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Designing vehicle structures using materials with a low carbon footprint

Abstract

The development of modern automotive structures is currently focused on energy optimisation to minimise their negative environmental impact. One of the key trends in this field is the implementation of renewable materials and composites reinforced with natural fibres. This article presents the results of static finite element method (FEM) simulations conducted on a newly designed self-supporting monocoque structure of a prototype vehicle developed for the international Shell Eco-marathon competition. The numerical analysis, carried out using Ansys Mechanical, compares the structural response of the chassis when configured with conventional carbon fibre-reinforced polymer (CFRP) versus a flax-fibre-based biocomposite. The numerical models were defined using orthotropic mechanical parameters determined by the authors through prior experimental testing. The structural analysis under the nominal driver weight demonstrated that a direct 1:1 material substitution results in a drastic, nearly 2.6-fold increase in maximum deformation, thereby disqualifying the structure on the basis of structural stiffness. It was shown that to maintain the monocoque's deflection at a consistent, safe level (below 1 mm), it is necessary to increase the number of flax fibre layers. This modification increases the laminate thickness by 30%, leading to a nearly twofold (91%) increase in the mass of the monocoque itself. The research demonstrated that sustainable materials of natural origin can be used to design a fully compliant and safe load-bearing vehicle structure, provided that their lower specific stiffness is compensated for during the wall-thickness optimisation stage.

1. INTRODUCTION

The modern automotive industry is developing intensively towards maximising energy efficiency. The main driver of this work is the significant increase in global energy demand, with the transport sector accounting for approximately 20% of world consumption (Catibog et al., 2019; Das et al., 2026). Consequently, the industry's key strategic objective is to comply with stringent environmental and legal regulations (e.g., European Union directives) that mandate reductions in carbon dioxide emissions and the implementation of circular economy principles (Catibog et al., 2019; Pallvi, 2025; Fruni, 2021). Concurrently, the progressive electrification of powertrains makes the energy efficiency of the entire vehicle structure a critical parameter, directly determining vehicle range (Fruni, 2021).

In response to these challenges, specific development trends in vehicle design can be divided into three main areas: weight reduction (Pallvi, 2025), the implementation of environmentally sustainable materials (Das et al., 2026; Fruni, 2021), and the advanced optimisation of aerodynamics and body architecture (Fruni, 2021).

A key structural trend remains the continuous reduction of vehicle curb weight, which translates directly into lower rolling resistance and higher fuel or energy economy. In the design of vehicle load-bearing structures, there is a visible trend shifting from conventional steels to aluminium alloys and composite materials, enabling a weight reduction of structural components by up to 45%. The greatest benefits in this field are achieved through the use of carbon fibre-reinforced polymers (CFRP). These materials, commonly used in structures such as monocoques, offer an excellent strength- and stiffness-to-weight ratio, enabling the design of exceptionally lightweight structures (Balo & Sua, 2024; Fruni, 2021).

In the field of aerodynamics, vehicle designs are optimised to minimise the drag coefficient (C_d) and frontal area (Balo & Sua, 2024). The objective is to shape the vehicle body in such a way as to minimise the flow separation zone and the size of the aerodynamic wake. Achieving these geometric goals is significantly easier when using composite structures. Due to their high strength and technological feasibility for manufacturing complex shapes, obtaining optimised aerodynamic profiles is much simpler than for metallic structures (Balo & Sua, 2024; Siouta et al., 2024).

Parallelly, materials engineering is developing rapidly in the search for ecological solutions. A significant trend is the replacement of petroleum-based matrices and reinforcements with biocomposites reinforced with natural fibres such as flax, hemp, kenaf, or jute (Catibog et al., 2019; Pallvi, 2025; Siouta et al., 2024). These materials, initially used in interior components (door panels, dashboards) and semi-structural body elements, allow for a significant reduction in the carbon footprint and facilitate vehicle recycling at the end of their life cycle (Siouta et al., 2024; Pecas et al., 2018). In the area of load-bearing monocoque structures, the first attempts have already been made to replace carbon reinforcement with environmentally friendly alternatives, including basalt and flax fibre reinforcements (Aapro & Toivonen, 2023).

The primary advantage of natural fibre-based composites includes their high specific strength. As shown in literature (Catibog et al., 2019; Le Bourhis & Touchard, 2021; Gholampour & Ozbakkaloglu, 2020; Westman et al., 2010; Frącz & Janowski, 2017), plant-derived fibres (e.g., flax, hemp, sisal, jute) exhibit a low density (typically in the range of 1.2–1.6 g/cm³), which allows for a favourable ratio of mechanical properties to component mass. Additionally, natural fibre-based materials have high vibration-damping capacity and thermal insulation. The inherently porous cellular structure of natural fibres provides excellent acoustic and vibroacoustic damping parameters (Fruni, 2021; Gholampour & Ozbakkaloglu, 2020; Westman et al., 2010).

