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Optimization, Design and Analysis of Steering Knuckle Component tailored for Nigerian Roads

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Abstract

The steering knuckle component is a valuable auto part that connects the multi-axial loads and fatigue stresses of the wheel hub, suspension and steering systems. Poor road conditions in Nigeria such as potholes and non-even surfaces among other factors coupled with overloading and poor maintenance of the roads contribute to the faster wear of the components, hence necessitating special design to increase durability and reliability. This study is dedicated to the design and analysis of a steering knuckle that is optimized for the Nigerian roads, which is in line with SDG 9 industry and infrastructure innovation. A 3D model was created in SolidWorks and was based on a Toyota Corolla of 2006, with the features of the suspension mount, tie-rod arm, and brake caliper mount. In ANSYS Workbench, a Finite Element Analysis (FEA) was utilized to check the performance under dynamic loads that comprise of the axial, inertia, and bending forces with a weight of 1250 kg and a dynamic factor of 2.0 to test it under harsh conditions. They were compared with two materials, which were ductile cast iron and aluminium alloy 6061. The findings revealed that ductile cast iron had reduced deformation (0.012 mm), stress (185 MPa), and better factor of safety (FOS) of 1.729, which would be better when subjected to rugged conditions. The streamlined design can be used to guide the indigenous engineers in their efforts to encourage lightweight but strong parts to enhance the safety and lifespan of the cars on the Nigerian roads.

Keywords
Steering Knuckle, Nigerian roads, Finite Element Analysis (FEA), Ductile Cast Iron, Von Mises Stress.

1. Introduction

The steering knuckle is a structural center, that combines the wheel hub, the suspension arm, and steering tie rod. It supports multi-axial loads, vertical loads due to mass of the vehicle, side loads due to manoeuvre and repetitive patterns of stress due to impact on the road.

1.1 Objectives

The objective is to find out whether the geometry and material selection of the steering knuckle is structurally feasible to apply into the use in the Nigerian vehicles. It is hoped that the outcomes would be used as a guide by local design engineers and researchers looking into enhancing the life cycle and performance of the automotive components when subjected to such environments.

2. Literature Review

Steering Knuckles are vulnerable to fatigue failure, and the design is of utmost importance, (Gillespie 2021). The steering knuckle is useful in changing the straight-line movement of the tie rod into the rotating movement of the stub axle (Kumar and Krishna 2020). Its significant structural parts comprise: as illustrated in Figure1:

1. Upper suspension or strut mounting point
2. Steering arm or tie rod connection
3. Lower suspension mounting or ball joint connection
4. Stub axle bore or ball bearing housing
5. Brake calliper attachment point

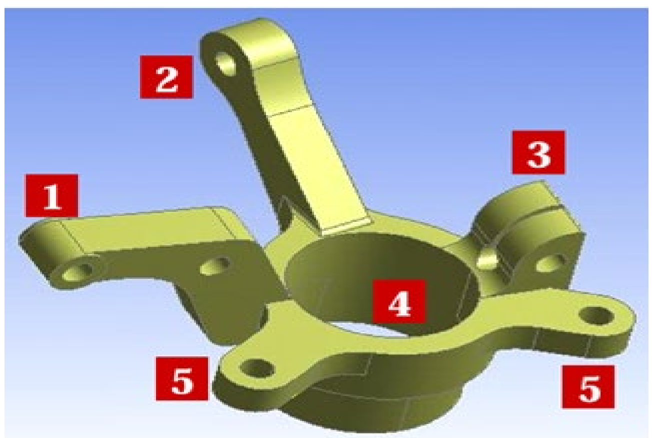

Figure 1. Components of a Steering Knuckle. (Yadav et al 2016)

In most developed nations where the road infrastructure is well established, steering knuckles are developed and optimized in an ideal situation like undulated surface, uniform vehicle weight, and maintenance characteristics. This is however not so with the developing countries like Nigeria where such components are exposed to harsh conditions. The steering knuckle is an instrument of significant value to the suspension and steering mechanism of a vehicle, connecting other parts through which the loads and the movement are transferred during the working process. Recent research has been dedicated towards the enhancement of its ratio of strength-to-weight as well as durability at affordable production cost. Additive manufacturing and topology optimisation have worked well to produce lighter structures without reducing stiffness and safety (Akilan and Reddy 2024). Also of interest is the reinforced aluminium composites that offer the benefit of having low weight and high strength particularly in the case of electric and compact cars, (Santana et al 2024). As indicated by Akuchie (2024), more than 60% of the Nigeria roads are in a poor condition and they are filled with numerous potholes and rough surfaces which supply high-impact dynamic loading to the suspension parts. Figure 2 shows the pathetic condition of the Nigerian roads.

