

Comparative Analysis of Flax & Carbon Fibers in Automotive
Structures with Life Cycle Analysis

by

MATTHEW JAMES DODD

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Abstract

This study aims to evaluate the environmental impact of utilising natural flax fibers over an industry-standard synthetic carbon fiber for the construction of an automotive vehicle chassis. A comparative life cycle analysis (LCA) focusing on the carbon emissions and resource usage from flax and carbon fiber chassis with equivalent strength is performed. Raw material production, manufacturing and use across a standard automotive life are explored.

The findings of this study indicate that using flax fibers in the chassis construction leads to net reductions of carbon emissions ranging from 4.1% to 6.3%. In total this is equivalent to over 1.2 tonne decrease in CO₂ equivalent emissions over the vehicle lifespan.

The reduction in carbon footprint is primarily attributed to significantly lower energy requirements during the production of flax fibers despite the lower mechanical properties and larger quantity of flax required to meet the same strength. The study concludes that flax fibers environmental impact should put them into consideration for automotive use – where sustainability and environmental impact are seeing greater importance. This study highlights the potential of natural fibers to reduce the environmental impact of the automotive industry.

1 – Introduction

1.1 - Motivation

The automotive and aerospace industries are currently undergoing a shift – moving focus towards sustainability. This is driven by increasing regulatory pressure, but also by consumer demand. Composite materials, known for their high specific strength and versatile capabilities, play a pivotal role in these industries. Traditionally, the focus has been on the use of synthetic composites such as those using carbon or glass fibers. This is due to their excellent mechanical properties - as higher yield strength and Young's modulus provide lighter structures for the same strength. However, the environmental impact of these materials – from their energy-intensive production processes to challenges in end-of-life disposal – has created interest in natural fiber composites. Among these, flax has been identified as a promising alternative offering a balance between performance and sustainability.

Flax fibers are derived from the flax plant (*Linum usitatissimum*) and have been used for centuries in the textile industry to form linen cloth. The appeal of flax fibers is in their biodegradability, renewability and relatively low environmental impact when compared to synthetic fibers. The mechanical properties (tensile strength, Young's modulus, Interlaminar shear strength and more) of flax fibers, while lower in magnitude than synthetic fibers such as carbon, can be enhanced through modern techniques or hybridisation with other fibers. This makes them a viable option in the automotive industry – if they pose a net decrease in carbon emissions when their extra mass is factored in.

This research work focuses on the analysis of the use of flax fibers in structural areas, specifically the Body in White (BiW), of automotive products. Life cycle analysis will be conducted to compare their environmental impact when compared to carbon fiber composites. The research question is to analyse whether the use of flax composites will result in a lower overall carbon footprint over the vehicle's life cycle, considering their mechanical properties for the same mass of material. This will involve analysing the life cycle of the materials, and the fuel consumption of the vehicle when adjusting for added mass.

1.2 - Background

Composite construction in the automotive industry has multiple benefits, most notably their lightweight nature - improving fuel efficiency and resulting in lower emissions. Composites have other benefits such as Noise vibration and harshness (NVH) improvements, structural efficiency, corrosion resistance, design flexibility, enhanced safety, and sustainability which all contribute to their attractiveness (Mangino et al., 2007).

Carbon fiber composites are known for their high strength-to-weight ratio have been used for aerospace and high-end automotive use. The production of carbon fibers is

highly energy-intensive, and the fibers are not biodegradable (while some resin systems are).

In contrast, flax fibers are biodegradable and renewable – offering a more sustainable option. They are less energy-intensive to produce – storing carbon as the plant grows. They can be processed using similar techniques to other composites. However, the mechanical properties of flax fibers are lower than that of synthetics. This creates a challenge in balancing their mechanical performance with their environmental impact. Flax, and other sustainable composite reinforcements, are already used in the automotive industry for non-structural components such as vehicle interiors – with sustainability, aesthetic and the acoustic/vibration damping properties a driving factor. Adding structural applications to this list could see a net reduction in carbon emissions for road going vehicles.

In 2020, McLaren Formula 1 team – competing in motorsport where material mass-efficiency is a top-level requirement - developed a race seat from a flax fiber epoxy composite. This seat was designed to act as payload for their drivers, who were under the minimum driver weight. It also exploited a property of the flax fibers – vibration absorption, where the flax seat was found to be 5 times better at absorbing road vibrations than the standard carbon seat. This highlights a clever use of the material where there is not a need for a reduction in mass. By using the seat itself as the additional driver payload, the material could be specified to provide a net benefit in both sustainability and vibration isolation. (Revealed: How McLaren is pioneering the use of sustainable composites in F1, nd).

Beyond racing seats, flax fibers are also use in other interior components of vehicles. Panels, dashboards and door trims made from flax fiber composites are becoming more common. These components benefit from the natural aesthetic appeal of flax and its ability to absorb sound and vibrations (D.V. Parikh et. al, 2006).

1.3 - Research Objectives

The aim of this research is to investigate the environmental impact of using a flax fiber composite in vehicle components comparing it to using carbon fibers while maintaining comparable strength. The objectives are:

1. Compare the mechanical properties of flax and carbon fibers using physical tensile testing on samples.
2. Use advanced composite analysis tools to estimate a change in vehicle mass, using a known quantity proxy structure.
3. To assess the net lifecycle impact of using a flax fiber composite. This involves:
 - a. Analysing the manufacturing process for both materials and the environmental impacts.
 - b. Estimating the impact on fuel consumption from the change in vehicle mass between the two materials.

4. Explore current research and advancements in flax fiber composites to understand how the material is developing.

1.4 - Significance of the Study

This study has significance for several reasons. It adds to the growing body of knowledge relating to sustainable materials in automotive applications. By providing a direct comparison of carbon and flax fibers within automotive applications, the research will provide insight into the trade-off between mechanical properties and environmental impact. Resultant of this is guidance for material selection for manufacturers – to help them adopt more sustainable practices. Furthermore, this study highlights the potential of sustainable composites to play a more significant role in reducing the carbon footprint of vehicles, thus contributing to broader efforts to tackle climate change worldwide.

2 – Literature review

2.1 – Comparing flax fibers to synthetic fibers

2.1.1 - Mechanical Response and Viscoelastic Behavior

Stochioiu et al. (2023) investigated the mechanical response in epoxy resin flax fiber composites under cyclic tensile loading, as well as creep recovery tests. The study found that there was an elastic bi-linear behaviour with a yield point at 20% of ultimate tensile stress and calculated a Young's Modulus of 35.9 GPa before yield and 26.3 GPa after yield. This is significantly lower than for carbon fibers which can reach 60 GPa before yield (Seifans et al., 2021).

