



Structural and Fatigue Analysis of Steering Knuckle under Multi-Axial Loading

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Abstract

The steering knuckle is a critical load-bearing component in automotive suspension systems, subjected to complex multi-axial loading conditions arising from braking, cornering, and road irregularities. In this study, a comprehensive structural and fatigue analysis of a steering knuckle is performed using finite element analysis (FEA) to evaluate its durability under realistic service conditions. A detailed three-dimensional model was developed using CAD software and analyzed in ANSYS Workbench. Three candidate materials—Aluminum Alloy 7075-T6, Forged Steel AISI 4140 (QT), and Stainless Steel AISI 304—were comparatively evaluated under identical boundary and loading conditions. Static structural analysis was conducted to determine deformation, equivalent stress, and strain, while fatigue analysis was carried out using the stress–life (S–N) approach under fully reversed loading conditions. The results indicate that maximum von Mises stress (56.77 MPa) remains significantly below yield limits for all materials. Aluminum exhibited the highest deformation (0.33076 mm), whereas AISI 4140 showed superior stiffness (0.1133 mm) and fatigue resistance. Fatigue analysis revealed life exceeding 10^6 cycles with negligible damage ($D < 1$) and safety factors greater than 2 for all materials. The study concludes that AISI 4140 provides optimal strength and durability, Aluminum 7075-T6 offers weight reduction with acceptable performance, and Stainless Steel 304 ensures corrosion resistance with moderate strength. The proposed framework provides a reliable methodology for durability-based design and material selection of automotive suspension components.

Keywords:

Steering knuckle, Multi-axial loading, Fatigue analysis, Finite element analysis, S–N curve, Automotive suspension, Material comparison



1. Introduction

The steering knuckle is a fundamental component in automotive suspension systems, acting as an interface between the wheel assembly, braking system, and steering mechanism. During service conditions, it is

subjected to complex multi-axial loading arising from vertical forces due to vehicle weight, longitudinal forces during braking, and lateral forces generated during cornering maneuvers [12]. These combined loading conditions result in non-uniform stress distribution and cyclic loading, which significantly influence structural integrity and fatigue durability.

Fatigue failure in steering knuckles is commonly initiated at stress concentration zones such as fillet regions, mounting interfaces, and geometric discontinuities, even when nominal stresses remain below the material yield strength [1], [3], [21]. This phenomenon is attributed to repeated cyclic loading and localized stress amplification, which accelerates crack initiation and propagation. Finite Element Analysis (FEA) has emerged as a powerful tool for evaluating stress distribution and predicting fatigue life of suspension components under realistic operating conditions [2], [11]. However, many conventional studies rely on simplified loading assumptions, which may underestimate the actual fatigue damage experienced under real-world service conditions [8], [10]. Therefore, there is a critical need for an integrated structural and fatigue assessment framework that incorporates realistic multi-load conditions and material comparison to ensure durability-oriented design.

2. Related work

Extensive research has been conducted on the structural and fatigue behavior of steering knuckles using numerical simulations and experimental validation. Previous investigations have consistently identified stress concentration at geometric discontinuities such as fillet transitions and mounting holes as the primary cause of fatigue failure [3], [21], [28]. Multi-load case analysis has been shown to provide more accurate and realistic stress prediction compared to simplified single-load conditions [12]. Fatigue life prediction using the

stress–life (S–N) method has been widely adopted for high-cycle fatigue analysis of automotive components [4], [19]. Furthermore, studies incorporating real driving load spectra have demonstrated improved prediction accuracy by accounting for variable amplitude loading conditions [8], [10]. Material selection plays a significant role in structural performance. Forged steels exhibit superior fatigue strength and stiffness, whereas aluminum alloys provide weight reduction with increased deformation, and stainless steels offer corrosion resistance with moderate mechanical properties [16], [30]. Despite these advancements, limited studies provide:

- Integrated multi-material comparison
- Identical loading conditions across materials
- Inclusion of biaxiality effects in fatigue evaluation

The present study addresses these limitations by providing a unified structural–fatigue assessment framework.

