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Optimizing Car Wheel Rim Mass and Design: A Composite Material Approach with Finite Element Analysis

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Abstract

Weight reduction in vehicles remains a central priority in the automotive industry, as it directly affects fuel economy and emissions. Wheel rims, being among the unsprung components, offer considerable scope for lightweighting through material and design optimization. This research evaluates the replacement of conventional aluminium alloy rims with advanced composite materials, aiming to minimize mass without compromising structural strength and durability. A comprehensive Finite Element Analysis (FEA) framework is employed to compare the baseline aluminium alloy rim with an optimized composite design. The investigation encompasses stress distribution, deformation characteristics, and modal response under representative static and dynamic loading conditions. The results reveal that composite rims can achieve notable reductions in weight while sustaining the required structural performance. While the optimized carbon fiber composite rim demonstrates significant mass reduction compared to the baseline aluminium alloy, it exhibits a modest increase in maximum deformation under peak loading conditions. Preliminary cost analysis indicates higher material and manufacturing expenses, highlighting a trade-off between performance gains and economic considerations. These findings demonstrate the potential of composite materials to enhance vehicle efficiency and support the broader goals of sustainable and energy-efficient automotive engineering.

Keywords

Finite Element Analysis (FEA), Car wheel rim, Lightweight wheel rim, Structural optimization, Hybrid composite materials, Rim construction

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1. Introduction

The drive toward greater fuel efficiency and reduced emissions is pushing the automotive industry to innovate with lighter vehicle designs. This is motivated by the direct relationship between vehicle weight and performance factors. Reducing vehicle mass directly translates into decreased fuel consumption and emissions, aligning with global efforts to mitigate environmental impact. The optimization of car wheel rims has emerged as a significant area of research. Wheel rims, as integral components of the wheel-tire system, contribute substantially to a vehicle's unsprung mass, which influences ride comfort, handling dynamics, and road holding ability. Reducing the weight of wheel rims while maintaining structural integrity and performance is paramount. This research field encompasses a multidisciplinary approach, drawing upon advancements in material science, manufacturing, and computational modeling. The evolution of lighter, stronger materials, such as high-strength aluminium alloys and composites, has opened new design possibilities for engineers. The implementation of modern manufacturing technologies has facilitated the creation of cutting-edge designs. Moreover, Finite Element Analysis has significantly reshaped the design and optimization workflows. FEA allows engineers to virtually simulate the behavior of wheel rims under various loading conditions, predicting stress distributions, deformations, and potential failure points. This virtual prototyping capability enables rapid design iterations and optimization cycles, accelerating the development process and reducing reliance on physical prototypes.

The automotive industry is constantly pursuing improved fuel efficiency and reduced emissions, driven by environmental concerns and stringent regulations. A significant contributor to vehicle weight and, consequently, fuel consumption is the wheel-tire system. Studies have shown a strong correlation between vehicle weight and fuel economy, with even small reductions in mass leading to measurable improvements. As a crucial component of this system, the car wheel rim presents a prime target for optimization [1].

Car wheel rims serve as the structural interface between the vehicle and the road, transferring loads and ensuring stability during various driving manoeuvres. Traditionally, aluminium alloys have been the material of choice due to their balance of strength and weight. However, the emergence of advanced composite materials, boasting superior strength-to-weight ratios, has opened new avenues for lightweighting. These materials, such as carbon fiber reinforced polymers, offer the potential for significant mass reduction without compromising structural integrity [2].

While lightweight materials significantly enhance performance and efficiency, their adoption must balance cost, manufacturability, and sustainability considerations. Advanced materials such as carbon fiber-reinforced polymers (CFRP) and titanium alloys offer excellent mechanical performance but remain expensive to produce and difficult to recycle, limiting their feasibility for high-volume manufacturing [3]. In contrast, materials like aluminum and advanced high-strength steels (AHSS) provide a more practical compromise between strength, weight, and affordability, making them suitable for both structural and safety-critical components [4]. Increasing attention is also being given to natural fiber composites and hybrid laminates, which combine mechanical efficiency with environmental benefits, aligning with circular economy principles [5]. However, achieving an optimal balance between performance and sustainability requires continued research into process optimization, cost modeling, and end-of-life recyclability [6]. FEA studies show that titanium alloy (Ti-6Al-4V) wheel rims outperform aluminum alloy (Al-Si-10Mg) rims in strength and deformation resistance [7]. Such an integrated approach ensures that lightweighting not only advances vehicle performance but also supports long-term ecological and economic viability.

Extensive research has been conducted on optimizing wheel rim design using Finite Element Analysis. Studies have explored various design modifications, such as spoke geometry alterations and material distribution optimization, to minimize mass while maintaining structural integrity. Despite advancements, limited research has been conducted on thoroughly evaluating the potential of replacing traditional aluminium rims with composites, particularly with regard to quantifying weight reduction and ensuring structural reliability under real-world loading conditions.

This paper addresses this gap by conducting a comparative study between a baseline aluminium alloy wheel rim and a redesigned composite material counterpart. Using FEA, we analyze stress distribution, deformation patterns, and modal behavior under various loading scenarios. The primary objective is to quantify the mass reduction achievable through the implementation of composite materials while ensuring the structural integrity of the redesigned rim. This work aims to investigate the effectiveness of composite materials for automotive wheel rims, to enhance vehicle efficiency through weight reduction.

