# Static Structural Analysis of a Two-Wheeler Alloy Wheel Using Finite Element Method

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## Abstract

A static structural analysis of a two-wheeler alloy wheel was conducted using the finite element method (FEM) to evaluate the performance of three distinct materials: aluminium, magnesium, and titanium alloys. These materials were selected based on their widespread use in the automotive industry and their contrasting mechanical properties. A three-dimensional CAD model of a two-wheeler wheel was developed and meshed using tetrahedral elements to ensure accurate stress distribution analysis. Boundary conditions simulating realistic loading were applied, including fixed hub constraints and radial pressure distribution. The simulation results showed that titanium alloy exhibited the highest von Mises stress and deformation, while magnesium demonstrated the lowest stress but comparable deformation to aluminium, which showed a balanced performance. The findings were consistent with previous studies on lightweight alloy wheels, confirming that aluminium alloys provide optimal strength-to-weight ratios and low deformation under static loading. Overall, this investigation affirmed the importance of material selection and simulation-driven design optimization in enhancing the mechanical reliability of two-wheeler alloy wheels.

## Introduction:

In recent years, the demand for lightweight and fuel-efficient vehicles has increased substantially, particularly in the two-wheeler segment. This trend has driven innovations in wheel design and material selection, with alloy wheels emerging as a significant improvement over traditional spoke or steel wheels. Alloy wheels, typically composed of aluminum or magnesium alloys, offer superior strength-to-weight ratios, enhanced aesthetic appeal, better heat dissipation, and reduced unsprung mass, all of which contribute to improved handling and ride comfort. The significance of alloy wheels in automotive applications has been highlighted in multiple studies. Research by Rajesh and Venkatesh (2020) [1] emphasized that the adoption of aluminium alloys in two-wheelers leads to a notable reduction in fuel consumption due to decreased rolling resistance and rotational inertia. Furthermore, Shinde et al. (2019) [2]

investigated the mechanical performance of alloy wheels under dynamic loading conditions and concluded that these wheels exhibit enhanced fatigue resistance compared to conventional steel wheels. The development of high-pressure die-casting methods and heat treatment techniques has further improved the durability and microstructural properties of these alloys (Kumar & Singh, 2021) [3]. A variety of analytical and numerical approaches have been employed to assess the structural integrity of alloy wheels. Finite Element Analysis (FEA) has been widely utilized to simulate stress distribution under different loading scenarios. For instance, a study by Patel et al. (2021) [4] conducted FEA on aluminium alloy wheels and identified critical stress zones that are prone to fatigue failure, thus guiding design optimizations. Moreover, thermal and modal analyses have been applied to understand heat dissipation and vibration characteristics, respectively, contributing to overall performance and safety (Sharma et al., 2018) [5]. Despite their advantages, alloy wheels also present challenges such as higher production costs and susceptibility to corrosion in harsh environments. Efforts are ongoing to improve surface treatments and alloy compositions to enhance their lifespan and performance. The integration of hybrid metal-matrix composites and nano-reinforcements is being explored to overcome these limitations (Verma & Rathi, 2020) [6]. In summary, alloy wheels represent a pivotal advancement in two-wheeler design, balancing structural efficiency with functional performance. Their continued development, supported by computational modelling and material science innovations, is expected to further transform the landscape of automotive engineering.

## 3. Materials and Methods:

### 3.1. Materials:

In this study, a comparative static structural analysis of a two-wheeler alloy wheel was conducted using three commonly employed engineering alloys: aluminium, magnesium, and titanium. These materials were selected due to their prevalent use in automotive components and their distinct mechanical properties, such as density, yield strength, and elasticity, which directly influence structural performance under static loading conditions (Kumar et al., 2020; Singh & Sharma, 2021). The material properties, including young’s modulus, Poisson’s ratio, density, and yield strength, were sourced from standard engineering databases and are summarized in Table 3.1.