Environmental considerations are also very important. These fibres are completely renewable and biodegradable, characterised by a low or negative carbon footprint over their life cycle (LCA) (Catibog et al., 2019; Le Bourhis & Touchard, 2021). Typical carbon footprint for flax composites is 2.9 to 3.3 kg CO₂ per kg, when CFRP is 19 to 26 kg CO₂ per kg – that's around 87% less (Margoto & Milani, 2025). Additionally, unlike synthetic fibres, natural reinforcing materials are non-toxic, do not cause respiratory or skin irritation during cutting and moulding processes, and minimise cutting tool wear (Catibog et al., 2019; Le Bourhis & Touchard, 2021). In combination with the high availability of agricultural crops, this translates into significantly lower sourcing costs for natural fibres compared to advanced synthetic fibres (Pecas et al., 2018), making natural fibre-based composites a highly strategic raw material that is widely available locally (with a short supply chain).

Despite numerous advantages, the widespread implementation of these materials in load-bearing structures faces significant technological and engineering barriers. The most critical disadvantages include: high hygroscopicity, limited thermal stability, a wide range of mechanical parameters, biodegradation and flammability.

Due to the presence of free hydroxyl groups in cellulose and hemicellulose, the fibres show a strong tendency to absorb moisture (up to several per cent by weight), leading to composite swelling, dimensional instability, and the generation of microcracks at the interface and within the matrix (Siouta et al., 2024; Le Bourhis & Touchard, 2021). Changes in humidity, therefore, affect both the strength and the durability of the composite. If we combine this with the fact that the mechanical and chemical parameters of natural fibres exhibit high dispersion, being strictly dependent on climatic conditions, soil type, vegetation phase, and extraction methods, this complicates precise numerical modelling of structures and prevents strict standardisation (Siouta et al., 2024; Le Bourhis & Touchard, 2021; Gholampour & Ozbakkaloglu, 2020; Westman et al., 2010). We obtain material with a wide range of properties.

Time is also a significant factor influencing the properties of the composite. Structures based on natural fibres are characterised by limited operational durability due to their susceptibility to microorganisms, fungi, UV radiation, and atmospheric conditions, as well as low fire resistance (Gholampour & Ozbakkaloglu, 2020; Westman et al., 2010; Imon, 2024; Phiri et al., 2024; Abdollahiparsa et al., 2023; Jagadeesh et al., 2022). Additionally, most natural fibres undergo thermal degradation processes (mainly the decomposition of hemicellulose and lignin) at temperatures as low as 200–250°C, which critically limits the processing window and the choice of polymer matrices (Siouta et al., 2024; Le Bourhis & Touchard, 2021).

The implementation of these materials in high-load applications remains an important research challenge due to their lower availability and limited documentation of their precise mechanical properties compared with conventional materials such as carbon or glass fibres (Balo & Sua, 2024). In materials engineering literature, compilations of the mechanical properties of natural fibres can be found; however, universal, standardised

material catalogues analogous to those commonly used for synthetic materials do not currently exist (Siouta et al., 2024). The primary reason for this is the inherent characteristics of biomaterials (Siouta et al., 2024; Le Bourhis & Touchard, 2021; Gholampour & Ozbakkaloglu, 2020; Westman et al., 2010). The substantial variability in the mechanical properties of raw fibres necessitates identifying parameters for each batch of supplied raw material.

From an engineering perspective, this implies that available literature data can only serve as preliminary material selection (e.g., using MCDM methods). Designing advanced load-bearing structures subjected to dynamic loads, such as vehicle monocoques, imperatively requires independent, standardised mechanical testing for the specific batch of composite being utilised. The empirical parameters gathered must then be validated in a numerical environment using macromechanical failure criteria adequate for orthotropic materials, such as the Tsai-Wu or Hashin criteria (Balo & Sua, 2024; Siouta et al., 2024; Estrada et al., 2019).

In terms of absolute strength parameters, plant fibres are inferior to carbon fibres, exhibiting lower tensile strength and a lower longitudinal modulus - Young's modulus (Gholampour & Ozbakkaloglu, 2020; Westman et al., 2010). Research indicates that while they can successfully serve as substitutes for synthetic materials in components where structural stiffness is the critical design parameter, they are less efficient as direct replacements in structures where the primary design criterion is ultimate tensile strength (Mohanty et al., 2018; Milanese et al., 2011). Nevertheless, the low density of natural fibres, typically oscillating between 1.2–1.6 g/cm³ (compared to 1.7–2.0 g/cm³ for carbon fibres), allows for a very favourable specific strength, defining them as a promising material for the construction of lightweight, thin-walled structures (Balo & Sua, 2024; Gholampour & Ozbakkaloglu, 2020; Westman et al., 2010).

