Analysis of Knuckle Joint for Structural Steel, Aluminium Alloy, And Titanium Alloy

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***Abstract*—The goal of this research is to investigate and determine the stresses in a knuckle joint using steady state analysis, with the objective of identifying the optimal material for the project. Three different materials, namely structural steel, aluminium alloy, and titanium alloy are analyzed for the knuckle joint. The study focuses on a knuckle joint designed for an applied force of 25 KN. Finite Element Analysis (FEA) results for tensile loading are compared and validated with total deformation. The findings indicate that the knuckle joint made of titanium alloy exhibits the lowest stresses, while the knuckle joint made of structural steel is capable of sustaining the highest tensile load without failure.**

Keywords- **Knuckle Joint, FEM, stress analysis, Titanium alloy, aluminium alloy, structural steel.**

1. INTRODUCTION

The knuckle joint is a mechanical joint used in various applications, known for its simplicity and effectiveness in transmitting motion and force between two rotating elements. It consists of two or more cylindrical or spherical components that are interconnected, allowing them to rotate relative to each other. The knuckle joint is commonly used in machinery, vehicles, and mechanical systems where flexibility and mobility are required, such as in steering systems, suspension systems, and linkages. One of the key advantages of the knuckle joint is its ability to accommodate angular misalignments, providing a flexible and reliable connection between components that are not perfectly aligned. This makes it ideal for applications where there may be variations in motion or force, or where there may be uneven loading. The knuckle joint is a versatile and widely used mechanical joint that continues to play a crucial role in many industrial and mechanical applications.

The knuckle joint is typically designed to withstand high loads and provide smooth rotational motion, making it suitable for heavy-duty applications. It can be made from various materials, such as steel, aluminum, or bronze, depending on the specific requirements of the application. The design of the knuckle joint is often optimized to ensure efficient power transmission and minimal wear, with considerations given to factors such as joint clearance, lubrication, and load distribution. Additionally, the knuckle joint can be customized to meet specific needs, with variations such as single, double, or triple knuckle joints, as well as adjustable or self-aligning options.

One of the notable features of the knuckle joint is its simple yet effective design, which allows for easy assembly, maintenance, and replacement. It can be disassembled and reassembled with relative ease, making it convenient for repairs or modifications. The knuckle joint is also cost-effective compared to other complex mechanical joints, making it a popular choice in many industries.

Despite its advantages, the knuckle joint also has some limitations. It may exhibit some backlash or play due to clearance between the components, which may affect precision applications. Careful consideration of the design, materials, and lubrication can help mitigate this issue. Additionally, in high-speed applications, the knuckle joint may generate vibrations or noise, requiring proper dampening measures.

In conclusion, the knuckle joint is a widely used mechanical joint known for its simplicity, flexibility, and reliability. It provides an efficient means of transmitting motion and force between rotating components, making it suitable for various applications. While it has some limitations, careful design and maintenance can ensure its optimal performance, making it a valuable component in many mechanical systems.

The knuckle joint finds application in a wide range of industries, including automotive, aerospace, marine, and industrial machinery. In automotive systems, it is commonly used in steering linkages, where it enables smooth and controlled motion for vehicle steering. In aerospace applications, the knuckle joint is utilized in control surfaces of aircraft, providing reliable and precise movement. In marine systems, it can be found in ship propulsion systems, ensuring efficient transmission of power between rotating shafts. In industrial machinery, the knuckle joint is used in various mechanisms, such as presses, conveyors, and crushers, where it facilitates motion and force transmission.

Moreover, the knuckle joint can be used in special applications where dynamic movements are required, such as in robotic arms, where it provides flexibility and adaptability to changing orientations. It can also be used in off-road vehicles, where it allows for articulation in suspension systems, ensuring smooth movement on uneven terrains. The versatility of the knuckle joint makes it a valuable component in many mechanical systems, providing reliability, durability, and efficiency.

In addition to its mechanical applications, the knuckle joint has also found its way into other fields, such as prosthetics and orthopedics. It can be used in the design of joint mechanisms for artificial limbs, enabling natural and fluid movements for amputees. In orthopedic devices, the knuckle joint can be utilized in joint implants or external fixators, providing stability and mobility in medical applications.

In conclusion, the knuckle joint is a versatile mechanical joint that is widely used in various industries and applications. Its simple design, reliability, and flexibility make it a popular choice for transmitting motion and force between rotating components. Whether in steering systems, control surfaces, suspension systems, robotics, or medical devices, the knuckle joint plays a vital role in enabling efficient and smooth movements in diverse applications.

