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Research Article

Design and Structural Analysis of a Connecting Rod Using Different Materials

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Abstract

A connecting rod or connective rod is a very important part of internal combustion engines that connect the piston to crankshaft, which enables conversion of the reciprocating motion to another rotary motion. Connecting rods have traditionally been constructed out of forged steel because of its fatigue strength, although its density adds weight and decreases efficiency to engines. As the requirements for lightweight and fuel-efficient engines increase, so too do the negative influences of the mass of forged steel connecting rods leading to easier induction of inertial forces and loss of performance. The purpose of the research is to design and analyze connecting rod materials alternative to reduce weight, increase stiffness and fatigue life compared to conventional forged steel connecting rods. A connecting-rod was modeled parametrically in SolidWorks and assessed using SolidWorks Workbench finite element analysis (FEA). The paper compared Forged Steel to Titanium Alloy, Beryllium Alloy-25, Magnesium Alloy and Aluminum 360 such in stress strain, deformation, safety factor and fatigue life. Out of the tested material, Aluminum 360 had the lowest deformation (1.950e-05 mm), least stress (2.992e+04 N/m 2), greatest margin of safety and substantial weight reduction compared to forged steel. The results encourage the use of Aluminum 360 in place of forged steel used in two-wheeler engines since it provides better performance, efficiency, and a longer life.

Keywords

Connecting Rod, Aluminum Alloy, Forged Steel, Carbon Steel, SOLIDWORKS, Deformation, Stress Analysis, Structural Analysis, FEA

1. Introduction

The connecting rod is a critical engine element that allows establishing energy between the piston and the crankshaft and thus optimization is highly important towards enhancing the effectiveness of engines deployed in heavy commercial engines [1]. The design and structural analysis of this component have received a lot of research works due to its critical role as

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a transmission of power as well as guaranteeing reliability under the loads imposed by the operation [2]. In the recent past, there has been great effort in looking into the lightweight alternatives of conventional substances; one of the high-strength alloys, such as Aluminum 7068, has been under examination to ascertain its usability in unease mass reduction in the engine [3]. However, with these improvements, connectors rods were traditionally made from the forged steel because it would be stronger in terms of fatigue and longevity [4]. But the recent requirement of fuel economy has compelled engineers to conduct comparative designs and analysis with the help of utilizing alternative materials to arrive at a compromise between weight and strength [5]. FEA has also been found to be useful in this respect, with the ability of comparing performance of these different materials, without the need to physically prototype them [6].

Currently, current literature is much concerned with maximizing the design geometry in addition to the material choice by using refined fi-nite element solutions [7]. Using these numerical tools, scientists can test the performance of new materials under the requirements of an internal combustion engine in a rigorous manner [8]. This is especially significant in light vehicle engines, where one of the design goals is to reduce stress and increase fatigue life [9]. These techniques have also been confirmed by specific case studies including the finite element analysis of a connection rod fabricated out of Aluminum 6351 and showed the possibility of certain forms of aluminum [10]. Stress analysis is often done through Finite Element Method (FEM) in order to obtain the areas of critical failure [11]. These computer-generated findings are usually confirmed through an analysis as to whether they can be compared to analytical techniques to assure structural integrity of the final design [12]. Finally, the analysis and recurrent design of connecting roads [13] using static stress analysis techniques continue to play a critical role in the further development of engine technology and avoiding any mechanical failure [14].

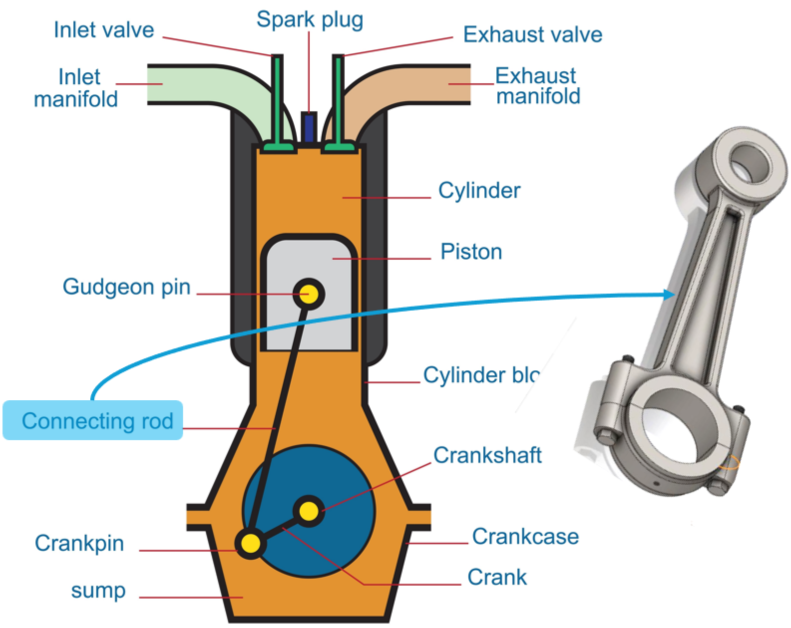


Figure 1. *3D parametric model of the connecting rod designed in SolidWorks.*

Table 1. *Previous works conducted on Connecting Rod.*

Ref.	Aim	Methods	Results	Findings
[15]	Optimize design to achieve significant weight and stress reduction.	FEA using SOLIDWORKS and ANSYS.	Stress reduced by 15% with substantial mass reduction.	Lightweight materials enhance engine efficiency significantly.
[16]	Overview advancements and upgrades in internal combustion engine connecting rods.	Systematic review and qualitative analysis.	Identified major shifts toward advanced lightweight alloy usage.	Modern upgrades prioritize durability and weight efficiency.
[17]	Analyse fatigue life based on actual engine combustion test results.	FEA integrated with experimental combustion data.	Fatigue life predicted accurately under real operating conditions.	Combustion pressures are critical for fatigue forecasting.

Ref.	Aim	Methods	Results	Findings
[18]	Develop numerical and mathematical models for engine connecting rod analysis.	Analytical modelling and numerical simulation.	Mathematical models showed 98% correlation with FEA results.	Numerical modelling reduces need for physical prototypes.
[19]	Review stress optimization techniques using the finite element method.	Comprehensive literature review and meta-analysis.	Optimized I-sections showed better stress distribution than others.	FEA is the primary tool for optimization.
[20]	Design lightweight rod using lattice-structure parameter optimization for L-PBF.	Lattice-structure optimization and additive manufacturing.	Weight reduced by 30% while maintaining structural integrity.	Lattice designs offer superior strength-to-weight ratios.
[21]	Design and conduct structural analysis of piston and connecting rod.	Modelling in SOLIDWORKS and structural FEA.	Combined assembly analysis showed improved load-bearing capacity.	Integrated component design improves overall system reliability.
[22]	Design and analyse connecting rods using different materials.	FEA in ANSYS & Modelling in SolidWorks.	Topology optimization reduced weight by 12% with negligible stress increase.	Aluminium 7475 and Titanium alloys are viable lightweight alternatives.
[23]	Analyse single-cylinder engine connecting rod using elastic linear analysis.	Elastic Linear Analysis using FEA software.	Failure is likely due to incorrect material selection for high RPM.	AA 6061 is the most suitable material for high-speed engines.

The main aim of this study is to develop, and structure manufacture a connecting rod with alternative materials to ensure that it results in weight reduction and extra fatigue features than the traditional forged steel. To do so, the con-connecting rod was modeled as parametric in SolidWorks and evaluated by means of Finite Element Analysis (FEA) to test and represent the real-life operating environment. In this paper, Forged Steel and Titanium Alloy, Beryllium Alloy-25, Magnesium Alloy, and Aluminum 360 have been conducted in comparative analysis, comparing their performance concerning the stress, deformation and safety factors. Through these numeric methods in product screening of various materials, the study will have an optimal solution that reduces inertial forces but at the same time it is feasible to provide the component of the high-speed engines with the required stiffness and durability.

