Acta Scientific COMPUTER SCIENCES

Volume 5 Issue 2 February 2023

Research Article

Comparative Analysis of Four Different Connecting Rod Materials for an Internal Combustion Engine Using Finite Element Method

Jacob K Nkrumah[1]*, Kuusana Yakubu[2] and Offei D Inusah[3]

[1]Automotive Research Institute, Jiangsu University, Jiangsu, China

[2]Mechanical Engineering Department, Sunyani Technical University, Sunyani, Ghana

[3]Automotive Engineering Department, Tamale Technical University, Tamale, Ghana

***Corresponding Author:** Jacob K Nkrumah, Automotive Research Institute, Jiangsu University, Jiangsu, China.

Received: December 21, 2022

Published: January 09, 2023

Abstract

Connecting rod is one of the most important moving components in an internal combustion engine. It is the link between the piston and the crankshaft. Its primary function is to transmit power from the piston pin to the crankpin by so doing converting the reciprocating motion of the piston to rotary motion of the crankshaft. The connecting rod was modelled using Autodesk Inventor 2017 software. The modelled connecting rod was then imported into Ansys for further analysis. Static structural analysis was carried out on the connecting rod of the four different materials namely: structural steel, titanium alloy, grey cast iron and aluminium 7075 T6 alloy to determine the total deformation, equivalent elastic strain, equivalent Von Mises stress and the safety factor. When the deformations were compared it was found that Al 7075 T6 connecting rod yielded the highest deformation of 0.62979 mm representing 36% of the total deformation of all the four connecting rods. Structural steel connecting rod was found to have yielded the lowest deformation of 0.22733 mm representing 13%. When the stresses were compared it was found that, Titanium alloy and Al 7075 T6 connecting rods yielded the lowest Von Mise stresses of 372.51 MPa and 375.52 MPa respectively. This will boost the local automotive industry in Ghana since the Aluminium 7075 alloy can be obtained locally.

Keywords: Connecting Rod; Reciprocating; Stress; Deformation; Simulation and Material

Introduction

The internal combustion engine consists of different components such as the connecting rod which connects the piston to the crankshaft. The core function of the connecting rod is to transmit force from the piston pin to the crankpin by converting the reciprocating motion of the piston into rotary motion of the crankshaft. The connecting rod has two ends: the big end which connects it to the crank pin and the small end which also connects to the piston by means of the piston pin. The connecting rod has a long shank which can be designed to take the form of rectangular, tubular, circular, I-section and H-section. Circular section is generally used on the slow speed engines while the I-section is used on high-speed engines. According to [10], I-section is both lightweight and strong but the type of material used limits its capacity to handle load. Whereas, H-section can handle much more stress without bending, so, they are used in high power engines. In the view of [4,12], the connecting rod should be able to sustain or be strong enough to withstand buckling load at both x-axis and y-axis. [13], opined that the connecting rod should be such that it can sustain the maximum load without any failure during high cycle fatigue. The connecting rod in the internal combustion engines is subjected to alternating direct compressive and tensile forces. Since the compressive forces are much higher than the tensile forces, therefore the cross-section of the connecting rod is design as a strut and the Rankine's formula is used to determine the dimensions of the connecting rod. With the government of Ghana agenda to industrialise the country and also expand the Automotive industry through the One District One Factory (1D1F) policy, the automotive industry in Ghana is now experiencing tremendous growth with the influx of the automotive assembly plants such as VW, Kantanka and Toyota Ghana

