Evaluation of a Filament-Winding Composite and Aluminium 6061 Frame for Electric Vehicles

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Abstract: This study evaluates the structural performance of electric motorcycle frames made of 6061 aluminium alloy and filament winding-based composites using the Finite Element Method (FEM) approach. The main objective of this study is to compare the deformation response, stress distribution, and safety factors of both materials in the same frame geometry and loading conditions, so that the influence of material characteristics on structural behaviour can be analysed objectively. FEM simulations were performed with static loading representing vehicle operating conditions, while aluminium was modelled as isotropic and composite as orthotropic to capture its anisotropic properties. The analysis results show that filament winding composite chassis tend to have more controlled deformation and higher safety factors than 6061 aluminium alloy, although the stress distribution in composites shows sensitivity to fibre configuration and profile thickness. These findings indicate that fibre orientation plays an important role in directing structural stiffness and load distribution in composite chassis. However, the interpretation of stress results and safety factors in composites needs to be done carefully because the Von Mises criteria have limitations in representing anisotropic material failure. The main contribution of this research lies in presenting a controlled structural comparison between metal and filament winding composite materials, as

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well as confirming the potential and limitations of composites as materials for electric vehicle chassis.

Keywords: Electric motor chassis, Filament winding composite, Aluminium 6061, Finite Element Method (FEM), Structural analysis.

Introduction

The development of electric vehicles has driven the need for lightweight, strong, and energy-efficient vehicle structures, particularly in chassis components as the main structural elements that support the entire vehicle load (Albatayneh, 2024; Garofano et al., 2023). In electric motorcycles, the chassis not only plays a role in ensuring strength and safety, but also greatly affects the energy efficiency and manoeuvrability of the vehicle (Liu et al., 2025; Schmauder et al., 2024). Therefore, optimising chassis design by considering the strength-to-weight ratio has become an important focus in the development of modern electric vehicles.

Aluminium alloy 6061 is widely used in light vehicle chassis because it has good mechanical properties, corrosion resistance, and ease of manufacturing (Khot et al., 2025; Nair et al., 2025). However, the demand for more aggressive weight reduction has driven the exploration of alternative materials with higher specific performance. Fibre-based composite materials, particularly those fabricated using the filament winding method, offer the advantages of low density and the ability to adjust the fibre orientation according to the direction of loading, thereby potentially producing structures with better mechanical efficiency than isotropic metallic materials (Mo et al., 2023; Mlýnek et al., 2022; Shiva et al., 2025).

However, studies on the use of filament winding composites as the main structure of electric motorcycle frames are still very limited. Most previous studies have focused on steel or aluminium frames, while composite studies are generally limited to non-structural components or do not use filament winding techniques (Fu et al., 2022; Rodriguez-Ortiz et al., 2025). Furthermore, studies that directly compare the performance of 6061 aluminium alloy and filament winding composites on identical frame geometries using a FEM approach that considers the anisotropic properties of composites are still rare. This gap indicates the need for more systematic and controlled comparative studies.

Based on this background, this study aims to compare the structural performance of electric motorcycle chassis made of aluminium alloy 6061 and filament winding composite using the Finite Element Method (FEM) under the same geometry, loading, and boundary conditions. The novelty of this study lies in the direct comparative evaluation between isotropic metal materials and anisotropic filament winding-based composites in frame structures, by incorporating the influence of material anisotropy characteristics in the FEM analysis. The results of this study are expected to contribute scientifically to the development of lighter and more efficient electric vehicle frames and to form the basis for the optimisation of filament winding-based composite designs in vehicle structural applications.

Research Method

Research Framework

This research was conducted using a numerical approach based on the Finite Element Method (FEM) to evaluate and compare the structural performance of electric motorcycle frames made from 6061 aluminium alloy and filament winding composite materials. The research began with a literature study to identify frame design parameters, material characteristics, and relevant FEM approaches. Next, the geometric design of the chassis was carried out using CAD software, followed by numerical modelling and determination of material properties. After that, FEM simulation was performed by applying boundary conditions and loads that represented the operational conditions of the vehicle. The final stage involved analysing the simulation results in the form of deformation, stress distribution, and safety factors, which were then compared to assess the effectiveness of each material in electric vehicle chassis applications.

