International Journal of Scientific Research & Engineering Trends
Volume 12, Issue 1, Jan-Feb-2026, ISSN (Online): 2395-566X

FEA-Based Design and Evaluation of a Steering Knuckle Joint

[1]Mr. Khartode V. M., [2]Prof. P. G. Sarasambi, [3]Prof. S. P. Godase, [4]Dr. S. D. Shinde
[1]Student , Department of Mechanical Engineering , Shree Ramchandra College Of Engineering, Lonikand, Pune, Maharashtra, India
[2]Assistant Professor, Department of Mechanical Engineering, Shree Ramchandra College Of Engineering, Lonikand, Pune, Maharashtra, India
[3]Associate Professor, Department of Mechanical Engineering, Shree Ramchandra College Of Engineering, Lonikand, Pune, Maharashtra, India

Abstract - The steering knuckle is a unique component that links the suspension, steering, braking systems, and wheel hub to the vehicle chassis. It bears vertical loads and is crucial for directional control. Given the diverse loads encountered in various situations, it is imperative to ensure high quality, durability, and precision without affecting the steering performance or the vehicle's overall behavior. In the automotive sector, reducing fuel consumption and achieving lightweight designs are critical requirements. A lighter steering knuckle improves performance and reduces production costs. This study aimed to optimize the material used for the steering knuckle joint. Currently, it is constructed from spheroidal cast iron, which provides good strength but is heavy and less resistant to corrosion than other materials. Thus, selecting a material with improved corrosion resistance and lower weight is necessary. The proposed approach investigates the use of Al matrix composites. Initially, the knuckle was designed analytically using mathematical equations. Subsequently, FEA was conducted for all alternative materials, and material optimization was performed. An experimental investigation was conducted to validate the results obtained from the FEA. Keywords: Steering Knuckle, Optimization, FEA, Matrix Composites, Lightweight Design.

Keywords - Steering Knuckle, Lightweight Design, Material Optimization, Finite Element Analysis (FEA), Aluminum Matrix Composites (AMC).

INTRODUCTION

IIn contemporary automotive engineering, the pursuit of lightweight, fuel-efficient, and high-performance vehicles has driven the ongoing enhancement and refinement of essential components. Among these, the steering knuckle is crucial, serving as a link between the suspension, steering, braking systems, and the wheel hub.[1]It not only bears the vehicle's vertical load but also significantly affects its handling and stability.Given its critical function and exposure to diverse dynamic loads, the steering knuckle must possess exceptional strength, durability, and precision. Traditionally crafted from spheroidal cast iron, this component offers adequate strength but is hindered by excessive weight and limited resistance to corrosion.[2] These limitations make it less suitable for achieving modern automotive objectives of weight reduction and improved fuel efficiency. Consequently, there is increasing interest in investigating alternative materials that preserve the structural integrity while reducing the weight and enhancing the corrosion resistance. This study aims to address these issues through the analytical design and finite element analysis (FEA) of the steering knuckle using advanced materials such as aluminum matrix composites. Aluminum matrix composites offer a promising combination of low density, high strength, and excellent corrosion resistance, making them ideal candidates for steering knuckle applications in the automotive industry. The integration of these materials can lead to significant weight savings without compromising the mechanical performance. This study employs finite element analysis to evaluate the structural behavior of the redesigned steering knuckle under various loading conditions, ensuring its reliability and safety in real-world scenarios.[3], [4]

II. METHODOLOGY

In this study, the initial stage focused on examining the geometry, aesthetics, and functionality of the steering knuckle, specifically for the Tata Indica V2 vehicle. This process involves pinpointing the areas that experience various loads and understanding how the knuckle integrates with suspension and steering systems. From the component analysis, mathematical equations were developed to calculate the forces acting on different parts of the knuckle. These forces were then applied as loading conditions in ANSYS. The current steering knuckle, made from spheroidal cast iron (FG350), was modeled in Creo and analyzed in ANSYS using Finite Element Analysis (FEA). The same load conditions were used to conduct simulations for the alternative materials, Al2014-T6 and Al6082, to assess their performance in terms of stress, deformation, and strain. The FEA results for these alternative materials were compared with those of the initial material to identify improvements in the strength-to-weight ratio, deformation behavior, and stress distribution. Based on this comparison, the most appropriate material is chosen.[5]

Experimental testing was conducted on the optimized material to validate the simulation results.