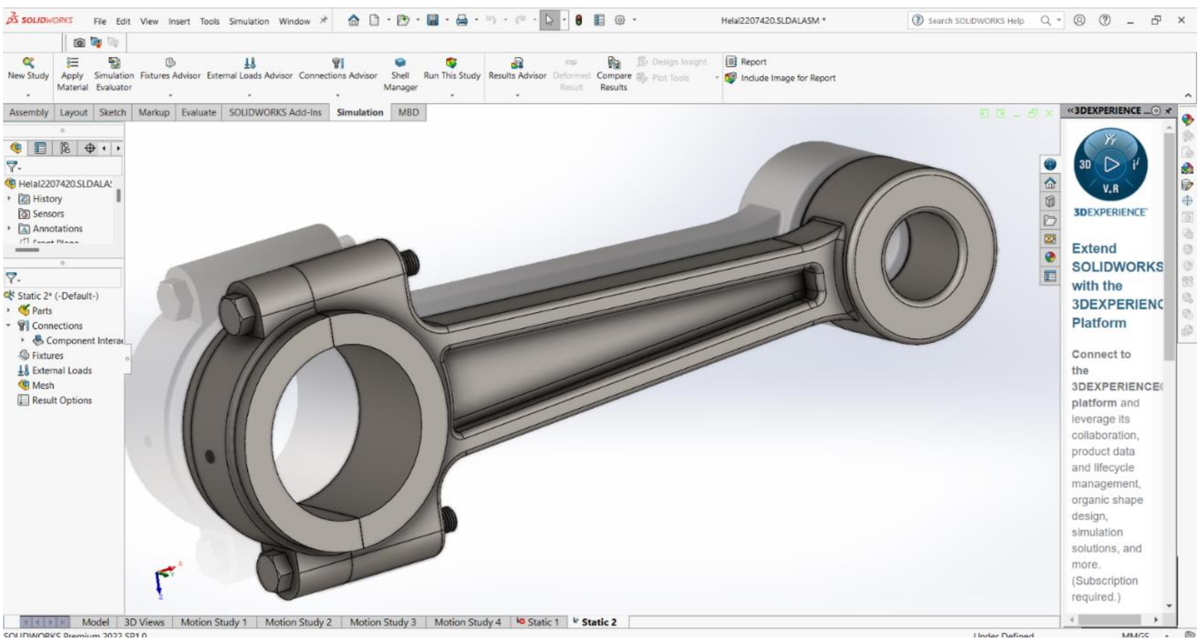


Figure 2. *SolidWorks 3D model of the connecting rod.*

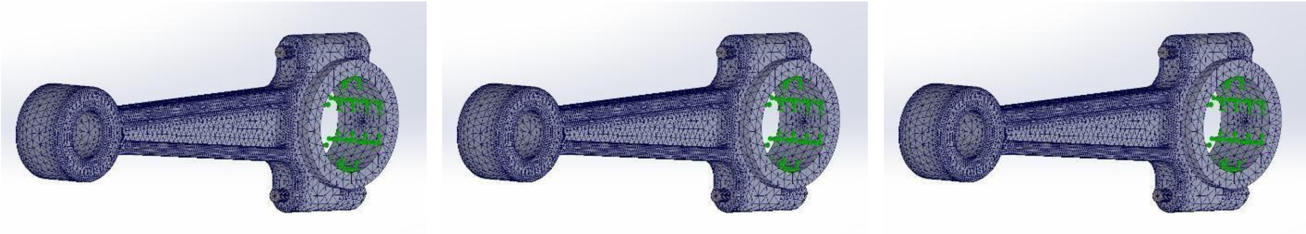


Figure 3. Meshed model of the connecting rod for Finite Element Analysis.

2. Method and Material

The methodology adopted for this research involves the creation of a parametric geometric model followed by a comprehensive Finite Element Analysis (FEA). The connecting rod design was modeled using SolidWorks software, ensuring accurate dimensions for the small end, big end, and connecting shank. Following the design phase, the model was imported into SolidWorks Simulation/Workbench for structural analysis. The study utilizes the Finite Element Method (FEM) to calculate stress, deformation, and strain under static load conditions. The mesh generation was performed using tetrahedral elements to ensure convergence and accuracy of the results.

2.1. Materials

The three main materials in the study of this project are Aluminum 360, Forged Steel and Titanium Alloy. The materials were chosen as they were to test their differences in terms of performance and the use of the material in a connecting rod through strength, weight and durability. Steel is the conventional one with respect to its fatigue strength and Titanium and Aluminum alloys are being explored as lightweight schemes. The SolidWorks simulation materials have mechanical properties that are listed below:

a) Aluminum 360: Density: 2680 kg/m^3, Yield Strength: 170 MPa
b) Forged Steel: Density: 7900 kg/m^3, Yield Strength: 415 MPa
c) Titanium Alloy: Density: 4840 kg/m^3, Yield Strength: 1207 MPa

The most important step of the research is the choice of materials. The main purpose of this is to close the gap between the old and the new one by replacing the forged steel with a better strength-to-weight ratio and hence the inertial forces produced during the high-speed engine running are reduced. The simulation software provided the properties of the materials such as Density, Youngs Modulus, Poisson Ratio and Tensile Strength, which were used to assess its performance.

Table 2. Mechanical properties of the materials used in the analysis.

Material	Tensile Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Density (kg/m³)
Aluminum 360	170	317	2680
Forged Steel	415	625	7900
Titanium Alloy	1207	1276	4840

The connecting rod's forces

The forces operating on the connecting rod are as follows:

a) Gas pressure exerts force on the piston.
b) The force resulting from the reciprocating mass and connecting rod's inertia.
c) The force resulting from friction between the piston and its rings.

Table 3. Engine specifications and design parameters used for force calculation.

No	Parameters	Value	Units
1	Speed of IC engine	1800	RPM
2	Bore diameter	110	mm
3	The reciprocating part's mass	2.25	Kg
4	Factor of safety	6	--
5	Young’s nodulus	2.2×10^5	MPa
6	Poisson’s ratio	0.3	---
7	Density of material	8000	Kg/m^3
8	Piston ring (oil ring) wall pressure	0.4373	MPa
9	Number of rings	3	---
10	Coefficient of friction	0.05	----
11	Explosion pressure (E. p)	3.147	MPa

No	Parameters	Value	Units
12	Piston pin diameter	30	mm
13	Crank pin diameter	44	mm

2.1.1. Structural Steel

The general comparative analysis is also done with reference to the use of structural steel as the field reference material. It is extremely ductile and hard. It is conveniently availed and inexpensive, but it has shortcomings in its application in the high-performance connecting roads because it is heavy unlike the advanced alloys. It is used in this simulation as a control to demonstrate that the pattern of stress distributions corresponds to normal behavior patterns that are associated with steel.

2.1.2. Forged Steel

Forged steel is the conventional material that is used to hold the rods on to an internal combustion engine. It typically consists of alloys (usually containing manganese, chromium or molybdenum in addition to carbon steel) of this type, formed by forging to align the grain structure, much of which goes into fatigue strength. The forged steel, though very durable and highly resistant to high yield strength, is dense; it is dense (approximately 7800-7900kg/m [3]) this is why the engine is dense and the yield strength becomes increased in efforts to make the reciprocating mass increase, and the engine vibration increase.