3. Experimental Work

3.1 Geometry Modeling

A high-fidelity three-dimensional CAD model of the steering knuckle was developed incorporating all critical interfaces such as hub bore, suspension arms, brake caliper mounts, and steering linkages. Special attention was given to fillet regions, as they significantly influence stress concentration and fatigue behavior [3], [21].



Fig. 1 CAD Model of Lower Control Arm

3.2 Methodology Flow Diagram

The adopted methodology follows a systematic FEA-based durability assessment:

CAD Modeling → Geometry Import → Material Assignment → Meshing → Boundary Conditions → Multi-Axial Loading → Structural Analysis → Fatigue Analysis → Comparative Evaluation

This approach aligns with standard simulation-based procedures in suspension component analysis [2], [11].



Fig. 2 Methodology Flow Diagram

3.3. Meshing Strategy

The geometry was discretized using higher-order 10-node tetrahedral elements (SOLID187) to accurately capture stress gradients. Mesh refinement was applied in critical regions such as fillets, bolt holes, and junctions. A mesh convergence study ensured solution independence and numerical accuracy [2], [11].

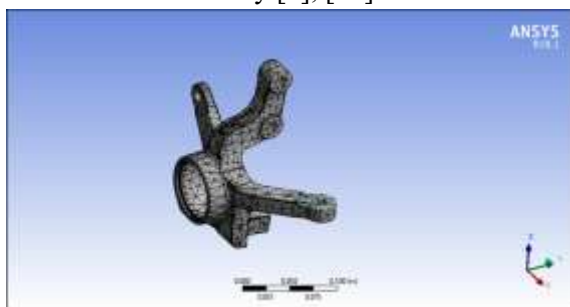


Fig. 3. Meshing

3.4. Boundary Conditions

Realistic boundary conditions were applied to replicate the installation environment of the steering knuckle. Fixed and cylindrical supports were used to simulate mounting constraints. Proper definition of boundary conditions is essential for accurate stress prediction [12], [24].



Fig.4. Boundary Conditions

3.5. Loading Conditions

Combined loading was applied to replicate real service conditions: Vertical load; Braking force; Cornering force. It has been shown that independent load analysis may underestimate stress levels, whereas combined loading provides realistic results [12]. Fatigue analysis was performed under fully reversed loading ($R = -1$), which is widely used for conservative fatigue life prediction [10], [19].



Fig. 5. Loading Conditions

4. Results and Discussion

4.1 Structural Behavior Analysis

The structural analysis revealed that the maximum von Mises stress (56.77 MPa) is significantly lower than the yield strength of all selected materials. The highest stress concentration was observed at the arm–hub junction, confirming findings from previous studies [3], [21]. Aluminum Alloy 7075-T6 exhibited the highest deformation (0.33076 mm) due to its lower elastic modulus, whereas Forged Steel AISI 4140 demonstrated the lowest deformation (0.1133 mm), indicating superior stiffness. Stainless Steel AISI 304 showed intermediate behavior. These results confirm that stiffness is strongly influenced by material modulus, consistent with earlier comparative studies [16], [30].



4.2 Fatigue Life Evaluation

The fatigue life exceeded 10^6 cycles for all materials, indicating high-cycle fatigue performance. This is attributed to the low equivalent alternating stress (~ 30 MPa), which is significantly below the endurance limits of the materials. Similar observations have been reported in fatigue studies under controlled loading conditions [7], [9].

