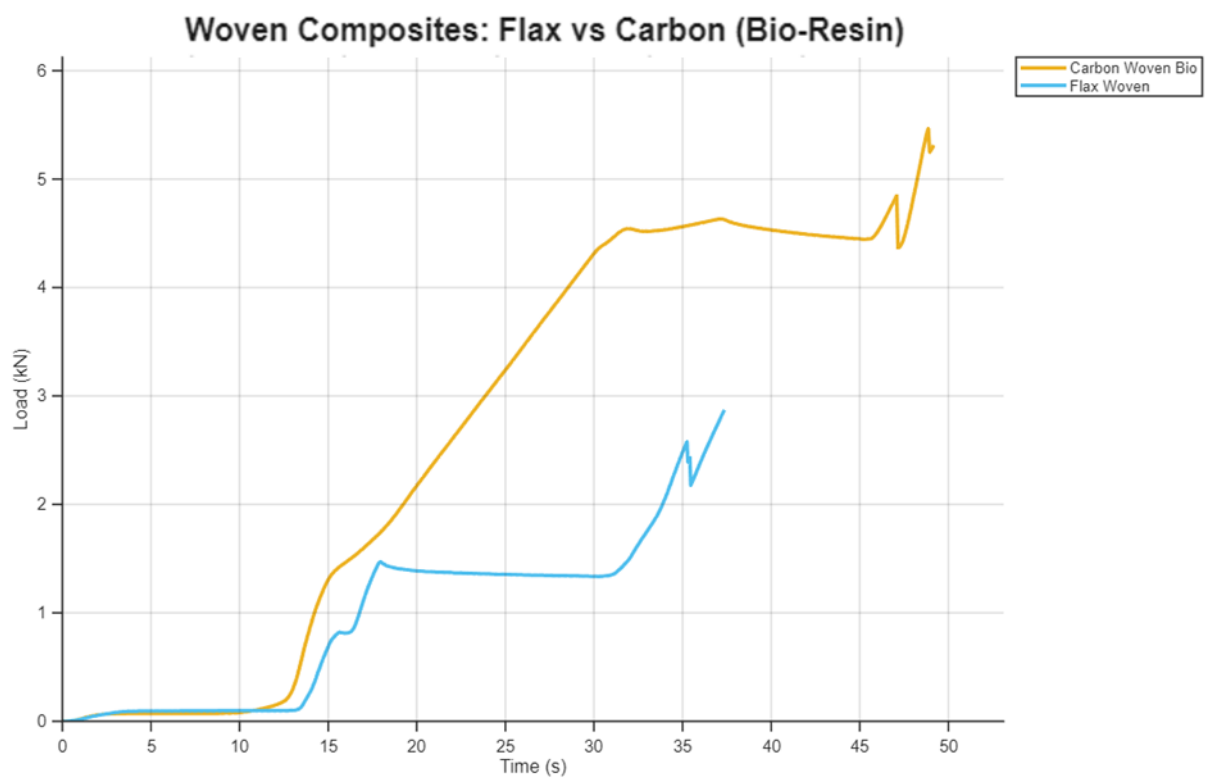


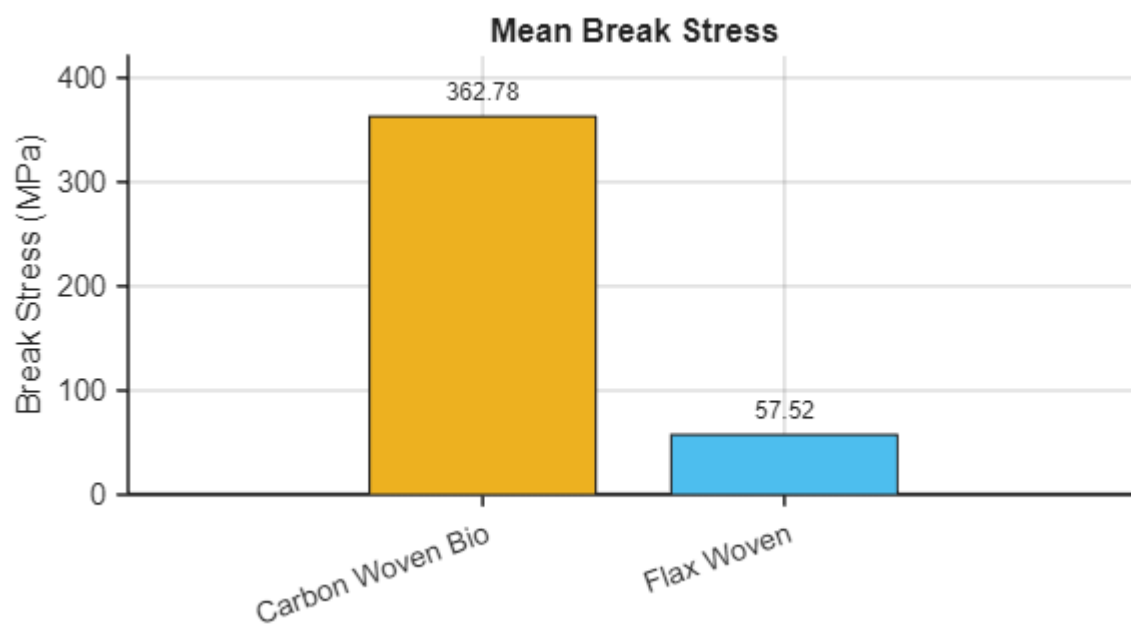