Consequently, the following research question arises: Will the lower strength of natural fibres, which necessitates increasing their volume fraction (or wall thickness) to maintain the required stiffness, be offset by their low density? The objective of this article is to compare the structural response of a prototype racing vehicle monocoque made of flax-fibre composite versus CFRP under the assumption of identical geometry, and to determine the necessary wall thickness modifications to achieve an equivalent deformation state while ensuring structural integrity. The analyses conducted will enable an assessment of the efficiency and structural applicability of natural fibre-based composite materials in vehicle design, where mass minimisation is a key optimisation criterion.

2. AIM AND SCOPE OF WORK

The subject of the investigative analyses is a new load-bearing vehicle structure of the “Prototype” class, designed by the Hydrogreen Team, a student research group at the Lublin University of Technology. The vehicle was developed strictly in accordance with the regulatory guidelines of the international Shell Eco-marathon competition. Engineering efforts were based on the reconfiguration of experiences from previous races and advanced CFD (Computational Fluid Dynamics) aerodynamic optimisation, which enabled the achievement of a minimal drag coefficient while maintaining optimal usability of the vehicle body (Figure 1).

The vehicle's structure is a three-wheeled self-supporting monocoque, where the driver occupies a semi-recumbent position in the front part of the passenger section. Behind a laminated bulkhead wall, a technical compartment houses the powertrain, which consists of an electric motor driving a single wheel and is powered by a PEM (Proton Exchange Membrane) hydrogen fuel cell.

The primary objective of this study is the numerical evaluation of the application feasibility of natural-origin fibre composites (flax) as a direct substitute for conventional carbon composites (CFRP) in the load-bearing monocoque structure. The structural stiffness of the chassis was selected as the fundamental comparative and optimisation criterion, as it dictates both the driver's passive safety and the retention of consistent aerodynamic geometry under load. According to the design assumptions, the maximum deflection at critical points must not exceed 1 mm.

Unlike most academic papers presenting studies of composite material specimens, the aim of this thesis is to determine the feasibility, macro-mechanical behaviour, and structural limits of a full-scale, three-dimensional, ultra-thin self-supporting monocoque subjected to real operational load paths. Furthermore, the analyses contained in this study aim to address the question of the “mass penalty” under a strict stiffness-governed criterion, which is so crucial in the case of ultra-lightweight structures.

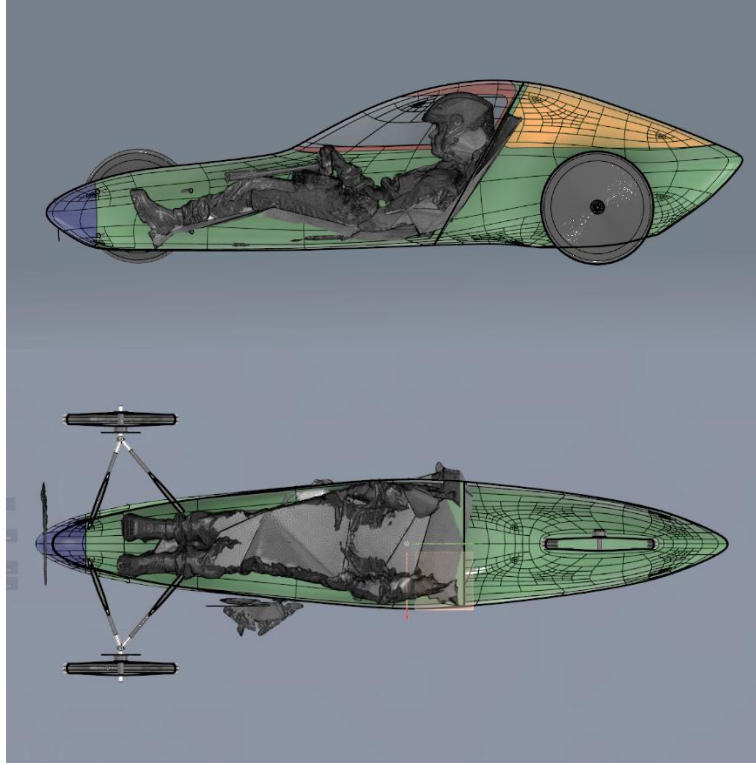


Fig. 1. Prototype vehicle design

3. NUMERICAL METHODOLOGY

The structural strength analyses were performed using the Finite Element Method (FEM) in the Ansys Mechanical environment, utilising the dedicated composite structures module (ACP – Ansys Composite PrepPost). The surface model of the monocoque was discretised using a computational mesh comprising 52,807 shell elements, designed for layered laminate analyses (Figure 2).

To replicate real operating conditions, the structure was subjected to a static model of operational loads consisting of:

- Driver weight load (Force A): a force vector with a value of 600 N directed vertically downward (-Z axis), uniformly distributed over the seat surface ($A = 472 \text{ cm}^2$);
- Seat backrest load (Force B): a force vector with a value of 400 N directed horizontally toward the rear of the vehicle (+Y axis), uniformly distributed over the backrest surface ($B = 1235 \text{ cm}^2$).
- The boundary conditions for support (blocking all degrees of freedom – Fixed Support) were defined at the suspension mounting nodes:
- Front suspension: 4 symmetrical zones of mounting holes with a diameter of $\phi = 8 \text{ mm}$ in the front section of the monocoque;
- Rear suspension: 2 mounting surfaces in the rear section, corresponding to the attachment points of the rear wheel axle.