The wheel rim plays a vital role in ensuring a vehicle's performance and safety, serving as the structural interface between the tyre and the suspension system. It bears dynamic loads, maintains tyre shape, and influences handling, braking, and ride quality; it bears the brunt of dynamic loads encountered during driving. These loads include forces from acceleration, braking, cornering, and road imperfections. The rim's ability to withstand these forces while minimizing weight directly impacts several key performance factors:

- *Unsprung Mass Reduction*: Lighter rims contribute to lower unsprung mass, which in turn improves ride comfort, handling agility, and road holding ability. This is because a lower unsprung mass allows the suspension to react more quickly to road irregularities, maintaining better tyre contact and control.

• *Fuel Efficiency*: Lowering the weight of the wheel rim directly aids in reducing the vehicle's total mass, which in turn enhances fuel efficiency and decreases harmful emissions. This is particularly significant as even small reductions in rotating mass can have a noticeable impact on fuel consumption.

• *Vehicle Dynamics*: The stiffness and strength of the wheel rim influence a vehicle's handling characteristics, affecting steering response, cornering stability, and overall driving dynamics. Optimizing rim design can contribute to enhanced handling precision and a more responsive driving experience.

Therefore, optimizing wheel rim design, particularly through the exploration of lightweight materials and innovative manufacturing techniques, is crucial for enhancing vehicle performance, efficiency, and sustainability.

2. Literature Review

Salunkhe and Pimpale [8] concluded that ZA21 alloy is the optimal material for alloy wheel rims due to its lowest deformation and stress levels, enhancing strength, fatigue life, and reliability while reducing weight and cost. Soori [9] analyzed the manufacturing processes of alloy wheels, highlighting recent advancements, simulation improvements, defect reduction, and machining efficiency enhancements, ultimately optimizing aluminum alloy wheels' safety and performance. Jiang et al. [10] proposed using truncated cone billets for Mg alloy wheels, finding that these billets significantly improve strain, recrystallization, and grain refinement during the forming process compared to cylindrical billets. Jiang et al. [11] optimized the die structure for Mg alloy wheels through numerical simulation, identifying that adjusting spoke thickness, inclination, and fillet radii improves fluidity and uniformity, reducing wheel defects. Korkut et al [12] conducted a comparative analysis of wheel rims for lightweight electric vehicles, concluding that specific design and material choices resulted in an 8.58% weight reduction and a 32.49% decrease in maximum equivalent stress. Aravind et al. [13] analyzed sisal/carbon fiber composite wheel rims, finding that the hybrid material minimises failure and extends lifespan, making it suitable for the specified design under various loads and pressures. Wacker [14] developed an adhesive joint for hybrid automotive wheels, offering a 6% weight reduction and enhanced radial and lateral support compared to conventional bolted designs. Navuri et al. [15] analyzed four motorcycle alloy wheel designs under various loading conditions, concluding that all designs have infinite life cycles under radial loads and are safe under impact, bending, and torsion loads. Jiang et al. [16] conducted a lightweight design analysis of automobile wheels, determining that AZ91 magnesium alloy offers superior stress performance and is more feasible for lightweight wheel designs compared to other materials. Al. [17] analyzed a spiral wheel rim for a four-wheeler, identifying stress patterns under different loading conditions and suggesting future work on impact, dynamic, and vibration analysis. Zhang and Xu [18] reviewed lightweight materials for automobiles, emphasising the shift from conventional materials to advanced alloys and composites, providing guidelines for material selection to improve fuel economy and reduce environmental impact. Vinodh and Kandasamy [19] focused on minimizing the environmental impact of automotive components through alternative materials and processes, achieving significant reductions in carbon footprint, water eutrophication, air acidification, and total energy consumption, highlighting the importance of material selection in product design.

While the automotive industry increasingly embraces lightweight materials, a crucial research gap persists in directly comparing the real-world viability of aluminum alloys versus carbon fiber for passenger car wheel rims. Existing literature, such as studies on aluminum alloy optimization [20] and carbon fiber applications [21], often focuses on individual material advantages. This material-specific focus makes it challenging for automotive manufacturers to make informed decisions about the most advantageous material for passenger car wheel rims, considering the complex interplay of performance, cost, and sustainability factors. However, a comprehensive life-cycle assessment encompassing performance, cost, manufacturability, and environmental impact across both materials remains underexplored. This gap hinders informed decision-making for manufacturers aiming to optimize vehicle efficiency and sustainability without compromising safety or affordability.

