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Modeling and Analysis of Motorcycle Wheel Rim with Carbon Fiber Reinforced Plastic and Alloy Materials Under Various Loads

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Abstract: The reduction of unsprung mass in motorcycles is an effective approach to improving vehicle handling, acceleration, fuel efficiency, and overall structural performance. This study presents the modeling and finite element analysis of a motorcycle wheel rim fabricated using three different materials: Carbon Fiber Reinforced Plastic (CFRP), Aluminum Alloy, and Magnesium Alloy. A three-dimensional wheel rim model was developed using CATIA V5 and imported into ANSYS Workbench for static structural analysis. Identical loading and boundary conditions, including an applied force of 1900.13 N and a pressure of 0.193 MPa, were considered to evaluate the structural behavior of each material. The performance was assessed in terms of directional deformation, total deformation, equivalent (von Mises) stress, and equivalent elastic strain. The simulation results indicate that the CFRP wheel rim exhibits the lowest deformation, stress, and strain among the three materials, demonstrating superior stiffness and load-carrying capability while offering significant weight reduction. In comparison, the aluminum and magnesium alloy rims experience higher deformation and stress under identical loading conditions. The findings suggest that CFRP is a promising alternative to conventional alloy materials for high-performance motorcycle wheel rims, providing enhanced structural integrity and reduced vehicle mass. The outcomes of this study can assist designers and manufacturers in selecting lightweight materials for improved motorcycle performance and durability.

Keywords: Carbon Fiber Reinforced Plastic (CFRP), Motorcycle Wheel Rim, Finite Element Analysis (FEA), Static Structural Analysis, Lightweight Composite Materials.

1 INTRODUCTION

Motorcycle wheel rims are among the most critical structural components of a two-wheeler, as they directly influence vehicle stability, steering response, braking performance, ride comfort, and overall safety. During service, the wheel rim is subjected to various static and dynamic loading conditions, including radial loads, lateral forces, braking torque, cornering loads, and impact forces generated by uneven road surfaces. Therefore, the structural design of a motorcycle wheel rim must ensure adequate strength, stiffness, durability, and fatigue resistance while maintaining minimum weight for improved vehicle performance [1]. In recent years, the automotive industry has focused extensively on reducing vehicle weight to improve fuel efficiency, acceleration, handling, and environmental sustainability.

Since the wheel assembly forms a significant portion of the unsprung mass, reducing the weight of the wheel rim can considerably enhance vehicle dynamics, suspension response, and rider comfort. Consequently, the development of lightweight wheel rims using advanced engineering materials has become an important research area in automotive design and manufacturing [2]. Conventionally, motorcycle wheel rims are manufactured using aluminum alloys and magnesium alloys because of their favorable mechanical properties, corrosion resistance, and manufacturability. Aluminum alloys provide a good balance between strength, weight, and production cost, whereas magnesium alloys offer additional weight reduction and improved vibration damping characteristics.

However, the increasing demand for lightweight and high-performance vehicles has encouraged researchers to investigate alternative materials with superior strength-to-weight ratios and enhanced fatigue performance [3]. Carbon Fiber Reinforced Plastic (CFRP) has emerged as one of the most promising lightweight composite materials for automotive applications due to its exceptional specific strength, high stiffness, low density, corrosion resistance, and excellent fatigue characteristics. Composite materials have gained considerable attention for manufacturing structural components where weight reduction is essential without compromising mechanical performance. The application of polymer composite materials in motorcycles has increased significantly because of their ability to improve structural efficiency while reducing overall vehicle mass [4].

Advances in Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) have enabled engineers to design and evaluate complex automotive components accurately before manufacturing [5]. Finite Element Analysis (FEA) has become one of the most reliable numerical techniques for predicting structural behavior under various loading conditions. Static structural analysis provides valuable information regarding stress distribution, deformation, strain, and structural safety, thereby reducing development time and prototype costs.

Several investigations have demonstrated the effectiveness of finite element methods for evaluating motorcycle wheel rims under different operating conditions. Structural optimization techniques have been employed to improve wheel performance while minimizing material consumption and weight. Experimental validation combined with numerical simulation has further confirmed the capability of finite element models to accurately predict wheel behavior under radial impact loading and other service conditions [8]. More recently, digital twin technologies have been introduced to simulate tyre-rim interaction under complex biaxial loading conditions, providing improved prediction of structural performance and durability.