These boundary conditions meet the conditions set out in the guidelines for structural endurance testing of vehicles for the Shell Eco-marathon. It involves a static load test with the drive and steering wheels locked, under a load from a driver whose weight exceeds the required weight by 20 per cent.

To ensure sufficient local stiffness, the structure was reinforced by defining additional composite layer sequences in two critical zones: the floor section beneath the driver and the bulkhead area (Figure 3). Numerical tests were implemented for three materials: carbon fabric, flax fabric, and a polyurethane foam core (sandwich structure). The properties of CFRP and the core were imported from the built-in Ansys material database, whereas the orthotropic properties of the flax composite were determined experimentally through the authors' own material testing (Table 1).

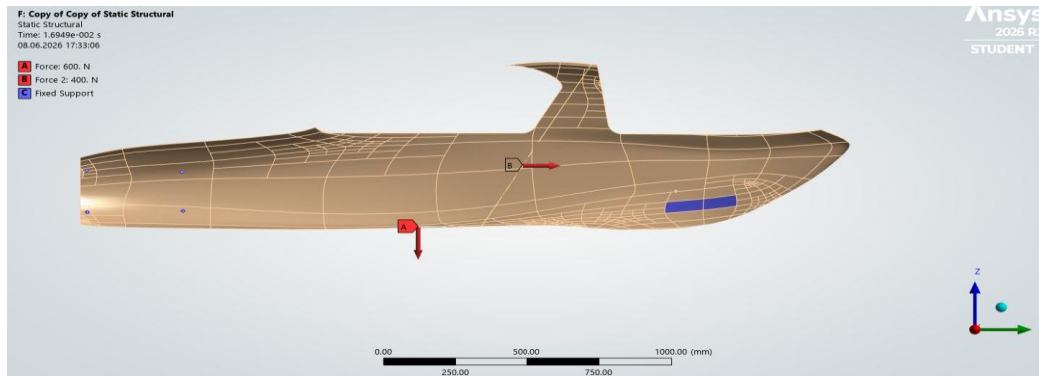


Fig. 2. Strength analysis model with boundary conditions marked

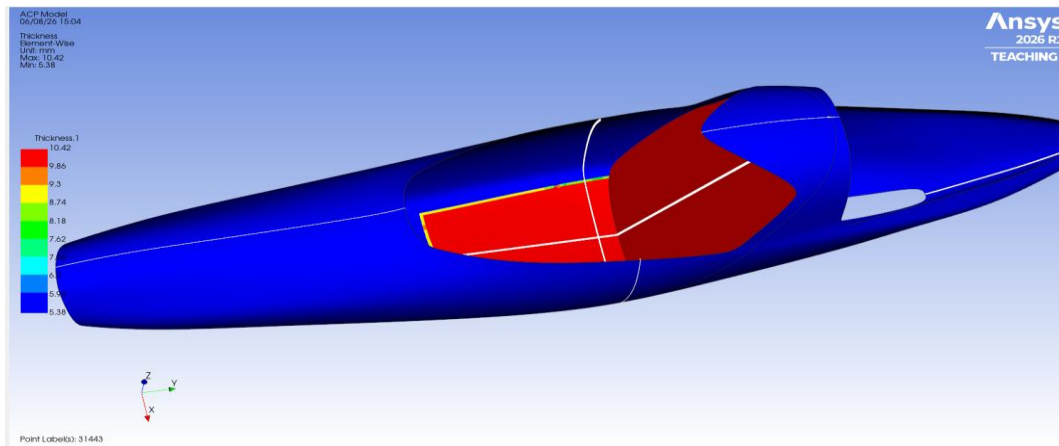


Fig. 3. Reinforcement areas defined during the simulation

Tab. 1. Mechanical properties of the composite plies and core adopted for simulations

Mechanical Parameter	Carbon Fiber (CFRP)	Flax Fiber (Linen)	Polyurethane Core
Single ply thickness	0.22 mm	0.17 mm	3.00 mm
Density	1420 kg/m ³	1318 kg/m ³	280 kg/m ³
Young's Modulus in X and Y axis (Ex, Ey)	61.3 GPa	5.87 GPa	5.30 GPa
Young's Modulus in Z axis (Ez)	6.90 GPa	3.00 GPa	0.32 GPa
Tensile Strength in X and Y axis (Rm)	805 MPa	71.2 MPa	5.0 MPa
Tensile Strength in Z axis	50 MPa	40.2 MPa	5.0 MPa
Shear modulus in XY and XZ (Gxy, Gxz)	3.58 GPa	2.05 GPa	0.59 GPa
Shear modulus in YZ axis (Gyz)	4.50 GPa	2.05 GPa	0.59 GPa
Poisson's ratio in XY and XZ	0.300	0.330	0.316
Poisson's ratio in YZ	0.320	0.351	0.316