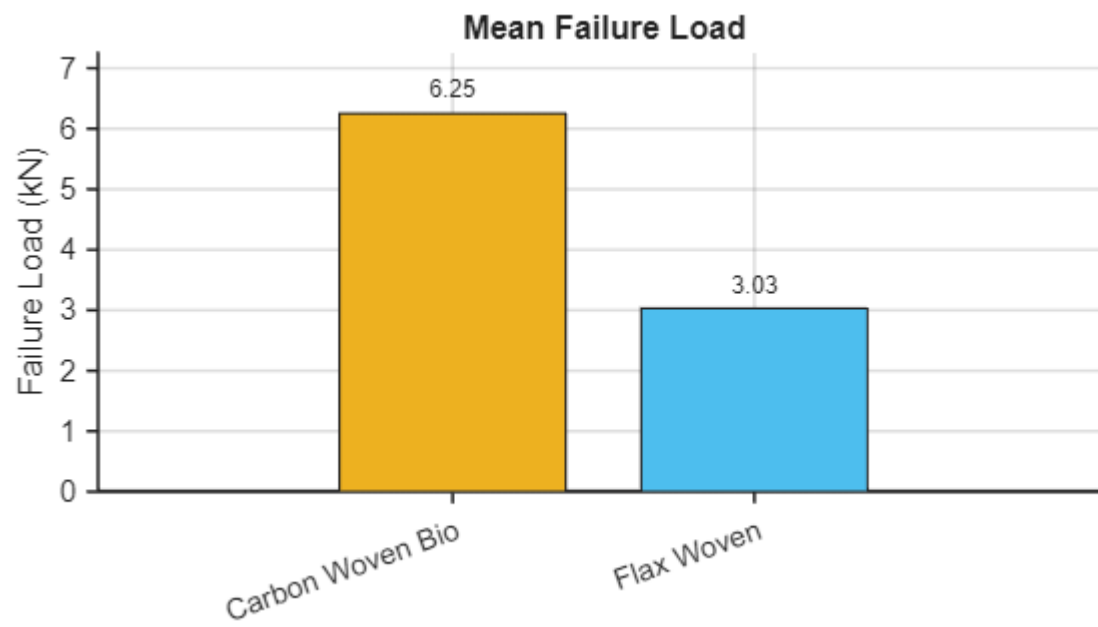