Chassis Modelling

Geometric modelling of the chassis was carried out using SolidWorks with reference to the chassis configuration of an electric scooter-type motorcycle. The process began with the creation of a basic sketch of the main frame representing the main structural load path, which was then developed into a three-dimensional tubular structure. The dimensions, angles and positions of the frame elements were determined based on the placement requirements of the vehicle's main components, such as the electric motor, battery, suspension and steering system. Once the main structure was formed, adjustments were made to the supporting components to ensure geometric compatibility and structural continuity. The entire model was then re-verified to ensure there were no geometric inconsistencies before it was used in the numerical analysis stage.

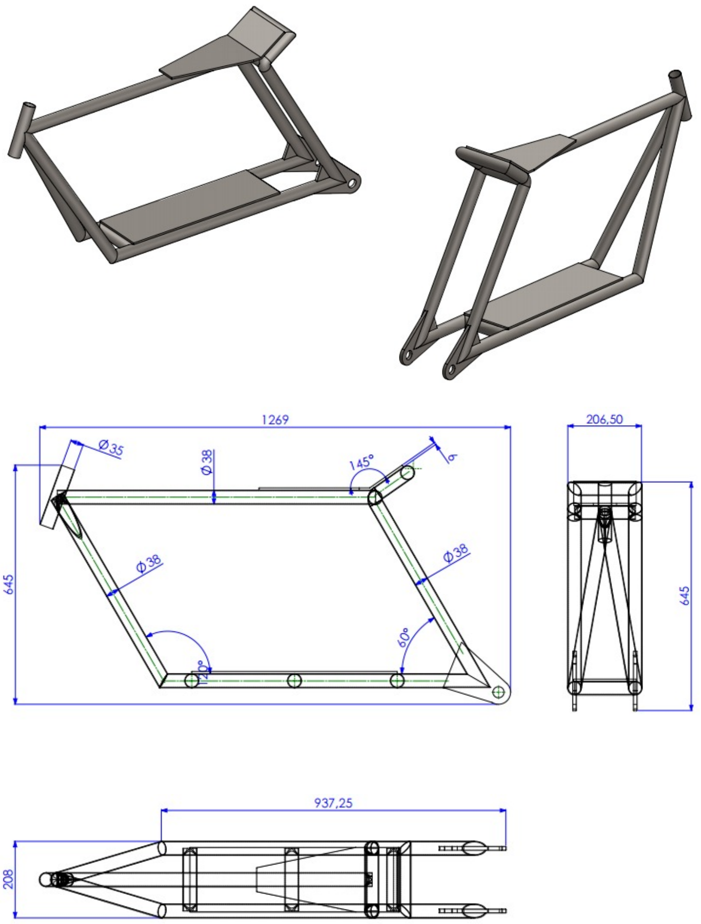


Figure 1 Chassis Design

Figure 1 shows the overall geometric design of the chassis in side, front, and top views. This multi-view presentation aims to show the spatial relationship between frame elements and as a basis for the meshing process and boundary condition definition in FEM simulations. The dimensions and angles of the frame are designed to meet the requirements of ergonomics, vehicle stability, and structural load distribution efficiency.

Material Properties

The mechanical properties of the composite material and Aluminium Alloy 6061 used in the FEM simulation are summarized in Table 1. Composite materials are anisotropic; therefore, the following mechanical parameters are required to be specified.

Table 1. Mechanical Properties of Composite Material and Aluminium Alloy 6061

Parameters	Composite	Aluminium alloy 6061
Modulus of elasticity (N/mm^2)	8000	$6{,}9.10^{10}$
Poisson's ratio	0.28	0,33
Shear Modulus (N/mm$^{2)}$	6000	$2{,}6.10^{10}$
Density (Kg/m$^{3)}$	2000	2700

Yield strength (N/mm^2)	1200	$5{,}5.10^7$
Ultimate tensile strength (N/mm^2)	1500	$1{,}25.10^8$

The material properties used in the FEM simulation were defined based on literature data and actual material specifications. Aluminium alloy 6061 was modelled as an isotropic material with key mechanical parameters such as elastic modulus, Poisson's ratio, and yield strength, which are commonly used in vehicle structural analysis (Khot et al., 2025; Nair et al., 2025). Meanwhile, composite materials are modelled as orthotropic materials to represent their anisotropic properties, incorporating mechanical parameters such as longitudinal and transverse elastic modulus, shear modulus, and Poisson's ratio between fibre directions. The definition of these parameters aims to capture the mechanical response of composites more realistically, especially in the context of the influence of fibre orientation on stiffness and stress distribution in structures.