The tests were therefore carried out on three configurations:

1. Base configuration: the entire structure consists of 2 layers of carbon fibre + 1 layer of core + 2 layers of carbon fibre; the reinforcements consist of 2 layers of carbon fibre + 1 layer of core + 2 layers of carbon fibre;
2. Lightweight linen configuration: entire structure 2 layers of flax fibre + 1 layer of core + 2 layers of flax fibre, reinforcement 2 layers of flax fibre + 1 layer of core + 2 layers of flax fibre;
3. Rigid flax configuration: entire body 7 layers of flax fibre + 1 layer of core + 7 layers of flax fibre, reinforcements 6 layers of flax fibre + 1 layer of core + 6 layers of flax fibre.

The following parameters were analysed: maximum deformation, the Tsai-Wu criterion and the mass of the composites.

4. SIMULATION TESTS AND THEIR ANALYSIS

The initial simulations were carried out for the base configuration. This configuration weighed 8.086 kg. Figure 4 shows the deformation results, with the deformations exaggerated for clarity. As shown, the greatest deformation occurs directly beneath the driver and is 0.902 mm. Significant deformations also occur at the edges of the upper boundary of the powertrain compartment (rear of the vehicle). However, the deformations there do not exceed 0.75 mm.

When analysing the degree of stress in the structure, it is evident that it is subjected to very little stress. As shown in Figure 5, the Tsai-Wua criterion reaches a maximum of 0.034. The greatest stress occurs at the junction of the floor and the bulkhead and is mainly associated with a change in the load direction to a direction perpendicular to the fibre orientation.