Recent studies have emphasized that the practical implementation of lightweight materials depends not only on their mechanical superiority but also on manufacturability, scalability, and sustainability. Taub and Luo [22] discussed how the high strength-to-weight ratio of CFRP and titanium alloys enables substantial weight savings but noted that their high production costs and complex processing limit widespread use. Kumar and Mehta [23] further elaborated that, while advanced composites offer excellent mechanical properties, their recycling difficulties and repair challenges hinder their cost-effective integration into mass-market vehicles. Complementing this, Zhang et al. [24] and Liu and Yao [25] highlighted the industrial preference for aluminium and advanced high-strength steels (AHSS) because they offer a practical balance between performance, affordability, and established manufacturing infrastructure. Studies by Capretti et al. [26] and Elseify et al. [27] introduced natural fiber composites and hybrid laminates as sustainable alternatives, citing their renewability and biodegradability as key advantages in achieving circular economy goals. Similarly, Wu et al. [28] and González et al. [29] emphasized the need for cost modeling, efficient forming processes, and recyclability assessment to ensure that lightweighting advances remain both economically and environmentally viable. Collectively, these works underscore that future automotive material strategies must integrate mechanical performance with life-cycle sustainability and production efficiency.

The objective of this paper is to close the existing gap by performing an in-depth comparison between aluminium alloy and carbon fiber wheel rims for passenger cars. Utilizing Finite Element Analysis and life cycle assessment methodologies, we evaluate both materials across key metrics:

- *Mechanical Performance*: Stress distribution, deformation patterns, and modal behavior under simulated driving loads.
- *Light Weighting Potential*: Quantifying mass reduction achievable with each material while maintaining structural integrity.
- *Economic Viability*: Manufacturing cost estimations, incorporating material, production, and potential scale-up factors.
- *Environmental Impact*: A comprehensive life cycle assessment is conducted, considering all stages from material extraction and manufacturing emissions to use-phase performance and end-of-life treatment.

By directly comparing these aspects, this research provides valuable data-driven insights to inform material selection for passenger car wheel rims, ultimately guiding the development of lighter, more efficient, and sustainable vehicles.

3. Composite Materials

Composite materials are created by integrating two or more distinct constituents, usually involving a reinforcing phase such as fibers embedded within a matrix phase like resin. This synergy allows the final material to exhibit superior mechanical properties by capitalizing on the strengths of its individual components. Carbon fiber, for example, offers outstanding strength and rigidity, while the matrix ensures cohesion and effective load transfer among the fibers.

3.1 Why Carbon Fiber?

Carbon fiber stands out among composite materials for its exceptional strength-to-weight and stiffness-to-weight ratios, surpassing even most metals, including aluminium [30]. This translates to significant weight savings without compromising structural integrity, a crucial factor for wheel rim performance. Key advantages of carbon fiber for this application include:

- *Enhanced Vehicle Dynamics*: Lower unsprung mass due to carbon fiber's lightweight nature improves acceleration, braking, and handling [31].
- *Improved Fuel Efficiency*: Reduced overall vehicle weight directly contributes to better fuel economy and lower emissions [32].
- *Design Versatility*: Carbon fiber's anisotropic properties allow for tailored designs, optimizing strength and stiffness in specific directions to meet the demanding loads experienced by wheel rims [33].

While carbon fiber manufacturing can be more complex and costly compared to aluminum, ongoing advancements in production techniques are making it increasingly viable for automotive applications [34]. This study aims to thoroughly evaluate the performance, economic viability, and environmental impact of carbon fiber wheel rims compared to their aluminium counterparts, providing valuable insights for future automotive design.

4. Project Methodology

4.1 Study and Assessment of Car Wheel Rim

- Conduct a comprehensive literature review to understand the historical development, design principles, and challenges associated with car wheel rims.
- Identify the key parameters that influence the performance and design of car wheel rims, such as weight, structural integrity, and material properties.

Selection of Representative Car Wheel Rim:

An existing car wheel rim model is selected (Figure 1) that serves as a representative sample for analysis and comparison.

Consider factors like material composition, design complexity, and availability of relevant data to guide the selection process.

Reverse Engineering and 3D Modeling of the Existing Car Wheel Rim:

Employ reverse engineering techniques to deconstruct and analyze the selected existing car wheel rim.

A detailed 3D model of the existing car wheel rim will be developed using Computer-Aided Design (CAD) software, ensuring precise representation of its geometry, dimensions, and key structural characteristics.

Finite Element Analysis of the Existing Material Car Wheel Rim:

Convert the 3D model of the existing car wheel rim into a finite element model.

Define appropriate boundary conditions, loading scenarios, and material properties for the FEA simulation.

Perform FEA simulations to analyze the structural performance, stress distribution, and deformation behavior of the existing car wheel rim under various loading conditions.

FEA of the Hybrid Composite Material Car Wheel Rim:

Develop a composite material model for the car wheel rim by integrating traditional materials with advanced composite materials.

Modify the existing car wheel rim model to incorporate the hybrid composite material.

Conduct FEA simulations to evaluate the structural performance and weight reduction potential of the hybrid composite car wheel rim compared to the existing material counterpart.

