



# A Review Of Finite Element Methods In Automotive Wheel Hub Design: Static, Modal, And Fatigue Perspectives

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**Abstract:** Automotive wheel hubs are critical load-bearing components that ensure structural integrity and dynamic performance of vehicle systems. Finite element methods (FEM) have become essential tools for analyzing static strength, modal behavior, and fatigue life under complex loading conditions. This review presents a systematic synthesis of recent FEM-based studies on wheel hubs, focusing on modeling strategies, material selection, boundary Engineering conditions, and realistic loading scenarios. Emphasis is placed on lightweight design and topology optimization for performance enhancement without compromising safety. Additionally, the role of multiaxial fatigue analysis and experimental validation is highlighted. Key research gaps, including the need for integrated multi-physics modeling and real-world load spectrum representation, are identified to guide future developments in advanced wheel hub design.

**Index Terms** - Finite Element Analysis; Wheel Hub; Fatigue Analysis; Modal Analysis; Lightweight Design; Topology Optimization; Automotive Engineering

## 1. Introduction

Wheel hubs must resist static loads, sustain dynamic excitations without resonance, and endure fatigue under realistic road and driving conditions. Finite element modeling provides a cohesive framework to evaluate stress, displacement, natural frequencies, mode shapes, and fatigue life, facilitating design optimization while reducing physical testing. Recent work demonstrates how static and modal analyses illuminate stiffness, strength, and resonance avoidance, while fatigue analyses reveal sensitivity to multi-axial and variable-amplitude loading and drive topology optimizations for weight reduction and reliability [1]. The hub's function as the interface among wheel, bearing, brake, suspension, and tire makes accurate representation of loads and boundary conditions essential, and several studies emphasize material choices (steel, aluminum, magnesium) and their implications for strength-to-weight trade-offs and safety factors [2]. In addition, innovations in topology optimization and lightweight hub concepts are increasingly integrated with FEM to achieve robust performance under mission-critical

loading with reduced mass [3]. The literature also stresses that real-world loading is multi-axial and time-varying, necessitating fatigue models that capture rotation, tire contact, and bearing influences [4]. Finally, experimental validation—modal tests, impact loading, and fatigue testing—is employed to anchor numerical results and guide design decisions [10].

## 2. Finite Element Modeling of Automotive Wheel Hubs: Geometry, Materials, and Boundary Conditions

- Geometry and discretization. Wheel hubs are complex, multi-part assemblies whose FEM models typically include the hub body, bearing interfaces, bolt holes, flange features, and connection to the wheel and brake assembly. The mesh density and element type are chosen to balance accuracy with computational cost, and local refinement is frequently applied at high-stress regions such as bolt holes and fillets [8].
- Influence of Material Selection on Static and Modal Performance of Wheel Hubs:
  - The selection of material plays a crucial role in determining the structural integrity, dynamic behavior, and lightweight potential of automotive wheel hubs. Commonly used materials include steel, aluminum alloys, and magnesium alloys, each offering distinct advantages in terms of strength-to-weight ratio, stiffness, and vibration characteristics.
  - Aluminum alloys are widely preferred due to their lower density and good balance between strength and manufacturability. For instance, ZAlSi7MgA aluminum alloy exhibits an elastic modulus of approximately 70 GPa and provides sufficient strength for load-bearing applications while enabling significant weight reduction. In contrast, steel offers higher stiffness but increases overall mass, which negatively affects fuel efficiency and dynamic response. Magnesium alloys provide further weight reduction but may suffer from lower fatigue resistance and higher cost.
  - Material properties such as density, Young's modulus, and damping characteristics directly influence both static deformation and modal behavior. A higher elastic modulus generally increases natural frequencies, reducing the likelihood of resonance, whereas lower density contributes to lightweight design but may decrease stiffness.
  - Modal analysis studies indicate that optimized wheel hubs exhibit natural frequencies significantly higher than typical excitation sources such as road irregularities (below 11 Hz) and engine vibrations (up to ~200 Hz), ensuring safe operation without resonance. However, material substitution can shift these frequencies, making comparative analysis essential.
  - Therefore, comparative evaluation of different materials under identical boundary conditions using finite element methods is essential to identify optimal trade-offs between weight reduction, strength, and vibration performance. Such comparative studies form the basis for advanced lightweight and high-performance wheel hub design.