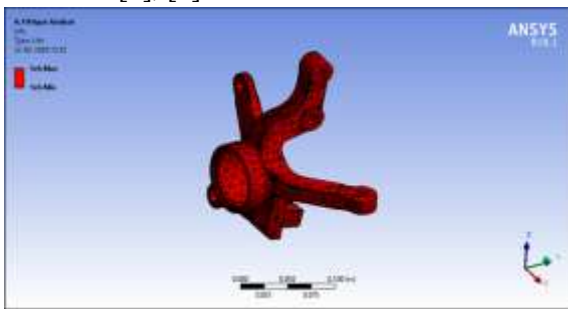


Fig:4.12. Fatigue life of steering knuckle (Forged Steel AISI 4140)

4.3 Fatigue Damage Assessment

Cumulative fatigue damage remained below unity ($D < 1$), confirming that the steering knuckle operates within safe fatigue limits. Damage localization was observed near stress concentration zones, consistent with Miner's rule-based fatigue predictions [10], [27].

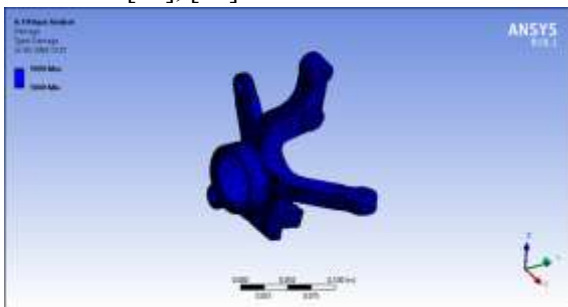


Fig:4.13. Fatigue damage of steering knuckle (Forged Steel AISI 4140)

4.4 Safety Factor Analysis

Fatigue safety factors greater than 2 were obtained for all materials, indicating sufficient reliability under cyclic loading conditions. This aligns with recommended design practices for automotive components [19], [27].

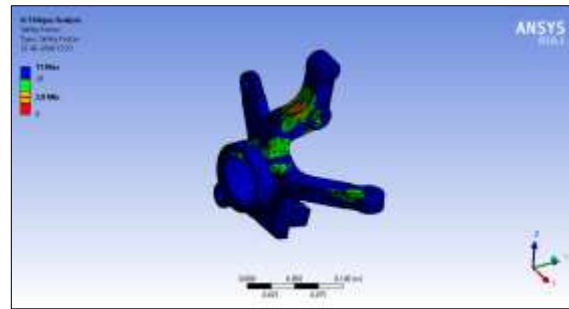


Fig:4.14. Safety factor of steering knuckle (Forged Steel AISI 4140)

4.4 Equivalent Alternating Stress

Maximum alternating stress (~ 30 MPa) was significantly lower than endurance limits of the selected materials, indicating low probability of crack initiation [1], [19].

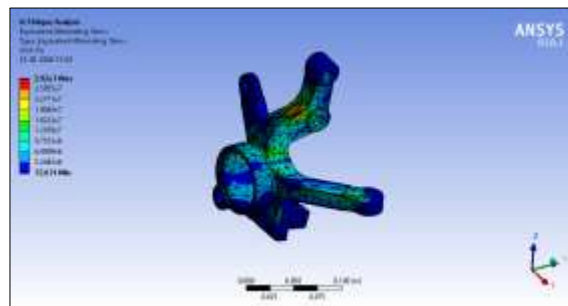


Fig:4.15. Equivalent alternating stress of steering knuckle (Forged Steel AISI 4140)

4.6 Multiaxial Stress (Biaxiality) Evaluation

Biaxiality analysis confirmed the presence of multi-axial stress states, particularly near critical regions. However, due to low stress magnitude, the effect of multiaxiality on fatigue life was minimal. Previous studies have emphasized the importance of considering multiaxial fatigue behavior for accurate life prediction [13], [26].