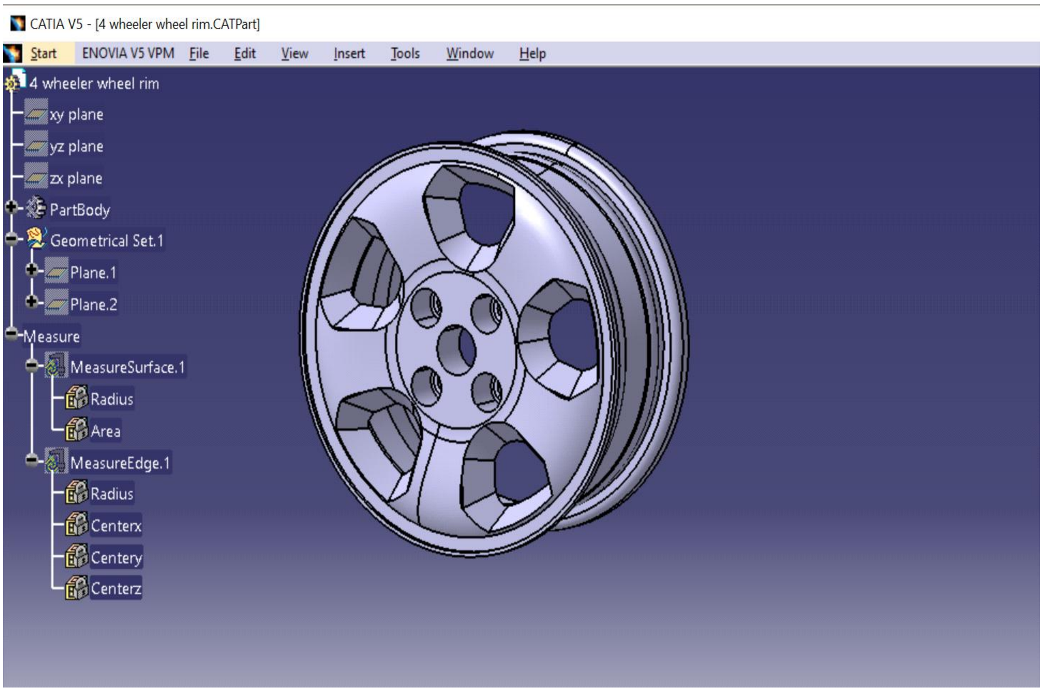

Figure 1. Existing wheel rim of a 4-wheeler car.

4.2 Comparison of Results

- Analyze and compare the FEA results obtained for the existing material car wheel rim and the hybrid composite material car wheel rim.
- Evaluate factors such as weight reduction, stress distribution, and overall structural integrity to assess the performance benefits of the hybrid composite material.

This study demonstrated the benefits of geometric optimization and material substitution in enhancing the performance of car wheel rims.

- The optimized wheel hub showed improved stress distribution, vibration resistance, and up to 71% weight reduction using carbon fiber.
- All critical performance metrics, including deformation and safety factor, remained within acceptable limits, validating the design improvements.

5. Design Model and Numerical Methodology

5.1 Design

- *Five-Spoke Pattern*: The rim features a classic five-spoke design, providing a balance of strength, weight, and visual appeal.
- *Material*: The model is designed using a standard aluminium alloy material known for its lightweight and corrosion-resistant properties.

- *Mounting*: The hub is designed for a standard four-bolt mounting pattern. The bolt holes are accurately positioned and dimensioned according to industry standards.
- *Hub*: The model includes a detailed representation of the hub, featuring the center bore and mounting flange.
- *Software*: The model is created using CAD Catia V5 software.

5.2 Boundary Conditions and Vehicle Parameters

The research emphasizes the structural evaluation of a car wheel rim, selecting a representative vehicle model whose key design and loading parameters are outlined below:

5.2.1 Vehicle and Loading Conditions

- *Total Vehicle Mass*: 1500 kg
- *Passenger and Luggage Mass*: 5 passengers × 80 kg/passenger + 50 kg luggage = 450 kg
- *Total Vehicle Mass*: 1500 kg + 450 kg = 1950 kg
- *Wheel Support Force*: Assuming equal load distribution across four wheels, each wheel supports approximately 1950 kg × 9.81 m/s² / 4 = 4777.5 N.

5.2.2 Rim Geometry and Hub Specifications

- *Rim Diameter*: 372 mm
- *Rim Thickness*: 4 mm
- *Inner Rim Bead Seat Bevel Width*: 109 mm
- *Hub Type*: 5° deep slot rim
- *Spoke Design*: Five-spoke plate design with fan-shaped vent structures.
- *Vent Geometry*: Triangular holes with a rounded radius of 10 mm.
- *Valve Orifice Diameter*: 11.3 mm, chamfered at 45 degrees.

5.2.3 Material Properties

The wheel hub is constructed from aluminium alloy 6061, with the following material properties:

- *Tensile Ultimate Strength*: 282 MPa
- *Tensile Yield Strength*: 190 MPa
- *Density*: 2700 kg/m³
- *Poisson's Ratio*: 0.33
- *Young's Modulus*: 68.9 GPa

The wheel hub is then compared with the Carbon Fiber, with the following material properties:

- *Tensile Yield Strength*: 294 GPa
- *Tensile Ultimate Strength*: 5880 MPa
- *Density*: 1800 kg/m³
- *Poisson's Ratio*: 0.28
- *Young's Modulus*: 228 GPa

These parameters will be used to define the boundary conditions, material properties, and loading scenarios for the Finite Element Analysis of the car wheel rim.

5.3 Meshing Strategy

To ensure a balance between computational efficiency and result accuracy, a mesh independence study was carried out. The outcome led to the adoption of an unstructured mesh composed mainly of tetrahedral elements for the wheel hub model. This approach was chosen due to its adaptability in capturing the intricate geometry of the wheel hub with precision.