Table 1 presents a comprehensive comparison of commonly used materials for automotive wheel hubs, including steel, aluminum alloys, magnesium alloys, and composite materials. The comparison is based on key mechanical, physical, and functional properties such as density, Young's modulus, yield strength, fatigue strength, damping capacity, corrosion resistance, manufacturability, and cost. From the table, it can be observed that steel exhibits the highest stiffness and fatigue strength, making it suitable for heavy-duty applications; however, its high density significantly increases the overall weight of the wheel hub. In contrast, aluminum alloys offer an optimal balance between strength, weight, and manufacturability, which explains their widespread adoption in modern automotive industries. Magnesium alloys provide further weight reduction and improved damping characteristics, but their lower fatigue resistance and corrosion susceptibility limit their application. Composite materials, particularly carbon fiber reinforced polymers (CFRP), demonstrate superior strength-to-weight ratios and excellent vibration damping properties. However, their high cost and complex manufacturing processes restrict their use to high-performance and specialized applications. Overall, the comparison highlights that material selection plays a critical role in determining the structural performance,

dynamic behavior, and lightweight potential of wheel hubs. Therefore, selecting an appropriate material requires careful consideration of trade-offs between strength, weight, fatigue life, and vibration characteristics.

*Table 1 Comprehensive Comparison of Wheel Hub Materials*

Property	Steel	Aluminum Alloy (e.g., ZL101A)	Magnesium Alloy	Composite (CFRP)
<b>Density (kg/m<sup>3</sup>)</b>	~7850	~2600–2800	~1700–1900	~1500–1800
<b>Young's Modulus (GPa)</b>	~200–210	~65–75	~40–50	70–150 (anisotropic)
<b>Yield Strength (MPa)</b>	250–600	150–300	100–250	500–1500
<b>Fatigue Strength</b>	Very High	Moderate	Low–Moderate	High (directional)
<b>Damping Capacity</b>	Low	Moderate	High	Very High
<b>Corrosion Resistance</b>	Low (needs coating)	Good	Poor (needs protection)	Excellent
<b>Thermal Conductivity</b>	Moderate	High	High	Low
<b>Manufacturability</b>	Easy (forging, casting)	Excellent (casting)	Difficult	Complex (layup, molding)
<b>Cost</b>	Low	Moderate	High	Very High
<b>Weight Reduction Potential</b>	Low	Moderate	High	Very High

- Load cases and boundary conditions. Hubs are constrained by wheel bearings, brake discs, suspension mounting points, and tire contact loads. Static analyses often apply representative quasi-static loads at bolt holes or flange interfaces, while modal analyses depend on accurately simulating boundary conditions to capture natural frequencies and mode shapes that could be excited by road inputs or drivetrain torque. Several works emphasize boundary-condition choices consistent with real-world mounting and load introduction to ensure credible stiffness and resonance predictions[8]. Bearing stiffness and bearing-hub interaction also emerge as critical factors affecting deformations and dynamic response [6].

- Validation needs. Validation is typically achieved by comparing FEM predictions to experimental modal tests, static loading tests, or fatigue tests. Several studies report good correspondence between FE results and measured natural frequencies or failure modes, reinforcing the credibility of FEM-driven hub designs [12].

### 3. Static Analysis Perspectives for Wheel Hubs

- Purpose and typical outputs. Static FE analyses quantify maximum von Mises stresses, peak displacements, and safety factors under service loads, enabling material selection and geometric tuning to meet strength criteria with a given mass constraint. Comparative studies show that static analyses can guide material substitutions and geometric refinements to balance safety margins and weight [13].

- Material and geometry effects on static performance. Several investigations demonstrate that weight reduction through material substitution or topology-optimized geometry can maintain or improve static safety factors while reducing mass. For example, lightweight hub designs with aluminum or composite-based geometries can meet or exceed static strength requirements while delivering mass reductions and improved performance metrics[8]. The body of evidence consistently indicates the

feasibility of substantial static-strength maintenance under reduced mass with appropriate design strategies[5].