Figure 2. Bad state of Nigerian roads

To add to this problem, there is the tendency to overload and the type of maintenance that is predominantly corrective as is used by drivers hence hastens the wear of steering parts (Ammawal and Liu 2023). The high prices and short supply of standard components compound it even more and the drivers are left with the only choice of either using the parts in their worn condition or using the substandard parts. This has posed a dire need of components that will not only be durable but should be reliable enough to work well in the Nigerian roads.

A steering knuckle with a smaller weight also improves the performance of the vehicle because the car will reduce vibration due to the reduced inertia. As a result, the steering knuckle should be very powerful, stiff, and need to be as light as possible to successfully transmit the driving force between the tie rod and the stub axle. The steering knuckle is subjected to compressive loads and tensile loads during steering or maneuvering in automobiles and torsional loads because of wheel rotation. Steering knuckle is one of the crucial components that pass all forces that are created at the tire to the chassis via the suspension system. In Nigeria, where cars often have to pass over unpaved roads and potholes, the contribution of the knuckle to maintaining stability is increased, and it will require a focus on durability and carry capacity.

The design of modern steering knuckle takes advantage of computer-aided design (CAD) software like SolidWorks and CATIA with a stress and fatigue analysis performed by the use of finite element analysis (FEA). Indicatively, mass reduction of up to 42.7 using topology optimisation and structural integrity under controlled loads has been achieved (Vijayarangan 2022). Equally, analysis of fatigue using genetic algorithm has enhanced component life during cyclic loading (Babu et al 2014). The methodologies however tend to make ideal assumptions such as smooth roads and the standard weights of the vehicles which do not represent the reality of doing business in Nigeria.

Precision of manufacturing has remained a significant issue, because the rigidity of fixtures during machining may have implications on the end performance of the component (Zhu et al 2017). The practical use of topology optimisation, in the case of racing and student competition vehicles, has proven advantageous, with the reduction of mass and enhanced handling properties being achieved. New designs have also improved on the environmental profile through sustainable production techniques, which include investment casting, recyclable material use, etc.

The proposed study is aimed at designing and simulating an automotive steering knuckle that can be used in the Nigerian roads, which can help to advance SDG 9 (Industry, Innovation and Infrastructure). To model the component in 3D SolidWorks is used, and the FEA packages like Ansys Workbench are used to analyse the knuckle at load conditions. The von Mises stress, total deformation, and safety factor (FOS) are some of the key performance indicators.

3. Methods

This study consists of two parts. Part one entails the development of the 3D model of the knuckle with the information that was captured using a 2006 Toyota Corolla steering knuckle, and it was developed using SolidWorks. The second section will be finite element analysis using ansys workbench simulation software. The process followed is depicted in figure 3;