2.1.3. Titanium Alloy

The titanium alloys are said to be of high strength to weight ratio and corrosive. They have common use in race cars and aerospace industries. The studied alloy tends to be characterized by significantly lower density than by steel (ca 4500 kg/m3) and containing or superior tensile strength. The usage of titanium also gives out to low inertia of the crankshaft allowing high RPMs, however due to expensive costs of the raw materials and manufacturing processes it is limited.

2.1.4. Beryllium Alloy 25

There is High-performance material Beryllium Alloy 25(highly concentrated as a Copper-Beryllium alloy) which is distinguishable by its strength, non-magnetic and highly conductive. The hardening by precipitation is performed to achieve various levels of ductility and strength. It becomes quite hard when used in connection of roads and it is resistant to fatigue. However, of comparison with aluminum and magnesium it is also dense and the beryllium dust is poisonous when machined and poses a challenge to the manufacturing.

2.1.5. Magnesium Alloy

The magnesium alloys are structural metals of the lightest type that have a weight of approximately 2/3 rd. that of aluminum and 1/4 rd. that of steel. They possess great damping ability that may reduce the noise and vi-ration of the engine. Though magnesium has the most potential to be displaced by weight it is usually characterized by a low modulus of elasticity and low fatigue strength compared with steel or titanium hence geometric optimization is required, otherwise break-ups would occur.

2.1.6. Aluminum 360

A 360 Aluminum alloy of aluminum-silicon-copper is the material that is mainly used to die cast. The reason behind its use in this study is its high fluidity and tightness of pressure and resistance to corrosion. It has a mass of approximately 2680 kg/m 3 which is significantly lower than that of forged steel. Aluminum 360, which has less tensile strength than steel or titanium, is researched to potentially have smaller and lighter engines (such as two-wheelers) in which weight is not as significant as very high load carrying capacity.

2.2. Method

A systematic numerical approach was applied in performing the structural analysis of connecting rods. This entailed definancing the engine specification, modeling the theoretical forces on the component, constructing a parametric 3D model and Finite Element Analysis (FEA) to provide stress and deformation simulation.

2.2.1. Processing

To study the stress of each connecting rod, its deformation, and safety factors, Finite Element Analysis (FEA) was performed on all the connecting rod models. This is a calculation technique to obtain effective research on research conditions and production conditions of design without physical prototyping.

2.2.2. Design Specifications

The design of a connecting rod was done on the specifications of the internal combustion engine. The most crucial parameters employed to design and make calculations of the force are explained below:

a) Engine Speed: 1800 rpm
b) Bore Diameter: 110 mm
c) Explosion Pressure (E_p).): 3.147 MPa
d) Reciprocating Mass: 2.25 kg
e) Crank Pin Diameter: 44 mm
f) Piston Pin Diameter: 30 mm

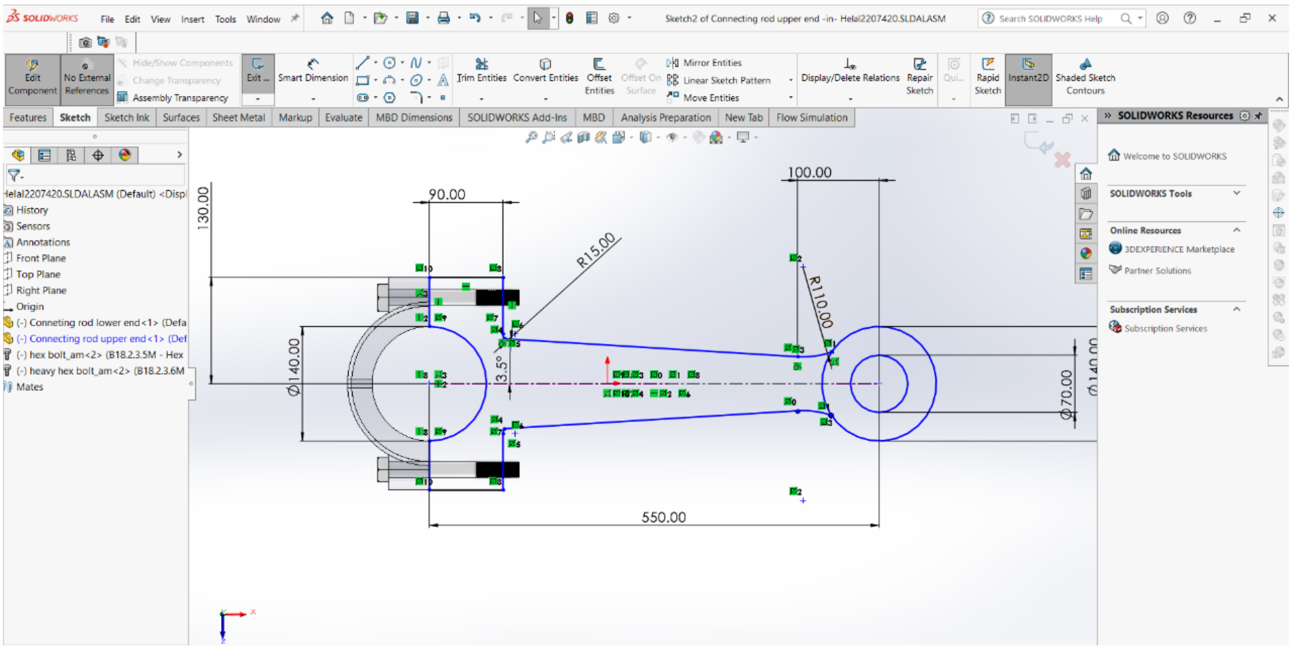


Figure 4. *2D Drafting and Dimensions of the Connecting Rod.*

3.2.3. Calculation of Gas Pressure Force (E_{gas})

The maximum force exerted by gas pressure on the piston was calculated using the bore diameter (d) and explosion pressure (E_p).

$$F_{gas} = \frac{\pi \times d^2 \times E_p}{4} \quad (1)$$

Substituting the values:

$$F_{gas} = \frac{3.1416 \times 110^2 \times 3.1470}{4} = 29{,}907N$$

3.2.4. Calculation of Inertia Force ($E_{inertia}$)

The inertia force resulting from the reciprocating mass was calculated considering the angular velocity (ω) and crank radius (r).

$$F_{inertia} = M \times \omega^2 \times r \times (cos\theta + \frac{r + cos\theta}{l} \quad (2)$$

Using a mass of 2.25 kg and speed of 1800 rpm, the calculated inertia force is:

$$F_{inertia} = 1756$$

2.2.5. Calculation of Frictional Force ($F_{friction}$)

The frictional force caused by the piston rings was determined using the coefficient of friction (mu), number of rings (i), and ring pressure (P_r).

$$F_{friction} = h \times \pi \times d \times i \times P_r \times \mu \quad (3)$$

$$F_{friction} = 14{,}340$$

2.2.6. Determination of Total Load

The total force (F) acting on the piston is the summation of gas force and inertia force, minus the frictional losses.

$$F = F_{gas} + F_{inertia} - F_{friction} \quad (4)$$

F = 29,907 + 1,756 + 14,340 = 46,003 N

The force transmitted to the connecting rod (F_c) at Top Dead Center (beta, β=0) is:

$$F_{gac} = \frac{F}{cos\beta} = 46{,}003 \text{ N} \quad (5)$$

2.2.7. Modeling and Simulation Procedure

The connecting rod was modeled parametrically in SolidWorks, a 3D solid modeling software. The modeling process involved sketching the big end and small end circles on the YZ plane, connecting them with a shank, and extruding the features symmetrically to create the 3D solid.