The knuckle joint assembly consists of the following major components:

i. Single eye.
ii. Double eye or fork.
iii. Knuckle pin.
iv. Collar
v. Tapper pin

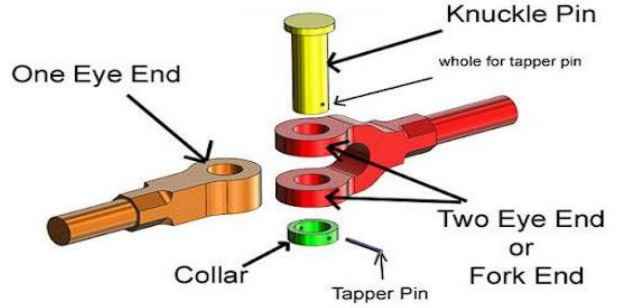


Figure 1 Knuckle Joint

1.1 Aluminum Alloy

Aluminum alloys are widely used in various industries due to their unique properties and advantages. These alloys are formed by adding small amounts of other elements, such as copper, magnesium, manganese, or zinc, to pure aluminum, resulting in improved mechanical, thermal, and electrical properties.

One of the primary advantages of aluminum alloys is their lightweight nature, which makes them ideal for applications where weight reduction is critical, such as in aerospace, automotive, and transportation industries. The low density of aluminum alloys allows for significant weight savings, leading to improved fuel efficiency, increased payload capacity, and reduced overall costs.

Aluminum alloys also possess excellent corrosion resistance, as they naturally form a thin oxide layer on their surface, which protects them from environmental degradation. This makes them suitable for applications where exposure to moisture, chemicals, or harsh environments is common, such as in marine, aerospace, and automotive components.

Moreover, aluminum alloys offer good formability and machinability, allowing for complex shapes and designs. They can be easily extruded, cast, or machined into intricate parts, making them versatile in manufacturing processes. Aluminum alloys also exhibit excellent thermal conductivity and electrical conductivity, making them suitable for heat exchangers, electrical conductors, and other thermal or electrical applications.

However, it's worth noting that aluminum alloys may have lower tensile strength compared to other materials, such as steel, which may limit their use in high-stress or heavy-load applications. Nevertheless, advancements in alloy composition and heat treatment techniques have resulted in high-strength aluminum alloys that can meet demanding requirements in various applications.

In conclusion, aluminum alloys are widely used in many industries due to their lightweight nature, corrosion resistance, good formability, and other desirable properties. They offer numerous advantages in diverse applications, but careful consideration of specific requirements, including load capacity, environmental conditions, and other factors, is necessary to ensure optimal performance.

1.2 Structural Steel

A vehicle with a zero turn makes a sharp turn around a Structural steel is a type of steel that is specifically designed and manufactured for use in construction and civil engineering applications. It is widely used in various structural elements, such as beams, columns, trusses, and frames, due to its high strength, durability, and versatility.

One of the primary advantages of structural steel is its exceptional strength-to-weight ratio. Structural steel is known for its high tensile strength, which allows it to withstand heavy loads and resist deformation under stress. This makes it ideal for supporting large structures and transferring loads safely and efficiently. Moreover, despite its high strength, structural steel is relatively lightweight compared to other construction materials, which can result in cost savings in terms of transportation, installation, and foundation requirements.

Structural steel also offers excellent durability and resistance to environmental factors. It is highly resistant to corrosion, which makes it suitable for outdoor and exposed applications where it may be subjected to moisture, chemicals, or other corrosive substances. This durability ensures a long service life and minimal maintenance requirements, resulting in cost-effective solutions for construction projects.

Furthermore, structural steel is highly versatile and can be fabricated into various shapes and sizes to suit specific design requirements. It can be easily cut, welded, bolted, or formed into complex shapes, allowing for efficient construction and customization. This flexibility in fabrication makes structural steel suitable for a wide range of applications, from simple buildings to complex structures such as bridges, stadiums, and high-rise buildings.

In addition, structural steel is environmentally sustainable as it can be recycled and reused. Steel is one of the most recycled materials globally, and recycling steel reduces the need for raw material extraction, conserves natural resources, and minimizes waste generation. This makes structural steel a sustainable and eco-friendly option for construction projects.

In conclusion, structural steel is a versatile, durable, and high-strength material that is widely used in construction and civil engineering applications. Its exceptional strength-to-weight ratio, durability, versatility, and sustainability make it an ideal choice for a wide range of structural elements in various construction projects.

I.3 Titanium Alloy

Titanium alloys are a group of materials that are known for their exceptional strength, low density, and excellent corrosion resistance. These alloys are formed by adding small amounts of other elements, such as aluminum, vanadium, or molybdenum, to pure titanium, resulting in improved properties for specific applications.