FEM Simulation Setup

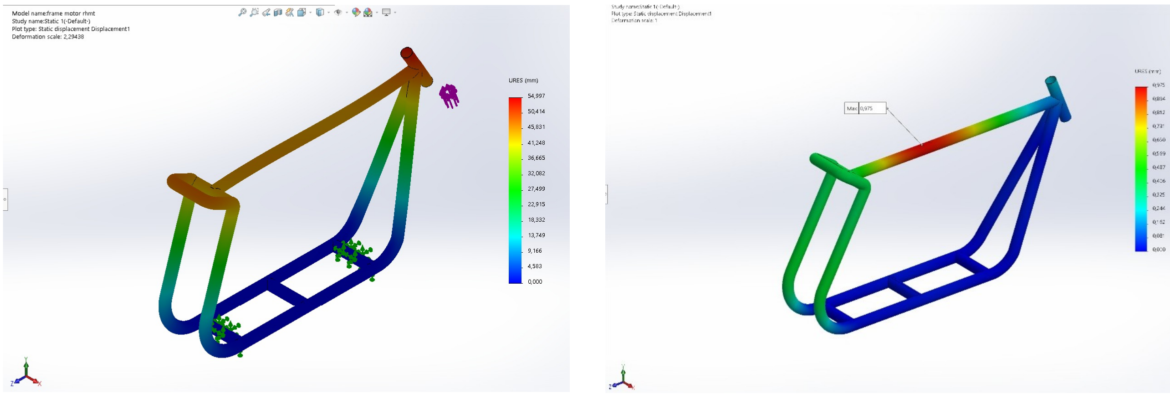
The mesh is created using elements shell mesh for composite tube structures and solid mesh for aluminium alloy (Duan et al., 2020). Numerical analysis was performed using SolidWork Simulations with a shell-based finite element approach, which is suitable for thin structures such as vehicle chassis. Shell elements were selected to obtain computational efficiency without compromising the accuracy of the simulation results (Mo et al., 2023). The meshing process was performed adaptively with higher mesh density in critical areas such as frame joints and load support points to improve the accuracy of stress and deformation calculations. Boundary conditions were set by fixing certain points representing the location of the suspension and main chassis mounts, while static loads were applied to represent the weight of the vehicle, battery, and driver. This approach allows the simulation to represent real operational conditions more accurately.

Data Analysis Procedure

The data analysis stage was carried out by evaluating the FEM simulation results in the form of maximum deformation, von Mises stress distribution, and safety factors for each material variation. Maximum values were extracted to identify critical areas that had the potential for structural failure. Next, the safety factor was calculated by comparing the working stress to the relevant material strength. The analysis results were then directly compared between the 6061 aluminium alloy chassis and the filament winding composite chassis to assess the effect of the material on structural performance. The final interpretation was carried out by correlating the numerical results with the mechanical characteristics of each material and their implications for the development of a lightweight and safe electric vehicle chassis.

Result and Discussion

Deformation and Displacement Analysis



a. Composite

b. Aluminium 6061

Figure 3 Simulation Result for Displacement Analysis

The deformation simulation results show significant differences in deflection characteristics between the 6061 aluminium alloy chassis and the filament winding composite chassis, as shown in Figure 3. The maximum deformation value in the aluminium chassis is higher than that in the composite chassis, indicating that the global stiffness of the aluminium structure is lower under the same loading conditions. However, this difference is not only reflected in the maximum values, but also in the pattern of deformation distribution along the chassis frame.

On the aluminium chassis, the high deformation zone (shown in red to yellow) is concentrated in the centre span and main frame joints, which are the locations with the greatest bending moment due to vertical loading. This is in line with the properties of aluminium as an isotropic material, where stiffness is determined primarily by the modulus of elasticity and cross-sectional thickness. In contrast, in composite chassis, the deformation distribution tends to be more uniform and areas with high deflection are more limited, as indicated by the dominance of green to blue colours. This pattern shows that the fibre orientation in filament winding composites contributes to directing structural stiffness along the load path, thereby suppressing local deformation despite the lower mass of the structure.