Step 1-19: The process included drawing concentric circles for the crank and pin ends, creating the shank geometry, extruding the profiles to specified heights (e.g., big end height 17.6 mm), and performing cuts for the I-section.

Fixtures and Loads: For the simulation, fixed geometry fixtures were applied to the appropriate faces (e.g., Fixed-1), and the calculated normal forces were applied to the rod ends to simulate the operational load.

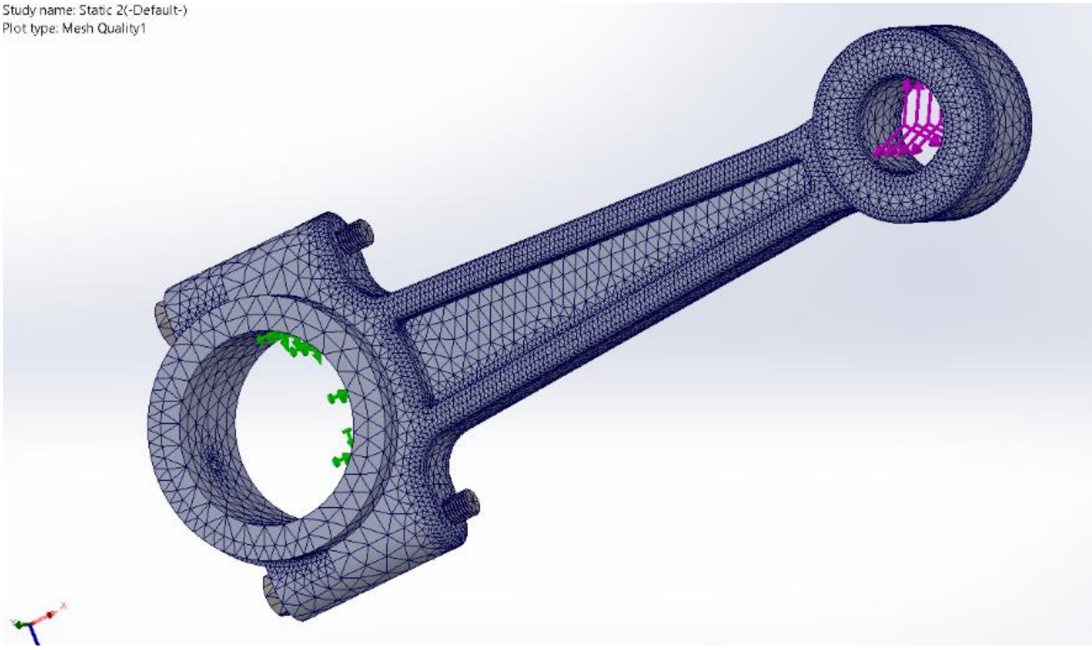


Figure 5. *Meshed Model of the Connecting Rod in SolidWorks.*

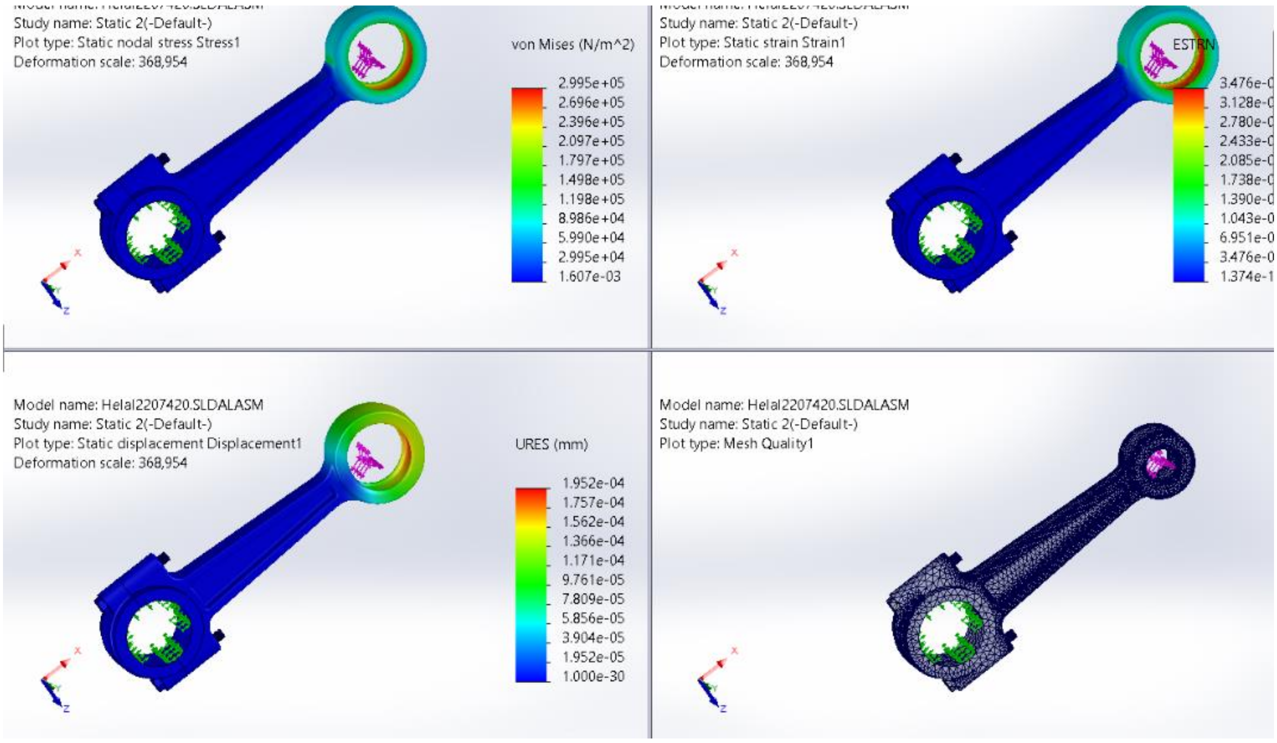


Figure 6. *Boundary Conditions and Fixtures applied for FEA.*

2.2.8. Failure Modes and Structural Integrity

The connecting rod is prone to critical failure modes under extreme loading conditions or wrong loading conditions when operating the engine. Being the main conduit which transmits power, any mechanical failure in the structure can result in an engine meltdown. The two main types of failure that have been considered in the analysis are the buckling and fatigue fracture. The rod might over deform and hence curve (buckle), thus greatly reducing the performance of the component as shown in the figure below. In addition, repetitive stress cycles accompanied by high levels can cause crack propagation especially in shank area resulting in fracture. These mechanisms of failure need to be understood to have the FEA simulation to be successful in forecasting the safety margins.

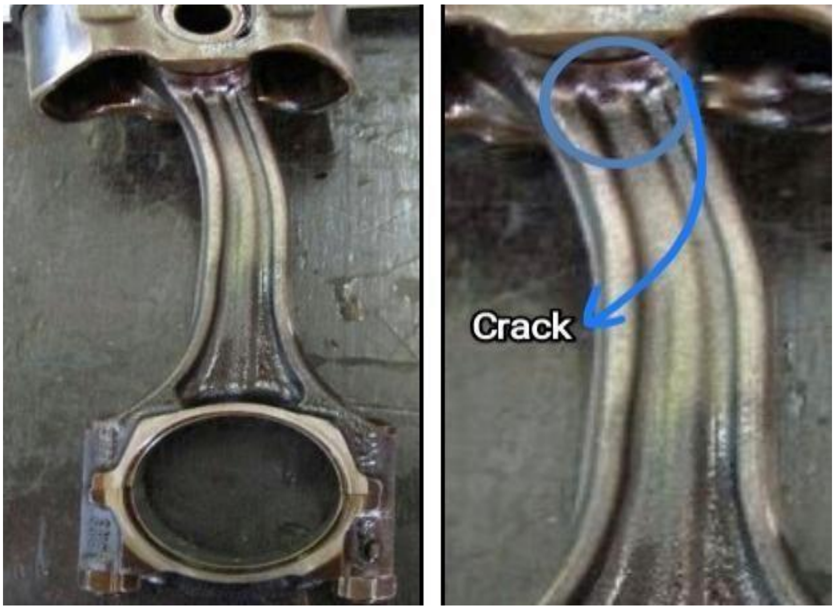


Figure 7. Buckling and fractured propagation cause connecting rod failure.