The composites tested experienced significant non-linear viscoelastic and viscoplastic components – with it accounting for up to 14% of the strain response. The study concludes that this response can be attributed to the amorphous matrix and microstructural reorganization of the fibers under load, and concludes that the mechanical properties explored above, as well as the eco-friendly nature of the flax fiber composite, makes them suitable for structural applications. It highlights the benefit of local manufacturing in temperate climates where flax plants comfortably grow. This study is relevant as it indicates that epoxy resin flax fiber composites respond differently to cyclic load than carbon fibers. This will result in different maximum loading requirements when used in a structural application.

2.1.2 – Damping characteristics

Flax fibers exhibit superior damping characteristics compared to synthetic composites (Cihan, 2020). In this study, nonwoven flax-PLA composites were hybridised with glass fibers to investigate how the damping properties could be improved. The study found up to a 33 % improvement in damping properties with a hybrid flax and glass sample. It was found that with the flax as the outermost face of the panel vibration damping is highest. This study highlights the potential use of flax as a bulking ply in hybrid panels to improve damping and therefore vehicle comfort.

2.2 – Recent development in flax fibers – improving performance

2.2.1 - Enhancement through Nanomaterials, Hybridization and Irradiation

Sathish and Saravanan (2024) explored modification of jute and flax fiber composites through the addition of carbon nanotube (CNT) fillers. The addition of these CNTs significantly improved the mechanical properties, including tensile strength, flexural strength and impact resistance. Optimal CNT concentration resulted in better bonding between fibers and the epoxy resin matrix, leading to better shear characteristics and therefore enhanced load transfer and overall performance. Bahrami and Bagheri (2022) reported improvements in mechanical properties through hybridisation with rubber. These both the CNTs and rubber were not assessed from a sustainability point of view, so it is unclear at this stage if they provide a net gain.

Pisupati and Deléglise Lagardère (2022) explored the use of glass fibers, recovered from waste composite components, as a core structure in flax fiber composites. This hybridisation of the composite improved flexural and tensile properties compared to the pure flax fiber composites. Use of waste product for bulking of composites not only enhances performance but also contributes to sustainability – and provides a recycling route for existing waste product. A logical next step would be to investigate the use of waste flax fibers as a core structure.

Habib et al (2019) evaluated the mechanical properties of a non-woven, unidirectional flax fiber composite in place of traditional woven composites. Their study saw an improvement in mechanical properties including tensile and flexural strength when the flax fibers were woven as is seen already with carbon and glass fibers. This is useful to this work as it creates further clear parallels between the performance of sustainable and synthetic fibers in structural applications.

Stelescu et al. (2024) examined electron beam irradiation's effect on the mechanical properties of an EPMD-flax fiber composite. This saw a significant improvement in mechanical and thermal response. This indicates that irradiation has potential to improve the performance of flax composites.

2.2.2 – Environmental effects and durability

Malloum et al (2019) and Kollia et al. (2020) investigated the effect of water aging on the tensile and fatigue characteristics of a green-epoxy flax composites, and tensile in bio-epoxy flax composites respectively. Water aging significantly affected the mechanical properties in both studies. Degradation is influenced by aging factors such as temperature, moisture and mechanical stresses – leading to reduction in stiffness in mechanical loading (Regazzi et al, 2016). This highlights a key difference between sustainable and synthetic fibers because of the previously noted increased water absorption in the former. Hachem et al. (2021) explored the dimensional changes seen in wet aged composites and how the addition of a coupling agent was able to reduce the swelling seen in the absorbent flax fibers.

Mu et al. (2024) explored hygrothermal aging on the mechanical properties of continuous fiber flax composites. As with other composites, a reduction in mechanical properties was seen. This highlights the need for an understanding of the environment the composites will be used in and the requirement for treatments to reduce its impact.

Overall, these studies highlight the complex interactions between the factors influencing the mechanical properties of flax fiber composites and show a clear difference to those of carbon fibers – with high permeability and indicates a need for fiber treatment to combat this, allowing use in humid or difficult environments. This work does

2.2.3 – Impact resistance and post-impact behaviour

Habibi et al. (2019) examined the post-impact behaviour of flax composites. The composites retained significant mechanical integrity after impact, demonstrating good

impact resistance as well. Kaboglu et al. (2021) built on this study by introducing a coupling agent to improve both the impact resistance and the post-impact behaviour in these composites. These studies highlight the potential of flax fibers in applications requiring good impact resistance – and indicates a potential gain over synthetic composites in this area.

2.2.4 – Wear resistance

Prabhu et al. (2023) explored the wear resistance of bamboo and flax composites, and the use of TiO₂ fillers. This saw significant improvement in wear resistance and emphasises a potential use case in dry-sliding applications such as runners or hinges – replacing standard plastics.

2.2.5 – Conclusion

The highlighted studies show that recent research into flax fibers is developing both the direct mechanical properties of the composite but also working to counter the detrimental difference between the sustainable composite and its synthetic counterpart. Methods such as chemical treatments and surface modifications are able to counteract the poor stability of the fibers. Reducing the downsides (more so than purely mechanical properties) of flax fibers will only aid their adoption in industry. None of the papers explored provide a direct analysis of the impact of their work in terms of environmental impact. This makes it hard to assess whether the improvements seen would improve net benefits over the lifespan of the product – and highlights a clear gap in this area.

2.3 - Life-Cycle Analysis (LCA) in the Automotive Industry

Life-cycle analysis (LCA) has emerged as a crucial methodology for the evaluation of the environmental impact of products throughout their life cycle. By tracking from raw material extraction through production, use and disposal – an accurate picture can be developed of the overall impact of a product. In the automotive industry LCA helps manufacturers optimise the selection of materials and processes to optimise sustainability. The integration of LCA with FEA results provides a comprehensive assessment of the environmental and performance trade-offs in material selection.

Mistry, Gediga and Boonazier (2024) provided a comprehensive LCA of nickel products, evaluating the environmental impacts associated with their production. The study covers all life cycle stages, highlighting significant energy consumption and greenhouse gas emissions found primarily in the production stage. The findings allow automotive manufacturers to better understand the impact of nickel-based products – primarily used in batteries and alloy made components.

Ead et al. (2021) provide a comprehensive review of the life cycle analysis (LCA) of green composites, for agricultural use, by comparing natural and synthetic fibers. The study explores the importance of evaluating sustainability through various life cycle stages, including raw material extraction, production, use, and end-of-life disposal. It highlights that natural fiber composites offer significant environmental benefits due to

a lower energy consumption and reduction in greenhouse gas emissions. The authors also discuss the challenges and opportunities in developing green composites, suggesting that local agricultural practices can enhance sustainability. This review serves as a guide for future research and agricultural applications for composite materials.

2.4 - Key Findings and Contribution to Knowledge

Literature indicates that there is significant research into the improvement of both the mechanical properties and usability of flax fibers. The latter aims to bring flax fibers closer to traditional synthetic fibers for use in automotive – improving properties in harsh environments. The former involves advanced processing methods that will increase material strength. Some literature has put focus on environmental impact or provides a comparison between flax and synthetic fibers, but no literature was found that compares these simultaneously in the context of automotive applications.