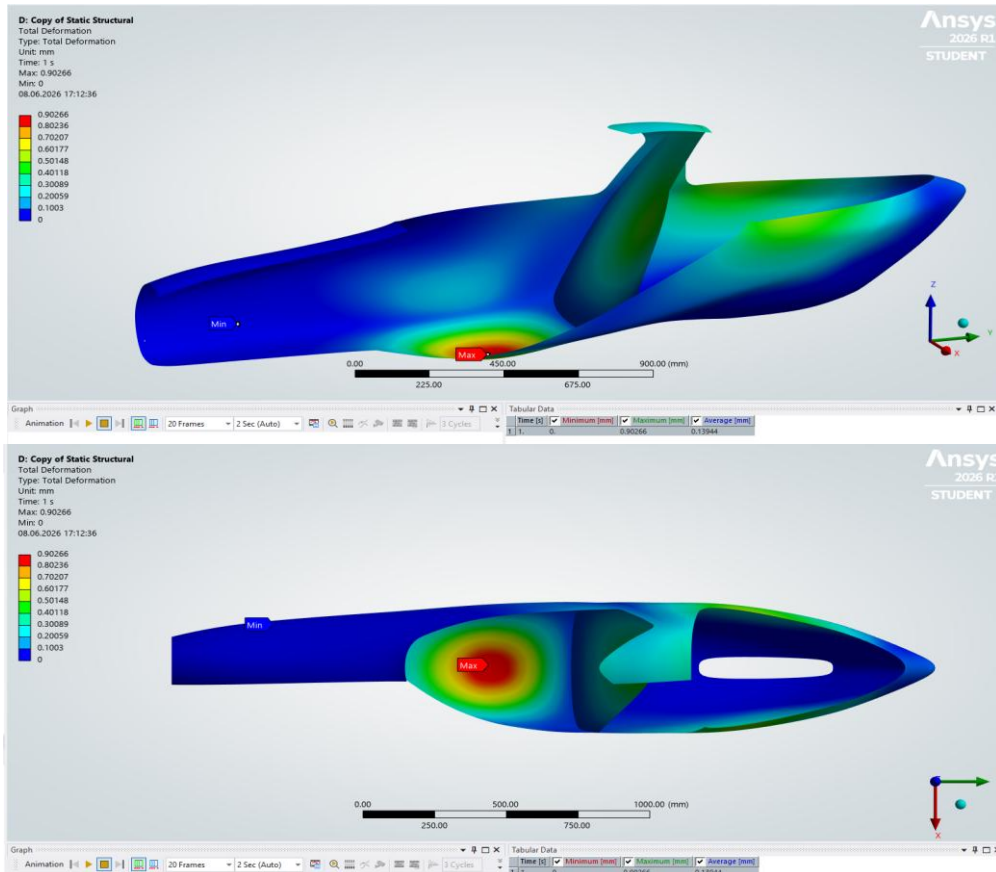


Fig. 4. Deformations in the base configuration structure

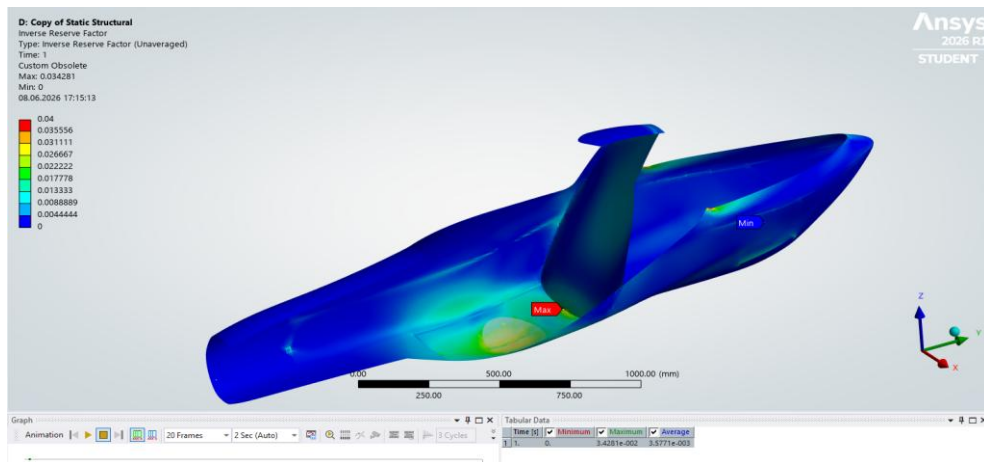


Fig. 5. The Tsai-Wua criterion for the base configuration

The lightweight linen configuration weighed just 6.822 kg, compared to the base configuration. However, the deflection of this configuration is significantly greater (Figure 6). As in the base configuration, the maximum deflection is located beneath the driver, but amounts to 2.392 mm. The deflection at the edge of the engine compartment is also greater, reaching 1.62 mm. This is primarily due to a significant decrease in the modulus of elasticity.

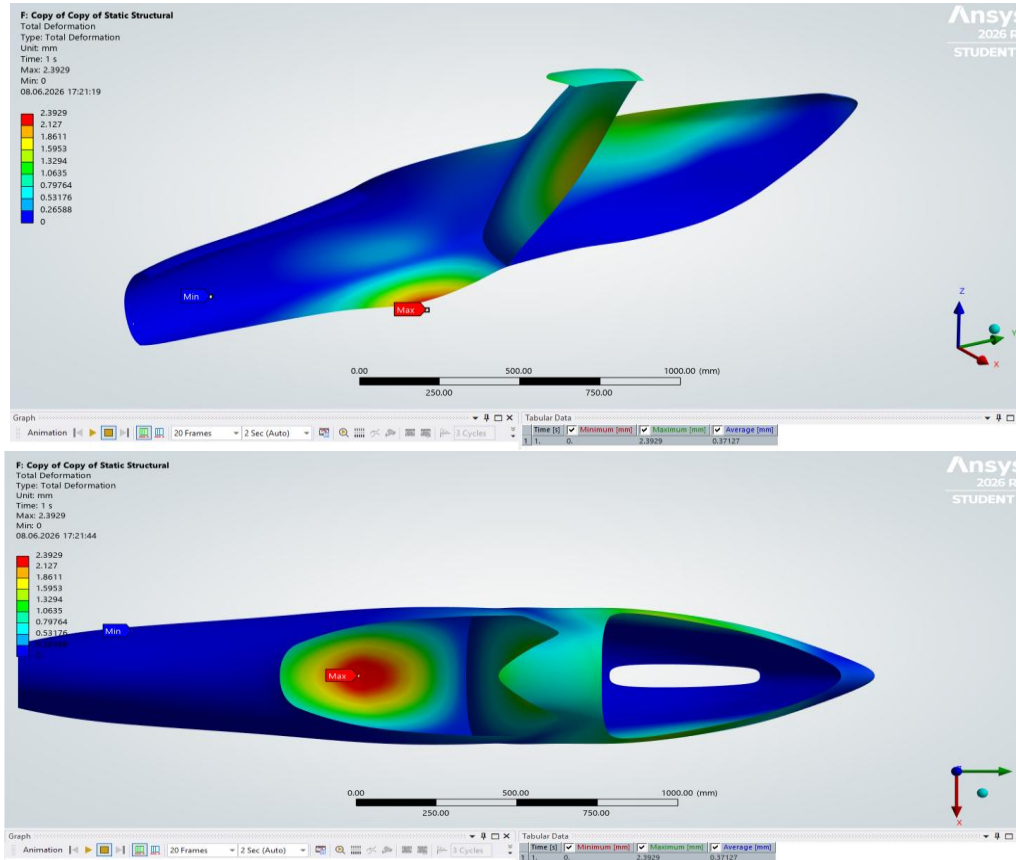


Fig. 6. Deformations in lightweight linen configuration

An analysis of the structural load reveals a significant increase in stress, although this remains well below critical values. As shown in Figure 7, the Tsai-Wu criterion reaches a maximum of 0.125. The highest stress levels are also found at the junction between the floor and the partition. An increase in stress resulting from the lower strength of the material is therefore evident, but the nature of this load does not change.