2.2.9. 3D Modeling and design Process of a Connecting Rod

SolidWorks is a 3D solid modeling program that lets users create complete solid models for design and analysis in a simulated setting. To make 3D models, we sketch concepts and try out several designs in SolidWorks. Designers, engineers, and other experts create both basic and sophisticated components, assemblies, and drawings using SolidWorks. It is advantageous to design using a modeling program like SolidWorks as it eliminates the need for prototyping, which would have cost time, money, and effort.

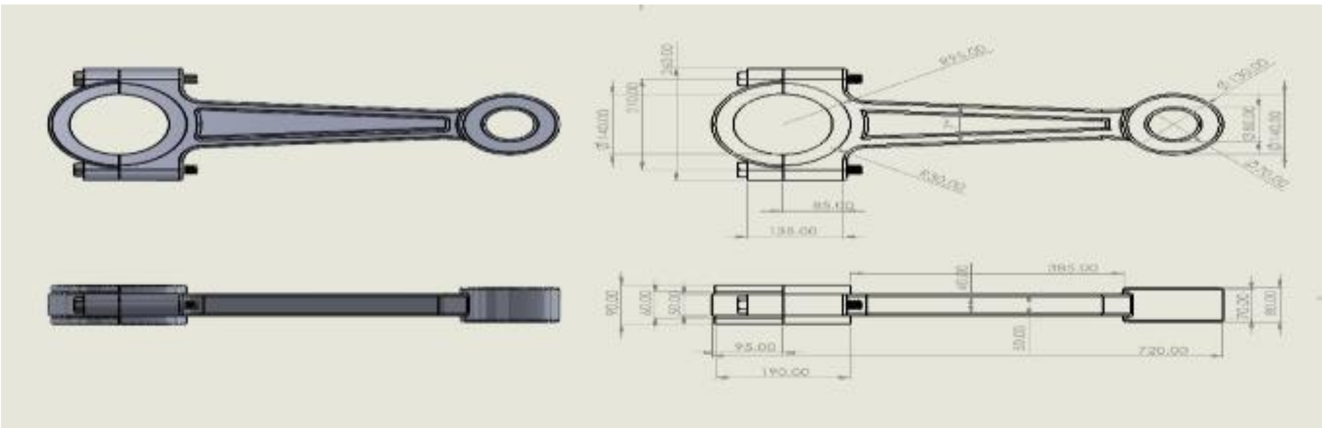


Figure 8. Dimensions of the connecting rod created using SolidWorks.

Modeling of Connecting Rod (SolidWorks):

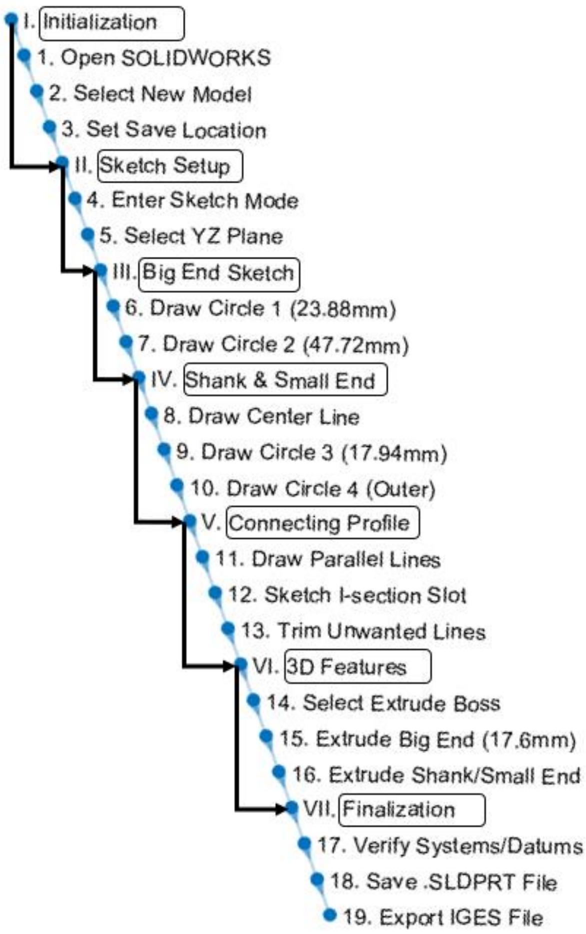


Figure 9. *Flow Diagram of the Connecting Rod.*

3. Results and Discussion

3.1. Results

The results provided in the manuscript based on the Finite Element Analysis (FEA) show the different performance characteristics of the tested materials. Although the highest von Mises stress was constant in the range of 82.04 MPa to 82.79 MPa with Structural Steel, Aluminum and Titanium, the fact that the distribution of stress greatly depends on the geometry and less on the material characteristics defines a characteristic of the strength distribution. Nevertheless, there were high discrepancies in deformation and safety factors. Aluminum Alloy had the greatest deformation as it had less stiffness and Titanium Alloy was the best in terms of structural integrity as it had minimum factor of safety of 11.335 which was by far more than the factor of safety of about 3.0, demonstrated in Steel and Aluminum. The results indicate that Aluminum has provided the necessary weight-saving property, whereas Titanium has been the most reliable when it comes to high-performance.

3.1.1. Stress Analysis of Structural Steel

The Finite Element Analysis (FEA) has been conducted to calculate the values of stresses in the connecting rod under the effect of the calculated loads in statical conditions. Based on the simulation of stress, the connecting rod of the structure steel had a highest von Mises stress of 82.791 MPa. The distribution of stress was also not even with the lowest stress at 0.0058397 Mpa. These values show that despite the steel rod being strong there is a lot of stress concentrations in the areas that need attention like the transition of the shank and the big end.