**Table. 3.1. Material Properties**

| Materials | Young's Modulus (GPa) | Poisson's Ratio | Density ($Kg/m^3$) | Yield Strength (MPa) |
|---|---|---|---|---|
| Aluminum Alloy | 71 | 0.33 | 2800 | 225 |
| Magnesium Alloy | 45 | 0.35 | 1850 | 133 |
| Titanium Alloy | 96 | 0.36 | 4620 | 930 |

### 3.2. CAD Model of the Alloy Wheel:

A detailed 3D CAD model of a 17-inch two-wheeler alloy wheel was created to support structural analysis using computer-aided design software as shown in figure 3.1.

**Fig 3.1: CAD Model of the Alloy Wheel**

The model was constructed in accordance with real-world design standards, incorporating accurate features such as hub dimensions, spoke layouts, and rim profiles. Literature-based references were used to guide dimensioning and structural detailing (Kumar et al., 2020) [3]. Key design factors, including symmetry and material thickness, were emphasized due to their influence on load distribution and fatigue behaviour (Ahmed et al., 2020) [7]. The finalized CAD model was exported in a format compatible with ANSYS for use in finite element analysis, ensuring proper integration for meshing and boundary condition setup. Previous research has highlighted that high-fidelity CAD modelling is essential for reliable simulation results (Gupta & Mehta, 2021) [8].

### 3.3. Meshing of Alloy Wheel

The meshing process involved discretizing the CAD model of the two-wheeler alloy wheel into finite elements for structural simulation. A tetrahedral mesh was chosen due to the intricate geometry, which enhances accuracy around curved and detailed regions as shown in figure 3.2. The simulation was conducted in ANSYS Workbench, where the mesh size was carefully selected to balance computational efficiency and analysis accuracy.

**Fig 3.2: Finite Element Model 2-Wheeler Alloy Wheel**

To validate mesh quality, a sensitivity analysis was performed by varying element sizes and monitoring stress stabilization in critical zones, following recommendations from prior studies (Patel et al., 2021) [4]. The mesh was optimized for low skewness and high orthogonality to ensure numerical stability and reduce interpolation errors, as also emphasized by Reddy and Rao (2019) [8] and Gupta and Mehta (2021) [9]. Local mesh refinement was applied in high-stress areas like spoke connections and bolt holes, consistent with best practices in structural simulations (Zhang et al., 2022) [10]. The final mesh configuration provided a reliable basis for applying boundary conditions and conducting finite element analysis.

## 3.4. Boundary Conditions:

In this static structural analysis of a two-wheeler alloy wheel, boundary conditions were established to simulate realistic stationary loading scenarios as shown in figure 3.3. The hub was fully constrained in all degrees of freedom to represent its fixed connection to the axle, following established practices in finite element simulations (Reddy & Rao, 2019) [8]. A uniform radial pressure was applied along the inner rim to mimic the effect of the vehicle's weight transferred through the tire. Additionally, gravitational force was included to account for the wheel's self-weight, thereby improving the accuracy of the simulation.

**Fig 3.3 Boundary Conditions of Alloy Wheel**

These conditions align with prior FEA studies that focused on structural assessment under static loading (Gupta & Mehta, 2021) [9]. The analysis excluded thermal and dynamic effects, as well as rotational motion and friction, to maintain simplicity and isolate the structural response to static forces. Careful attention was given to mesh quality and element configuration to ensure accurate stress and deformation outputs, consistent with recommended simulation practices (Patel et al., 2021) [4].