Composite wheel designs have also been investigated to improve dynamic characteristics and structural efficiency. Carbon fiber reinforced composite wheels exhibit higher stiffness, lower deformation, and superior strength-to-weight ratios compared with conventional metallic wheels, making them suitable for high-performance automotive applications. Efficient computational algorithms and numerical approaches have further enhanced the accuracy of wheel structural analysis, enabling reliable prediction of stress concentration and deformation characteristics. In addition, finite element techniques have been widely applied in modeling various automotive components, demonstrating their effectiveness in evaluating complex structural systems subjected to different loading scenarios.

Although significant research has been conducted on alloy wheel optimization, modal analysis, impact behavior, composite materials, and numerical modeling, comparatively fewer studies have performed a comprehensive comparison of Carbon Fiber Reinforced Plastic (CFRP), Aluminum Alloy, and Magnesium Alloy motorcycle wheel rims under identical static loading conditions using a unified finite element framework. Such a comparative investigation is essential for selecting the most suitable lightweight material capable of providing high structural performance, reduced deformation, and improved safety.

Therefore, the present work focuses on the three-dimensional modeling and static structural analysis of a motorcycle wheel rim using CATIA V5 and ANSYS Workbench. Three candidate materials, namely Carbon Fiber Reinforced Plastic (CFRP), Aluminum Alloy, and Magnesium Alloy, are evaluated under identical loading and boundary conditions. The structural performance is assessed based on directional deformation, total deformation, equivalent (von Mises) stress, and equivalent elastic strain. The comparative results provide useful insights into the suitability of advanced composite materials for lightweight and high-performance motorcycle wheel rim applications.

2 LITERATURE SURVEY

Finite element analysis (FEA) has become one of the most widely adopted numerical techniques for evaluating the structural performance of motorcycle wheel rims and spoke designs under different loading conditions. Structural analyses have demonstrated that FEA effectively predicts deformation, stress distribution, and strain characteristics, enabling designers to identify critical regions and optimize wheel geometry for enhanced mechanical performance while maintaining lightweight structures. Design optimization studies have further shown that appropriate modification of wheel rim geometry can significantly improve structural strength, stiffness, and overall vehicle efficiency by reducing unnecessary material without compromising safety [2].

Modal investigations on aluminium-based carbon fiber reinforced wheel structures have indicated that composite reinforcement enhances natural frequencies and structural rigidity, thereby improving vibration characteristics and dynamic performance compared with conventional metallic wheels [3]. Numerical simulation combined with experimental validation has been extensively employed to investigate the structural integrity of automotive wheels under severe loading conditions. Radial impact analyses have demonstrated that finite element models accurately predict stress concentration and deformation behavior during impact loading, providing reliable tools for evaluating wheel durability and failure mechanisms.

In addition to structural loading, advanced computational approaches have been developed for motorcycle braking systems, where carbon-based materials and multi-sensor estimation techniques have been utilized to improve braking torque prediction and friction coefficient estimation, thereby contributing to enhanced vehicle safety and performance. Recent developments in digital twin technology have further enabled realistic tyre-rim interaction analysis under biaxial loading conditions, allowing more accurate prediction of structural behavior and service performance under complex operating environments. Efficient computational algorithms have also contributed significantly to wheel structural analysis by reducing computational complexity while maintaining numerical accuracy for spoked wheel systems [6], [7].

Numerical simulation techniques have additionally been employed to investigate motorcycle crash scenarios and rider injury mechanisms, emphasizing the importance of structurally reliable wheel and chassis components in improving vehicle safety during accident conditions [8]. Comprehensive review studies on polymer composite materials have highlighted the increasing adoption of Carbon Fiber Reinforced Plastic (CFRP) in motorcycles because of its high specific strength, excellent stiffness, superior fatigue resistance, corrosion resistance, and remarkable weight reduction capability, making it an attractive alternative to conventional alloy materials for structural applications [9].

The versatility of finite element methods has also been demonstrated in broader automotive safety applications, where numerical models have been successfully employed to analyze complex structural responses under dynamic loading conditions and predict injury mechanisms during vehicle collisions [10]. Further investigations on aluminium-based carbon fiber reinforced wheel structures have consistently confirmed that composite reinforcement significantly improves structural stiffness, vibration characteristics, and overall mechanical performance while reducing component weight [11].