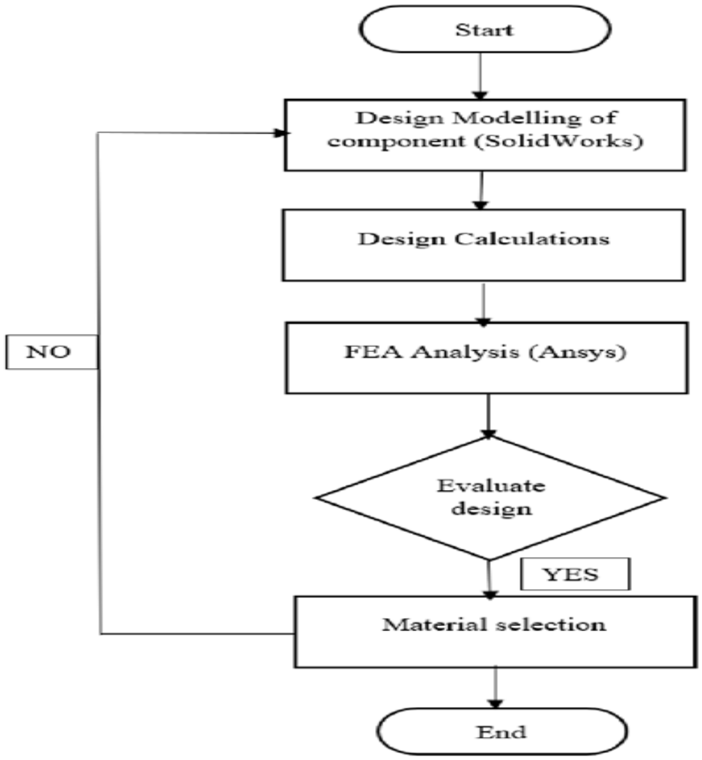

Figure 3. Flowchart illustrating the process followed in the methodology

3.1 Design Modelling: Steering knuckle design

SolidWorks was used to build the component by sketch, boss extrusive of the component, revolves, and cut operations with the accurate depiction of the complex geometries including fillets, holes, and cylindrical joints. The sketches were highly parameterized to control geometry relations and dimensions in a complete way during the model development. There was also the use of reference planes and symmetry tools to maintain consistency in designing and to save on the time spent modelling. The design tree structure of SolidWorks was also helpful as it enabled effective changes to be made and monitored on design changes and this was also applicable during the iteration stage. The last model was then produced to produce detailed orthographic and isometric views with complete annotations as shown in Figure 4 and Figure 5 respectively. These drawings form the basis of the further analysis and manufacturing planning.