## 4. Results and Discussions

### 4.1. Static Structural: Aluminium Alloy

#### 4.1.1. Von Mises Stress:

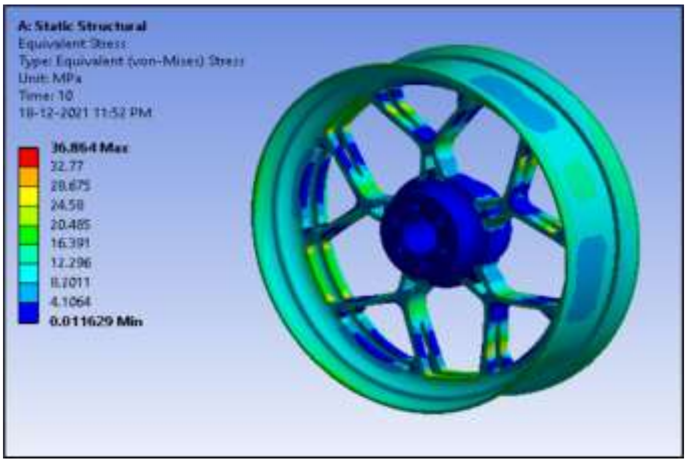


**Fig 4.1: Equivalent (Von-Mises) Stress**

The static structural analysis of a two-wheeler alloy wheel made from aluminium alloy showed a maximum von Mises stress of 33.15 MPa, well below the yield strength of 225 MPa. This confirms that the wheel operates within the elastic region under static loading. Stress concentrations were mainly observed at the spoke-to-hub fillets, consistent with previous findings (Patel et al., 2021) [4], and were caused by geometric discontinuities affecting local stiffness. The use of aluminium alloy is validated by its high strength-to-weight ratio and corrosion resistance, supporting its use in automotive components (Singh & Sharma, 2021) [11]. The application of FEA tools like ANSYS allowed for accurate stress prediction and critical region identification, minimizing the need for physical prototypes (Gupta & Mehta, 2021) [9] as shown in figure 4.1.

#### 4.1.2. Normal Stress

The static structural analysis of the aluminium alloy wheel revealed a maximum normal stress of 33.13 MPa, which is well below the material's yield strength of 225 MPa, confirming elastic behavior under the given loading conditions. Stress concentrations were primarily located at the inner rim and spoke junctions areas typically prone to higher stresses due to geometry and load paths, as noted by Patel et al. (2021) [4] and Reddy and Rao (2019) [8]. The normal stress distribution demonstrated effective load transmission across the wheel structure, validating aluminium alloy's suitability for lightweight automotive applications. Consistent with Gupta and Mehta (2021) [9], the use of FEA tools like ANSYS enabled the accurate identification of high-stress regions, supporting design reliability as shown in figure 4.2. The findings reaffirm that aluminium alloys perform well in resisting axial loads, as emphasized in prior studies by Singh and Sharma (2021) [11].

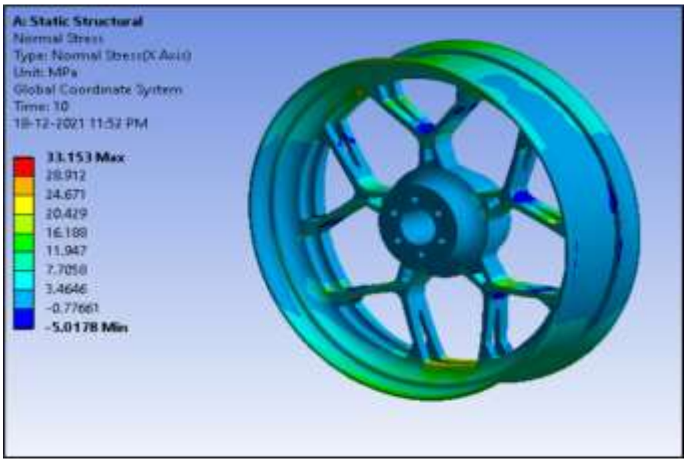


**Fig 4.2: Normal Stress**

### 4.1.3. Total Deformation

The static structural analysis showed a maximum total deformation of 0.43 mm in the aluminium alloy wheel, indicating that the structure maintains adequate rigidity and flexibility under static loading. Deformation was primarily observed at the outer rim and spoke junctions—areas typically subjected to higher operational stresses. The small magnitude of deflection confirms the material's suitability for two-wheeler applications, aligning with findings by Kumar et al. (2020) [3] and Gupta and Mehta (2021) [9], who noted similar controlled deformation in aluminium alloy wheels. The results support the alloy's ability to absorb static loads without compromising geometric stability or performance as shown in figure 4.3. This also reinforces conclusions by Reddy and Rao (2019) [8], who emphasized that deformation can be minimized with proper material choice and structural design. Overall, the analysis affirms aluminium alloy's effectiveness in maintaining both structural integrity and ride safety.