One of the key advantages of titanium alloys is their high strength-to-weight ratio. Titanium is known for its outstanding strength, comparable to that of steel, but with approximately half the density. This makes titanium alloys ideal for applications where weight reduction is crucial, such as in aerospace, automotive, and military industries. The lightweight nature of titanium alloys allows for improved fuel efficiency, increased payload capacity, and enhanced performance in aerospace and other high-performance applications.

Titanium alloys also exhibit excellent corrosion resistance, making them highly suitable for applications in aggressive environments. Titanium has a natural oxide layer on its surface that provides a protective barrier against corrosion, even in harsh conditions involving saltwater, acids, and other corrosive substances. This makes titanium alloys well-suited for marine, chemical, and biomedical applications, where corrosion resistance is critical.

Moreover, titanium alloys offer excellent biocompatibility, making them ideal for medical and dental implants. The biocompatibility of titanium allows it to integrate well with living tissue, reducing the risk of rejection or adverse reactions. Titanium alloys are widely used in orthopedic implants, dental implants, and other medical devices due to their ability to provide long-term, reliable performance in the human body.

Furthermore, titanium alloys have excellent high-temperature strength and resistance to extreme temperatures. They can withstand elevated temperatures without losing their mechanical properties, making them suitable for applications in aerospace, automotive, and industrial settings that involve high temperatures or thermal cycling.

However, titanium alloys can be challenging to machine and fabricate due to their high melting point, low thermal conductivity, and high reactivity with cutting tools. Specialized equipment and techniques are often required for machining and fabrication of titanium alloys, which can add to the production costs.

In conclusion, titanium alloys are a group of materials that offer exceptional strength, low density, excellent corrosion resistance, biocompatibility, and high-temperature performance. They are widely used in aerospace, automotive, medical, and other demanding applications where high performance and reliability are critical. Despite their challenges in machining and fabrication, titanium alloys are valued for their unique combination of properties and their ability to provide innovative solutions in various industries.

2. LITERATURE REVIEW

In this chapter, an overview of the contributions made by various researchers and authors in the field of manufacturing is provided. This includes methods, mathematical modeling, input parameters, and output results.

Somase Anil R discussed how advancements in material science have opened the possibility of using polymers such as Teflon in the manufacturing of knuckle joints. With increasing competition and innovation, it has become necessary to modify existing products or replace outdated ones with new and advanced materials. The knuckle joint was analyzed using different materials including structural steel, stainless steel, aluminum alloy, Teflon, and gray cast iron. The findings revealed that aluminum alloy is the optimal material among the selected options. Finite Element Analysis (FEA) results for tensile loading were validated with tensile testing results obtained from Universal Testing Machine (UTM). It was observed that knuckle joints made of magnesium experienced the least amount of stress, while knuckle joints made of aluminum were able to sustain the maximum tensile load without failure.

Dr. Rohit Rajvaidya suggests considering the use of Teflon in the manufacturing of knuckle joints. The rapid advancement of technology in recent decades has resulted in cost and weight reduction of materials, making modified systems popular in industry and research. This has led to improved safety and reduced accidents. Many industrial systems utilize knuckle joints, which are typically composed of cast iron and stainless steel. Dr. Rajvaidya's work proposes modifying the knuckle joint by replacing cast iron with a composite polymer material. The proposed system offers several advantages, including simplified device manufacturing, increased safety, and environmental friendliness. The analysis of the system demonstrates these aforementioned features. The decision to consider polymers is due to their properties, which are similar to those of metals, with composite polymers offering high flexibility. Recent technological advancements have allowed for reduced stress and strain. ANSYS 13 was used for analyzing the knuckle joint with the modified material under varying loads. Parts made from composite materials are cost-effective to produce and can reduce overall system costs by eliminating secondary operations such as machining, as well as reducing part count compared to metal parts. The stresses developed in the knuckle joint made of Teflon were lower than those developed in steel, although the steel knuckle joint was observed to sustain the maximum tensile load without failure.