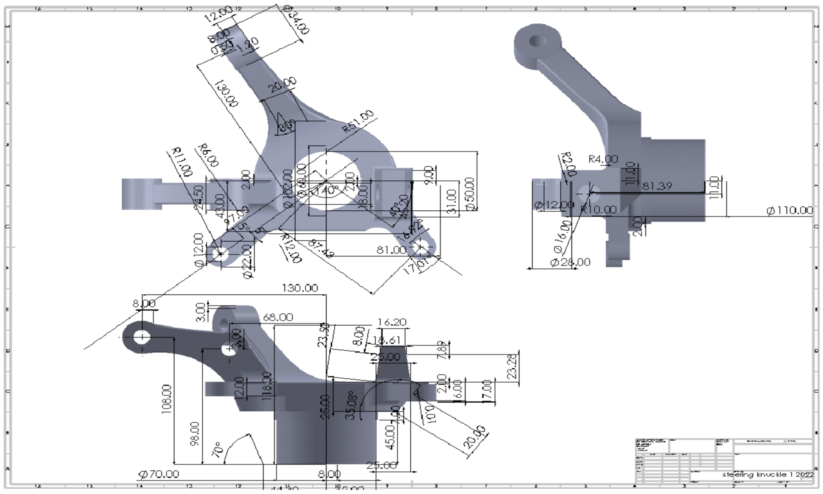

Figure 4. Image showing orthographic 3D model representation

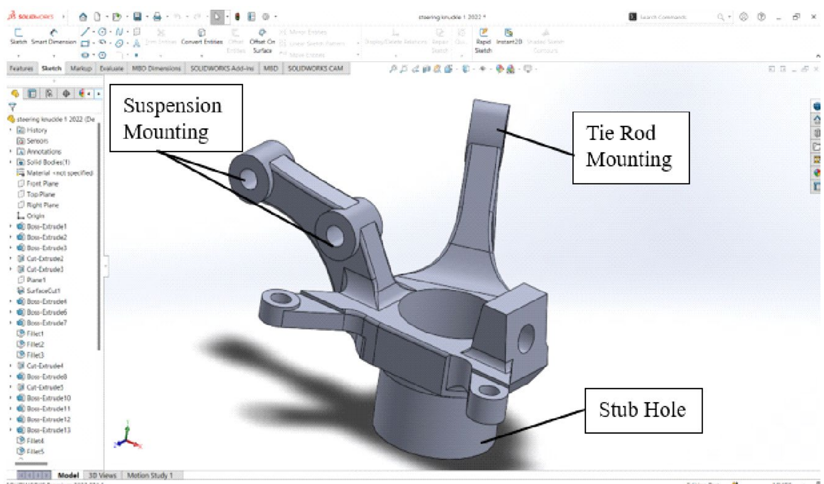

Figure 5. Image showing the Isometric view of the 3D model

3.2 Design Calculations

3.2.1 Calculation of Load

Steering knuckle loads vary with the weight of a vehicle, the roads and the dynamics of driving a vehicle. In this design itself, the weight of the vehicle was taken to be 1250 kg which is common with a mid-size car in Nigeria. In addition to this, there is the additional dynamic loading due to potholes and rough surfaces. The load is placed on four wheels and the dynamic factor is more 2.0 to indicate worse conditions on the roads in Nigeria.

A. Axial Loads

Axial loads involve tensile and compressive forces as a result of steering and suspension loads that are escalated by the irregularities of the road. The computations of the stresses are:

i. Tensile Load (P_t) = Tensile Stress × Area (1)

ii. Compressive Load (P_c) = Compressive Stress × Area (2)

Using a cross-sectional area (A) of 200 mm² at critical points (e.g., tie rod mounting), and using a dynamic factor of 2.0:

- Tensile stress (σ_t) = 100 MPa (estimated based on material yield strength and safety factor).
- $P_t = 100 \times 10^6$ Pa $\times 200 \times 10^{-6}$ m² = 20,000 N.

Compressive load is assumed equal in magnitude under alternating conditions: P_c = 20,000 N.

B. Inertia Load

Inertia load results from moving parts, amplified by road unevenness [6]. The formula is:

$F_a = \omega^2 R [\cos\theta + (\theta/L)\cos(2\theta)]$ (3)

Where:

ω = 50 rad/s (wheel speed ~60 km/h, typical in Nigeria).
R = 0.3 m (wheel radius).
θ = 30° (steering angle).
L = 0.5 m (knuckle arm length).

$F_a = (50)^2 \times 0.3 [\cos(30°) + (30/0.5)\cos(60°)]$
$F_a = 750 [0.866 + 60 \times 0.5] = 750 \times 31.166 = 23{,}149.5$ N
This value is high due to dynamic effects from rough roads, consistent with Nigerian conditions.

C. Bending Load

Bending load arises from vehicle weight and road impacts and tends to bring about the outward bending of the steering knuckle away from its normal position:

$Fb = (\rho\ At\ L \sin(\theta + \varphi)) / 2$ (4)

Where:
- ρ = 7.1 g/cm³ (density of ductile cast iron).
- A_t = 200 mm² = 0.0002 m² (cross-sectional area).
- L = 0.5 m (knuckle arm length).
- $\theta + \varphi$ = 45° (combined angle).

F_b = (7100 kg/m³ × 0.0002 m² × 0.5 m × sin (45°)) / 2
F_b = (7100 × 0.0002 × 0.5 × 0.707) / 2 = 0.251 N
With a dynamic factor of 2.0 for road impacts:
F_b = 0.251 × 2 × 9.8 = 4.92 N

3.2.2 Mathematical Calculation of Stresses

A. Stress (Axial Loads)

$\sigma = P / A$ (5)
$\sigma_t = 20{,}000 / (200 \times 10^{-6}) = 100$ MPa
σ_c = 100 MPa (compressive)

B. Stress (Inertia Bending Force)

Bending moment (M) at x = 0.2 m from the small end:

$M = (x/a) [1 - (x^2/L^2)] \times Fa$ (6)

Where a = 0.3 m:
$M = (0.2/0.3) [1 - (0.2^2/0.5^2)] \times 23{,}149.5$
$M = 0.667 [1 - 0.16] \times 23{,}149.5 = 0.667 \times 0.84 \times 23{,}149.5 = 12{,}970.2$ Nm
Section modulus (Z) for a rectangular section (t = 0.02 m):
$I = 419 \times (0.02)^4 = 6.704 \times 10^{-5}$ m⁴
$Z = I / (0.5 \times t) = (6.704 \times 10^{-5}) / 0.01 = 6.704 \times 10^{-3}$ m³
$\sigma_b = M / Z = 12{,}970.2 / (6.704 \times 10^{-3}) = 1.93$ MPa (7)

The bending stress of 1.93 MPa derived from the inertia load (F_a = 23,149.5 N), the section modulus Z = 6.704×10^{-3} m³, and bending moment M = 12,970.2 Nm is far below the yield strengths of ductile cast iron (344MPa) and aluminum alloy 6061 (240MPa). While this result confirms that the bending load component alone does not constitute a structural risk, it represents only one load case acting on an isolated cross-section under simplified, statically resolved assumptions.