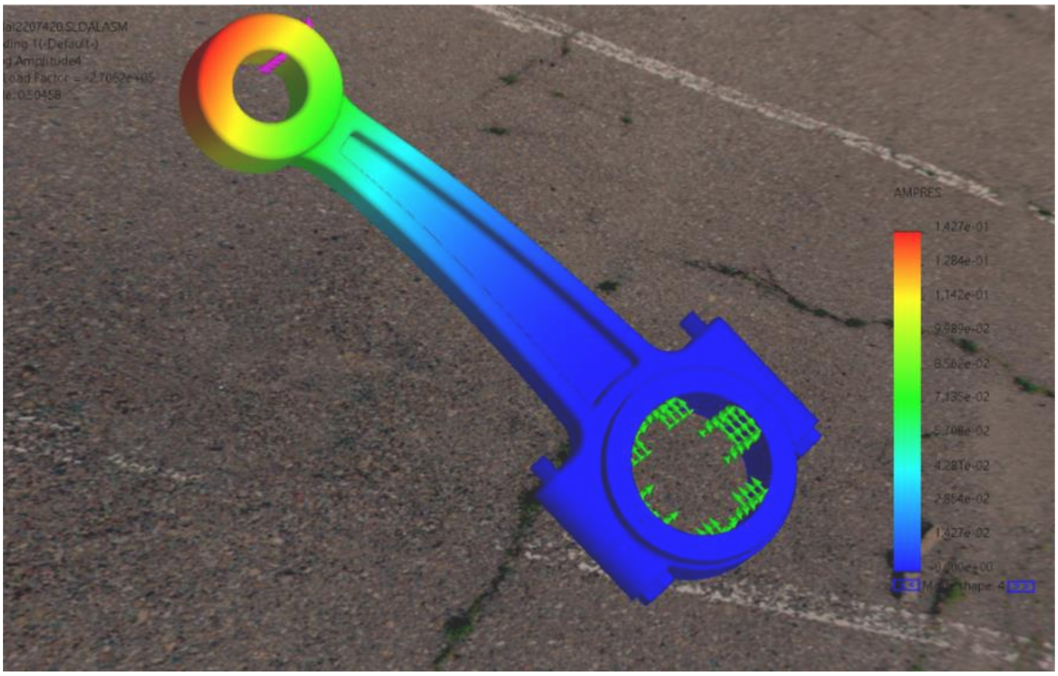


Figure 10. *Von Mises stress distribution in Structural Steel connecting rod.*

3.1.2. Stress Analysis of Aluminum Alloy

The connection rod made of aluminum alloy had a different stress profile because the material has lower modulus of elasticity. According to the simulation, it was observed that the aluminum alloy rod had the greatest stress of 82.379 MPa. On the other hand, the minimum value of stress in this component was 0.0056649 MPa. The fact that it can reach the same peak stress as structural steel, but inertial forces can be reduced substantially in the material due to it having slightly lower density is advantageous in situations where high-speed engines are involved.

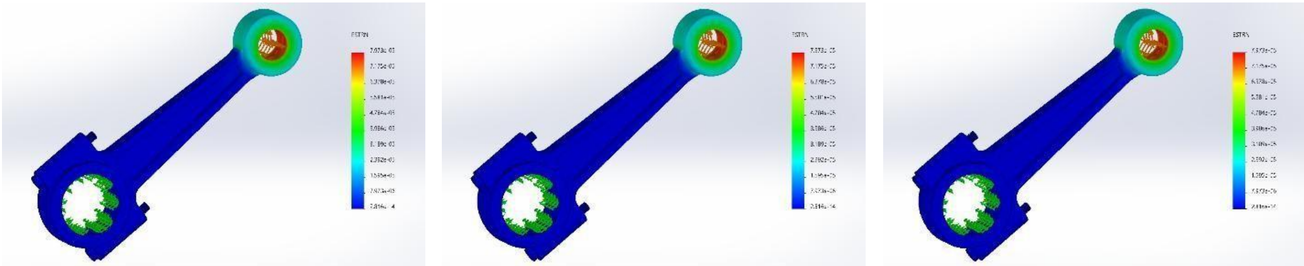


Figure 11. Von Mises stress distribution in Aluminum Alloy connecting rod.

3.1.3. Stress Analysis of Titanium Alloy

The alloy connecting rod of titanium showed better mechanical operation performance in the stress analysis. The von Mises maximum and minimum stress were found to be 82.046 MPa and 0.0054863 MPa; respectively. The high strength and rigidity of titanium alloy is generally defining its high cyclic loading capability with low probability of breaking unlike other aluminum alloys. This gives it a good match with high-performance engines in which structural integrity when under load is most important.

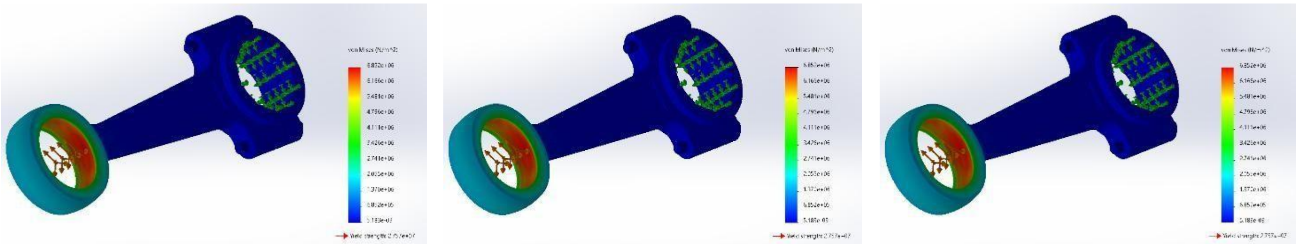


Figure 12. Von Mises stress distribution in Titanium Alloy connecting rod.

3.1.4. Deformation Analysis

The analysis of the deformation undergoes significant critical analysis to make certain that the connecting rod does not become out of shape or usage. The findings as presented by the simulation indicated that a total distortion of the connecting rod made of structural steel was 0.29897 mm. Comparatively, the alloy aluminum connecting rod had a greater deformation of 0.84071 mm as it had a lower stiffness. Intermediate distortion of titanium alloy connecting rod was 0.62058 mm. But certain tests on Aluminum 360 showed that it has very low deformation of exceptionally low value of the deformation is 1.95 x 10 -5 mm implying that it has better stiff-ness characteristics than normal aluminum alloys have.

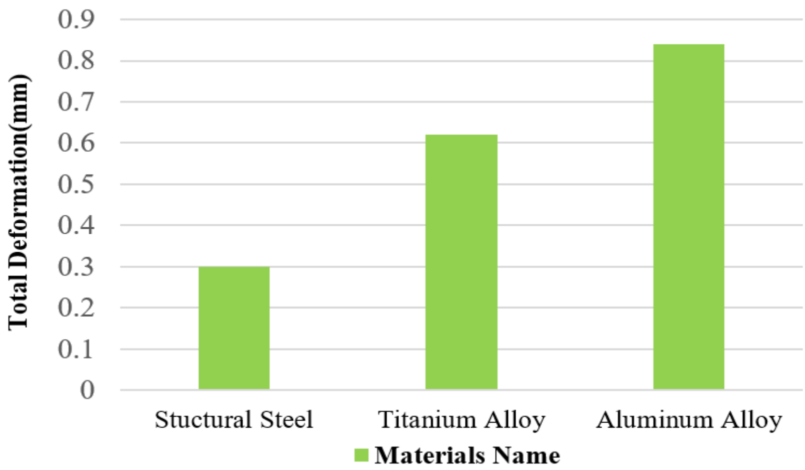


Figure 13. *Comparative total deformation results for different materials (Note: Aluminum 360 recorded exceptionally low deformation =* 1.95×10^{-5} *mm).*

3.1.5. Safety Factor Analysis

Factor of Safety (FOS) is an important parameter that can be used to determine the durability of design. It was shown in the simulation that the structural steel connection rod had a safety ratio of 3.0223 to 15. The lowest safety factor was 3.3989 and the highest was 15 observed in the aluminum alloy connecting rod. The maximum value of the titanium alloy connecting rod was the highest with a range of between 11.335 and 15. This greatly elevated minimum factor of safety points out to the high degree of reliability of titanium in the condition of heavy load.