Bhokare Kiran have used analytical techniques and computer-aided engineering (CAE) to predict the fatigue behavior of the steering knuckle arm in a sport utility vehicle. Components and structures in automobiles are subjected to cyclic loading, which can result in fatigue

damage over time. The steering knuckle, which is part of the vehicle's steering and suspension systems, experiences time-varying loads during its service life. This study involves analyzing the steering knuckle under the main operating conditions using the Finite Element method. The aim is to determine the fatigue life of the steering knuckle through numerical simulations and analysis.
In their research paper, Prof. Nipun Kumar and his team study different materials used in the manufacturing of knuckle joints. The knuckle joint is subjected to a tensile load of 50 KN, and various materials, including magnesium alloy, aluminum alloy, stainless steel, structural steel, and gray cast iron, are considered. The stresses developed in the knuckle joint made of magnesium alloy are found to be the least at 170.6 MPa, while the maximum stresses are observed in the knuckle joint made of gray cast iron at 176.77 MPa. It is noted that the knuckle joint made of aluminum alloy has the highest factor of safety at 1.641 among the considered materials, making it the most suitable choice for the 50 KN loading condition.

Prof. Swati Datey et.al have explained the joint used in Mahindra Tractors, which is commonly used in rural and urban transportation for agriculture and goods transport due to its cost-effectiveness. The effective design of mechanical devices requires predictive knowledge of their behavior under working conditions, including forces and stresses developed during operation. This project aims to study the stresses on the knuckle joint and improve its performance using CATIA V5 and finite element analysis (FEA). Failure analysis is an important process in engineering disciplines to determine the cause of failures and prevent their recurrence. Fracture may result from multiple failure mechanisms or root causes, and failure analysis helps identify the appropriate root cause. Factors such as varying load on the pin and trailer, as well as sudden impact due to road unevenness, can increase stress and cause pin failure. Based on the study of knuckle joints used in tractor-trailers and analysis of knuckle pin, the following conclusions can be drawn: theoretical calculations and FE analysis yield similar results for a 35 mm diameter at 50 KN load; material properties, such as grey cast iron (ASTM grade 20 (EN-JL 1020), ASTM grade 35 (EN-JL1040), ASTM grade 60 (EN-JL 1070)), stainless steel, and titanium alloy, play a crucial role in stress reduction on the joint, especially the pin; deviations in equivalent stress (von Mises), shear stress, and total deformation occur at the same load and diameter where maximum stresses are observed; increasing the force increases von Mises stress on the pin and can cause bending, but increasing the pin diameter can sustain maximum stress at the same force without bending.

Shankar Majhi and his team discuss the importance of tractor-trailer combinations in agriculture and transportation in both rural and urban areas. A knuckle joint is used to connect the tractor and trailer, consisting of eye forks and a pin. The design of this component is critical for its effective operation. During the operation of the knuckle joint, stresses are always developed in the pin due to the forces acting on it when the vehicle is in motion. These forces can be tensile or compressive, depending on the direction. The team plans to calculate the forces acting on the fork and pin using theoretical and analytical methods, and then study the high stresses in the pin using CATIA V5 and finite element method for analysis.

3. PROBLEM IDENTIFICATION

To recommend the most suitable material for the knuckle joint, taking into consideration cost-effectiveness and durability in order to extend the lifespan of the knuckle joint.

3.1 Need to study

- To determine the optimal material for the knuckle joint among the available options, considering their load-carrying capacity.
- To conduct stress analysis using ANSYS software calculations.
- To enhance the lifespan of the knuckle joint.

3.2 Aim

To identify alternative materials that can reduce the cost and weight of the knuckle joint while improving its lifespan. To conduct a study on various types of materials for this purpose.

4. THEORETICAL CALCULATIONS

For the theoretical calculations we will assume Factor of Safety (F.O.S) as 3 (i.e., F.O.S=3) for all the materials.

4.1 Structural Steel

Young’s Modulus = 20,0000 MPa
Poisson’s ratio = 0.3
Yield strength = 250 MPa

Factor of safety = 3
Permissible stress = Yield strength /F. O. S
= 83.3334 MPa

4.2 Aluminium Alloy

Young's Modulus = 71,000 MPa
Poisson's ratio = 0.3
Yield strength = 280 MPa
Factor of safety = 3
Permissible stress = Yield strength/F. O. S
= 93.3334 MPa

4.3 Titanium Alloy

Young's Modulus = 96,000 MPa
Poisson's ratio = 0.3
Yield strength = 930 MPa
Factor of safety = 3
Permissible stress = Yield strength/F. O. S
= 310 MPa

Table 1: Permissible Stress for Different Materials

Material	Permissible Stress
Structural Steel	83.3334 MPa
Aluminium Alloy	93.3334 MPa
Titanium Alloy	310 MPa

5. DESIGNING AND TOOLS USED

CAD modelling was done in CATIA V5 and for analysis of the designed knuckle joint ANSYS R19.2 was used.