[8]. Furthermore, the Government of Ghana is currently advocating for "Ghana Beyond Aid" agenda, which supports the government's desire to prudently manage the country's natural resources in a manner that will allow the country's development agenda to be financed without recourse to external assistance [8,9]. The ultimate objective of these policies was to position Ghana on the path of industrialisation. Ghana is endowed with abundant natural resources including bauxite. Alumina is obtained from refined bauxite [1], hence, if the design and actualisation of a connecting rod of an internal combustion engine made with local aluminium alloy becomes fit for purpose, then connecting rods made with aluminium alloy can be commercialised using localised materials for production. This would go a long way to support the government of Ghana industrialisation drive. Automobile designers worldwide are working very hard to reduce the weight of the vehicle in order to maximise the efficiency of the vehicle [2]. A reduction in weight of the vehicle will enhance fuel efficiency and increase the speed of the vehicle. The challenge here is, getting an alternative material which is both strong and light in weight to replace the known materials used to manufacture automotive components. The new material should have the same or better properties than the known materials for that component. The connecting rod is well known to be made of steel and its alloys. In the view of [13,17], "connecting rods are most usually made of steel for production engines, but can be made of aluminium for lightness, affordability and it has the ability to absorb high impact". Many researchers have written extensively on connecting rod design and manufacture but little has been said about materials for connecting rod for weight optimisation. [23] share the opinion in their "Design and comparative Performance Analysis of Two-Wheeler Connecting Rod with Silicon Nitride and Aluminium 7068 by Finite element Analysis" that, A connecting rod is an intermediate link between the Piston and the Crankshaft. The primary function of the connecting rod is to transmit the motion from the piston pin to the crank pin, thus converting reciprocating motion of a piston into the rotary motion of crank. Connecting rod plays an important role while designing the Diesel or Petrol Engine. The changes in the material (Al7068 alloy and Si3N4) of the connecting rod to increase its strength to weight ratio while maintaining or reducing the maximum stress, maximum strain and the maximum deformation developed during loading. [18,19] in their study into connecting rod optimisation for weight and cost reduction opined that, to reduce the weight and the manufacturing cost of a forged steel connecting rod subjected to by cyclic load comprising the peak compressive gas load and the peak dynamic tensile load, then there has to be material removal from less stress regions or different material should be considered. The structural factors they considered for weight reduction during the optimization process included fatigue strength, static strength, buckling resistance, bending stiffness, and axial stiffness [20,25]. Additional constraints imposed during the optimisation process included maintaining the forgeability as well as interchangeability of the optimised connecting rod with the existing one [19,22]. In their findings, they found that, Cost was reduced by changing the material of the existing forged steel connecting rod to crackable forged steel (C-70) [24]. Their finding was an admission that, the cost and weight of the connecting rod depends largely on the type of material used. [12,14] conducted a study into analysis and optimising connecting rod for weight and cost reduction and concluded that, to reduce weight and manufacturing cost of steel connecting rod when it is subjected to by cyclic load composing of compressive gas load and the dynamic tensile load at different speed, corresponding with various crank angles. [11,16] indicated that cost was reduced by changing the material of the existing C45 steel connecting rod to C70 steel. The widely used materials in connecting rod manufacturing are carbon steel, cast iron, wrought steel or powder metal. So, there is a scope to try other materials like Titanium alloy, carbon fibre, aluminium alloy, glass fibre etc to produce light weight alternative. As these are light in weight, mass of the part will reduce. Therefore, the connecting rod can be optimised for weight reduction with the use of such materials [7,15]. [6,21] orated in their study into optimisation of connecting rod used in heavy commercial vehicles with the aim of evaluating alternate material for connecting rod manufacturing with lesser stresses and lighter weight. Hence, the decision to assess the suitability of using local aluminium alloy to manufacture connecting rod is very innovative and encouraging for the automotive industry in Ghana.

Method and Material

The material that was selected for this study is Aluminium alloy 7075 which has the composition of 90.0% Al, 5.6% Zn, 2.5%Mg, 0.23% Fe, and 1.6% Cu, though these percentages nominally fluctuate depending upon manufacturing factors. The material has a density of , which is relatively light compared to metals such as structural steel, grey cast iron and Titanium alloy for the purpose of weight and cost optimisation. Aluminium alloy 7075 is one of the strongest aluminium alloys available, making it valuable in high-stress situations [3,24]. The copper content in aluminium 7075 increases its susceptibility to corrosion, but this sacrifice is necessary to make such a strong-yet-workable material. The measure of a material's resistance to deformation is given by its modulus of elasticity (E) and shear modulus (G) [11]. The modulus of elasticity for aluminium 7075 is , and its shear modulus is . Generally, this alloy is strong and resists deformation well, which makes it suitable for applications which needed a tough-yet-light metal. Aluminium 7075 alloy has a tensile yield strength of 480 MPa, which means it takes 480 MPa of stress on a piece of 7075 alloy before it cannot return to its original shape. This value shows the huge benefit of alloying aluminium, and why aluminium 7075 is the best material for structural designs. Table 3.1 shows the properties of the selected material.