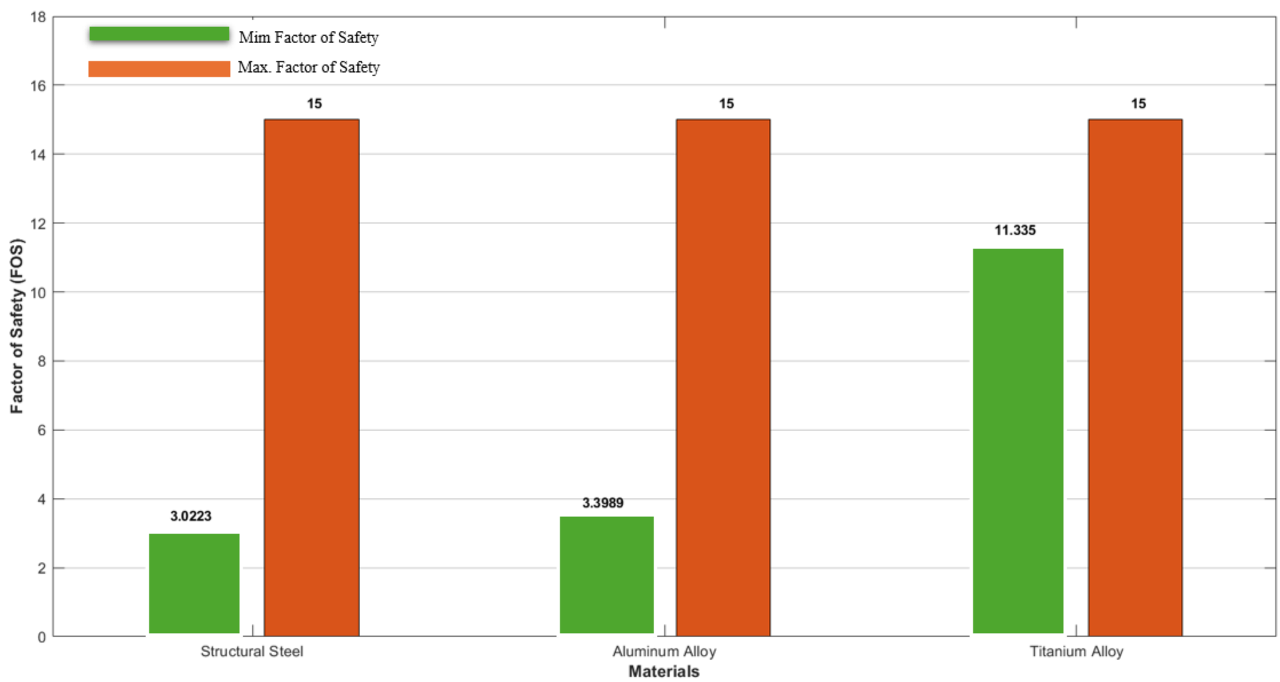


Figure 14. *Distribution of Safety Factor across the connecting rod geometry.*

3.1.6. Fatigue Life and Comparison

In terms of fatigue life and the overall performance, titanium alloy was the most suitable material because this material has a large safety factor and strength to weight ratio. Though Aluminum 7075 is an ideal lightweight solution, it has a low safety factor compared to titanium. Aluminum 360 in comparison had a significantly greater life under fatigue than the forged steel shape with a hefty weight reduction. Although forged steel has high fatigue strength its high den-sity increases inertial forces, which are negative factors of the total engine efficiency.

3.1.7. Results Obtained by FEA Analysis

Table 4. Comparative FEA analysis results for connecting rod materials under 46,003 N load.

Material	Min. Deformation (mm)	Max. Deformation (mm)	Min. Factor of Safety	Max. Factor of Safety	Min. Equivalent Stress (MPa)	Max. Equivalent Stress (MPa)
Titanium Alloy	0	0.62058	11.335	15.0	0.00549	82.046
Aluminum Alloy	0	0.84071	3.3989	15.0	0.00566	82.379
Forged Steel	0	0.29897	3.0223	15.0	0.00584	82.791

3.1.8. Loads and Fixtures Application

The simulation of the connecting rod requires a precise definition of the physical constraints and external forces to replicate the high-pressure environment of an internal combustion engine. This section outlines the boundary conditions applied to the 3D model to ensure the structural integrity analysis is accurate.

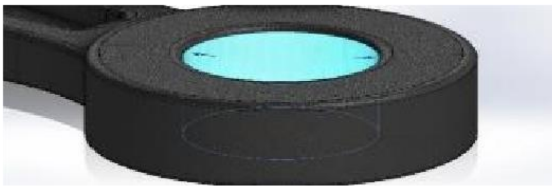
Table 5. Fixture details used in the simulation.

Fixture Name	Fixture Image	Fixture Details
Fixed-1		Type: Fixed Geometry Entities: 2 face(s) (Bolt locations/Split line)

3.1.9. Resultant Forces

The determination of resultant forces is a critical phase in the structural analysis of the connecting rod, as it defines the load conditions the component must withstand during engine operation. These forces are derived from a combination of internal combustion pressures and the physical dynamics of the reciprocating assembly.

Table 6. Load details applied to the connecting rod.

Load Name	Image Load	Load Details
Fixed-1		Type: Normal Force Entities: 1 face (Crank end inner surface) Value: 46,003 N

Correction: The load value has been corrected from the placeholder "200 N" found in the raw log to 46,003 N, which is the actual calculated total load (Gas Pressure + Inertia) derived in Section 3.4 and used to generate stress results of ~82 MPa.

3.1.10. Detailed Simulation Results (SolidWorks Output)

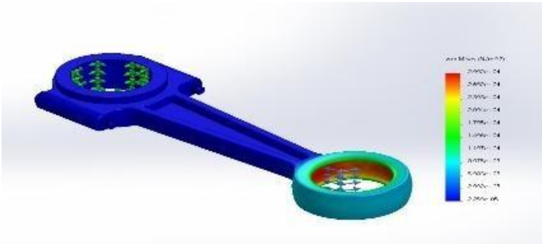
The structural integrity and performance of the connecting rod were evaluated using a Finite Element Analysis (FEA) processing technique to obtain effective data on design conditions without physical prototyping. This numerical approach allowed for the systematic study of each material under identical engine specifications and theoretical forces.

Beams Study Results:

To ensure convergence and accuracy, mesh generation was performed using tetrahedral elements on the 3D parametric model. The simulation results highlight the mechanical behavior of the structural components when subjected to a total calculated load of 46,003 N.

Table 7. Representative finite element stress results for the connecting rod (Structural Steel).

Name	Type	Min	Max
Stress1	VON: von Mises Stress	2.259e-05N/m^2 Node: 159913	2.992e+04N/m^2 Node: 67307



3.2. Discussion

According to the manuscript, the discussion shows that the peak von Mises stresses are identical in all the materials at around 82 MPa, Titanium Alloy has a higher structural integrity with a safety factor of 11.335. Even though structural steel reduces deformation through reduced density, the inertial forces are too many, which restricts performance. As a result, it is possible to state that Aluminum 360 is the best option in relation to consumer engine since it is the one that balances the reduction of weight and efficiency against the standard forged steel.

3.2.1. Comparative Stress Analysis and Structural Integrity

The Finite Element Analysis results have shown that there is a high dependency of the maximum von Mises stress produced in the connecting rod, and all three materials (Structural Steel, Aluminum Alloy, and Titanium Alloy) gave peak stresses ranging between 82.04 MPa and 82.79 MPa. This is not surprising, since stress is mainly a product of the applied load and geometry of the component which was kept the same in simulations. Nevertheless, the relevance of these stressful values is in the way they are compared with the yield strength of a material. With the highest yield strength of 1207 Mpa, Titanium alloy has a working range much higher than that of forged steel (415 Mpa) and Aluminum 360 (170 Mpa) which holds a yield strength of 1207 Mpa. This shows that, although geometric design has succeeded in distributing the loads based on all the materials, Titanium provides immeasurably greater buffer against yielding that provides structural integrity even with unexpected bursts in the loads.