In the actual operating environment of Nigerian roads, the knuckle simultaneously sustains axial loads of 100 MPa, inertia bending forces of 23,149.5 N, braking loads of 6,131.25 N, and lateral hub forces exceeding 12,262.5 N across a complex 3D geometry featuring fillets, mounting holes, stub axle bores, and caliper attachment points none of which are fully captured by hand calculations. Additionally, the dynamic factor of 2.0 applied here addresses peak transient loading, but does not account for fatigue degradation under repeated pothole impact cycles over the vehicle's service life. FEA in ANSYS Workbench is therefore employed not because the hand calculations predict imminent failure, but precisely because the stress state is multidimensional, the geometry is irregular, and local stress concentrations at critical features, which are where real-world fatigue cracks initiate, are only resolvable through numerical simulation. This approach is consistent with established practice in steering knuckle analysis (Babu et al., 2014; Kumar and Krishna, 2020) and is essential for a component whose failure mode in Nigerian conditions is typically fatigue-driven rather than single-event static overload.

3.2.3 Loading Condition on Knuckle

Vehicle weight = 1250 kg, weight per wheel = 312.5 kg. Loading conditions are shown in Table 1.

Table 1. Loading Values of the Steering knuckle

Loading Parameters	Magnitude
Braking Load	6131.25 N
Side Load	12262.5 N
Steering Load	3065.63 N
Knuckle hub (X-direction force)	12262.5 N
Knuckle hub (Y-direction force)	12262.5 N
Knuckle hub (Z-direction force)	3065.63 N

3.3 Material Selection

The steering knuckles are typically made of aluminium, mild steel, or cast iron which have been selected with regard to the mechanical strength, weight, and durability. In the case of the steering knuckle design, the two materials that are viewed are ductile cast iron and the aluminium alloy (6061 Aluminium). These materials are chosen according to their mechanical properties, weight and aptitude to the rough conditions of the Nigerian roads which are characterised by potholes, rough surfaces and high dynamic loads.

Table 2 and Table 3 present their properties. The performance of both materials under the calculated loads will be compared with the help of ANSYS Workbench so that the most appropriate material could be selected.
The properties of Ductile cast iron are stated in Table 2.

Table 2a. Physical properties of Ductile cast iron

Physical properties	Measurement	Unit
Material Density	7.1	g/cm^3

Table 2b. Mechanical properties of Ductile cast iron

Mechanical properties	Measurement	Unit
Tensile Strength, Ultimate	548	MPa
Tensile Strength, Yield	344	MPa
Young’s Modulus	170	GPa
Poisson’s Ratio	0.275	-

The properties of Aluminium alloy (6061 Aluminium) are stated in Table 3.

Table 3a. Physical attributes of Aluminium alloy

Physical Properties	Value	Unit
Density	2.7	g/cm^3

Table 3b. Mechanical attributes of Aluminium alloy

Mechanical attributes	measurement	Unit
Maximum tensile strength	310	MPa
Yield Tensile Strength	240	MPa
Young’s Modulus	69	GPa
Poisson’s Ratio	0.33	-

Both the materials will be analyzed by FEA with ANSYS Workbench to determine deformation, stress, and safety margins under the specified load conditions (i.e., braking force of 6131.25 N, resultant force of 17364.6N). The analysis will see which material is more balanced in terms of durability, weight and performance of the steering knuckle in the context of Nigeria.

2.4 Meshing of the Component

Once the steering knuckle design is finished in SolidWorks it is meshed in ANSYS Workbench. This meshing is necessary since it gives the basis on which the Finite Element Analysis is carried out. Quality mesh ensures that the simulation is a true model of the physical behaviour of the model. To conduct a fine analysis, meshing of the produced 3-D model into a specified number of divisions or components is done. The number of nodes and elements is presented in Table 4.