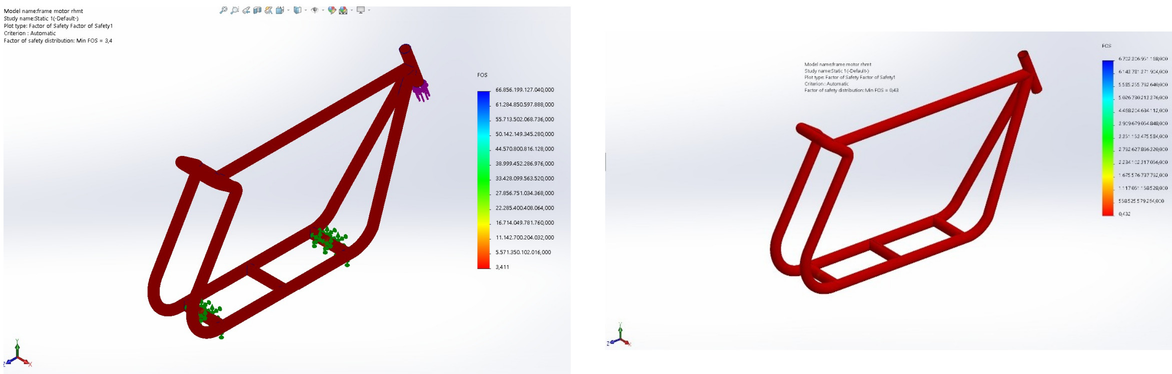
Table 2 Maximum Displacement of Material Comparison

Parameter	Composite	Aluminium 6061
Max. Displacement	≈55 mm	≈1 mm
Stiffness	Low	High
Structural Response	More flexible	More stable

Table 2 presents a comparison of deformation parameters between composite and 6061 aluminium alloy chassis. Although this table shows clear numerical differences, technical interpretation needs to be linked to material properties and structural configuration. The smaller deformation in composites is not solely due to material strength values, but is more influenced by a combination of fibre direction elastic modulus, lay-up configuration, and load transfer effectiveness along the frame.

In aluminium 6061, the higher deformation value reflects the limitations of isotropic materials in controlling deflection in slender structures without increasing thickness or mass. Conversely, in filament winding composites, although the transverse elastic modulus is relatively lower, the orientation of the fibres in line with the load direction allows for an increase in the effective stiffness of the structure. Therefore, the results in Table 1 should be understood as a reflection of the interaction between material properties, frame geometry, and boundary conditions, rather than a comparison of absolute values alone.

Factor of Safety (FOS)



a. Composite **b. Aluminium 6061**

Figure 4 Simulation Result for Factor of Safety (FOS)

The distribution of the factor of safety (FOS) shown in Figure 4 reveals a clear difference in structural safety levels between the two materials. In the aluminium chassis, areas with low FOS are concentrated in the frame joints and zones with high bending stress, indicated by red to orange colours. These areas are critical points that are prone to failure when loads increase or additional dynamic conditions occur.

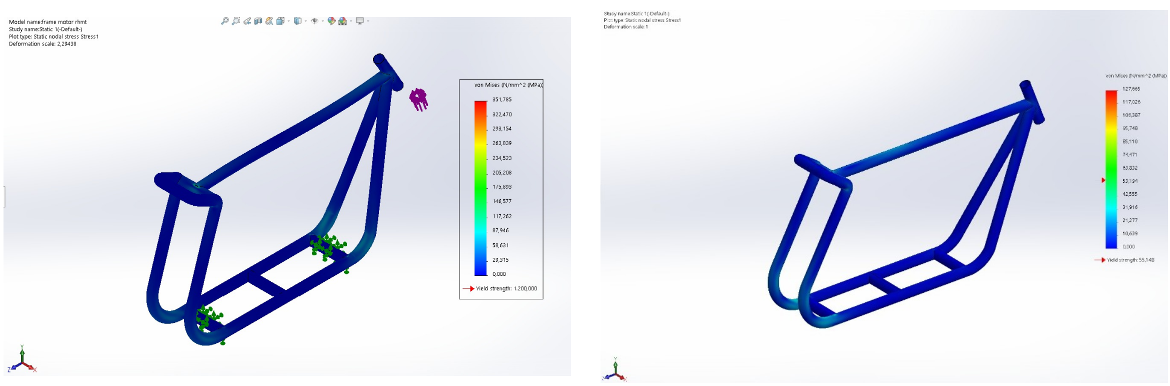
The composite chassis shows higher FOS values overall, with a colour distribution dominated by green to blue, indicating a greater safety margin. This difference is influenced by the ability of filament winding composites to distribute loads through fibre orientation, so that stress is not extremely localised at a single point. However, the interpretation of FOS in composite materials must be done carefully because Von Mises stress-based FOS calculations have limitations for anisotropic materials. Therefore, the FOS value in composites in this study is considered an initial indicator of design feasibility, not a final failure criterion.