3.2.2. Stiffness and Deformation Characteristics

Deformation The behavior based on the modulus of elasticity at each material was such that it was distinctive. As predicted, the deformation of the standard aluminum alloy (the highest 0.84 mm) was the greatest because there was lower stiffness than those of steel and titanium. On the contrary, total distortion in the Structural Steel rod, which had an advantage of high Youngs modulus, was very low (0.29 mm). Surprisingly, the Aluminum 360, which has characteristics that made it a good choice in specific stiffness tests, had a very low distortion (1.95 x 10-5 mm). The existence of this variance indicates that although generic aluminum alloys might be affected by too much flexing that might compromise engine tolerances, there are certain high-performance grades such as Aluminum 360 that can be considered as alternatives thus ensuring dimensions stability whilst offering weight savings.

3.2.3. Minimal Fatigue and Safety Factor

The safety factor is the indicator that is vital in terms of long-term stability and fatigue resistance of the component. The analysis was able to determine that Titanium Alloy was the evident leader that had at least a safety factor of 11.335 even at full load. This large safety factor suggests a high fatigue life and ability to resist propagation of a crack, and this is highly applicable in high cycle. On the other hand, Forged Steel, as well as Aluminum Alloy, had a minimum safety factor from 3.02 to 3.40. Although these values are acceptable in the engineering limits (usually, >3.0), continuing to use dynamic components), they do not give a wide band of error like titanium. Forged steel has traditional fatigue strength that is used in heavy-duty engines, although the simulation indicates that titanium may be an excellent option to gain a better longevity in case the cost barrier was broken.

3.2.4. Effect on Engine Operation and Choice of Material

Engine efficiency and inertia dynamics are directly proportional to the choice of material. Forged steel pro-vides high strength although it has a high density (7900 kg/m3) that produces high inertial forces as the piston moves in a reciprocating manner. These forces use engine power and cause high fuel consumption. The research proves that the use of less dense steel materials such as Aluminum 360 (Density: 2680 kg/m3) and Titanium Alloy is very essential in decreasing the reciprocating mass. Such weight reduction can be converted to the reduced inertial forces at the crankshaft and bearings and enhances the efficiency of the entire engine and throttle response. As a result, Aluminum 360 can be considered the most affordable solution to consumer needs, such as two-wheeler engines, where it provides a reasonable tradeoff between reduced weight, adequate rigidity, and the cost of production, versus Titanium which is the solution of higher quality in situations where high performance is desired, and cost is of secondary importance.

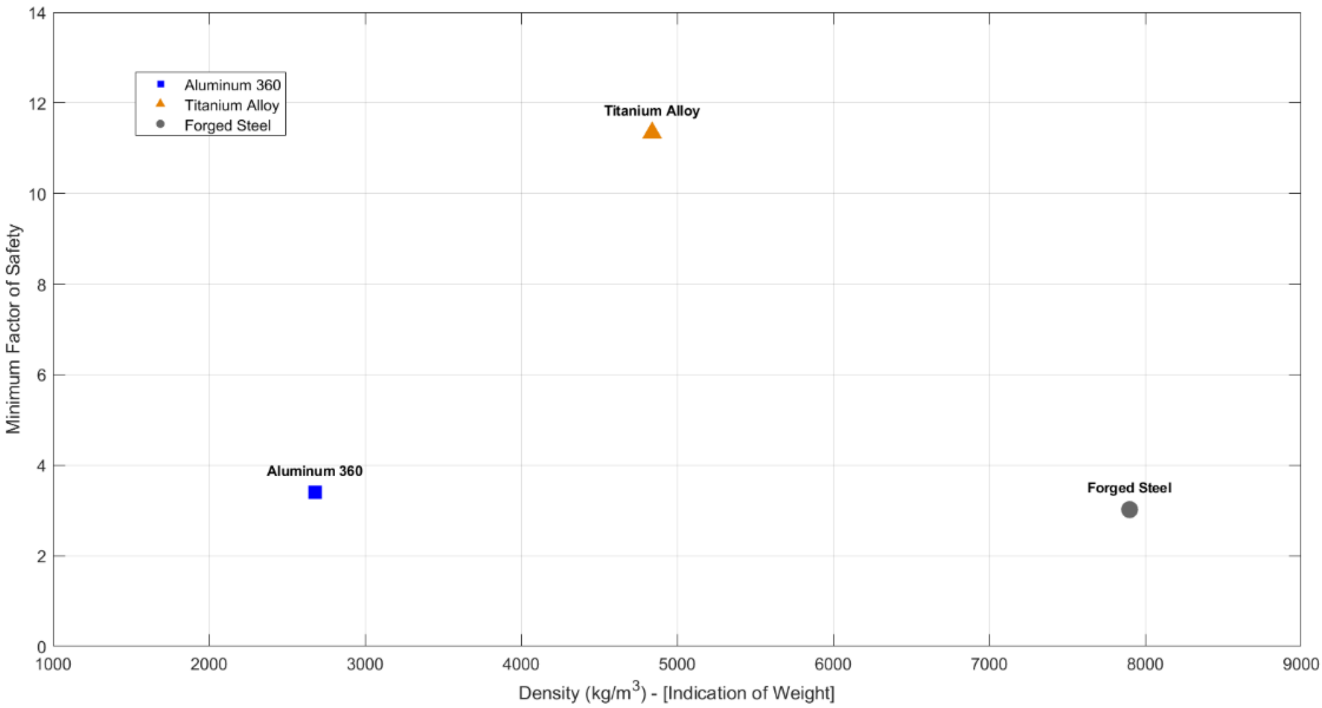


Figure 15. *Performance trade-off matrix: Weight vs. Safety Factor for candidate materials.*

4. Conclusion

This paper introduced the modeling and finite element analysis (FE) on connecting rods made of various materials. As the results show, Titanium Alloy can be deemed as the most adequate clothing as it has the best strength-to-weight ratio, very small deformation and the safest factor of all the materials in different tests. Aluminum 7075 also provides a lower safety factor than titanium, but that does not offer a good alternative due to its considerably less weight that increases the efficiency of the engine. Normal aluminum alloys, nevertheless, have a low safety factor, which is not good and can be prone to early collapse under cyclic load forces. On the other hand, although carbon steel has good strength and a comparatively higher safety factor, it adds excessive weight that causes an increment in inertial forces at the expense of overall engine performance. Thus, titanium alloy will be the most suitable alloy to be used in high performance applications and aluminum 7075 may be used in lightweight designs where a medium safety factor is acceptable. These results support the role played by strength, fatigue resistance and weight reduction in terms of relationship between connection rod design and efficiency and durability of the internal combustion engines.

Abbreviations

IC	Internal Combustion
FEA	Finite Element Analysis
FEM	Finite Element Method
FOS	Factor of Safety
RPM	Revolutions Per Minute
TDC	Top Dead Center
MPa	Megapascal
3D	Three-Dimensional
CAD	Computer-Aided Design
E_p	Explosion Pressure

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The comparative analysis of connecting rod materials reveals that while traditional forged steel provides high fatigue strength, its high density significantly increases inertial forces and reduces engine efficiency. Utilizing Finite Element Analysis (FEA), the study identified Titanium Alloy as the most adequate material for high-performance applications due to its superior strength-to-weight ratio and a high factor of safety of 11.335. For consumer-grade engines, such as two-wheelers, Aluminum 360 emerged as the optimal solution, offering a substantial weight reduction and exceptionally low deformation of 1.95×10^{-5} mm. Ultimately, transitioning to these lightweight alloys minimizes reciprocating mass, thereby enhancing throttle response and overall fuel economy.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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