Table 4. Number of nodes and elements of the 3D Model

Nodes	27050
Elements	14622

On the constructed model, which is seen in Figure 6, an automatic mesh is built.

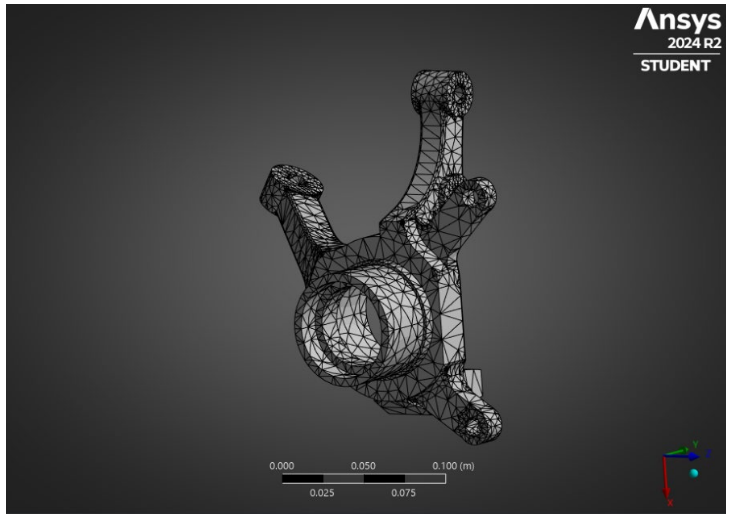

Figure 6. Generated Mesh using ANSYS

4. Data Collection

Data for this study were collected through a combination of reverse engineering and analytical calculations tailored to Nigerian road conditions. Geometric dimensions of the steering knuckle were obtained by direct measurement of an original component from a 2006 Toyota Corolla using digital calipers and precision tools. Key features including suspension mount points, tie-rod arm length, stub axle bore, and brake caliper attachment, were recorded to create an accurate 3D model in SolidWorks.

Loading parameters were derived from vehicle dynamics principles: a 1250 kg vehicle mass (312.5 kg per wheel) was multiplied by a dynamic factor of 2.0 to simulate pothole impacts and rough surfaces. Braking, side, and steering loads were calculated using standard formulas. Material properties for ductile cast iron and aluminium alloy 6061 were sourced from established engineering databases and literature. This process ensured all inputs for the ANSYS simulation realistically reflected local operating conditions.

5. Results and Discussion

The steering knuckle of both materials (i.e., Aluminium alloy 6061 and ductile cast iron) are subjected to structural analysis in ANSYS Workbench such that they are first fixed in place with the tie rod and suspension mount and then a load is applied to the stub hole to ascertain total deformation (Table 5), von Mises stress and factor of safety (FOS).

5.1 Numerical Results

Based on the simulation findings, it is clear that the structural response of the steering knuckle is affected by the choice of material and this is demonstrated in Figure 10. The total deformation of aluminium alloy 6061 was higher than that of ductile cast iron, which means that it is less stiff under a load. The same was true of von Mises stress distributions. The comparison in finite element analysis of aluminium alloys like A356.0 -T6 and grey cast iron suggests that substitution of heavier metals can be done by aluminium without compromising the safety margins of the materials used (Kolesynk et al 2024). The optimization of steering axle parameters and the knowledge of forces that influence the steering resistance also help to enhance the efficiency and handling comfort of the vehicle to the driver (Hassan et al 2023).

Table 5. Analysis of steering knuckle

Parameter	Ductile Cast Iron	Aluminium 6061
Total Deformation	0.0003652m	0.00089566m

Von-Mises stress distribution	142.99Mpa	144.37Mpa
Minimum FOS	1.7293	0.91744

Metal-matrix composites have demonstrated good performances in enhancing fatigue life and reliability in general during the repeated stress conditions (Almonti et al 2025). The research on dynamic performance optimisation shows that the steering response and stability of the vehicle can be improved by refining geometry and vibration properties of the vehicle (Kashyzadech 2023). Composites of carbon-fibre-reinforced polymers with aluminium have also been found to give superior strong and robust designs and decreased overall mass (Zhang 2025), (Surjeetsingh 2024), (Ikpe et al 2021).