5.1 CAD Modelling

Various components of the knuckle joint were modelled and assembled in CATIA V5 software and .igs file of the assembly was imported in ANSYS

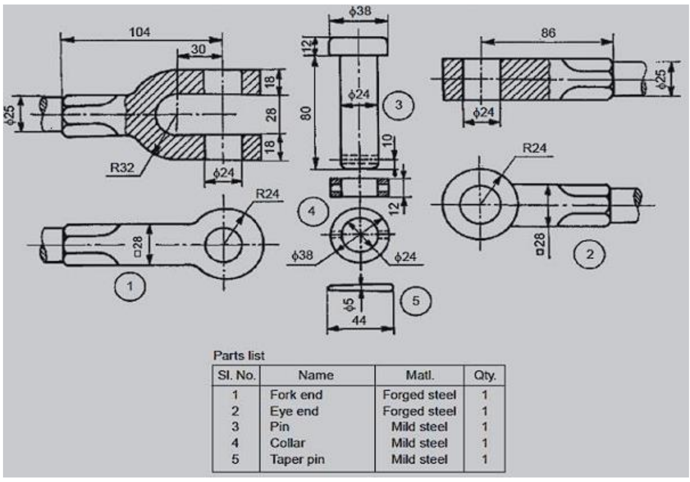


Figure 2 Dimensions of different components of Knuckle Joints

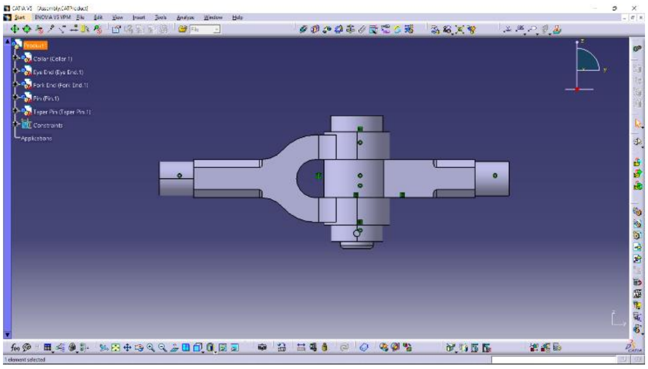


Figure 3 Assembly of Knuckle Joint in CATIA V5

5.2 Analysis

In this study, Ansys R19.2 software was utilized for analyzing natural frequencies and static deflection of a structure. ANSYS Mechanical is a comprehensive finite element (FE) analysis tool that offers a wide range of capabilities for structural analysis, including linear, nonlinear, and dynamic studies. It provides a complete set of element behaviors, material models, and equation solvers for various mechanical design problems. Additionally, Ansys Mechanical offers advanced thermal analysis and thermal-structural, and thermo-electric analysis. With a strong foundation in element and material technology, Ansys structural analysis software offers various advanced modeling methods for different applications. Furthermore, Ansys finite element analysis (FEA) tools provide advanced capabilities for simulating various physics phenomena, such as thermal-stress, electromechanical, structural-acoustics, mass diffusion, and simple thermal-fluid analysis.

5.2.1 Static Analysis

A static structural analysis is used to determine the displacements, stresses, strains, and forces in structures or components caused by loads that do not cause significant inertia and damping effects. It assumes steady loading and response conditions, where the loads and the structure's response change slowly over time. The ANSYS solver can be used to perform a static structural load analysis.