3 – Methodology

To meet the aim and objectives of the study, a project flowchart was created (Figure 1).

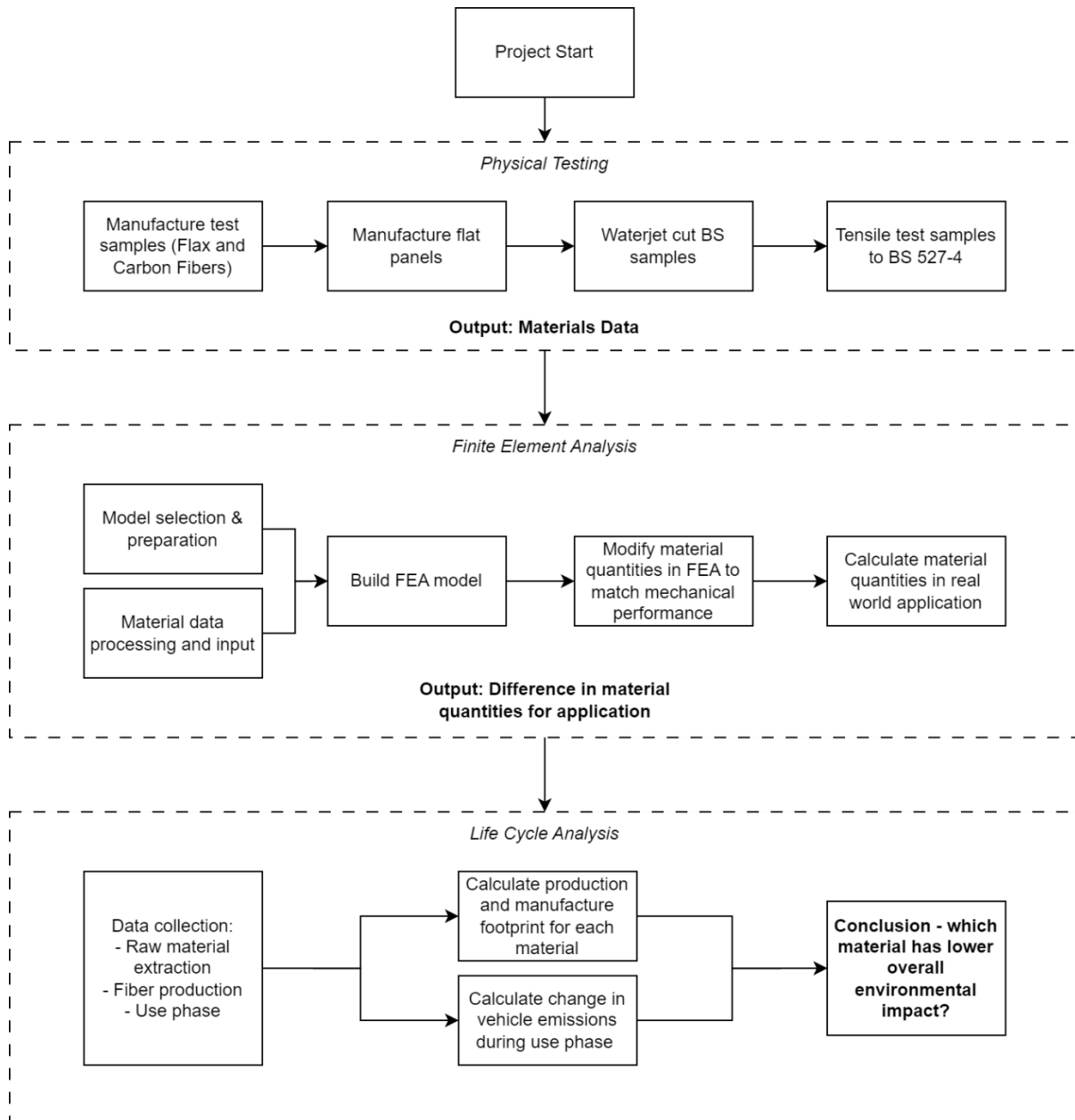


Figure 1 - Project methodology flowchart

The methodology presented above (Figure 1) follows a structured approach to the assessment of the environmental impact of the materials. It is divided into three primary phases – Physical Testing, Finite Element Analysis and Life Cycle Analysis. Each phase builds upon the information found in the previous.

Phase 1: Physical Testing

The primary output of this phase is an understanding of the mechanical properties of the materials to allow further analysis. This involves:

1. Selection and manufacturing (externally) of raw material.
2. Manufacturing flat panels: Using raw materials flat panels of each material can be produced. This consists of lamination, vacuum bagging and heat curing.
3. Waterjet cutting: Flat panels are CNC waterjet cut to final shape using a waterjet cutter
4. Samples are tensile tested matching programme detailed in BS 527-4

Raw data from the tensile testing is now fed into Phase 2.

Phase 2: Finite Element Analysis

Following physical testing, Finite Element Analysis (FEA) is conducted to model and simulate the performance of materials under various conditions. This involves:

1. Model Selection & Preparation: An appropriate FEA model is chosen based on the intended application. The key focus was determined to be that of torsional stiffness as it allows analogous comparison to existing structures where data is available.
2. Material Data Processing and Input: The materials data obtained from tensile testing is integrated into the FEA model to ensure accurate simulations.
3. Building the FEA Model: A computational model is created to analyze the mechanical behavior of flax and carbon fiber materials under realistic conditions.
4. Modifying Material Quantities to Match Performance: Since the two materials exhibit different mechanical properties, the FEA model is adjusted to ensure that both materials provide comparable mechanical performance. This step allows for a direct comparison in terms of material quantity needed for real-world applications.
5. Calculating Material Quantities for Real-World Application: Based on the FEA results, the amount of material required for a given application is determined.

Therefore, the output of this phase is the mass differential between the two materials, which is crucial for assessing the environmental impact.

Phase 3: Life Cycle Analysis

In this final phase a **Life Cycle Analysis (LCA)** is performed to estimate the carbon footprint of both materials across a vehicle lifespan. This process includes:

1. **Data Collection:** This step involves gathering information on:
 - **Raw Material Extraction:** Energy and resource consumption associated with obtaining flax and carbon fibers.

- **Fiber Production:** The manufacturing processes and emissions related to transforming raw materials into usable fibers.
 - **Use Phase:** The impact of using these materials in real-world applications, such as their effect on vehicle weight and fuel consumption.
2. **Calculating Production and Manufacturing Footprint:** The total environmental footprint, including energy use, carbon emissions, and waste production, is determined for each material.
 3. **Calculating Change in Vehicle Emissions:** Since composite materials are often used in transportation applications, their impact on vehicle emissions during operation is evaluated. Lighter materials typically reduce fuel consumption and emissions.