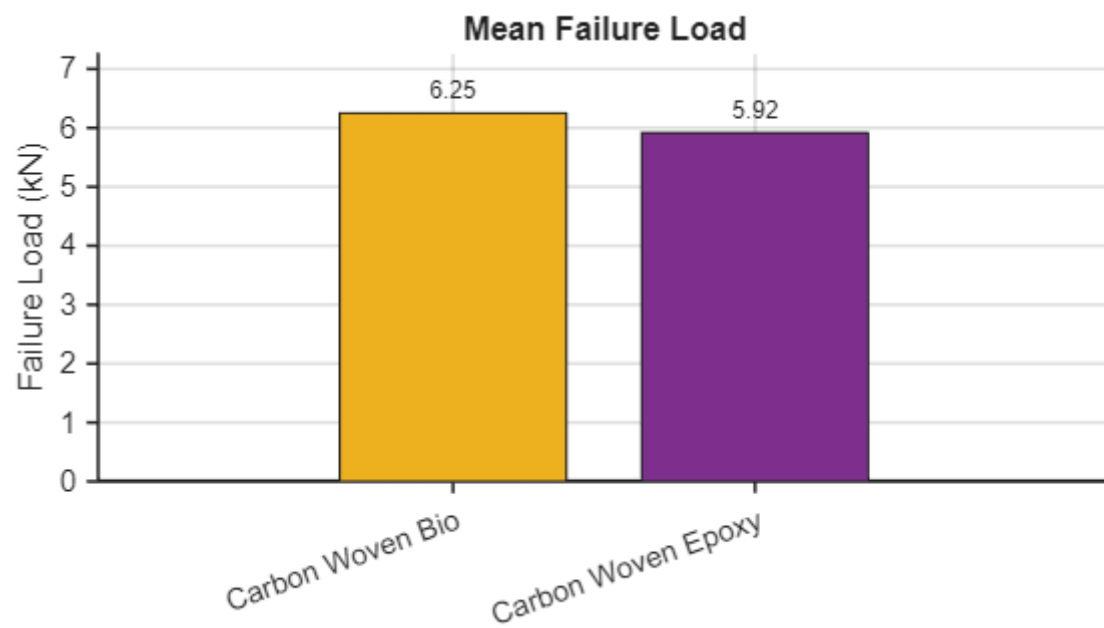
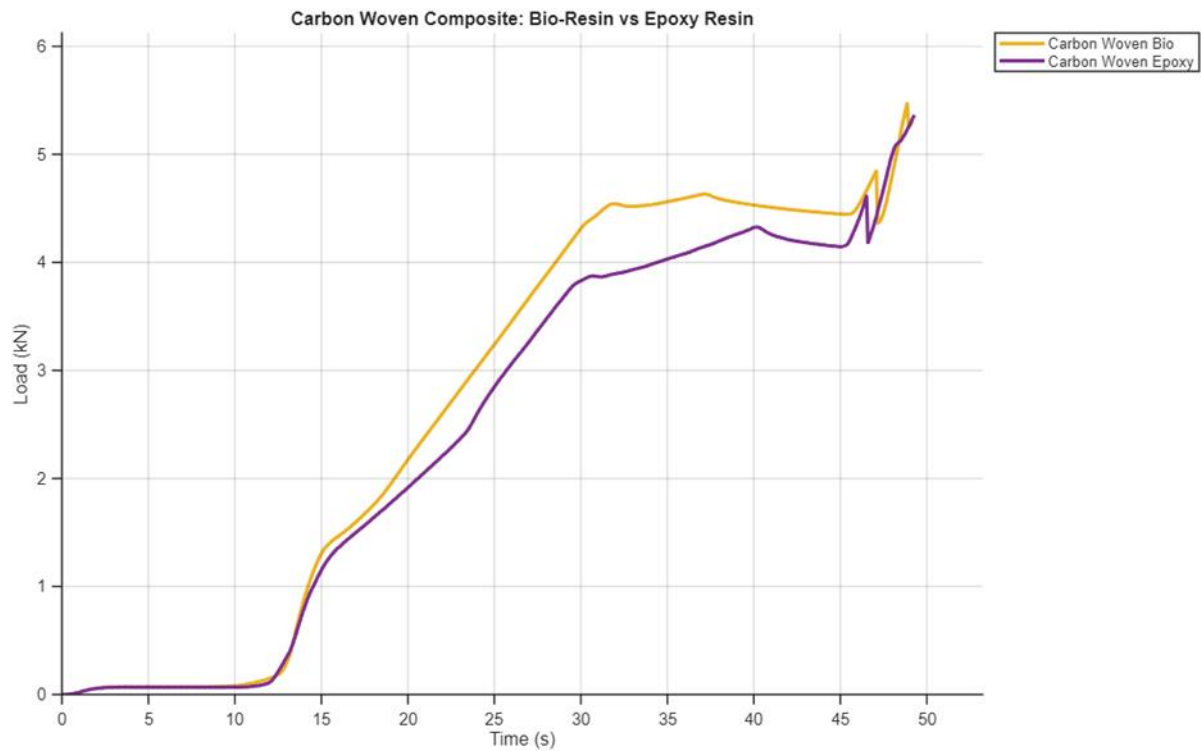