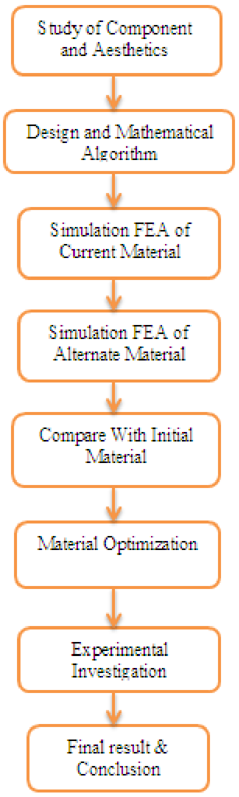

Fig.1: Flowchart of Methodology Used in Research Work

Mathematical Modeling

In this study, the steering knuckle was manufactured for Indica V2 by Tata Motors, India. The specifications of the Tata Indica V2 are provided in tabulated format.

Table.1: Specifications of Tata Indica V2

Parameter	Value
Max Power	48.2 bhp @ 5000 rpm
Max Torque	85 Nm @ 2500 rpm
Overall Length (mm)	3690 mm
Overall Width (mm)	1655 mm
Overall Height (mm)	1485 mm
Kerb Weight (Kgs)	995 Kg
Gross Vehicle Weight (GVW)	1595 Kg
Body Option	Hatchback
Mileage (Diesel Fuel)	18Kmpl

Fig.2:

Components of Steering Knuckle Where,
- Suspension Mounting Upper Arm/Strut Mount
- Tie Rod Mounting / Steering Arm
- Lower Ball Joint /Suspension Mounting Lower Arm
- Ball Bearing Location / Stub Hole
- Brake Caliper Mounting

Table 2: Total Force System acting on the Steering Knuckle Body

No.	Parameter	Notation	Design Value	Ultimate Value
1	Upper Arm	P1	6000 N	15000 N
2	Steering Arm	P2	50 N	125 N
3	Lower Arm	P3	6000 N	15000 N
4	Brake Calliper Mounting	P4	510000 N.mm	1275000 N.mm
5	Stub Hole	P5	510000 N.mm	1275000 N.mm
6	Knuckle Hub and Body	P6	11800 N	29500 N

Calculation
The Knuckle Belongs to Indica V2 vehicle, whose curb and gross masses are 995 and 1595 kg, respectively. To ensure design safety, the gross mass of the vehicle was considered to be 1600 kg . Hence, mass on single wheel is 1600/4,

m = 400 Kg.

The Suspension mounting arm or the upper arm is subjected to the lateral force (P1) acting on it, which is given as, P1 = 1.5 x m x g

P1 = 1.5 x 400 x 9.81 = 5886 N

Hence Lateral Force (P1) acting on the upper arm is 6000 N. (Safety)
The Steering force, P2 = 1.5 x m1 x 9.81 (Where m1 = 3Kg = Human Force for Steering)

P2 = 44.14N
Hence, Steering force (P2), can be given as 50N (Safety)
The Lower Arm is subjected to the same force as that of the upper arm. Hence , the force acting on the lower arm (P3) can be considered as 6000N.
Stub hole is subjected to the braking torque, which can be given as,
Braking Torque (P4) = Braking force x Perpendicular Distance

The perpendicular distance is the C.D of Steering and Point of Application, that is, 85 mm.