The commonly known materials for connecting rod manufacturing are; steel and its alloys, cast iron, Titanium and its alloys and aluminium alloys. For the purpose of this research, analysis of the connecting rod has been based on comparing connecting rod made of gray cast iron, titanium and structural steel to a connecting rod made with aluminium alloy 7075.

Table 1: Properties of the Material (Al 7075 T6).

Parameters	Value	SI Unit
Density	2.81	g/cm^3
Ultimate Tensile Strength	572	MPa
Tensile Yield Strength	480	MPa
Compressive yield Strength	607.9	MPa
Poisson's Ratio	0.33	
Young's Modulus	71.7	GPa
Shear Modulus	26.9	GPa
Shear strength	331	MPa
Thermal Conductivity	196	W/m .K
Fatigue Strength	159	MPa

Table 2: Properties of Cast Iron, Titanium Alloy and Structure Steel.

Materials	Tensile Yield strength (MPa)	Compressive Yield Strength	Tensile strength (MPa)	Density (Kg/m^3)	Poisson's ratio	Young's Modulus (MPa)
Grey Cast Iron	130	943 MPa	200	7196	0.3	170
Titanium Alloy	1207	848 MPa	1276	4840	0.31	116
Structural Steel	540	720 MPa	845	7900	0.3	210

Engine specification and pressure calculations

Vehicle Model: Nissan NP 300 Pickup Double Cab 2.5 litres

Displacement: 2488 cc (cm^3)

Volume per cylinder $= \frac{2488}{4} = 622\ \text{cm}^3 = 622 \times 10^3 \text{mm}^3$

Fuel type: Diesel

Maximum power: 98 Kw at 3600 r. p. m

Maximum Torque: 304 Nm at 2000 r. p. m

Compression ratio: 16.5: 1

Number of Cylinders: 4

Cylinder bore and Stroke: 100 mm × 114 mm

Gearbox: 5 Speed, manual

Pressure developed by the engine

Engine: 2488 cc Diesel 4 in line cylinder (water cooled)

Volume per cylinder $= \frac{2488}{4} = 622\ \text{cm}^3 = 622 \times 10^3 \text{mm}^3$

Density of diesel: $832 \times 10^{-9}\ \text{kg/mm}^3$

Operating temperature(T) $= 210°\text{C}$

Molecular weight of diesel $= 230\ \text{g/mole} = 230 \times 10^{-3}\ \text{kg/mole}$

$$\text{Gas constant (R)of diesel} = \frac{\text{Universal gas constant}}{\text{Molecular weight of diesel}}$$

$$= \frac{8314.3}{230 \times 10^{-3}} = 36.15\ \times 10^3\ \text{J/kgmol}$$

From the ideal gas equation

$$PV = mRT$$

$$P = \frac{mRT}{V}$$

But

$$\text{Density}(\rho) = \frac{\text{mass (m)}}{\text{Volume (v)}}$$

Mass (m) = density of diesel × volume per cylinder

$$= 832 \times 10^{-9} \times 622 \times 10^3 = 0.517504\text{kg} = 51.7504\ \times 10^{-2}\text{kg}$$

Pressure developed in a cylinder (P) $= \frac{51.7504\times10^{-2}\times36.15\times10^{3}\times210}{622\times10^{3}}$

$= \frac{3928631.616}{622\times10^{3}} = 6.32\ \text{N/mm}^2$

Forces acting on the connecting rod

The connecting rod is designed by taking the force of the connecting rod equal to the maximum force on the piston (F_P) due to gas pressure.

$$F_C = F_P = \frac{\pi D^2}{4}\times p = \frac{\pi(100)^2}{4}\times 6.32 = 49637.2\ \text{N}$$

The connecting rod is designed for buckling about x-axis. The factor of safety is taken as 5.5, therefore the buckling load,