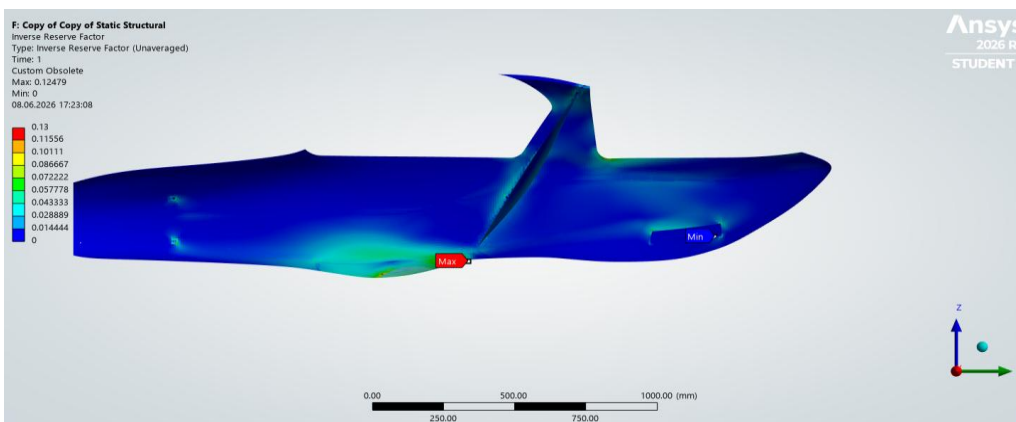


Fig. 7. The Tsai-Wu criterion for a lightweight linen configuration

The final configuration analysed (rigid linen) was reinforced by increasing the number of layers in order to achieve a deformation similar to that of the base configuration. As shown in the deformation analysis (Figure

8), the maximum deformation was 0.919 mm. As in the previous configurations, this deformation occurs beneath the driver. The deformation on the upper surface of the engine compartment does not exceed 0.75 mm. Consequently, similar levels and shapes of deformation were achieved as in the base configuration. However, this resulted in a significant increase in the monocoque's mass, reaching up to 15.442 kg in this configuration.

The increase in the number of layers also reduced material stress compared to the lightweight flax configuration. The maximum value of the Tsai-Wu criterion, which also occurs at the junction of the floor and the bulkhead, is 0.060. This is higher than in the base configuration, but, as in previous cases, it is far from critical values.