Above all, the aspect of safety values is a clear distinction between the two materials. Ductile cast iron gave a minimum FOS of 1.7293, and the Aluminium 6061 gave a lower value of 0.91744, which is less than the standard value of 1.5 that is deemed structurally safe. This shows that, ductile cast iron is a safer and more reliable alternative to use in rough environment like the Nigerian roads, under the same loading conditions.

5.2 Graphical Results

The analysis generated the results that are depicted in Figures 7,8, 9 and Table 5.

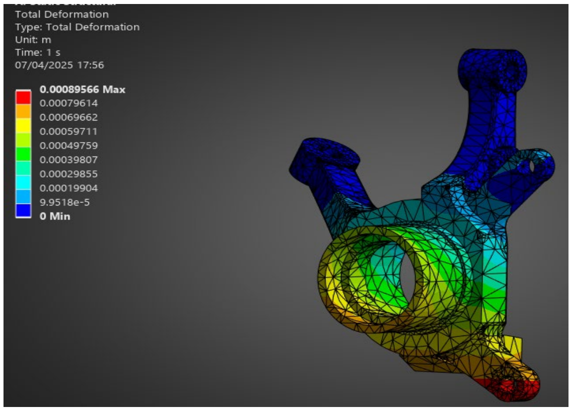

Figure 7a. Total deformation of Aluminium alloy 6061

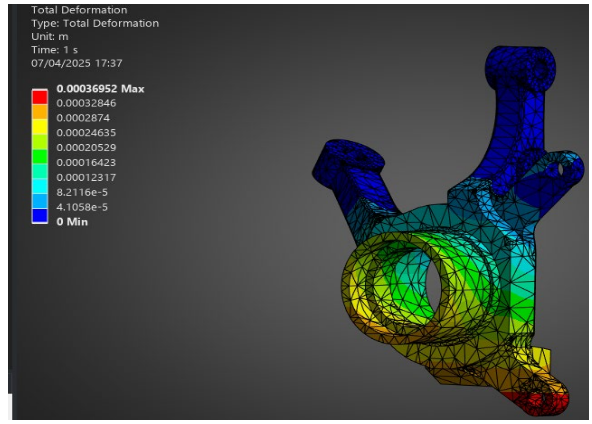

Figure 7b. Total deformation of Ductile Cast Iron

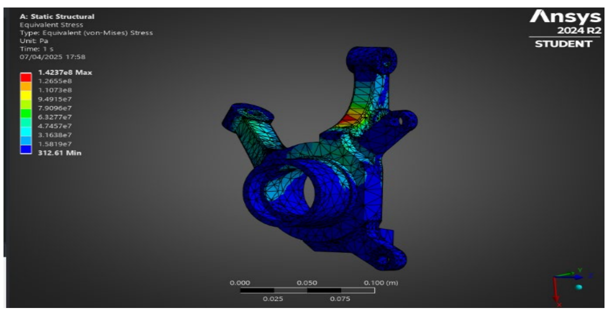

Figure 8a. Von Mises stress of Aluminium alloy 6061

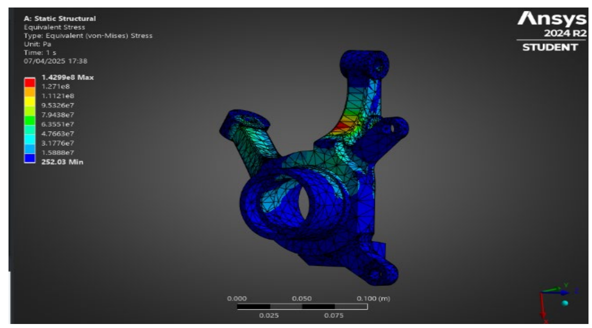

Figure 8b. Von Mises stress of Ductile Cast Iron

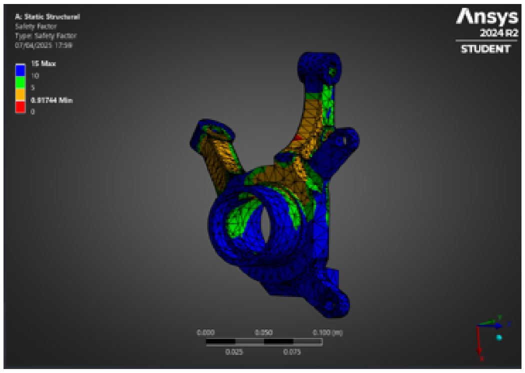

Figure 9a: Safety Factor for Aluminium alloy 6061

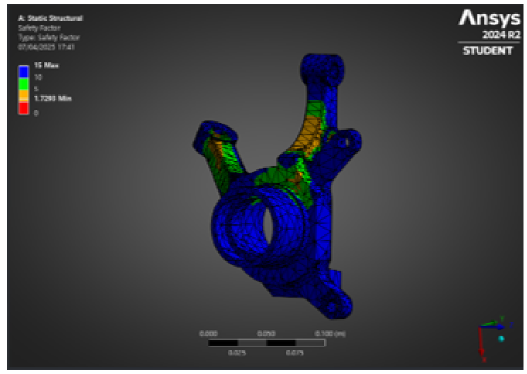

Figure 9b: Safety Factor for Ductile Cast Iron

Figure 10a: Graph of Total deformation for the two materials

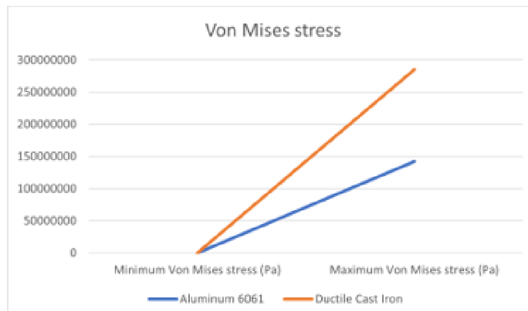

Figure 10b: Graph of Von Mises stress for the two materials

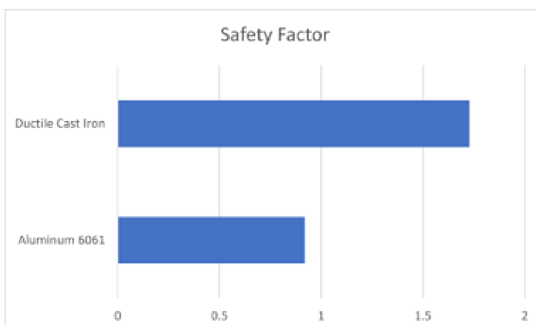

Figure 10c: Graph of Safety Factor for the two materials

6. Conclusion

The study sought to develop a steering knuckle that would fit the Nigerian road conditions based on engineering design principles. The steering knuckle was simulated and designed with the help of computer-aided design (CAD) and finite element analysis (FEA) and loaded dynamically with loads that are representative of the problematic road conditions in Nigeria. The analytical findings showed