$W_B = F_C\times$ F.S = 49637.2 × 5.5 = 273005 N

The radius of gyration of the section about x-axis is;

$$K_{xx} = \sqrt{\frac{I_{xx}}{A}}$$

$$K_{xx} = \sqrt{\frac{419t^4}{12}\times\frac{1}{11t^2}} = 1.78t$$

Length of crank, $r = \frac{\text{Stroke of Piston}}{2} = \frac{114}{2} = 57\ \text{mm}$

Length of the connecting rod is 2 × times the stroke, $l = 228$ mm

According to Rankine's formula, the buckling load about x-axis is:

$$W_B = \frac{\sigma_c\times A}{I+a(\frac{l}{K_{xx}})^2}$$

The compressive yield strength of the Aluminium alloy (Al7075)=607.9 MPa.

The Young' s modulus of the material (Al 7075)=71.7 GPa

$$a = \frac{\sigma_C}{\pi^2\times E} = \frac{607.9\times10^6}{\pi^2\times71.7\times10^9} = \frac{607.9\times10^6}{7.0765\times10^{11}} = 8.59\ \times10^{-4} = 0.000859$$

$$273005 = \frac{607.9\times11t^2}{1+0.000859\,(\frac{228}{1.78t})^2}$$

$$\frac{273005}{607.9} = \frac{11t^2}{1+0.000859(\frac{51984}{3.1684t^2})} = \frac{11t^2}{1+\frac{44.654}{3.1684t^2}}$$

$$449 = \frac{11t^2}{1+\frac{14.09}{t^2}}$$

$$449 = \frac{11t^2}{\frac{t^2+14.095}{t^2}}$$

$$449 = \frac{11t^2\times t^2}{t^2+14.095}$$

$$449(t^2+14.095) = 11t^4$$

$$449t^2 + 6328.66 = 11t^4$$

Dividing through by 11 and rearranging the equation gives:

$$t^4 - 40.82t^2 - 575.33 = 0$$

Using the formula to solve the quadratic equation gives:

$$t^2 = \frac{40.82\pm\sqrt{(40.82)^2+4\times575.33}}{2} = \frac{40.82\pm62.99}{2}$$

$$= 51.905\ (taking + ve\ sign)$$

$$t = \sqrt{51.905} = 7.2\ mm\ say\ 7mm$$

Dimensions of the I-Section of the connecting rod

Thickness of the flange and web of the section t=7 mm

Width of the section, B=4t=4×7=28 mm

Depth of the section H=5t=5×7=35 mm

These dimensions are at the middle of the connecting rod. The width (B) is kept constant throughout the length of the rod, but the depth (H) varies.

The depth near the big end or crank end is kept as 1.1H to 1.25H

H_1 = 1.2H = 1.2 × 35 = 42 mm

The depth near the small end or piston end is kept as 0.75H to 0.9H.

H_2 = 0.85H = 0.85 × 35 = 29.75 mm say 30 mm

Therefore,

Dimensions of the section near the big end = 42 *mm* × 28 *mm* and

Dimensions of the section near the small end =30 *mm* × 28 *mm*

Since the connecting rod is manufactured by forging or casting, therefore, the sharp corners are rounded off.

To determine whether the section chosen is satisfactory, then,

$$\frac{I_{xx}}{I_{yy}} = 3.2.$$

$$I_{xx} = \frac{419}{12}t^4 = \frac{419}{12}\times7^4 = 83834.92\ mm^4$$

$$I_{yy} = \frac{131}{12}t^4 = \frac{131}{12}\times7^4 = 26210.92\ mm^4$$

$$\frac{I_{xx}}{I_{yy}} = \frac{83834.92\ mm^4}{26210.92mm^4} = 3.198 = \mathbf{3.2}$$

This is an indication that the section chosen is satisfactory.