A mesh independence study was conducted (Table 1) to confirm that the simulation results were unaffected by element size refinement. The analysis compared 10 mm and 5 mm global element sizes for all three design configurations. The difference in maximum deformation was below 4 %, indicating mesh convergence. Therefore, the 10 mm element size, originally used in the study, was deemed appropriate as it ensures reliable results with optimal computational efficiency.

Table 1. Maximum deformation for different element sizes.

Element Size (mm)	Maximum Deformation (mm)	% Change vs. 10 mm)
10 mm	0.056	—
5 mm	0.057	+3.57 %

A finer mesh, with an element size of 10 mm, was utilized in critical regions characterized by significant load transfers and stress concentrations. These regions include the hub mounting points, spoke junctions, and the tyre contact patch. This localized mesh refinement ensures accurate stress and deformation results in these critical areas (Figure 2).

Conversely, less critical areas of the model, where stress gradients are expected to be less steep, were meshed with coarser elements. This approach helps to reduce the overall computational cost without compromising the accuracy of the solution in areas of interest.

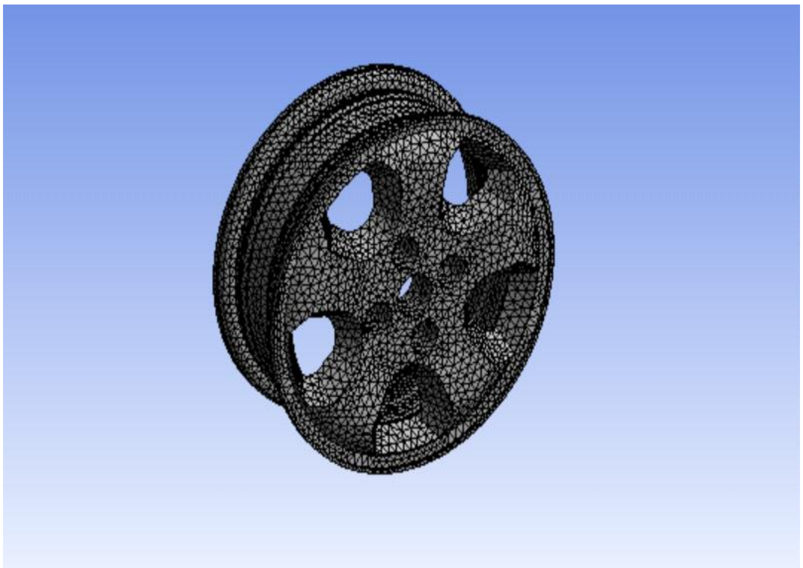

Figure 2. Mesh model of wheel rim.

5.4 Initial Conditions and Simulation Analysis Methods

The structural integrity of the wheel hub is paramount and is influenced by factors such as loading conditions and material properties. To accurately simulate real-world scenarios, fixed constraints are applied to the wheel hub at five bolt holes and the mounting surface, effectively anchoring it for analysis.

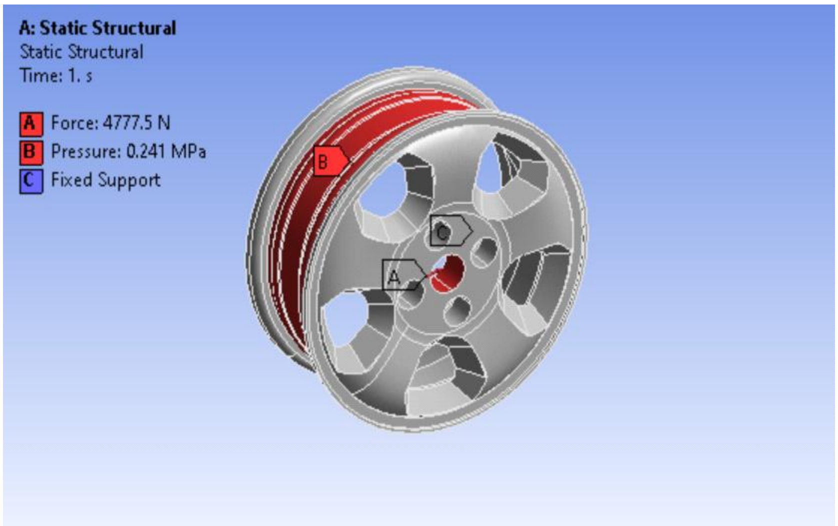

Figure 3. Initial conditions and constraints. **(A)** Fixed support on the wheel hub; **(B)** pressure load on the rim and spokes; **(C)** torque applied on bolt hole surfaces.

The wheel hub is subjected to three primary load components (Figure 3):

- *Support Force (P1)*: A uniformly distributed load of 0.68 MPa is applied to the lower surface of the wheel hub's rim seat over a π/3 arc segment. This loading condition simulates the force transmitted from the vehicle to the wheel hub and is used to evaluate its effect on structural elements such as the wheel spokes and ventilation openings.
- *Tire Pressure (P2)*: A pressure of 0.241 MPa acting on the wheel rim, representing the inflated tire's contribution to the overall load distribution.
- *Driving Torque (T)*: A torque of 265 N·m, representing the rotational force transmitted from the engine, is applied to the bolt hole surfaces. This loading condition simulates the operational torque experienced by the wheel hub during vehicle motion.