Table 3 Factor of Safety of Material Comparison

Parameter	Composite	Aluminium 6061
FOS Minimum	≈3,4 Mpa	≈0,54 MPa
Status	Safety	Failure potential

Table 3 presents a comparison of FOS values between aluminium and composite chassis, where it should be emphasised that FOS is a dimensionless quantity (without units). The minimum FOS value for the aluminium chassis is close to or below the safe design limit, especially in the main joint area, indicating potential structural failure if used without additional reinforcement. In contrast, composite chassis show higher and more uniform minimum FOS values, indicating a better level of structural safety under the same loading conditions. This FOS distribution shows that composite chassis have advantages in terms of structural efficiency, but still require further evaluation using more appropriate composite failure criteria to ensure long-term safety.

Von Mises Stress Analysis



a. **Composite**

b. **Aluminium 6061**

Figure 5 Simulation result for Von Mises Stress

Von Mises stress analysis in Figure 5 shows different stress distribution patterns between the two materials. In aluminium 6061, the use of Von Mises criteria is relevant due to its isotropic properties, and simulation results show that the maximum stress is still below the material's yield point, so the design is considered structurally safe. High stress zones are concentrated in areas with geometric changes and frame joints, which are common characteristics in vehicle frame structures.

In composites, although Von Mises results are used as a visual approach to identify areas of stress concentration, it should be emphasised that this criterion does not fully represent the failure mechanism of anisotropic materials. The red colour on the composite stress contour indicates areas with relatively high stress, but does not necessarily indicate material failure. Therefore, these results should be interpreted as an indication of critical locations that require further evaluation using more representative composite failure criteria.

Table 4 Von Miss Stress of Material Comparison

Parameter	Composite	Aluminium 6061
Max Stress	≈350 Mpa	≈128 MPa
Criteria of failure	Not fulfilled (Von Mises analysis invalid)	Safe
Stress distribution	High at the joint	Even and low
Indication	Lay-ups need optimisation	Safe for static loads

Table 4 summarises the comparison of stress values and failure indications between aluminium and composite chassis. The higher stress in composites can be attributed to load concentration in certain layers due to fibre orientation and profile thickness. While aluminium exhibits a more homogeneous stress distribution, composites show greater sensitivity to lay-up configuration. These findings indicate that although filament winding composites have advantages in deformation control and safety factors, their design requires further optimisation of fibre orientation and layer thickness to minimise local stress concentration. Thus, the results in Table 3 not only show a comparison of performance, but also provide design guidance for the development of more optimal composite chassis.

Conclusions

This study shows that filament winding-based composite materials have superior potential compared to 6061 aluminium alloy as a material for electric motorcycle frames in terms of structural efficiency. In general, composite frames are capable of producing more controlled deformation and higher safety factors under the same loading conditions, while aluminium frames show a tendency for deformation concentration and a decrease in safety margins in certain areas. This difference is mainly influenced by the composite's ability to direct stiffness through fibre orientation, which allows for more effective load distribution compared to isotropic metallic materials. These findings confirm that the use of filament winding composites has the potential to support the development of lighter electric vehicle frames without compromising structural safety.

Thus, it can be concluded that the use of filament winding composites in electric motor chassis design is very promising but must be supported by proper lay-up design and load-direction-based local reinforcement strategies. Further research is needed to optimise the winding pattern, analyse composite failure using the Tsai-Wu or Hashin criteria, and conduct experimental testing to validate the numerical simulation results obtained in this study. However, the analysis results also show that the application of filament winding composites to chassis structures requires special attention to lay-up configuration and profile thickness to avoid local stress concentrations. Therefore, further research is recommended to integrate more representative composite failure criteria and consider dynamic loading conditions and experimental testing to validate the numerical results. This approach is expected to produce a more optimal, reliable composite chassis design that is ready for practical application in electric vehicles.

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