Hence, Braking Torque = P1 x 85 = 6000 x 85

Hence, the Braking Toque (P4) can be given as 510000 N.mm
The Brake Caliper Mounting was subjected to the same loading as the Stub Hole.
Hence, the Braking Toque (P5) is similar as that of can be given as 510000 N.mm
The total Force Acting on Knuckle Hub is also the force acting on the body of the Knuckle Joint. This force is due to the combined effect of the forces and torque acting on the sections of the joint as well as the weight applied to the joint.
The total force acting on the joint can be divided by the X, Y, and Z axes, where the Force in X, Y, Z axes is 3 × m × g = 11772 N.

Hence Force acting on Knuckle Body (P6) can be determined as 11800 N (Safety)

Modeling and Analysis
In this study, The Joint was first modelled in Creo software version 2.0. The Creo file was further saved in IGES (The Initial Graphics Exchange Specification) format, which enabled the export of the model to another software called Ansys. FEA was performed using Ansys 19.0. The material properties and boundary conditions were defined to accurately simulate the real-life operating scenarios. Mesh generation was performed to discretize the model, ensuring sufficient element quality for precise results. Finally, a static structural analysis was conducted to evaluate the stress distribution and deformation under applied loads.

Analysis of Steering Knuckle Joint which is made of spheroidal Cast Iron (FG350)
The Knuckle body is selected for case study when Static loading (P6) acting on Knuckle Hub and Body

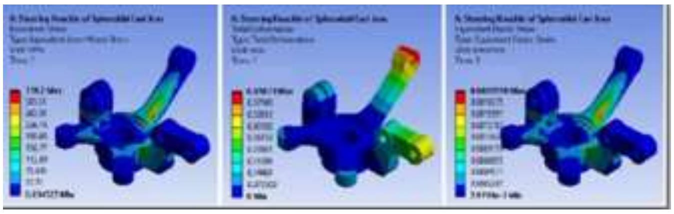

Fig.3: FEA Results for Static Loading applied on Knuckle Hub and Body

The loading was generated by the weights of the wheel and wheel rim components. In the figure above, the first image illustrates the stress that develops, the second image depicts the deformation within the section, and the third image shows the strain that occurs as a result of the stress and deformation when the section is subjected to static loading.

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Analysis of Steering Knuckle Joint which is made of Al2014 -T6

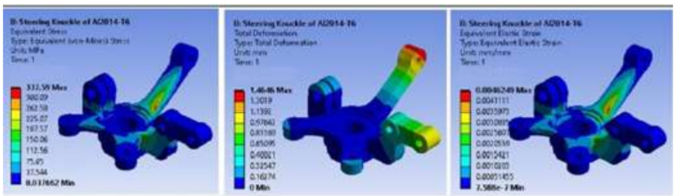


Fig.4: FEA Analysis for Static Loading on Knuckle Body

Analysis of Steering Knuckle Joint which is made of Al6082

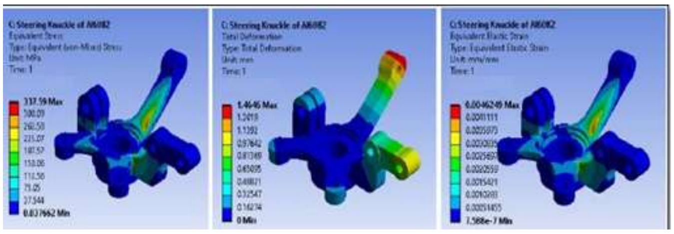


Fig. 5: FEA Analysis for Static Loading on Knuckle Body

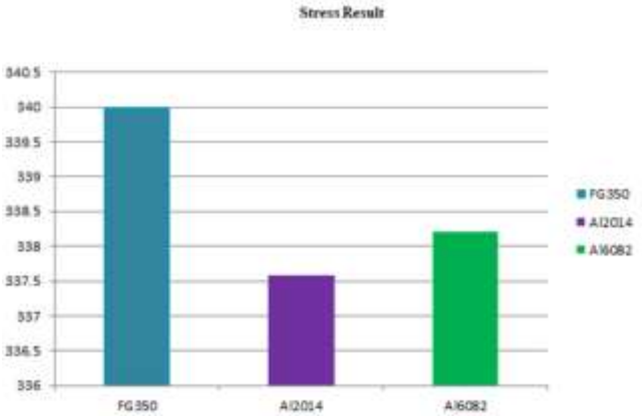
Table.3: FEA results of Steering Knuckle Joint For Different Materials