Accurate simulation results are ensured by applying well-defined loads, forces, and pressures to the wheel hub model. The material properties, such as Young's modulus, Poisson's ratio, and density, are chosen to reflect the specific characteristics of the wheel rim material.

A static structural analysis is conducted to evaluate the wheel hub's behavior under the specified loading conditions. This analysis utilizes a finite element analysis software package to compute stress, strain, displacement, and other relevant parameters. Results are obtained for individual nodes and elements within the model, followed by post-processing and analysis to interpret the structural behavior.

Modal analysis is performed to identify the wheel hub's natural frequencies and corresponding mode shapes. By identifying resonance risks, the study contributes to a better understanding of the structure's dynamic performance. Appropriate parameters, including material properties, boundary conditions, and constraints, are configured within the analysis software to ensure accurate results.

Through the use of advanced analysis methods and suitable solvers, a thorough understanding of the wheel hub's structural response under different loading scenarios is obtained. These insights are essential for optimizing the design, improving performance, and ensuring long-term reliability.

6. Results and Discussion

6.1 Static Structural Analysis

The static analysis performed on both the baseline and optimized wheel hub models provided critical insights into their mechanical response under applied loading conditions (Figure 4 & Figure 5). The baseline model exhibited a maximum stress of 175.49 MPa, which approached the material's yield limit, particularly in regions with small fillet radii. This posed potential risks for fatigue failure under long-term usage. In contrast, the optimized model with increased fillet radii and refined spoke geometry showed a reduced maximum stress of 162.41 MPa. Although the maximum deformation increased from 0.056 mm (baseline) to 0.087 mm (optimized). The maximum deformation observed in the optimized wheel hub is 0.087 mm.

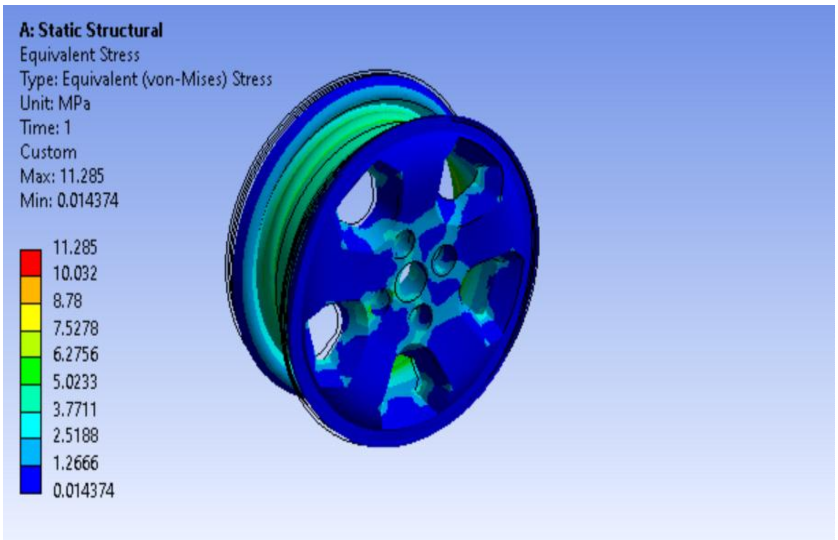

Figure 4. Total deformation of wheel rim.

To assess its acceptability for a carbon-fiber composite, The corresponding elastic strain under the applied load (*σ_max ≈ 200 MPa*) is calculated as:

$$\varepsilon = \sigma\_max / E = 200 \text{ MPa} / 228{,}000 \text{ MPa} \approx 0.000877 \ (0.088\%) \quad (1)$$

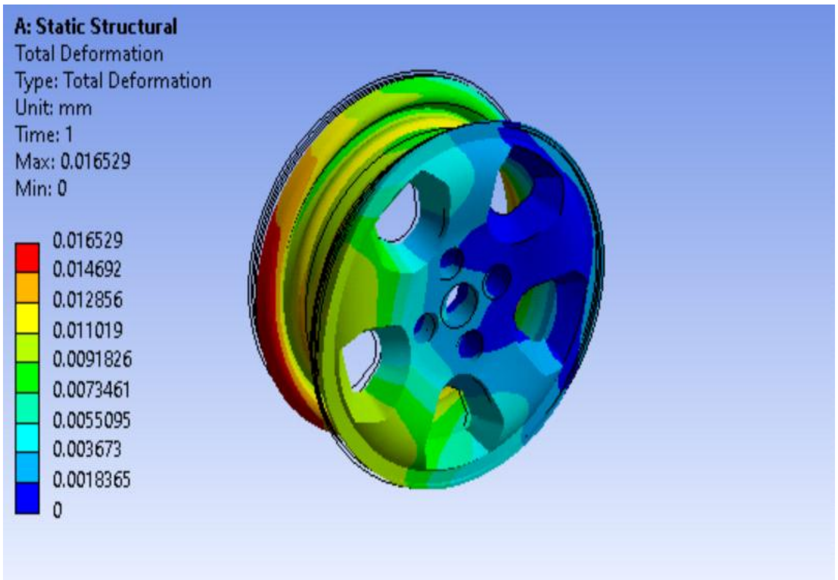

Figure 5. Equivalent strain of wheel hub.