The final step in the methodology allows a conclusion to be formed. The key question answered is: Which material has the lower overall environmental impact? By integrating data from physical testing, FEA, and LCA, the study determines which material offers the best balance between mechanical performance and sustainability across the full vehicle lifespan.

This methodology ensures a scientific, data-driven approach to material selection, helping industries make environmentally conscious decisions while maintaining structural integrity and performance requirements.

4 – Determination of Material Mechanical Characteristics

4.1 – Materials and Methods

4.1.1 Manufacturing of Specimens

The compared materials in this study utilised an Evopreg® EPC300 (Chesterfield, England) medium temperature cure epoxy prepreg resin – reinforced with two different material weaves. Both materials were woven in a 2x2 Twill configuration. Table 1 provides detail of the materials used.

These materials were chosen as they were readily available with the same resin system enabling a more direct comparison between the two materials. This consistency in resin allows us to expect similar performance characteristics, isolating the effects of the fiber type.

Table 1 - details of the two materials tested

Material	Reinforcement	Cloth Weight
ampliTex™ Flax	2x2 Twill Flax Fiber	300 gsm
Evopreg® C205T	2x2 Twill Medium Modulus Carbon Fiber	205 gsm

The difference in material weight (grams per square meter, gsm) was not of concern as the cross-sectional area of the material is used to determine its tensile strength.

Tensile samples were produced by hand-lamination onto glass sheet. 400 mm x 300 mm single-ply sheets of both materials were laid onto the same glass sheet and cured at the same time using the datasheet standard cycle – in an EPC Industries OV301 Precision Composites Curing Oven. Cured composite sheets were abrasive waterjet cut to final shape (as detailed in BS ISO 572-4) using a WAZER waterjet. They were then allowed to dry fully before being tensile tested.

Using 10 samples of each material provides a robust sample size that enhances the reliability and validity of the results. A larger sample set reduces the impact of variability and anomalies, allowing for more accurate statistical analysis and comparisons. It ensures that any observed differences in performance between the flax and carbon composites are statistically significant and not due to random chance. Additionally, having multiple samples facilitates a better understanding of the material properties and its behaviour, contributing to more informed conclusions and insights in the evaluation of the two composites.

4.1.2 – Experimental setup

British Standard tensile samples were used and tested on an Instron 34TM-30 – equipped with a 30 kN load cell - to match the requirements of BS ISO 572-4:2023. Tensile speeds of 1.5 mm per minute were set to match the requirements of the British Standard.

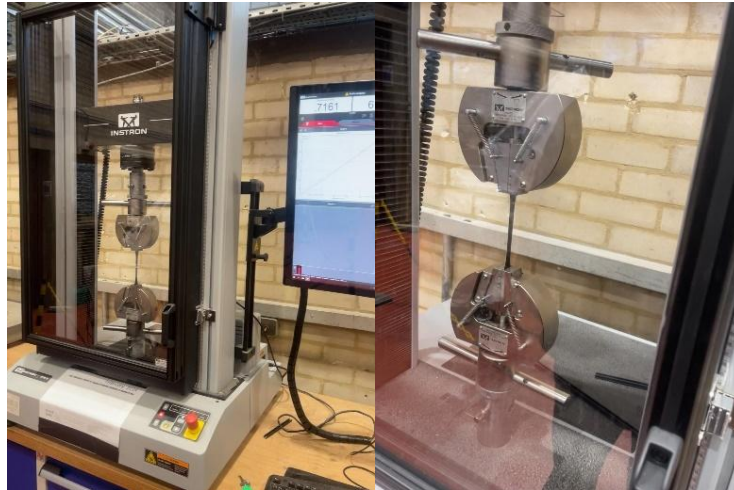


Figure 2 - a) Instron 34TM-30 used for tensile testing b) carbon fiber sample in gripper jaws of the machine

4.1.3 – Data processing

A MATLAB script was developed to extract the required material properties from each specimen data set and find an average. Specimen dimensions were input and then the maximum stress was found. From there the Young's modulus was found from the slope of the stress-strain curves linear portion.

Ultimate Tensile Strength (UTS) = Average of Maximum stress before failure

Young's Modulus (J) = Average of stress – strain curve slope during linear portion

4.2 – Results and Discussion

Results for the flax samples show significant variation in UTS but with relatively consistent gradients (Young's Modulus). Figure 3 a&b shows the tested samples against their ultimate tensile strength and Figure 4 shows graphs of all 10 samples tested. Table 2 provides the calculated UTS and Young's modulus for each.

All of the flax fiber samples broke within the thinned section of the tensile sample – as expected. Failure was brittle tension in the individual bundles of fibers. Figure 6 shows a macro image of failure in sample 1.