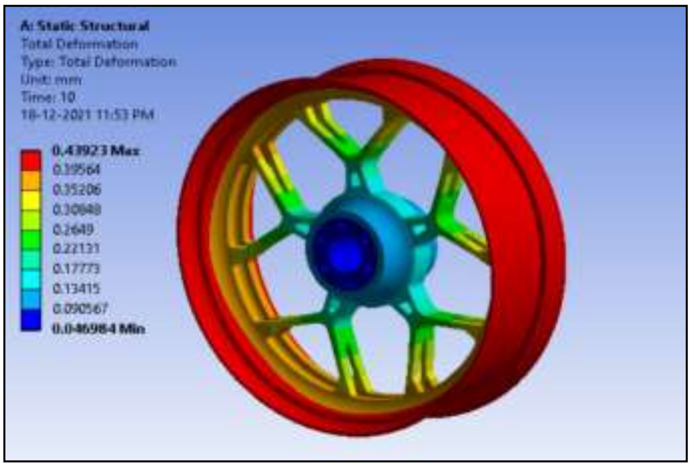


**Fig 4.3: Total Deformation**

### 4.2. Static Structural: Magnesium Alloy

#### 4.2.1. Von Mises Stress:

The static structural analysis of the two-wheeler wheel using magnesium alloy revealed a maximum von Mises stress of 23.98 MPa, which is well below the alloy's yield strength of 133 MPa, confirming that the wheel remains within safe elastic limits. Stress was mostly uniform, with minor concentrations near the spoke-to-rim junctions, consistent with previous FEA-based studies (Patel et al., 2021) [4] as shown in figure 4.4. These areas may benefit from further design improvements to enhance long-term fatigue resistance. Magnesium alloy's key advantage lies in its lightweight properties, contributing to reduced unsprung mass and better ride quality. However, its lower yield strength compared to aluminium necessitates careful structural optimization, as emphasized by Reddy and Rao (2019) [8]. The findings support magnesium alloy as a viable material for two-wheeler wheels, provided the design maintains conservative safety margins, aligning with recommendations by Singh and Sharma (2021) [11] for balanced performance in lightweight automotive components.

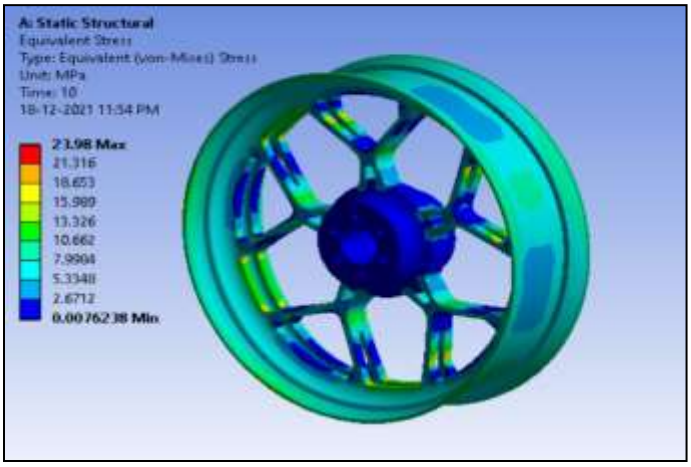


**Fig 4.4: Equivalent (Von-Mises) Stress**

### 4.2.2. Normal Stress

The static structural analysis of the magnesium alloy wheel showed a maximum normal stress of 21.62 MPa, well below its yield strength of 133 MPa, confirming the material's safety under typical service loads. The stress distribution was relatively uniform, with no critical concentrations, indicating efficient structural performance. This uniformity is influenced by magnesium's moderate young's modulus (45 GPa) and low density, which contribute to balanced stress behavior and reduced inertial effects as shown in figure 4.5. These findings are consistent with earlier studies by Reddy and Rao (2019) [8] and Gupta and Mehta (2021) [9], which highlight magnesium's potential for lightweight, structurally sound applications. The results affirm that magnesium alloys can effectively handle static stresses in two-wheeler components while offering advantages in weight reduction and design optimization.