Considering a rim characteristic length of 109 mm, the resulting deformation is:

$$\delta = \varepsilon \times L = 0.000877 \times 109 \text{ mm} \approx 0.096 \text{ mm} \tag{2}$$

Since the simulated deformation (0.087 mm) is below the calculated elastic limit (0.096 mm) and far below the material's yield and ultimate limits, the deformation is within the elastic range, confirming structural safety under the applied torque.

6.2 Modal Analysis

The modal analysis (Figure 6) indicated that the optimized wheel hub model exhibits natural frequencies ranging from 1273.8 Hz to 3981.9 Hz. To evaluate the likelihood of resonance, these frequencies were compared with typical excitation sources encountered in passenger vehicles. According to established studies and ISO/SAE standards, engine excitation frequencies for mid-sized internal combustion engines generally range from 20 to 300 Hz, extending to the tenth engine order at higher engine speeds and configurations [35]. Similarly, road-induced vibration frequencies primarily occur below 100 Hz, influenced by surface irregularities and tire–road interaction [36].

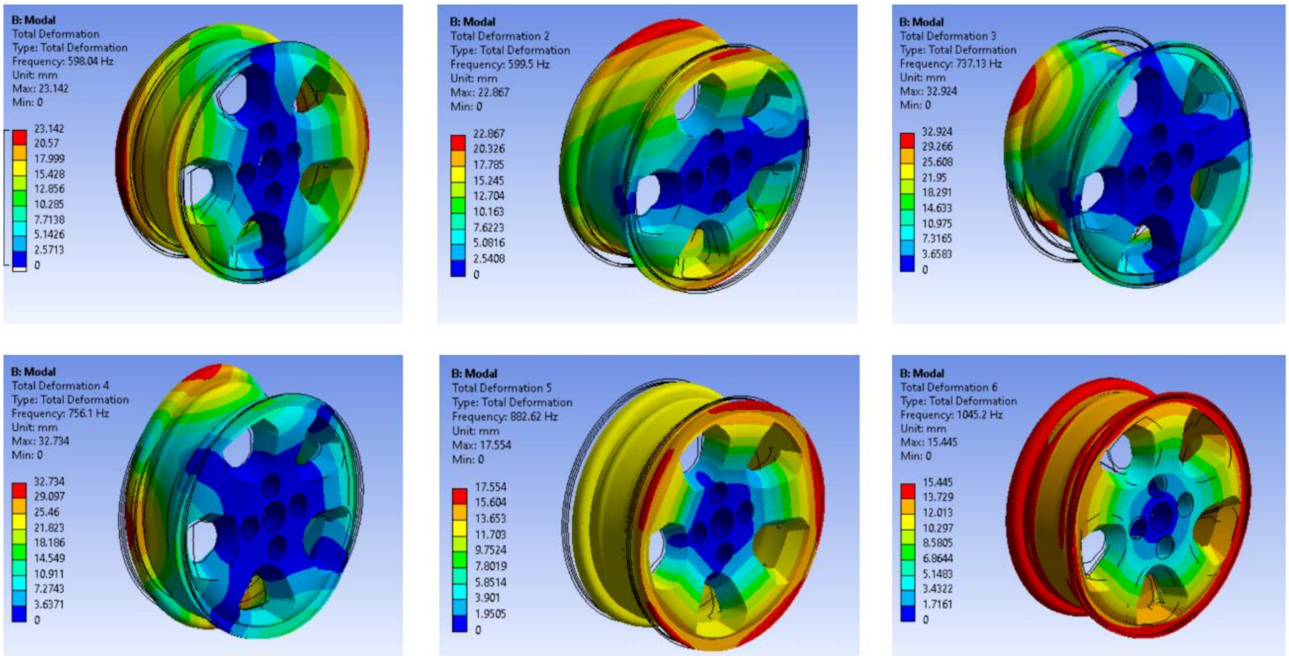

Figure 6. Mode shapes for natural frequency.

Since all calculated natural frequencies for the wheel hub lie well above these excitation ranges, the structure is unlikely to experience resonance under normal operating or road conditions. This validates that the optimized design provides adequate stiffness and dynamic stability. The results also suggest that further enhancements to damping properties could help mitigate vibration transmission in extreme cases, such as pothole impacts or rough terrain, ensuring the long-term reliability of the wheel assembly.

6.3 Optimization Results

The optimization process led to a substantial reduction in the overall mass of the wheel hub (Figure 7). The baseline model weighed 3.642 kg, while the optimized version was reduced to 1.928 kg, achieving a 47% decrease in mass. Despite the reduced weight, structural performance improved, as evidenced by lower peak stress and acceptable deformation limits.

Stress concentration zones were notably minimized, and improved load distribution was achieved through the optimized geometry. These results validate the effectiveness of the optimization approach in meeting both performance and lightweighting goals.