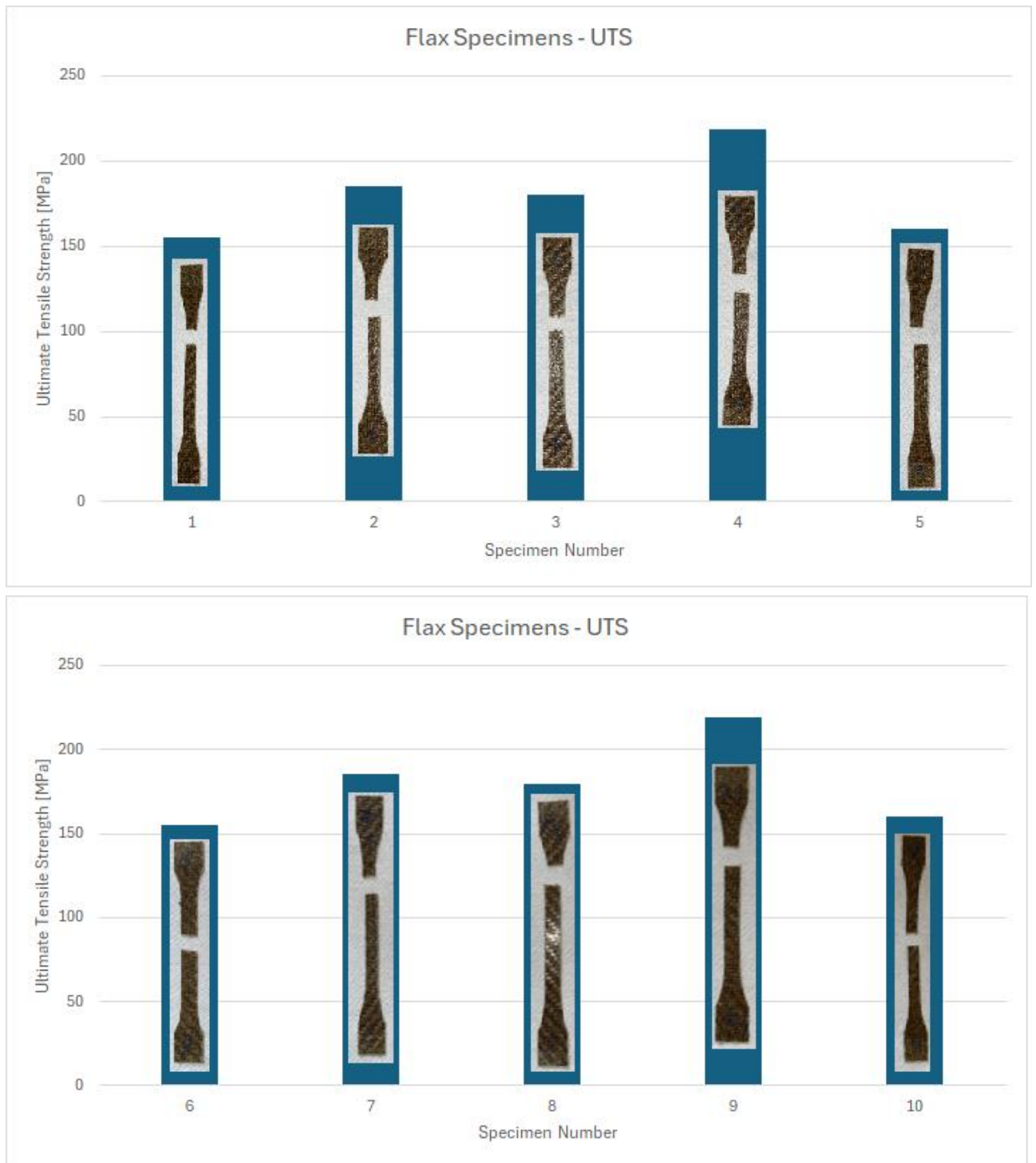


Figure 3 - Ultimate tensile strength overlayed with post-test sample geometry for specimens 1-5 (a) and 6-10 (b)

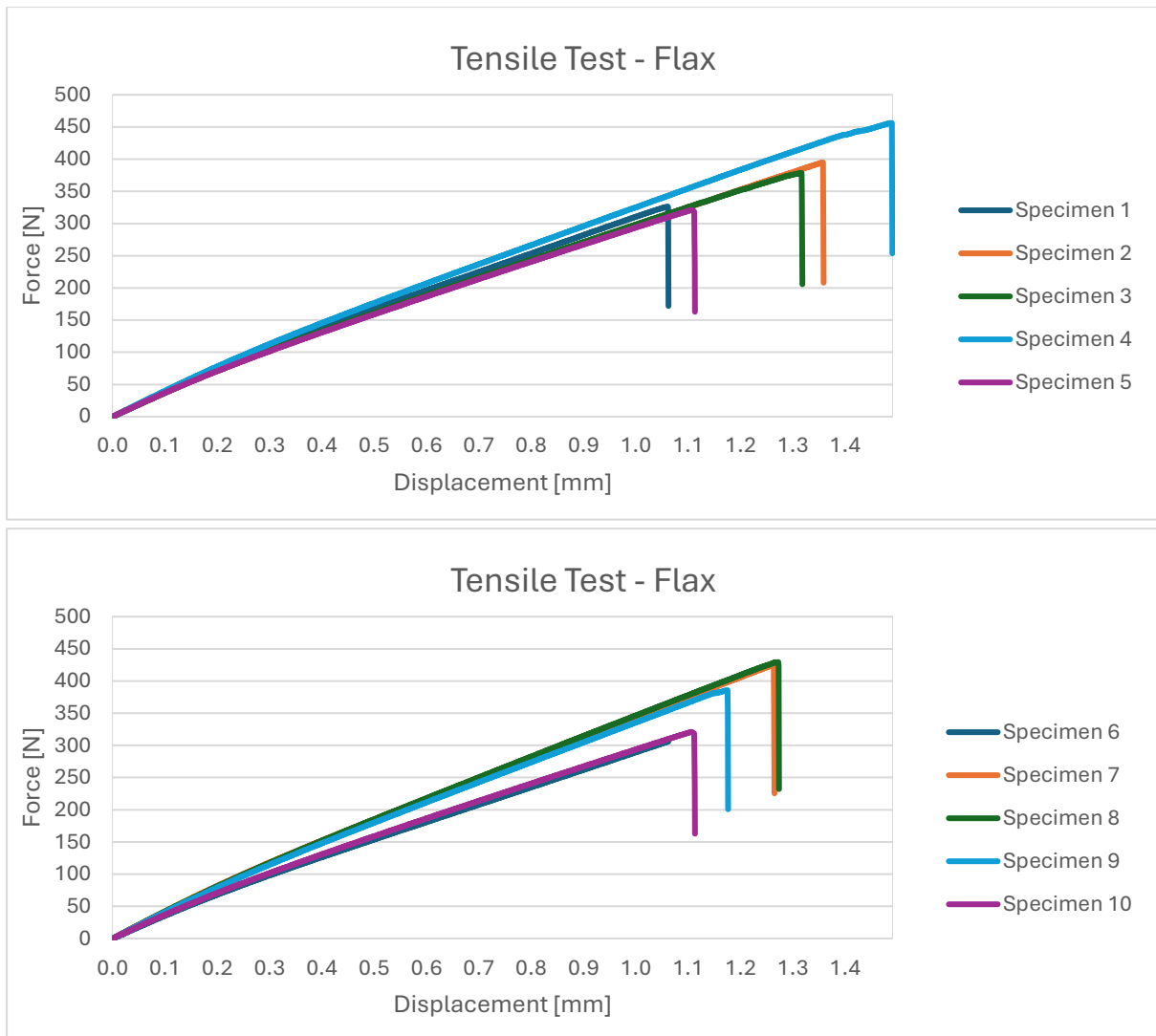


Figure 4 - Graphical representation of the results of the tensile testing of the flax samples

Table 2 - Calculated values for the ten flax samples

Specimen	1	2	3	4	5	6	7	8	9	10
UTS (MPa)	155.08	185.31	179.91	218.99	160.46	197.79	202.71	204.52	188.09	200.74
Young's Modulus (GPa)	16.29	15.28	15.29	16.42	15.14	14.83	17.67	17.90	17.40	15.87



Figure 5 - Macro image showing the brittle tensile failure in specimen 1

Table 3 provides final, averaged material properties determined through physical testing.

Table 3 – Results of the testing completed

Material	Flax Fiber	Carbon Fiber	Unit
Young's Modulus	16.2	55.3	GPa
Ultimate Tensile Strength	189.4	521	MPa
Density	1450	1480	g/cm ³
Specific tensile strength	130.62	352.03	Nm/kg
Elongation at Break	1.8	1.5	%

4.3 – Conclusions

Results show significantly lower tensile strength for flax fiber compared to carbon fibers., indicating that 175 per cent more flax would be required to reach the same stiffness as carbon fibers. Due to their similar density this would result in a 170 per cent increase in mass.