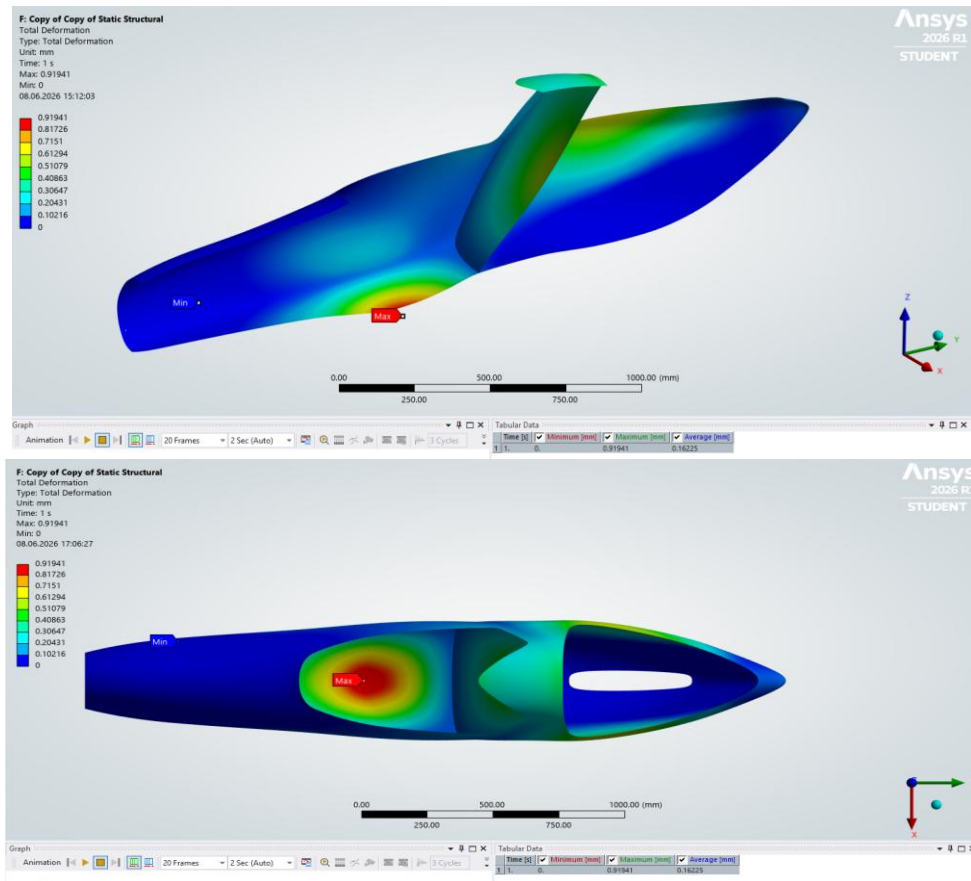


Fig. 8. Deformations in a rigid linear-configuration structure

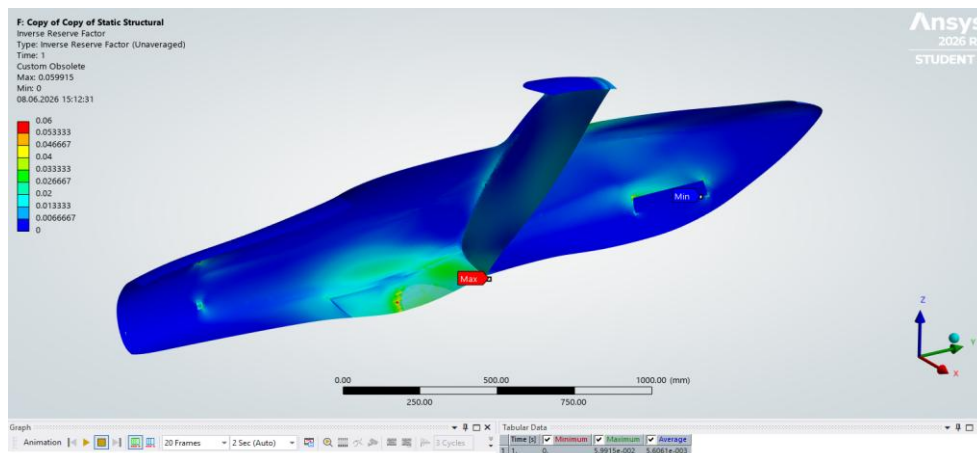


Fig. 9. The Tsai-Wu criterion for a rigid linen configuration

5. CONCLUSIONS

Based on the conducted experimental material characterisation and static finite element analyses (FEA) of the prototype vehicle's monocoque structure, several key conclusions regarding the structural performance of natural fibres can be formulated. First, the research demonstrates that natural-fibre-reinforced composites, specifically flax/epoxy, can serve as a viable alternative to conventional carbon-fibre-reinforced polymers (CFRP) in load-bearing, self-supporting structures. Utilising flax reinforcement yields a structurally sound assembly that maintains its integrity under nominal operational loads (600 N and 400 N), with the material effort evaluated via the Tsai-Wu failure criterion remaining exceptionally low (0.060) and well below the critical threshold.

However, the structural performance is governed more by stiffness than by strength. A direct 1:1 material substitution preserving identical ply counts, representing the lightweight flax configuration, results in a severe, nearly 2.6-fold increase in maximum deformation, from 0.902 mm to 2.392 mm. This is a direct consequence of the low orthotropic longitudinal elastic modulus of the flax laminate ($E_{x,y} = 5.87$ GPa) compared to the CFRP counterpart ($E_{x,y} = 61.3$ GPa). Consequently, for thin-walled, load-bearing vehicle structures, the primary dimensioning constraint for biocomposites is structural stiffness rather than ultimate material strength. To match the structural stiffness of the baseline CFRP monocoque and restrict peak deflection to under 1.0 mm, the flax reinforcement layup had to be expanded from 2 to 7 plies. While this increased the laminate thickness, the lower density of the flax composite ($\rho = 1318$ kg/m³ vs. $\rho = 1420$ kg/m³) was insufficient to offset the volume increase. As a result, securing equivalent stiffness introduced a 91% mass penalty on the monocoque chassis, increasing its weight from 8.086 kg to 15.442 kg.

Despite these weight and stiffness trade-offs, the overall structural response remains highly predictable. Evaluation of the numerical stress and displacement fields revealed that substituting synthetic fibres with natural ones does not alter the spatial distribution of stress and strain concentrations. Across all investigated configurations, the critical zones exhibiting the highest deflection and peak Tsai-Wu values consistently remained the floor panel directly beneath the driver and the transitional fold connecting the floor to the structural bulkhead. This localised behaviour dictates the necessity of targeted structural reinforcement, such as local ply interleaves, rather than global thickening of the laminate. Finally, this study highlights a crucial methodological contribution: because of the inherent scatter and variability in bio-based material properties, standardised literature data should be referenced only for preliminary design stages. Engineering a safe, reliable, and low-carbon load-bearing structure requires independent destructive testing of each fibre/matrix batch to populate FE models with precise, empirically validated orthotropic parameters.

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Conflicts of Interest

The authors declare no conflict of interest.

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