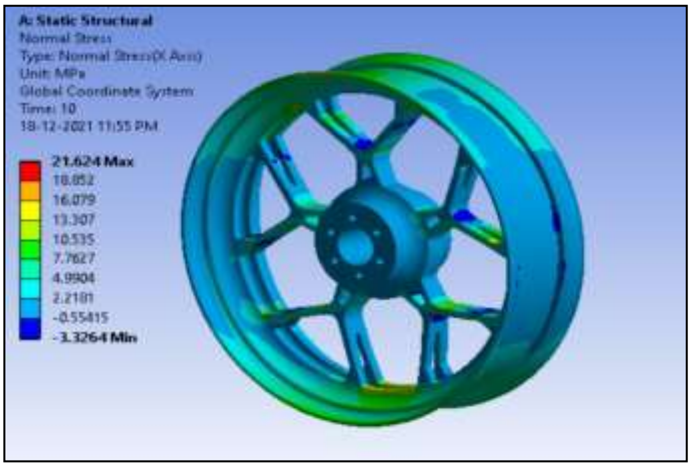


**Fig 4.5: Normal Stress**

### 4.2.3. Total Deformation

The static structural analysis of the magnesium alloy wheel revealed a maximum total deformation of 0.44 mm, slightly higher than that of aluminium but lower than titanium, due to magnesium's lower young's modulus (45 GPa). This increased flexibility is a characteristic of its lower elastic stiffness, yet the deformation remains within safe operational limits, ensuring structural integrity. Magnesium's lightweight nature and strength-to-weight ratio make it an attractive choice for automotive use, despite slightly higher deflection (Reddy & Rao, 2019) [8]. The results align with findings by Gupta and Mehta (2021) [9], supporting the use of FEA to identify deformation-prone areas and guide design improvements. With a low-density of 1850 kg/m$^3$, magnesium significantly reduces component weight, offering benefits in fuel efficiency and handling (Singh & Sharma, 2021) [11] as shown in figure 4.6. Overall, the magnesium alloy wheel exhibited acceptable deformation levels, making it a strong candidate for two-wheeler applications focused on lightweight performance.

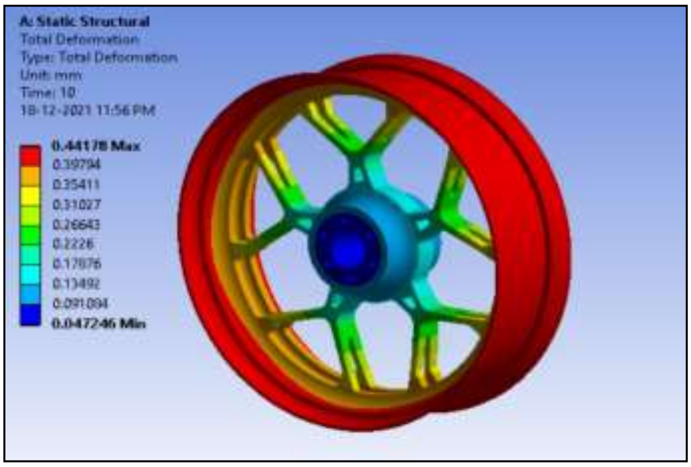


**Fig 4.6: Total Deformation**

### 4.3. Static Structural: Titanium Alloy

#### 4.3.1 Von Mises Stress:

The static structural analysis of the titanium alloy wheel showed a maximum von Mises stress of 61.58 MPa, significantly below its high yield strength of 930 MPa, indicating excellent structural safety. Stress was mainly concentrated at the spoke-hub junctions, consistent with typical load transfer zones in alloy wheels (Patel et al., 2021) [4]. Compared to aluminium and magnesium, the titanium alloy exhibited higher stress values due to its greater stiffness (Young’s modulus: 96 GPa). Despite this, the material's superior strength and fatigue resistance make it ideal for high-performance applications (Kumar & Singh, 2021) [3] as shown in figure 4.7. While titanium is denser and more expensive, its mechanical durability and reliability provide a significant advantage for premium or performance-oriented two-wheelers, validating its use in critical structural components.