5 – Determination of Equivalent vehicle structure strength via Finite Element Analysis

5.1 – Model calibration

To offer a real-world focused approach, the existing vehicle structure that is already built from carbon fiber reinforced epoxy resin was initially tested to provide a baseline. This baseline was then to be matched with the material modified to the properties of the flax fiber physically tested in the previous chapter. The model consisted of the geometry of an existing single seater, provided by the University of Birmingham's Formula Student team. Use of this model allows validation to the real world with existing torsional testing already being completed by the student team – as well as allowing a baseline stiffness target to match. The exterior surfaces of the model, seen in Fig. 7 were extracted and formed the outermost ply of the composite stack-up created in ACP.

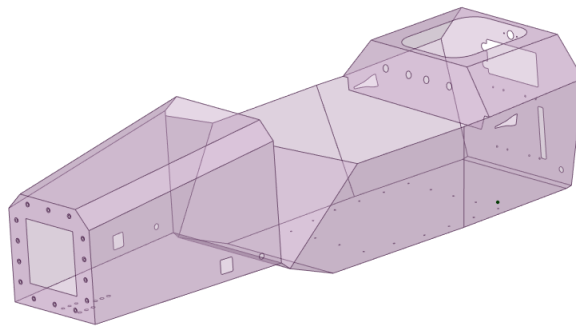


Figure 6 - External surfaces extracted from model

5.2 – Model Setup

5.2.1 – Boundary conditions

Ansys ACP, the composites analysis module, within Ansys Workbench 2024 R1 was selected to compare the torsional stiffnesses of a single seat vehicle structure with each material physically tested.

The boundary conditions of the FEA were created to match the real-life testing completed – which can be seen in Figure 8. This consisted of a simplified test where the base of the chassis was fixed to a slotted table, with a beam attached to the forward face via existing mounting holes.

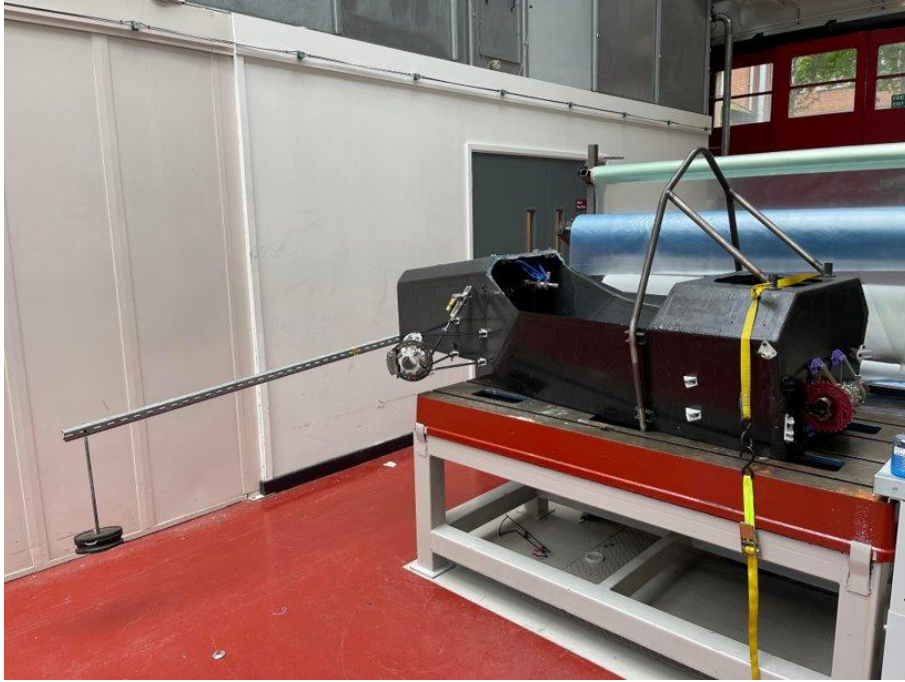


Figure 7 - Torsional testing completed by the Formula Student team (Dodd, 2023).

Figure 9 (a&b) shows the simulation setup adapted from this physical testing. This test has limitations in that it is not a realistic assessment of the vehicle's stiffness in real-world use (as the direct suspension mountings – the real world loaded points – are not the origins of the torsional force) but for a material comparison as is being completed here, it will give an assessment of the difference in torsional rigidity over a real-world structure with openings and other factors. This is more representative than, for example, a tube as the geometry is more complex and relevant.

The testing completed previously had good accuracy to the finite element model. It is therefore demonstrated that it provides a good analogy to the real world.