Material	Stress (N/mm^2)	Deformation (mm)	Strain
Spheroidal Cast Iron	340	0.66	0.0021
Al2014	337.59	1.47	0.0047
Al6082	338.21	1.51	0.0051

Results and Discussion

In the static analysis, the FEA results are shown in the graph below:

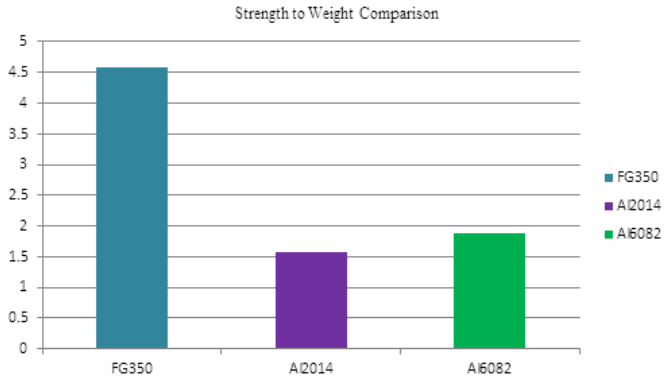
FE Stress Results for Steering Knuckle Joint



Graph.1: FE Stress Result For Steering Knuckle Joint

From Graph 1, the equivalent stress produced in the Steering Knuckle Joint for Spheroidal cast iron(FG350) is 340 N/mm2, the Stress in Al2014 Steering knuckle joint is 337.59 N/mm2, and in the case of Al6082, it is 338.21 N/mm2. . According to the stress results, the stress produced in Al2014 was less than that produced in the spheroidal cast iron. Therefore, Al2014 can be used as an alternative material for cast iron to manufacture steering knuckle joints.

Strength-to-weight comparison results:



Graph.2: Strength to Weight comparison Result for Steering Knuckle Joint

From Graph 2, the use of FG-350 Material weighs the component for 4.58 kg, whereas the use of Al2014 weighs up to 1.58 kg, and the use of Al6082 weighs up to 1.89 kg. Hence, the difference in the weight reduction for Al2014 can be obtained up to 3 kg. Hence we can use Al2014 as an alternative material for spheroidal cast iron.

III. CONCLUSION

Thus, from Table 3, it is clear that Al2014 provides optimized results, that is, less stress and weight. The standard yield strength of Al2014 is 414 N/mm2, and the analytical yield strength value is 337.59 N/mm2, which is less than the value of the standard yield strength. Therefore, the design is safe.

This study shows that the weight of the steering knuckle joint can be reduced without losing strength by replacing the current material, Spheroidal Cast Iron (FG350), with aluminum alloys such as Al2014.

The weight reduction of the steering knuckle component was found to be 65% compared to the cast iron currently used. The experimental results also matched the computer simulations, confirming that Al2014 is a good choice for manufacturing steering knuckles in vehicles.

Future Scope

The design of the steering knuckle joint can be enhanced by utilizing software tools that eliminate unnecessary material while maintaining strength, a process known as topology optimization, to make the component lighter. Exploring other lightweight and durable materials, such as fiber-reinforced composites or hybrid materials, could reveal alternatives that outperform aluminum alloys. Future research could involve fatigue and vibration testing to assess the performance of the steering knuckle under repeated stress and vibrations, ensuring its long-term durability. Additionally, crash tests can be conducted in future studies to evaluate the behavior of the steering knuckle during collisions. Further investigations should focus on the cost savings and environmental benefits of using lighter or alternative materials. Testing the steering knuckle on actual vehicles under various road conditions could validate the simulation results and enhance safety.

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