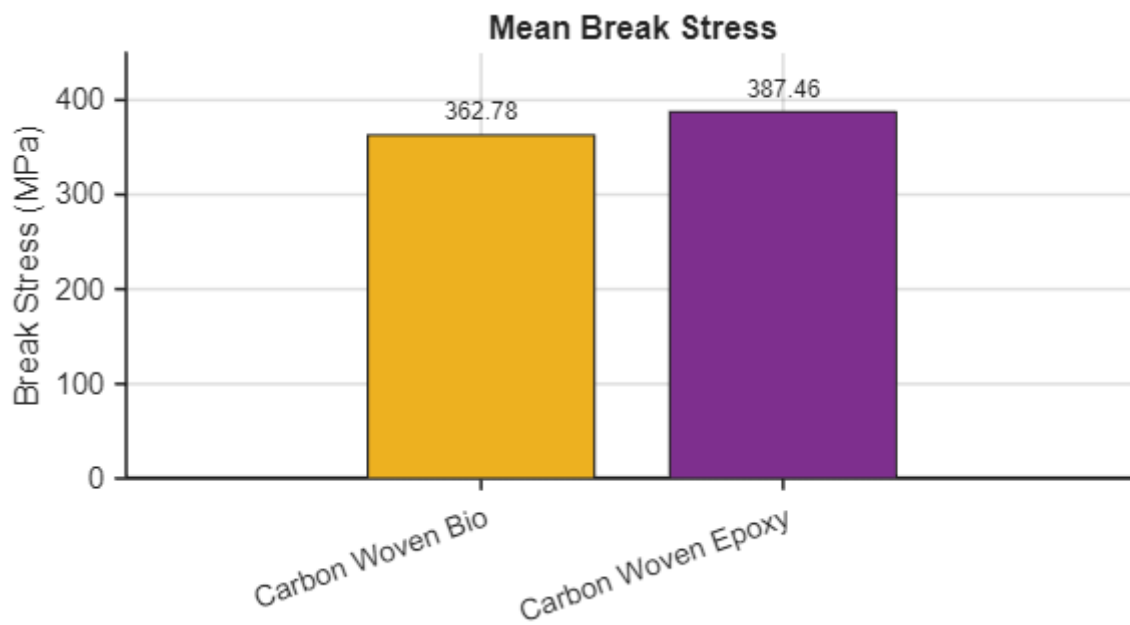
Appendix BB – Additional Flax and Carbon Graphs