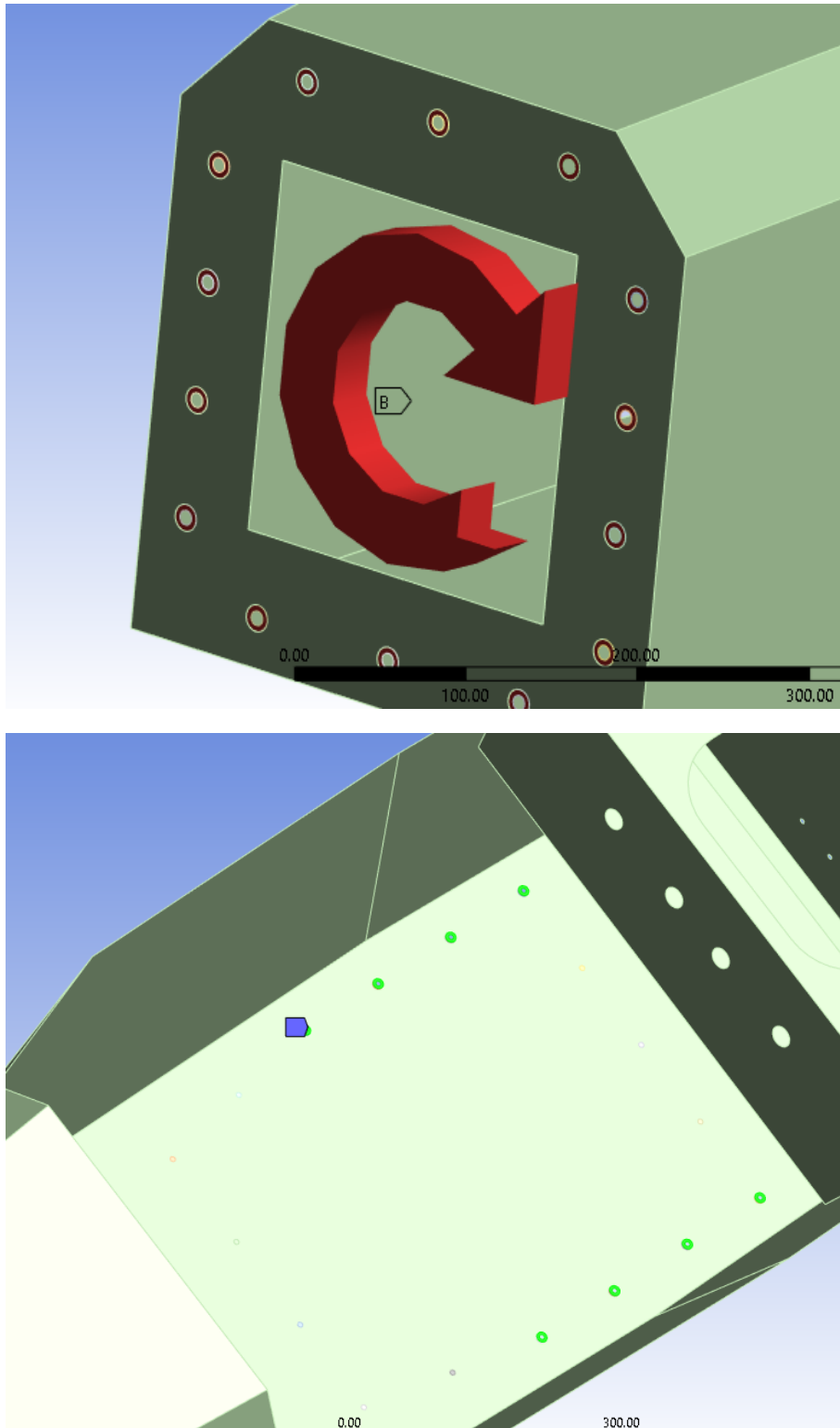


Figure 8 - Finite element setup (a) Torsional force applied to the front mounting holes (b) Rigid (fixed) support at the floor of the vehicle

5.2.2 – Materials input

The material data calculated in Chapter 4 was input to the Engineering Data module of Ansys. For the context of the testing, the only data that modified the results was the Young's modulus. Figure 10 shows the input at Ansys. Due to the symmetrical weave of the material tested the tensile strength and Young's modulus could be applied bidirectionally and is extrapolated using standard methods (as with existing carbon fibers) between.

Young's Modulus X direction	16.2	GPa	▼
Young's Modulus Y direction	16.2	GPa	▼
Tensile X direction	189.4	MPa	▼
Tensile Y direction	189.4	MPa	▼

Figure 9 - Materials input in Ansys Engineering Data module

5.3 – Results and Discussion

The results of the simulation indicate that the composite skins had to be doubled in thickness between carbon fiber and flax fiber. This contrasts with the increase required to match performance in tensile strength – resulting from the torsional load case having different parameters. Increase in skin thickness moves material further from the neutral axis – so less is required in a torsional case.

The resultant change in structure mass seen is 11.2 kg or a 66% increase – as shown in Table 4.

Table 4 - Simulation results for both carbon and flax fiber

Constituent Material	% of structure	Mass - Carbon Fiber [kg]	Mass – Flax [kg]	% increase, flax
Composite Ply [kg]	66%	11.14	22.37	101%
Core Material [kg]	34%	5.76	5.76	-
Total [kg]	-	16.9	28.13	66%

5.4 – Conclusions

Simulation results show that a significant increase in material thickness, and therefore mass, is required to achieve the same torsional stiffness when comparing flax fibers to carbon fibers. This is analogous but in different magnitude to the values seen directly through tensile testing. The values found can therefore be used to estimate the carbon footprint of the structure.

6 – Estimation Carbon Footprint via Life Cycle Analysis

Throughout this section data used to estimate the carbon footprint in each stage of the vehicle's life is provided by Ansys Granta Edupack. Each stage is estimated individually to provide a clearer picture of the estimated costs. The data was provided by Granta Edupack 2024 R1.

6.1 – Determination of Material Quantities

To effectively compare the quantities of materials required to build an automotive structure, a proxy is used. This proxy is the BMW i3 – an electric/hybrid electric automotive product with a full carbon fiber chassis. Due to the automotive industry only beginning to use carbon fibers, this is currently the only mass-produced automotive product utilising a carbon fiber structure.

The BMW i3 passenger capsule weighs 150 kg (Gutowski et al., 2017) and is analogous in construction to the structure analysed in this study. Table 5 provides estimated constituent masses from construction – based on the estimated increases calculated in chapter 5.

Table 5 - Extrapolated estimated mass changes for the BMW i3 using flax fibers

Constituent Material	% of structure	Mass - Carbon Fiber [kg]	Mass – Flax [kg]	% increase, flax
Composite Ply [kg]	66	98.88	198.55	101
Core Material [kg]	34	51.12	51.12	-
Total [kg]		150	249.67	66

6.2 – Impact of Manufacturing the Materials

Table 6 shows the estimated CO₂ produced during production of the composite materials. Due to the similar structures and there being no change in the mass of the core material it is not required to calculate the carbon footprint of this portion of the structure as this would not impact totals.

Table 6 - Calculated change in production emissions between a flax and carbon fiber BMW i3 structure

Carbon Footprint - Primary Production - Virgin Materials

Material	Quantity [kg]	CO2-eq [kg/kg]	Total CO2-eq [kg]
Carbon Fiber	52.40	64.90	3401.03
Resin Matrix	46.47	5.54	257.45
Total			3658.48

Flax Fiber	105.23	1.08	113.65
Resin Matrix	93.32	5.54	516.99
Total			630.64

6.3 – Impact of Manufacturing the Product

The change in mass of the chassis due to the change in material results in a higher energy usage during the (as examined in this study) autoclave production process – as there is more material to heat up to curing temperature. Figures can be found in Table 7.

Table 7 - Change in CO₂ emissions resulting from more thermal mass during heat-curing

Autoclave Moulding CO2 [kg/kg]	CO2 Produced, Carbon [kg]	CO2 Produced, Flax [kg]
1.67	250.50	416.96

The total reduction in CO₂ emissions during production of the structure is 2.9 Tons or 73 % over the carbon structure. Next, the effect on fuel usage and emissions must be calculated.

6.4 – Impact of Utilisation - Fuel Consumption

A study by Tolouei and Titheridge (2009) found statistical significance in the change of fuel usage as a result of a 100 kg change in vehicle mass – with worst case automatic diesel fuelled vehicles seeing an increase of up to 6.2 percent.