Earlier numerical modeling studies on motorcycle tires established reliable computational frameworks for analyzing tire deformation and load transfer behavior, providing valuable insights into tire-wheel interaction and the overall structural performance of motorcycle wheel assemblies under service loading conditions [12]. Although previous studies have extensively investigated wheel rim optimization, modal behavior, radial impact performance, tyre-rim interaction, braking systems, computational algorithms, composite materials, and finite element modeling techniques, limited research has comprehensively compared the static structural performance of Carbon Fiber Reinforced Plastic (CFRP), Aluminum Alloy, and Magnesium Alloy motorcycle wheel rims under identical loading and boundary conditions. Therefore, the present work focuses on the comparative finite element analysis of these three materials by evaluating directional deformation, total deformation, equivalent (von Mises) stress, and equivalent elastic strain to identify the most suitable lightweight material for high-performance motorcycle wheel rim applications.

3 METHODOLOGY

3.1. Overall Research Framework

The present study aims to evaluate the structural performance of a motorcycle wheel rim fabricated using three different materials: Carbon Fiber Reinforced Plastic (CFRP), Aluminum Alloy, and Magnesium Alloy. A finite element–based comparative analysis was carried out to identify the most suitable lightweight material capable of withstanding the applied loading conditions. The research methodology consists of geometry modeling, material assignment, finite element discretization, application of boundary conditions, static structural analysis, and comparative performance evaluation. The same wheel rim geometry, loading conditions, and mesh configuration were maintained for all three materials to ensure a fair comparison. Fig. 1 shows the architecture of the proposed methodology.

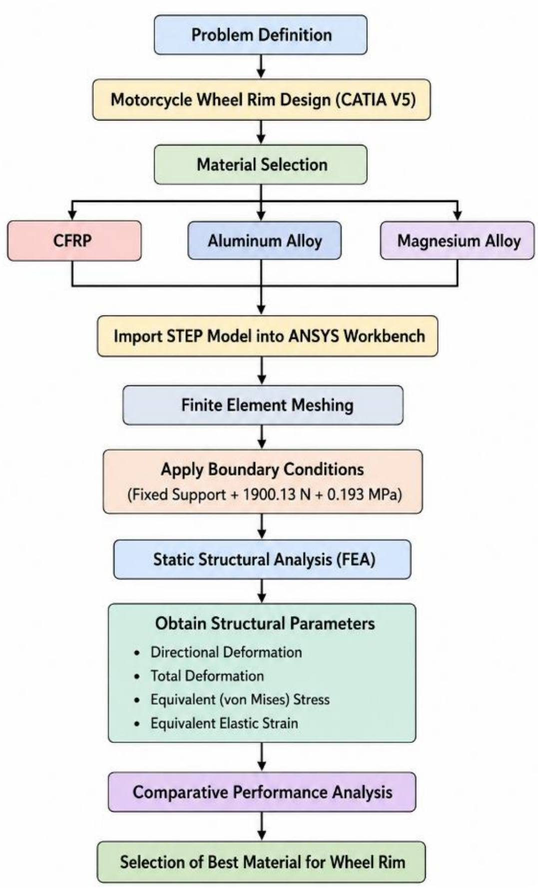

Fig. 1. Overall Research Methodology for Modeling and Structural Analysis of the Motorcycle Wheel Rim

3.2. Wheel Rim Modeling and Material Selection

A three-dimensional motorcycle wheel rim model was developed using CATIA V5 based on standard geometric dimensions. The wheel rim consists of the hub, spokes, and outer rim designed according to conventional motorcycle wheel specifications. After completing the CAD model, it was exported in STEP format and imported into ANSYS Workbench for structural analysis. Three engineering materials were selected for comparative evaluation: Carbon Fiber Reinforced Plastic (CFRP), Aluminum Alloy, and Magnesium Alloy. These materials were chosen because they are commonly used in automotive applications and exhibit different mechanical properties with respect to density, Young's modulus, strength, and stiffness. Identical wheel geometry was maintained for each material so that the influence of material properties alone could be evaluated.