5.2.3 Contact

5.2.3.1 Bounded Contact

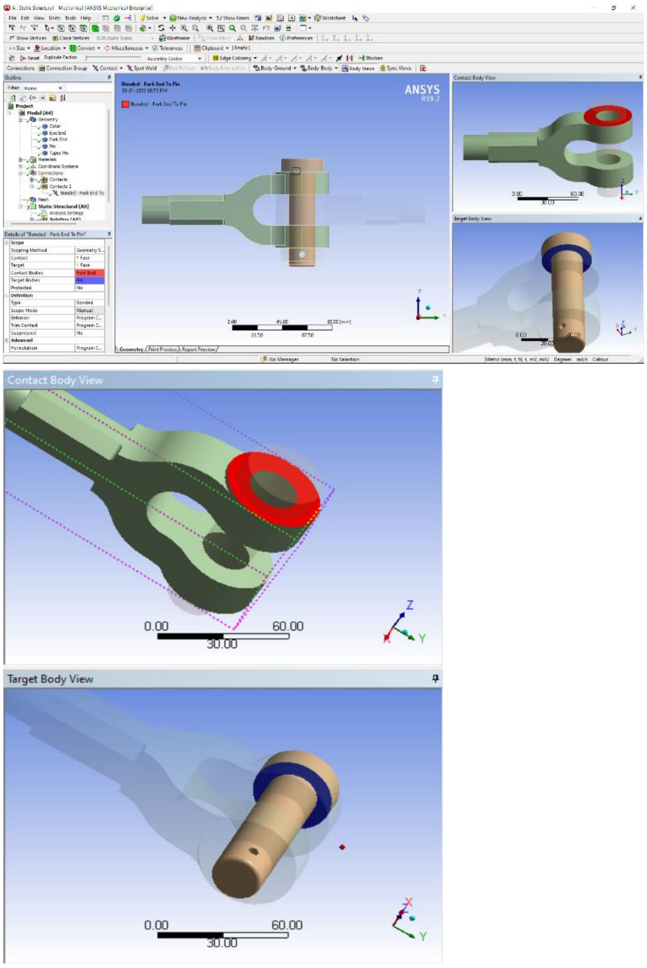
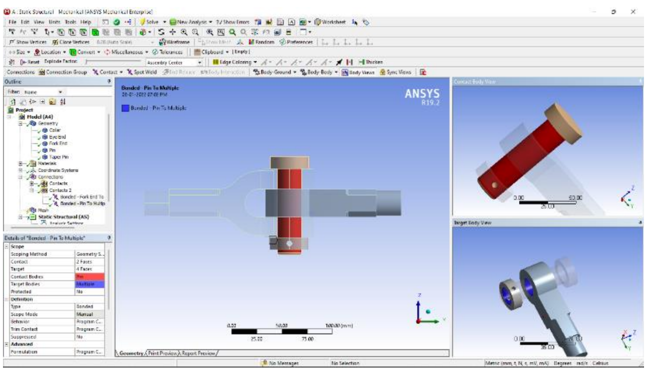


Figure 4 Bounded Contact

5.2.3.2 Frictional Contact



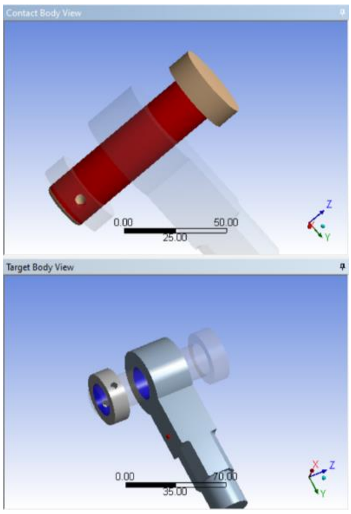


Figure 5 Frictional Contact

5.2.4 Meshing

Meshing is the process of creating a discretized representation of a complex geometry by dividing it into smaller, finite elements. This allows for numerical analysis to be performed on the geometry. Meshing is a fundamental step in finite element analysis (FEA) and computational simulations, as the quality and characteristics of the mesh can greatly impact the accuracy and reliability of the analysis results. Different meshing techniques, such as structured, unstructured, or hybrid meshes, can be used depending on the type of geometry, analysis requirements, and software being used. Proper meshing is critical for obtaining accurate and reliable analysis results.

Meshing involves discretizing a complex geometry into smaller finite elements, which are interconnected at nodes. These elements can be of various shapes, such as triangles, quadrilaterals, tetrahedra, or hexahedra, depending on the type of analysis being performed and the geometry of the structure.

Different meshing techniques are available, including structured, unstructured, and hybrid meshes. Structured meshes have a regular arrangement of elements and nodes, while unstructured meshes have irregular arrangements. Hybrid meshes combine elements of both structured and unstructured meshes, allowing for better resolution in certain areas of the geometry while maintaining regularity in other areas.

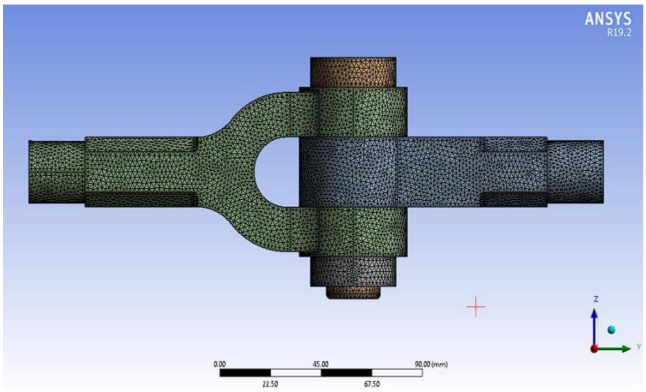


Figure 6 Meshing of the model.

5.2.5 Load and Boundary Conditions

The eye end is constrained in all directions and a force is applied to the fork end. The same boundary conditions are applied to all cases, regardless of the material being used. Force of 25KN is applied on the fork end.