- Design guidelines and safety factors. Static analyses underpin safety-factor determinations for rims and hubs under ISO-like or vehicle-duty loads; comparisons across materials reveal the trade-offs between weight, stiffness, and safety margins, with carbon-fiber-based solutions often emerging as favorable for static strength in some configurations and manufacturing contexts [13]. The literature also notes that static safety assessments should be complemented by fatigue analyses to capture long-term reliability under dynamic environments [13].

#### 4. Modal Analysis Perspectives for Wheel Hubs

- Objective of modal analysis. Modal analyses identify natural frequencies, mode shapes, and damping characteristics to ensure that hub excitation (e.g., road inputs, engine harmonics, and wheel-spin dynamics) does not coincide with a structural resonance, which would amplify stresses and vibrations. The ability to tune hub design to avoid external excitation frequencies is highlighted in several hub-focused studies [3].

- Modal insights for lightweight designs. Modal analysis is commonly paired with topology-optimization or material-change strategies to verify that weight reductions do not push the hub's natural frequencies into problematic ranges. Several studies report that optimized hubs exhibit natural frequencies that avoid common excitation spectra, supporting the viability of light-weight hub designs without compromising dynamic performance [5].

- Experimental validation of modal predictions. Experimental modal testing (impact hammer/dynamic tests) is used to validate FE-predicted mode shapes and natural frequencies, providing confidence in the modeling approach and offering calibration opportunities for boundary conditions and material properties [12]. This validation is essential when introducing new lightweight materials or novel geometries into hub designs.

#### 5. Fatigue Life Perspectives for Wheel Hubs

- Fatigue as a design driver. Fatigue under repeated loading—particularly high-cycle fatigue with complex load paths—is a central concern for hubs, given exposure to road irregularities, braking events, cornering, and drivetrain torques. Fatigue life predictions rely on multiaxial or equivalent-stress criteria, time-history loads, and spectrum-based methods to approximate damage accumulation [9].

- Multiaxial and variable amplitude loading. Studies show that fatigue life predictions for wheel components must account for axial, bending, torsional, and multi-input loading histories that reflect steering knuckle/bearing/arm interactions, tire contact, and road profiles. In particular, multiaxial variable-amplitude loading significantly influences fatigue life predictions and is best assessed with probabilistic or critical-plane approaches when comparing with experimental data [9].

- Fatigue life models and damage criteria. Fatigue assessments in hub contexts employ time histories of stress (root-mean-squared, peak stresses, or equivalent stresses) and damage models (e.g., Liu-Zenner equivalent stress approach, Dirlik-type spectral methods, or other multiaxial criteria). Comparative studies indicate that probabilistic approaches can yield results that align more closely with experimental observations, especially for complex geometries and loading histories [9].

- Role of topology optimization in fatigue reduction. Topology optimization and weight-reducing geometries can reduce peak stresses and redistribute load paths, thus extending fatigue life. Studies show that hub spokes, flanges, and mounting regions can be redesigned to achieve substantial mass reductions while maintaining or enhancing fatigue life via optimized stress distributions [15]. This is reinforced by topological optimization efforts on wheel spokes and hub assemblies that report fatigue-life improvements with modest weight savings.

#### 6. Lightweight Design, Topology Optimization, and Multi-Objective Design in Hubs

- Rationale for lightweight hubs. Reducing hub mass improves vehicle efficiency and performance without sacrificing safety, provided structural stiffness and fatigue resistance are preserved or enhanced. A number of works demonstrate measurable mass reductions (often in the range of a few

percent to over 7–8% depending on the hub and design) while maintaining or improving static and modal performance [8].