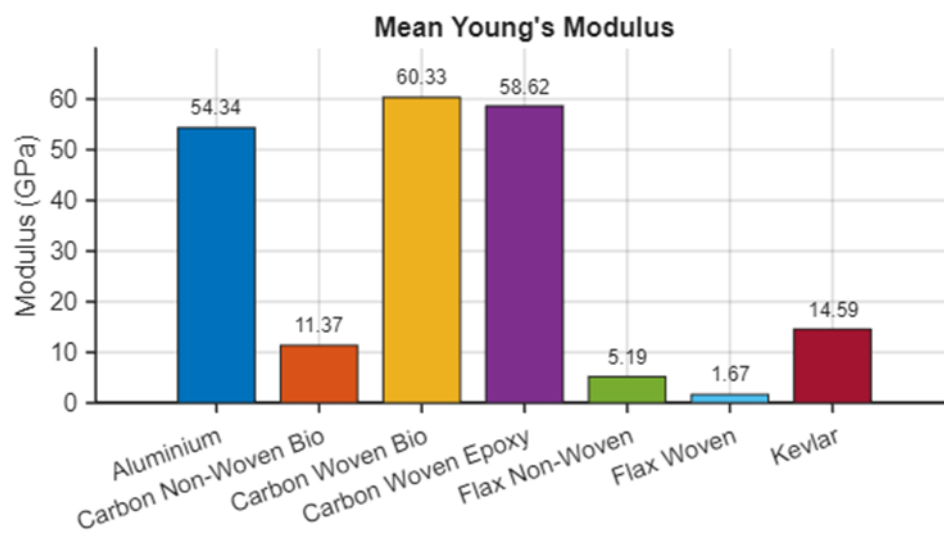


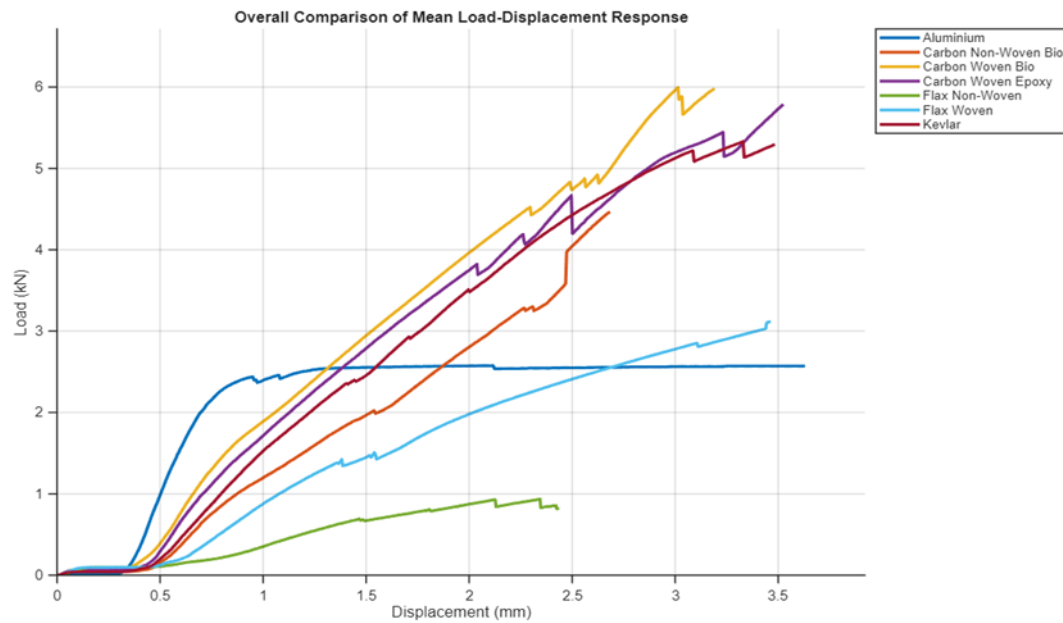
Appendix BC – Additional Bio-Resin and Conventional Epoxy Graphs





Appendix BD – Additional Comparison with Kevlar





Appendix C - Datasheet Information

Appendix CA – Carbon Fibre Non-woven

Mechanical Properties

Indicative data provided for a typical epoxy-matrix cured laminate with 30% fibre-fraction.