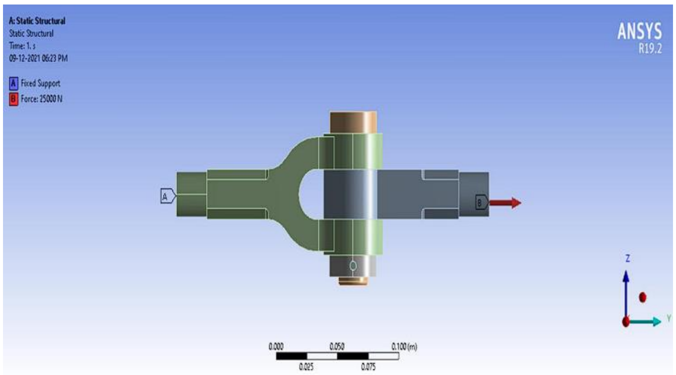


Figure 7 Load and Boundary Condition

6. RESULT AND DISCUSSION

6.1 Total Deformation in Knuckle Joint

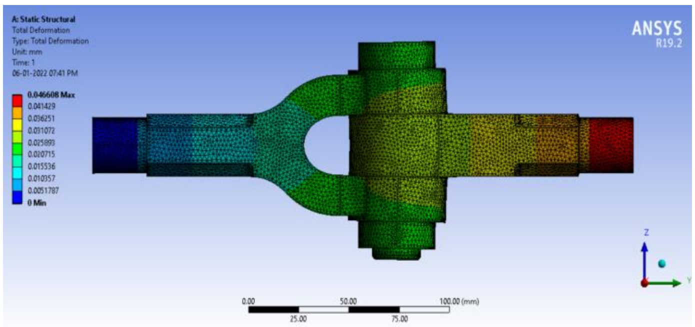


Figure 8 Deformation in Structural Steel

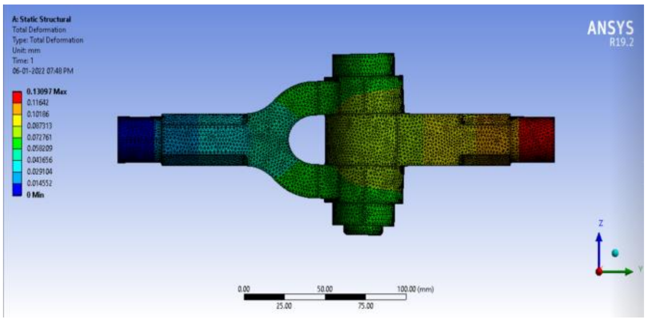


Figure 9 Deformation in Aluminum Alloy

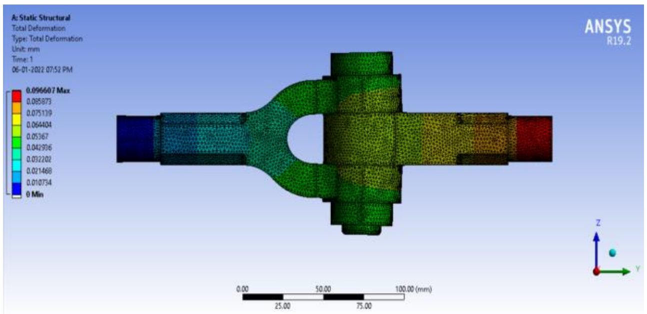


Figure 10 Deformation Titanium Alloy

From Fig.8, Fig.9 and Fig.10 we get to know that minimum total deformation takes place in structural steel. Deformation of Structural Steel is very less compared to Aluminium alloy and Titanium alloy.

The above results show that the maximum elongation at the two ends of the joints is as follows:

Table 2: Deformation of Different Material

Material	**Deformation**
Structural Steel	0.046608mm
Aluminium Alloy	0.13097mm
Titanium Alloy	0.096607mm

6.2 Von Mises Stress in Knuckle Joint

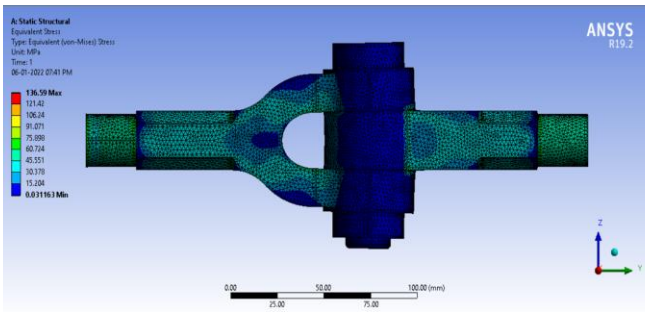


Figure 11 Equivalent Stress in Structural Steel

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 08 Issue: 08 | Aug - 2024 SJIF Rating: 8.448 ISSN: 2582-3930