Dimensions of the crankpin or the big end bearing

Taking,

$d_C = Diameter\ of\ the\ crankpin\ or\ big\ end\ bearing$

$l_C = Length\ of\ the\ crankpin\ or\ big\ end\ bearing = 1.3d_C$

$P_{bc} = bearing\ pressure = 10.8\ to\ 12.6\ N/mm^2$

$The\ load\ on\ the\ crank\ pin\ or\ big\ end\ bearing$

$= Projected\ area \times Bearing\ pressure$

$= d_c \times l_c \times P_{bc} = d_C \times 1.3d_C \times 12 = 15.6(d_C)^2$

The crankpin or the big end bearing is designed for maximum gas force , therefore, equating the load on the crankpin or big end bearing to the maximum gas force gives;

$15.6\,(d_C)^2 = F_P = 49637.2$

$(d_C)^2 = \frac{49637.2}{15.6} = 3182$

$Therefore,$

$d_C = \sqrt{3182} = 56.4\ mm \approx 56\ mm$

The length of the crankpin is given as;

$l_C = 1.3d_C = 1.3 \times 56 = 72.8\ mm \approx 73\ mm$

The big end has a removable precision bearing shells or brass or bronze or steel with a thin lining (1 mm or less).

Dimensioning of the piston pin or small end bearing

Taking

$d_p = Diameter\ of\ the\ piston\ pin\ or\ small\ end\ bearing$

$l_p = length\ of\ the\ piston\ pin\ or\ small\ end\ bearing = 2d_p$

$P_{bp} = Bearing\ pressure = 15\ N/mm^2$

$The\ load\ on\ piston\ pin\ or\ small\ end\ bearing$

$= Projected\ area \times Bearing\ pressure$

$= d_p \times l_p \times P_{bp} = d_p \times 2d_p \times 15 = 30(d_p)^2$

The piston pin or the small end bearing is designed for the maximum gas force , therefore, equating the load on the piston pin or the small end bearing to the maximum gas force,

$30(d_p)^2 = 49637.2$

$(d_p)^2 = \frac{49637.2}{30} = 1654.573333$

$d_p = \sqrt{1654.6} = 40.7 \approx 41\ mm$

$l_p = 2d_p = 2 \times 41 = 82\ mm$

The small end bearing is usually a phosphor bronze bush of about 3 mm thickness.

Determination of the outer diameters of big end and small end

$The\ inner\ diameter\ of\ the\ Big\ End\ (D_{in})$

$= The\ diamter\ of\ crankpin\ (d_c) + Thickness\ of\ the\ bush\ (t_b)$

$The\ inner\ diameter\ of\ the\ Big\ End\ (D_{in}) = 56 + 2 = 58\ mm$

Taking:

$Marginal\ thickness\ (t_m) = 5\ to\ 15\ mm$

$Bolt\ diameter (d_b) = 17\ mm$

$Thickness\ of\ the\ bush\ (t_b) = 2\ to\ 5mm$

$Diameter\ of\ the\ crankpin\ (d_c) = 56\ mm$

$The\ outer\ diameter\ of\ the\ big\ end\ (D_{out})$

$= d_c + 2t_b + 2d_b + 2t_m$

$= 56 + 2 \times 2 + 2 \times 17 + 2 \times 5 = 56 + 4 + 34 + 10$

$= 104\ mm$

$The\ inner\ diameter\ of\ the\ Small\ End\ (d_{in})$

$= The\ diamter\ of\ piston\ pin\ (d_p) + Thickness\ of\ the\ bush\ (t_b)$

$The\ inner\ diameter\ of\ the\ Small\ End\ (d_{in})$

$= 41 + 2 = 43\ mm$

$The\ outer\ diameter\ of\ the\ small\ end\ (d_{out})$

$= d_p + 2t_b + 2t_m = 41 + 2 \times 2 + 2 \times 5$

$= 41 + 4 + 10 = 55\ mm$

Table 3: Specifications of the connecting rod.

Serial No.	Connecting Rod Parameters (mm)
1	*Thickness of the connecting rod (t)=7*
2	*Width of the section (B=4t)=28*
3	*Height of the section (H=5t)=35*
4	*Height at the Big End (H_1=1.2H=42*
5	*Height at the small end(H_2)=0.85H=30*
6	*Inner diameter of the Small End=43*
7	*Outer diameter of the Small End =55*
8	*Inner diameter of the Big End=58*
9	*Outer diameter of the Big End=104*
10	*Diameter of the bolt=17*
11	*Thickness of the big end cap=17*
12	*Length of connecting rod=228*
13	*Crank pin diameter=56*
14	*Length of crank pin=73*
15	*Piston pin diameter=41*
16	*Length of piston pin=81*

Procedure for the numerical methods

This section of the study presents the procedure for the numerical methods which includes: meshing of the component, grid independence test and the boundary conditions set for this study.