3.3. Finite Element Modeling and Static Structural Analysis

The imported CAD model was discretized using an appropriate finite element mesh to accurately capture the stress and deformation behavior of the wheel rim. Mesh quality was verified using element quality and aspect ratio metrics to ensure numerical stability and solution accuracy. Static structural analysis was performed under identical loading conditions for all three materials. The hub region of the wheel rim was constrained using fixed support to simulate actual mounting conditions. A downward force of 1900.13 N and a uniformly distributed pressure of 0.193 MPa were applied to represent service loading conditions experienced by the motorcycle wheel during operation. The finite element solver computed the structural response by solving the governing equilibrium equations for each material.

3.4. Performance Evaluation and Comparative Analysis

The structural performance of each wheel rim material was evaluated using four important response parameters: Directional Deformation, Total Deformation, Equivalent (von Mises) Stress, and Equivalent Elastic Strain. These parameters provide information regarding structural stiffness, deformation resistance, stress distribution, and elastic behavior under applied loads. The obtained simulation results for CFRP, Aluminum Alloy, and Magnesium Alloy were systematically compared to determine the material exhibiting superior structural performance. The comparison focused on minimizing deformation and stress while maintaining high stiffness and lightweight characteristics. Based on the numerical results, the most suitable material for motorcycle wheel rim applications was identified.

3.5. Meshing Strategy

The quality of the finite element mesh significantly influences the accuracy and convergence of structural analysis. After importing the CAD model into ANSYS Workbench, the wheel rim geometry was discretized using three-dimensional solid elements. An appropriate mesh size was selected to achieve a balance between computational efficiency and solution accuracy. Mesh quality was evaluated using standard parameters such as orthogonal quality and aspect ratio to ensure that the generated mesh satisfied finite element quality requirements. The generated mesh consisted of approximately 58,950 nodes and 29,003 elements, providing adequate resolution for accurate stress and deformation analysis.

3.6. Boundary Conditions and Loading

To simulate the actual operating conditions of the motorcycle wheel, suitable boundary conditions and external loads were applied during the static structural analysis. The hub region of the wheel rim was constrained using a fixed support to represent the wheel mounting condition. A downward force of 1900.13 N was applied to simulate the vehicle load transmitted through the wheel assembly, while a uniformly distributed pressure of 0.193 MPa was applied over the rim surface to represent the contact pressure experienced during service. Identical loading and boundary conditions were maintained for Carbon Fiber Reinforced Plastic (CFRP), Aluminum Alloy, and Magnesium Alloy to enable a consistent comparison of their structural performance.

3.7. Evaluation Parameters

The structural behavior of the motorcycle wheel rim was assessed using four important performance parameters obtained from the finite element analysis. Directional deformation was used to determine the displacement of the wheel rim along the applied loading direction, while total deformation represented the overall displacement experienced by the structure. Equivalent (von Mises) stress was evaluated to determine the stress concentration within the wheel rim and to assess structural safety under the applied loading conditions. Equivalent elastic strain was calculated to evaluate the elastic deformation characteristics of each material. These response parameters were compared for CFRP, Aluminum Alloy, and Magnesium Alloy to identify the material providing the best combination of structural strength, stiffness, and lightweight characteristics.

4 Results And Discussion

4.1. Finite Element Analysis Results

Static structural analysis was performed on the motorcycle wheel rim using ANSYS Workbench for three candidate materials: Carbon Fiber Reinforced Plastic (CFRP), Aluminum Alloy, and Magnesium Alloy. The same wheel geometry, mesh configuration, loading conditions, and boundary conditions were maintained throughout the analysis to ensure consistency in performance comparison. A downward force of 1900.13 N and a uniformly distributed pressure of 0.193 MPa were applied to simulate actual operating conditions. The structural responses were evaluated in terms of directional deformation, total deformation, equivalent (von Mises) stress, and equivalent elastic strain.

4.2. Deformation Analysis

Directional deformation and total deformation are important indicators of structural stiffness and dimensional stability. Lower deformation values indicate that the wheel rim possesses greater rigidity and is capable of maintaining its original geometry under applied loading conditions. Among the three materials, CFRP exhibited the lowest directional deformation (4.9312×10^{-6} m) and the lowest total deformation (1.0636×10^{-5} m), indicating excellent stiffness and superior resistance to structural displacement. Magnesium Alloy exhibited higher total deformation (2.6213×10^{-5} m), while Aluminum Alloy showed the highest directional deformation (8.0288×10^{-5} m). These results demonstrate that the composite material provides better dimensional stability than conventional metallic alloys.