Table 8 - Percentage increase for a 100 kg mass increase – adapted from (Tolouei and Titheridge, 2009)

Fuel type	Transmission type	Percent change in fuel consumption	
		Urban cycle	Extra-urban cycle
Petrol	Manual	2.3	2.8
	Automatic	3.3	3.9
	Other	No significance	0.9
Diesel	Manual	3.8	5.1
	Automatic	4.8	6.2
	Other	NS	3.2

Using the UK most popular car of 2024 (Ford Puma 1.0 petrol manual) and the most popular diesel car (BMW 320d 2.0 diesel automatic) as a basis for the change in fuel consumption the following fuel consumptions are calculated. These cars were selected as a best case and worst case within Table 8. As fuel consumption is directly

proportional to CO₂ emissions (Riemersma and Mock, nd), we can simply use the provided CO₂ figures to calculate the change in emissions of the vehicle.

Table 9 below shows the estimated emissions increase as a result of the multipliers from above. Vehicle life-time mileage is taken from Elliott et al., (2024). Figure 11 illustrates these results graphically.

Table 9 - Changes in tailpipe emissions for each vehicle

Ford Puma 1.0 L petrol

CO ₂ g/km	Tonne CO ₂ lifetime	Tonne CO ₂ Lifetime, mass adjusted	Difference, kg
121	26.93	27.55	619.44

BMW 320d automatic

CO ₂ g/km	Tonne CO ₂ lifetime	Tonne CO ₂ Lifetime, mass adjusted	Difference, kg
126	28.05	29.78	1738.80

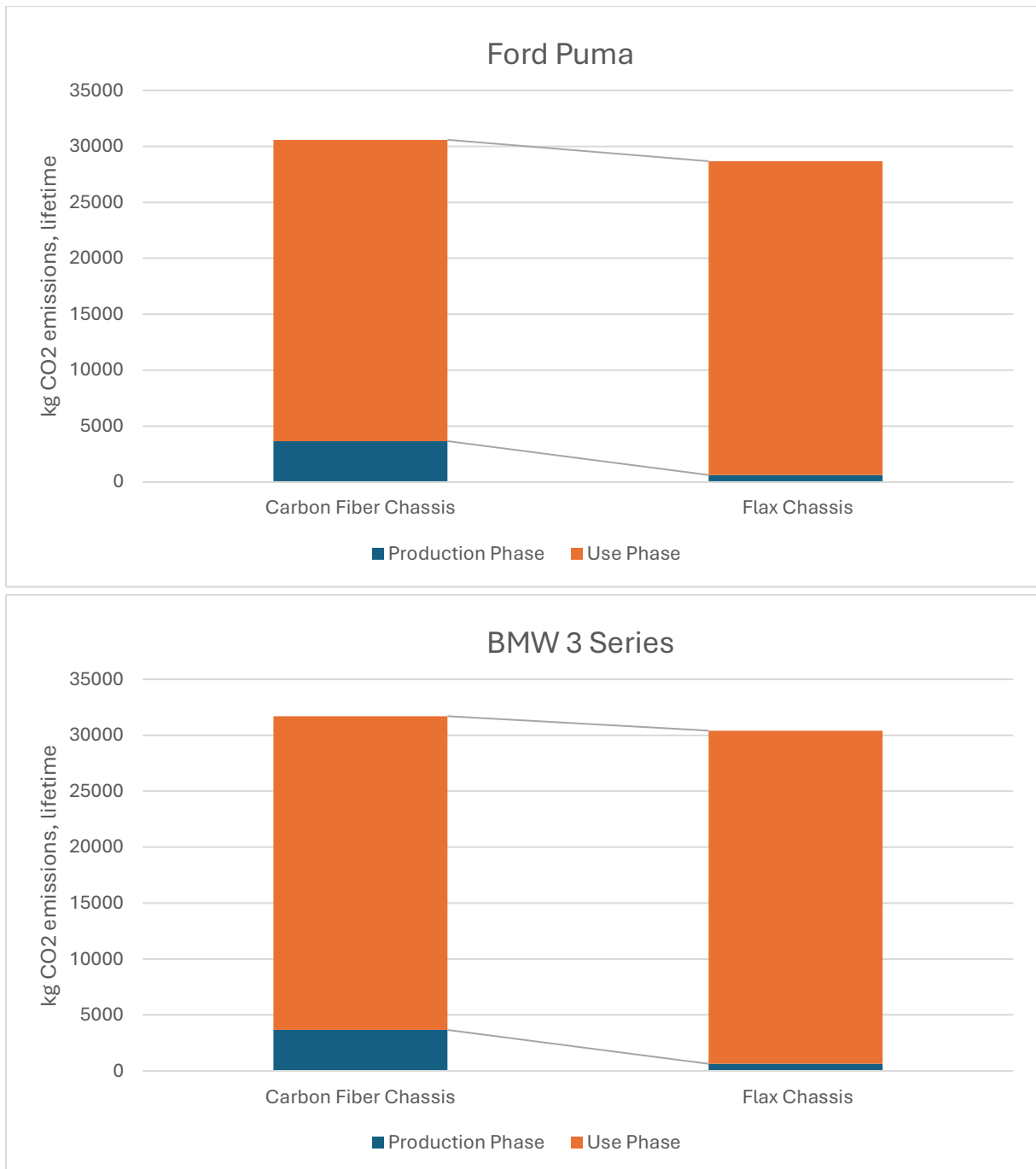


Figure 10 - Graphical representation of the life-time emissions of (a) Ford Puma (b) BMW 3 series - substituting a carbon structure for a flax structure.

6.5 – Conclusions

It is shown from this data that the change in fuel economy from use of a flax fiber chassis would not outweigh the overall reduction in material production. In the worst case, for an automatic diesel vehicle, a 1289 kg (4.1 %) reduction is expected over the average lifespan of a vehicle. In the best case, for the petrol vehicle, a reduction of 6.3 % (1915 kg) is expected. This indicates that flax fiber construction, while heavier, provides a net reduction in carbon emissions over the vehicle lifespan.

7 – Conclusions and Future Work

The life cycle analysis conducted as part of this study demonstrates the environmental benefit of the use of a flax fiber composite over a carbon fiber for automotive structural use. By replacing carbon fibers with flax fibers, a net reduction of up to 6.3 % in the environmental impact can be achieved. This amounts to up to 1.9 tonnes of carbon equivalent emissions over the vehicle's lifespan.

This overall carbon footprint reduction is largely driven by the lower energy requirements of flax fiber during its production. The lower mechanical properties of the flax fiber resulting in larger quantities of flax fiber and the higher energy usage during manufacturing do not outweigh the lower energy consumption during production. This highlights their potential in the automotive industry.

The adoption of flax fibers in automotive structural manufacturing could contribute to a more sustainable vehicle production system, contributing and aligning with global efforts to mitigate climate change and reduce greenhouse gas emissions. Future research should focus on optimising the mechanical properties of flax composites further – enhancing their applicability within the automotive industry. Studies should also focus on the monetary impact of the use of a flax fiber to explore the feasibility of widespread adoption. Overall, the findings suggest that flax fibers offer a promising pathway toward greener automotive technologies.

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