Due to the recycled nature of the material and the unknown origin of the feed stock these values must be considered approximate.

Property	Unit	Transverse	Longitudinal
Tensile Strength	MPa	330	290
Tensile Modulus	GPa	35	25
Compressive Strength	MPa	330	270
Compressive Modulus	GPa	30	20
Flexural Strength	MPa	500	370
Density	g/cm ³	1.51	

Appendix CB – Carbon Fibre Woven

Typical Properties of Carbon Fiber

PYROFIL™

	Type	Number of Filaments	Filament Diameter	Yield	Tensile Strength				Tensile Modulus			Elongation	Density
			μ m		mg/m	kg/mm2	Mpa	Ksi	ton/mm2	GPa	Msi	%	
HT Series	TR 30S 3L	3,000	7	200	420	4,120	600		24.0	234	34	1.8	1.79
	TR 50S 6L	6,000	7	400									
	TR 50S12L	12,000	7	800	500	4,900	710		24.5	240	35	2.0	1.82
	TR 50S15L	15,000	7	1,000									
	TR 50D12L	12,000	7	800	510	5,000	720		24.5	240	35	2.1	1.82
	TRH50 18M	18,000	6	1000	540	5,300	770		25.5	250	36	2.1	1.82
	TRH50 60M	60,000	6	3,200	490	4,830	700		25.5	250	36	1.9	1.81
	TRW40 50L	50,000	8	3,750	420	4,120	600		24.5	240	35	1.7	1.80
IM Series	MR 60H 24P	24,000	5	960	580	5,680	820		29.5	290	42	1.9	1.81
HM Series	MS 40 12M	12,000	6	600	450	4,410	640		35.0	345	50	1.3	1.77
	HR 40 12M	12,000	6	600	450	4,410	640		40.0	395	57	1.1	1.82
	HS 40 12P	12,000	5	430	470	4,610	670		46.0	455	65	1.0	1.85

GRAFIL™

	Type	Number of Filaments	Filament Diameter	Yield	Tensile Strength				Tensile Modulus			Elongation	Density
			μ m		mg/m	kg/mm2	Mpa	Ksi	ton/mm2	GPa	Msi	%	
HT Series	34-700	12,000	7	800									
		24,000	7	1,600	490	4,830	700		24.0	234	34	2.0	1.80
	37-800	30,000	6	1,675	560	5,520	800		26.0	255	37	2.1	1.81

Appendix CC – Flax Non-woven

Product properties

Property	Value	Unit	Standard
Moisture content	9 ±1	%	NF EN ISO 3344
Surface weight	300 ±30	g.m ⁻²	NF G07-150
Fiber density	1,45	g.cm ⁻³	-

Tensile mechanical properties¹

Property	Data		Unit	Standard
	CD	MD		
Tensile Strength	44 ±4	37 ±2	MPa	ISO 527-5
Young Modulus ²	5 ±1	5 ±1	GPa	ISO 527-5
Elongation at break	1,3 ±0,2	1,2 ±0,1	%	ISO 527-5
Thickness of 1 impregnated ply	1,10 ±0,06		mm	NF EN ISO 5084

Appendix CD – Flax Woven

Product properties

Property	Value	Unit	Standard
Moisture content	9 ±1	%	NF EN ISO 3344
Surface weight	220 ±22	g.m ⁻²	NF G07-150
Fiber density	1,45	g.cm ⁻³	-

Tensile mechanical properties¹

Property	Data		Unit	Standard
	Weft direction	Warp direction		
Tensile Strength	58 ±2	61 ±6	MPa	ISO 527-5
Young Modulus ²	6 ±1	7 ±1	GPa	ISO 527-5
Elongation at break	1,8 ±0,1	1,5 ±0,2	%	ISO 527-5
Thickness of 1 impregnated ply	0,59 ±0,02		mm	NF EN ISO 5084