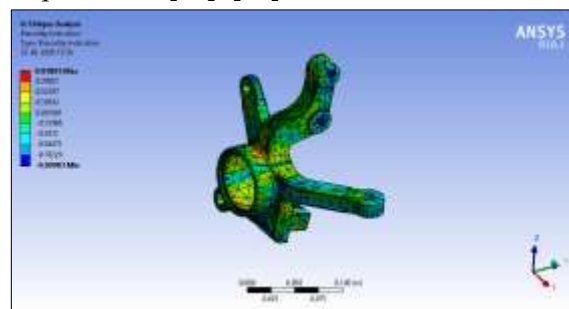


Fig:4.16. Biaxiality indication of steering knuckle (Forged Steel AISI 4140)



4.6 Comparative Material Performance

A detailed comparative evaluation of Aluminum Alloy 7075-T6, Forged Steel AISI 4140 (QT), and Stainless Steel AISI 304 was conducted to determine their suitability for steering knuckle applications under multi-axial loading conditions. The analysis clearly demonstrates that the mechanical response of the component is strongly governed by material stiffness, strength, and fatigue resistance. Among the selected materials, Forged Steel AISI 4140 exhibited the lowest deformation due to its high Young's modulus, thereby ensuring superior structural stiffness and dimensional stability under combined loading. Additionally, its significantly higher endurance limit resulted in enhanced resistance to fatigue damage, making it the most reliable candidate for durability-critical automotive applications.

In contrast, Aluminum Alloy 7075-T6 showed comparatively higher deformation, which is primarily attributed to its lower elastic modulus. However, the magnitude of deformation remained within acceptable service limits relative to the overall geometry of the component, indicating that structural integrity is not compromised. The key advantage of aluminum lies in its low density, which contributes to substantial weight reduction and improved fuel efficiency, making it a suitable choice for lightweight vehicle design where performance-to-weight ratio is a critical consideration.

Stainless Steel AISI 304 demonstrated intermediate behavior in terms of deformation and stress distribution. While its strength and stiffness are lower than those of forged steel, it provides superior corrosion resistance, which is particularly beneficial for components exposed to aggressive environmental conditions such as moisture, road salts, and temperature variations. However, its relatively lower fatigue strength compared to AISI 4140 limits its applicability in high-cycle, high-load conditions.

Overall, the comparative results indicate that Forged Steel AISI 4140 is the most suitable material for applications requiring maximum strength, stiffness, and fatigue durability. Aluminum Alloy 7075-T6 offers an effective

alternative for lightweight design with acceptable structural performance, whereas Stainless Steel AISI 304 provides a balanced compromise between mechanical properties and corrosion resistance. This integrated material assessment establishes a practical and application-oriented framework for selecting suitable materials in the design of automotive suspension components subjected to multi-axial loading conditions.

Table 4.1 Comparative Performance of Selected Materials

Parameter	Al 7075-T6	AISI 4140 (QT)	SS 304
Density (kg/m ³)	2810	7850	7850
Young's Modulus (GPa)	72	210	193
Max Deformation (mm)	0.33076	0.1133	~0.15
Max Stress (MPa)	56.77	56.77	56.77
Yield Strength (MPa)	503	655	215–250
Endurance Limit (MPa)	~150	~400–450	~200
Fatigue Life (cycles)	>10 ⁶	>10 ⁶	>10 ⁶
Fatigue Safety Factor (min)	~2.6	~2.8	>2

The comparative results clearly indicate that while all materials satisfy structural and fatigue requirements, significant differences exist in stiffness, weight, and fatigue resistance. AISI 4140 demonstrates superior fatigue performance and structural rigidity, whereas Aluminum 7075-T6 provides substantial weight reduction with acceptable deformation. Stainless Steel 304 offers moderate performance with enhanced corrosion resistance.

5. Conclusion

A comprehensive structural and fatigue analysis of a steering knuckle under multi-axial loading conditions was performed using finite element



analysis. The results confirm that stress levels remain within elastic limits, fatigue life exceeds one million cycles, cumulative damage is negligible, and safety factors are above acceptable limits. Forged Steel AISI 4140 demonstrated superior durability, while Aluminum 7075-T6 provided weight advantages. Stainless Steel AISI 304 showed moderate performance with corrosion resistance benefits. The study validates the effectiveness of multi-load-case FEA for durability-based design of automotive suspension components and provides a reliable framework for material selection and structural optimization.

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