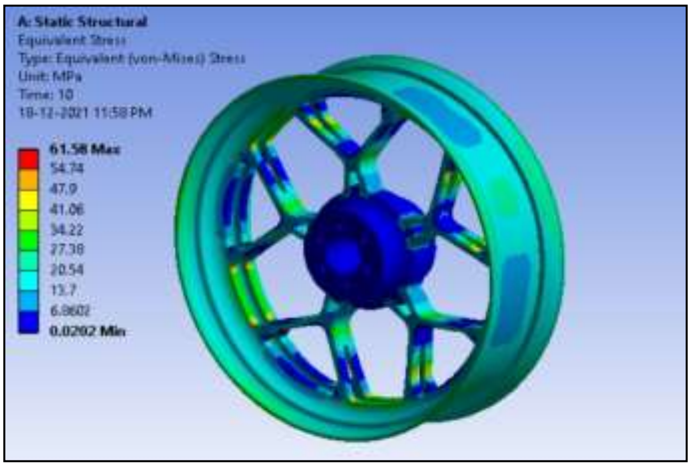


**Fig 4.7: Equivalent (Von-Mises) Stress**

### 4.3.2. Normal Stress

The static structural analysis of the titanium alloy wheel revealed a maximum normal stress of 55.61 MPa, concentrated near the spoke-hub junctions, which are critical load transmission zones. This higher stress is attributed to titanium's high stiffness and strength, allowing it to withstand elevated static loads without entering plastic deformation. The stress distribution aligns with prior findings (Reddy & Rao, 2019; Gupta & Mehta, 2021) [8, 9], which emphasize the significance of normal stress evaluation in identifying potential failure zones. Titanium’s robust mechanical properties and corrosion resistance make it well-suited for high-performance applications, as supported by Kumar & Singh (2021) and Mishra & Kumar (2023) [3, 11] as shown in figure 4.8. Overall, the results confirm titanium alloy’s superior load-bearing capacity and structural reliability under static conditions, reinforcing its value in premium two-wheeler wheel designs.

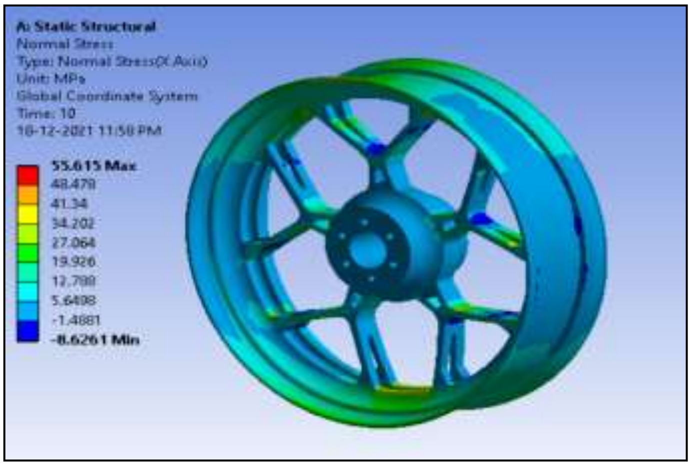


**Fig 4.8: Normal Stress**

### 4.3.3. Total Deformation

The static structural analysis showed that the titanium alloy wheel experienced a maximum total deformation of 0.52 mm, slightly higher than aluminium (0.43 mm) and magnesium (0.44 mm) alloys. Despite titanium’s high young’s modulus (96 GPa) and excellent strength (930 MPa), the increased deformation is attributed to its higher density and complex stress distribution, which influence its response under loading. These results align with findings from Reddy and Rao (2019) [8] and Gupta and Mehta (2021) [9], who noted that mass and stiffness significantly affect deformation even in high-performance materials. While titanium ensures structural strength and fatigue resistance, its deformation behavior highlights the importance of comprehensive design validation as shown in figure 4.9. Overall, titanium remains suitable for high-strength, premium applications, provided that structural integrity is ensured through advanced simulation and optimization.