4.3. Stress and Strain Analysis

Equivalent (von Mises) stress is commonly used to evaluate the structural safety of engineering components. Lower stress values indicate more uniform load distribution and reduced risk of structural failure. Similarly, equivalent elastic strain reflects the elastic deformation experienced by the material under external loading. The simulation results reveal that CFRP experiences the lowest equivalent stress (8.0291×10^{5} Pa) and the lowest equivalent elastic strain (7.304×10^{-5}). Aluminum Alloy and Magnesium Alloy exhibit considerably higher stress and strain values, indicating comparatively lower structural stiffness under identical loading conditions. The lower stress concentration observed in CFRP demonstrates its superior load-carrying capability and higher resistance to elastic deformation.

4.4. Comparative Performance Analysis

The comparison clearly indicates that Carbon Fiber Reinforced Plastic (CFRP) outperforms both Aluminum Alloy and Magnesium Alloy in all structural performance parameters. The significantly lower deformation values demonstrate greater stiffness, while the reduced equivalent stress and elastic strain indicate improved load distribution and enhanced structural integrity. Although Aluminum Alloy provides lower total deformation than Magnesium Alloy, it exhibits the highest directional deformation and equivalent stress. Magnesium Alloy performs moderately but experiences the largest total deformation among the three materials. Table 1 presents the comparative structural performance of the three candidate materials obtained from the finite element analysis.

Table 1. Performance Analysis of Motorcycle Wheel Rim Materials

Material	Directional Deformation (m)	Total Deformation (m)	Equivalent Stress (Pa)	Equivalent Elastic Strain
Magnesium Alloy	1.2478×10^{-5}	2.6213×10^{-5}	8.1211×10^{6}	1.8062×10^{-4}
Aluminum Alloy	8.0288×10^{-5}	1.6673×10^{-5}	8.1646×10^{6}	1.1510×10^{-4}
Carbon Fiber Reinforced Plastic (CFRP)	$\mathbf{4.9312 \times 10^{-6}}$	$\mathbf{1.0636 \times 10^{-5}}$	$\mathbf{8.0291 \times 10^{5}}$	$\mathbf{7.304 \times 10^{-5}}$

4.5. Discussion

The finite element analysis confirms that material selection has a significant influence on the structural performance of motorcycle wheel rims. Due to its high strength-to-weight ratio and superior stiffness, Carbon Fiber Reinforced Plastic exhibits better resistance to deformation while maintaining lower stress and strain levels under identical loading conditions. These characteristics make CFRP highly suitable for lightweight automotive applications where structural performance and weight reduction are primary design objectives. Compared with conventional Aluminum Alloy and Magnesium Alloy, CFRP offers improved dimensional stability, greater structural rigidity, and enhanced load-carrying capability. The reduction in deformation contributes to better wheel alignment, improved handling characteristics, and increased operational safety. Furthermore, the lower equivalent stress indicates a greater safety margin against material failure during service conditions.

5 CONCLUSION

This study presented a comparative finite element analysis of a motorcycle wheel rim fabricated using Carbon Fiber Reinforced Plastic (CFRP), Aluminum Alloy, and Magnesium Alloy under identical static loading conditions. A three-dimensional wheel rim model was developed in CATIA V5 and analyzed in ANSYS Workbench by applying a force of 1900.13 N and a pressure of 0.193 MPa. The structural performance was evaluated using directional deformation, total deformation, equivalent (von Mises) stress, and equivalent elastic strain. The simulation results demonstrated that CFRP exhibited the lowest deformation, stress, and strain among the three materials, indicating superior stiffness, higher load-carrying capability, and improved structural stability. Although Aluminum Alloy and Magnesium Alloy provided acceptable performance, they experienced comparatively higher deformation and stress values. The findings confirm that CFRP is the most suitable material for lightweight motorcycle wheel rim applications, offering enhanced mechanical performance, improved durability, reduced unsprung mass, and better overall vehicle efficiency.

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ETHICS STATEMENT

This study did not involve human or animal subjects and, therefore, did not require ethical approval.

STATEMENT OF CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest related to this study.

LICENSING

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