Appendix CE – IB2

Mechanical Properties

Cured Resin Properties

Property	Units	Post Cure		
		16hrs Ambient + 24hrs 40 °C	16hrs Ambient + 16hrs 60 °C	16hrs Ambient + 8hrs 80 °C
Tensile Modulus	GPa	3.04	2.79	2.64
Tensile Strength	MPa	68.0	65.0	60.0
Elong. at Break	%	5.3	5.9	9.5
Flexural Modulus	GPa	3.07	2.78	2.61
Flexural Strength	MPa	109.0	107.0	101.0
ILSS	MPa	43.0	42.0	41.0
Comp. Strength	MPa	91.0	87.0	82.0
Impact Resistance	KJ/m ²	99.0	86.0	89.0
Tg Onset	°C	71.0	85.0	82.0

Properties

The table below shows the typical uncured properties:

Property	Units	Resin	Hardener	Combined
Material	-	Epoxy Resin	Formulated Amine	Epoxy
Appearance	-	Clear Liquid	Amber Liquid	Clear Liquid
Viscosity @20 °C	mPa.s.	1350	7	185
Density @20 °C	g/cm ³	1.16	0.944	1.12

Appendix CF - IN2

Mechanical Properties

Cured Resin Properties

	Units	AT30 SLOW	AT30 FAST
Colour		Pale yellow	Pale yellow
Machinability		Excellent	Excellent
Density 25°C	g/ml	1.08 – 1.12	1.08 – 1.12
Hardness 25°C	Shore D/15	84 – 88	84 – 88
Maximum Tg	°C	92 – 98	82 – 88
Water absorption (24h RT)	%	0.10 – 0.20	0.20 – 0.30
Water absorption (2hr 100°C)	%	0.60 – 0.70	0.90 – 1.00
Flexural strength	MN/m ²	110 – 120	107 – 120
Compressive Strength	MN/m ²	88 - 100	94 - 100
Maximum strain	%	5 – 7	5 – 7
Strain at break	%	6 – 8	7 – 12
Flexural modulus	MN/m ²	3100 – 3500	2800 – 3200
Tensile strength	MN/m ²	68.5 – 76	74.0 – 80.0
Elongation at break	%	6 – 8	6.5 – 9.5

Properties

The table below shows the typical uncured properties:

Property	Units	Resin	Hardener	Combined
Material	-	Epoxy Resin	Formulated Amine	Epoxy
Appearance	-	Clear Liquid	Amber Liquid	Clear Liquid
Viscosity @20 °C	mPa.s.	500 – 800	10 - 20	200 – 450
Density @20 °C	g/cm ³	1.08 – 1.18	1.07 – 1.13	1.12 – 1.18

Appendix D – Calculations

Appendix DA – Law of Mixtures Equations

The Voigt and Reuss forms were used as idealised longitudinal and transverse bounds, based on the assumed fibre volume fractions and the fibre and matrix modulus values used for each material (Abdalla, 2025; Yu, 2024).

Voigt rule of mixtures

$$E_c = V_f E_f + V_m E_m$$

Reuss rule of mixtures

$$E_c = \left(\frac{V_f}{E_f} + \frac{V_m}{E_m} \right)^{-1}$$

Appendix DB – General Tensile Testing Equations

Cross-sectional area

$$A = w t$$

A = area, w = coupon width, t = coupon thickness

Engineering stress

$$\sigma = \frac{F}{A}$$

σ = stress, F = tensile load, A = cross-sectional area

Engineering strain

$$\epsilon = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0}$$

ϵ = strain, L_0 = original gauge length, ΔL = extension

Percentage strain

$$\epsilon_{\%} = \epsilon \times 100$$

Used when strain is reported as a percentage

Young's modulus

$$E = \frac{\Delta \sigma}{\Delta \epsilon} = \frac{\sigma_2 - \sigma_1}{\epsilon_2 - \epsilon_1}$$

Gradient of the linear elastic part of the stress-strain curve

Sample standard deviation

Spread of results about the mean

$$s = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n - 1}}$$