- Topology optimization and design strategies. Topology optimization methods are widely used to generate lightweight hub geometries (e.g., monobloc designs, optimized spoke configurations, and optimized flange geometries) while preserving required stiffness and fatigue resistance. Several studies explicitly discuss topology optimization as a critical component of modern hub design workflows and demonstrate how optimized geometries reduce mass and/or enhance performance metrics under specified loading conditions [15].
- Multi-objective design under bearing and rotor constraints. Some work integrates hub optimization with bearing stiffness considerations and rotary load paths to ensure compatible interactions with in-wheel motors or braking systems, reflecting a broader systems perspective on hub design for advanced propulsion architectures. These studies emphasize that optimization must consider coupled mechanical subsystems to avoid unintended performance penalties.

## 7. Validation and Experimental Correlation

- Modal validation. Experimental modal tests (impact hammer) are commonly used to validate FE-predicted natural frequencies and mode shapes. Reported agreements within a few percent for certain hub geometries validate the FEM approach and provide confidence for predictive design in lightweight hub concepts [12].
- Static and fatigue experiments. Some studies perform static loading tests, radial fatigue tests, or other mechanical tests (e.g., ISO-based fatigue testing) to corroborate FE predictions and to benchmark materials and geometries under representative service conditions. These efforts help calibrate material data, load paths, and boundary conditions used in simulations.
- Bearing and hub integration experiments. Investigations into hub bearing stiffness and its effect on the hub's deflection and dynamic response provide experimental grounding for FE models that couple structural hub behavior with bearing interfaces and rotor/housing interactions, which has direct implications for in-wheel motor applications.

## 8. Gaps, Nuances, and Areas for Future Research

- Integrated multi-physics hub modeling. Despite robust static, modal, and fatigue analyses, truly integrated models that couple tire contact, axle bearing dynamics, brake interactions, and drive torque with hub structural response remain a fertile area for deeper exploration. The bearing-hub interaction and tire loading are recognized as influential but challenging to model accurately in a single framework [6].
- Realistic load spectra and road input. While several works use representative load cases, there is an ongoing need for standardized, validated road-load spectra and driving-condition datasets to drive fatigue analyses for hub assemblies, particularly under multi-axis and high-frequency excitations [10].
- Material and manufacturing innovations. The literature shows strong interest in lightweight materials (e.g., aluminum-magnesium alloys, high-strength steels, composites) and manufacturing methods (e.g., topology optimization-embedded designs, additive manufacturing) to reduce hub mass while preserving reliability. Continued work on material models, residual stresses, and manufacturing-induced anisotropy will enhance FEM accuracy for fatigue predictions and dynamic behavior [5].
- Validation breadth. While modal validation is common, broader validation for fatigue under realistic road sequences and for complex hub assemblies (e.g., steering knuckle–hub–bearing interactions) would strengthen confidence in life-prediction approaches and support more aggressive weight reductions [9].
- Applications to advanced propulsion architectures. In-wheel motors and brake-hub assemblies introduce additional design drivers such as high torque density, NVH constraints, and thermal management. FEM studies focusing on hub-bearing interfaces, rotor/stator housing, and structural damping in this context are emerging and warrant further development [8].

## 9. Conclusions

- The finite element analysis of automotive wheel hubs has matured into a multi-faceted discipline that addresses static strength, dynamic modal behavior, and fatigue life under increasingly realistic loading and interaction scenarios. Static analyses provide robust guidance for material selection and geometry to achieve required safety factors with mass reductions, while modal analyses ensure that hub designs avoid resonant excitation bands and maintain acceptable dynamic performance under lightweight configurations. Fatigue life predictions, including multi-axial and variable-amplitude loading, are essential for ensuring long-term reliability under real-world road and drive conditions, and they are enhanced by integrating topology optimization and load-path considerations to achieve lightweight yet robust hubs .
- The combination of topology optimization and FEM enables substantial weight reductions without compromising (and often improving) static, modal, and fatigue performance, suggesting a clear path toward next-generation hub designs for both conventional and advanced propulsion architectures. Experimental validation, particularly modal testing and fatigue testing, remains a crucial counterbalance to simulations and a key to translating design innovations into manufacturing-ready products.
- Overall, FEM-based hub design has proven adept at delivering lightweight, safe, and reliable wheel hubs, with ongoing opportunities to deepen integrated multi-physics modeling, broaden experimental validation, and extend optimization frameworks to emerging technologies such as in-wheel motors and novel bearing assemblies.

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