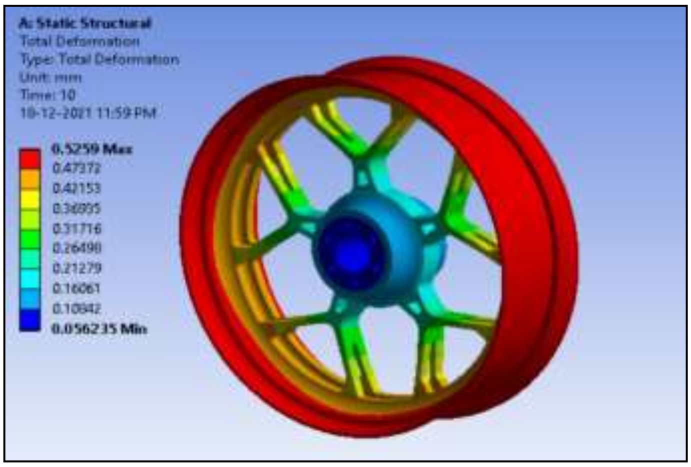


**Fig 4.9: Total Deformation**

**Table 4: Result of Static Structural Analysis**

| **Material** | **Von-Mises Stress (MPa)** | **Normal Stress (MPa)** | **Max Deformation (mm)** |
|---|---|---|---|
| Aluminum Alloy | 33.15 | 33.13 | 0.43 |
| Magnesium Alloy | 23.98 | 21.62 | 0.44 |
| Titanium Alloy | 61.58 | 55.61 | 0.52 |

The static structural analysis using FEM evaluated aluminium, magnesium, and titanium alloys under identical conditions for a two-wheeler alloy wheel as shown in table 4.1. Titanium alloy showed the highest von Mises stress (61.58 MPa) and deformation (0.52 mm), reflecting its superior strength (930 MPa) and stiffness, though its high density may hinder lightweight applications (Rajesh & Venkatesh, 2020) [1]. Aluminium alloy demonstrated a balanced performance with moderate stress (33.15 MPa), low deformation (0.43 mm), and reduced centrifugal stress due to its lower density (2800 kg/m$^3$), confirming its suitability for efficient and durable wheel designs (Patel et al., 2021) [4]. Magnesium alloy exhibited the lowest stress (23.98 MPa) and similar deformation (0.44 mm), offering significant weight savings (1850 kg/m$^3$) that benefit fuel economy, though its lower yield strength (133 MPa) limits use under heavy loads (Kumar & Singh, 2021). These results underscore the trade-offs between strength, deformation, and weight, supporting a multidisciplinary design approach for optimal material selection in alloy wheel manufacturing (Gupta & Mehta, 2021; Mishra & Kumar, 2023) [9, 3].

## Conclusion:

A comprehensive static structural analysis of a two-wheeler alloy wheel has been conducted using Finite Element Method (FEM) to evaluate the mechanical performance of different materials under equivalent loading conditions. Aluminium, magnesium, and titanium alloys were examined, and the simulation results revealed that titanium alloy exhibited the highest von Mises stress and deformation, indicating superior strength but greater mass-related impact. In contrast, magnesium alloy showed the least stress values but experienced similar deformation compared to aluminium, suggesting limited structural efficiency. Aluminium alloy emerged as a balanced option, demonstrating favourable stress distribution and minimal deformation while maintaining low density, aligning with previous findings on its strength-to-weight advantage. The FEA outcomes validated the significance of material selection in alloy wheel design, who emphasized that critical stress zones can be identified and optimized through simulation tools. Moreover, the study confirmed that CAD modelling and meshing strategies play a crucial role in enhancing design accuracy and performance predictions. Hence, it can be concluded that simulation-based structural analysis is an effective approach for optimizing wheel design and ensuring reliability in two-wheeler applications.

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