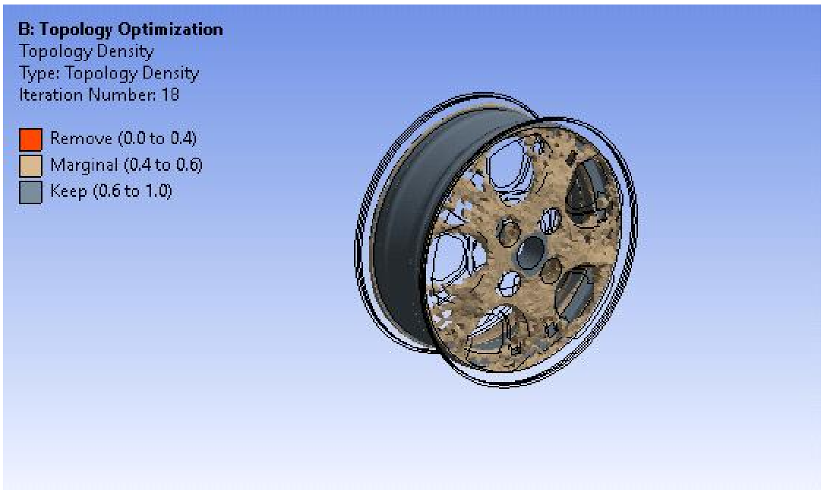

Figure 7. Results of topology optimization.

Lightweighting can introduce localized stress concentrations that affect fatigue life and long-term durability. Composite materials, though high in specific strength and stiffness, show complex fatigue behavior due to factors like fiber–matrix debonding and delamination [37]. In the aluminum design, stresses remain below the fatigue endurance limit, ensuring good durability, whereas in the carbon fiber composite, localized stress near bolt holes may reduce fatigue life under variable road conditions.

6.4 Lightweight Material Evaluation

Further weight reduction was explored by replacing aluminum alloy with carbon fiber composite (Table 2). The carbon fiber model reduced the mass to 1.086 kg, a 71% decrease compared to the baseline. Although carbon fiber introduces different stress behavior due to anisotropy, the model maintained structural stability and performance under the same loading conditions.

This suggests that carbon fiber composites are viable candidates for next-generation lightweight wheel hubs, especially in high-performance and electric vehicles where weight efficiency is critical.

Table 2. Key findings for lightweight materials.

Aspect	Baseline	Optimized (Al Alloy)	Optimized (Carbon Fiber)
Mass (kg)	3.642	1.928 (↓47%)	1.086 (↓71%)
Max Stress (MPa)	175.49	162.41	161.12
Max Deformation (mm)	0.056	0.087	0.089
1st Natural Frequency (Hz)	1273.8	1438.2	1584.9
Safety Factor	1.08	1.17	1.18

A preliminary cost analysis shows aluminum alloy wheel hubs are more cost-effective, with material costs around \$3/kg and unit costs of \$10–25, produced via casting with ~390 s cycle time. Carbon fiber hubs offer weight reduction and higher performance but at \$20–50/kg and \$300–1,000/unit, with labor-intensive processes like pre-preg molding and High-Pressure Resin Transfer Molding (HP-RTM). While carbon fiber improves performance, aluminum remains practical for cost-sensitive applications. Future work should include complete life-cycle and economic assessments to better evaluate material selection trade-offs.

6.6 Implications and Future Work

These findings highlight the advantages of geometric optimization and composite material usage for automotive wheel hub design. Future research should focus on:

- Experimental validation of simulation results
- Investigation of dynamic and impact load scenarios, such as pothole or curb strikes, to ensure structural integrity under transient conditions.
- Fatigue and life cycle analysis under variable road conditions.
- Cost-benefit analysis for composite implementation.

7. Conclusions

This study optimizes automotive wheel hub design for lightweight construction and cost efficiency using finite element analysis, offering insights for enhanced performance.

The static structural analysis of the automotive wheel hub yielded critical insights into its behavior under various loading conditions. The results showed that modifying the fillet radius significantly improves stress and displacement distributions, enhancing overall structural performance. Modal analysis further demonstrated that the optimized design exhibits natural frequencies well separated from typical external excitations, indicating strong vibration resistance and effective resonance avoidance.

Design optimization led to notable improvements in both strength and stiffness, alongside a substantial reduction in mass. Stress and deformation analyses under multiple load cases confirmed that performance was enhanced in the optimized model. Stress concentrations were primarily located near load application zones, especially in areas with smaller fillet radii, suggesting that increasing the fillet size in these regions can effectively reduce stress intensities. Although a slight increase in maximum deformation was observed, the optimized hub achieved a 47% reduction in weight compared to the baseline design.

Lightweighting studies revealed that replacing the conventional material with advanced alternatives such as carbon fiber further reduced the hub's mass while maintaining structural integrity and functional performance. These findings provide a solid foundation for future development of lightweight, high-performance automotive wheel hubs.

Future research can explore the use of other composite materials, multi-objective optimization strategies, and experimental validation to refine and enhance the design even further.

Abbreviations

FEA	Finite Element Analysis
CAD	Computer-Aided Design
CFRP	Carbon Fiber Reinforced Polymer
AHSS	Advanced High-Strength Steel
HP-RTM	High-Pressure Resin Transfer Molding
ISO	International Organization for Standardization
SAE	Society of Automotive Engineers
NVH	Noise, Vibration, and Harshness

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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