that there were reasonable deformations, stress, and factor of safety with good values, which showed that the structure could support realistic loads, such as pothole strikes, overweight vehicles, and steering forces. This study has also shown that ductile cast iron is a safer and more reliable alternative to use in rough environment like the Nigerian roads than Alumiium 6061, under the same loading conditions.

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Biographies

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Awodoyin Emmanuel Tomisin is a first-class graduate from the Department of Mechanical Engineering, Bells University of Technology, Ota, Nigeria. He earned B.Eng. in Mechanical Engineering. A dedicated learner with hands-on industry experience, Emmanuel completed internships at TotalEnergies and Shell Energy. At Total Energies he supported field operations and maintenance, mastering production equipment, P&ID development with AutoCAD, and HSE compliance. At Shell he contributed to gas infrastructure projects and LNG process optimization, sharpening his project-delivery and safety skills. As team lead, he spearheaded an international Al project tackling food waste in supply chains with Manchester Metropolitan University, and directed the design and simulation of durable automotive spare parts tailored for Nigerian roads using SolidWorks and Ansys. Recognized as the best graduating Mechanical Engineering student with the Prof. Bart O. Nnaji Award, the College's Award for Academic Excellence, and the Nigerian Society of Engineers Award, he holds certifications in Oil & Gas Operations, HSE Engineering, Piping Design, Data Analysis, and Al. His interests include Design and Manufacturing, Simulation and Oil & Gas Production.