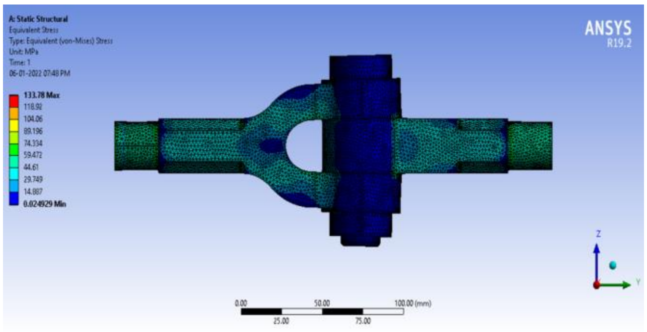


Figure 12 Equivalent Stress in Aluminium Alloy

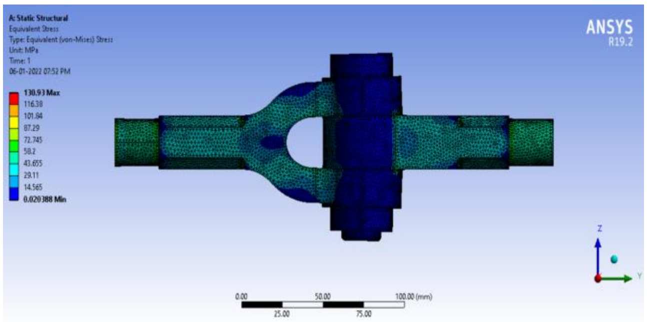


Figure 13 Equivalent Stress in Titanium Alloy

From Fig.11, Fig.12 and Fig.13 we get to know that maximum equivalent stress is least in
Titanium alloy.
With a factor of safety of 3, knuckle joint made of Structural steel and Aluminium alloy will have failure because the induced stress is more than the permissible stress.
The above results show that the maximum equivalent stress in knuckle joint is as follows:

Table 3: Equivalent Stress for Different Materials

Material	Equivalent Stress
Structural Steel	136.59MPa
Aluminium Alloy	133.78MPa
Titanium Alloy	130.93MPa

7. CONCLUSIONS

After analyzing structural steel, aluminium alloy and titanium alloy for knuckle joints, it has been observed that Titanium Alloy demonstrates the least amount of stress when compared to Structural Steel and Aluminium Alloy. This is attributed to Titanium's impressive strength-to-weight ratio, which makes it a strong and lightweight option for knuckle joints. Additionally, Titanium's high strength-to-weight ratio translates to a longer lifespan for the knuckle joints, as it can withstand high loads without significant deformation. However, it should be noted that Titanium is also more expensive than Steel and Aluminium, which may impact the overall cost of manufacturing knuckle joints. On the other hand, Steel is known for its minimal deformation characteristics, making it a viable option for knuckle joints. Furthermore, Titanium knuckle joints also have a higher Factor of Safety (FOS) than the minimum requirement of 3, indicating an added safety margin.

- Knuckle joints made of Structural Steel and Aluminium Alloy will fail when subjected to a load of 25KN, assuming a Factor of Safety (FOS) of 3.
- It has been observed that knuckle joints made of Titanium Alloy exhibit the least amount of stress.
- Titanium possesses a strength comparable to that of steel, yet it is 45% lighter in weight. In addition, it is twice as strong as aluminum, but its weight is only 60% of that of aluminum.
- Titanium is approximately 3 to 4 times stronger than stainless steel, which results in a longer lifespan for generations. But Titanium is significantly more expensive than Steel and Aluminium.
- Deformation of Steel is minimal compared to Aluminium and Titanium.

8. FUTURE SCOPE OF STUDY

Knuckle joints are commonly made of materials such as structural steel or steel alloys due to their high strength, durability, and affordability. Steel is a popular choice for knuckle joints as it provides excellent mechanical properties, such as high tensile strength and good fatigue resistance, making it suitable for heavy-duty applications. However, other materials such as aluminum alloys or titanium alloys may also be used for specific applications where factors such as weight, corrosion resistance, or specialized performance requirements are critical. The selection of material for a knuckle joint depends on the specific application, design considerations, and engineering requirements.

More optimized and cost-efficient materials can be considered and analyzed for knuckle joints to optimize it more without compromising with strength and performance.

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