Meshing of component

Meshing is very important step in static structural analysis process. Meshing is an integral part of the engineering simulation process where complex geometries are divided into simple elements that can be used as discrete local approximations of the larger domain. The mesh influences the accuracy, convergence and speed of the simulation. If meshing is accurate, then the results are also anticipated to be feasible. The meshing details of the model connecting rods are: number of nodes 22570 and element size 12764. The meshing of the Nissan Pickup connecting rod is as shown in figure 1.

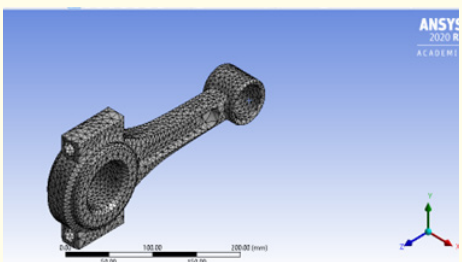

Figure 1: Connecting rod Meshed in Ansys.

The boundary conditions set for the analysis

Analysis of the connecting rods made with four different materials was done in Ansys software version 2020 R2 using static structural analysis. The big end of the connecting rod was constraint (fixed) and a compressive load of 49637.2 N was applied at the small end portion of the connecting rod. Compressive load was considered because, connecting rods are designed for the maximum gas load acting on the piston. This load subject the connecting rod to compression, the connecting rod comes under tension due to the inertial of the reciprocating and rotating parts of the engine. The calculated maximum gas load for the engine which connecting rod is under consideration is 49637.2N. The parameters that were considered during the static structural analysis were: total deformation, equivalent elastic strain, equivalent (Von Mises) stress and safety factor of the four (4) materials assigned to the model.

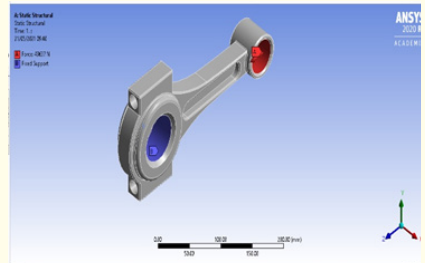

Figure 2: The boundary condition for the analysis.

Presentation of Results and Discussion

Titanium alloy material

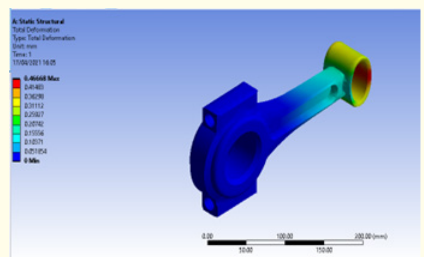

Figure 3: Total Deformation of Titanium Alloy Material.

The Total maximum deformation induced in the titanium alloy connecting rod when a compressive load of 49637.2N was applied is 0.46668 mm. Titanium has a percentage reduction of 23% which is far greater than the induced deformation when the load was applied. So, the model will remain safe with the induced deformation in the titanium alloy connecting rod. The maximum deformation was observed to have occurred at the small end of the titanium alloy connecting rod where the load was applied. The big end of the connecting rod did not suffer any visible form of deformation as shown in figure 3.

The magnitudes of the maximum and minimum equivalent elastic strain induced in the model titanium alloy connecting rod are 0.0039991and respectively for the given loading condition. It was observed that the equivalent elastic strain in the model connecting rod was more pronounce at the piston end of the connecting rod. The big end of the connecting rod experienced the minimum elastic strain as shown in figure 4.

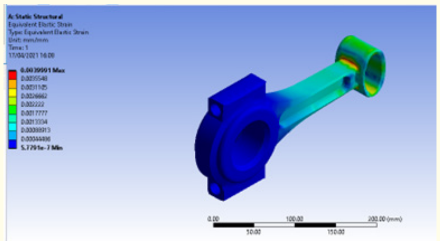

Figure 4: Equivalent Elastic Strain of Titanium Alloy Material.

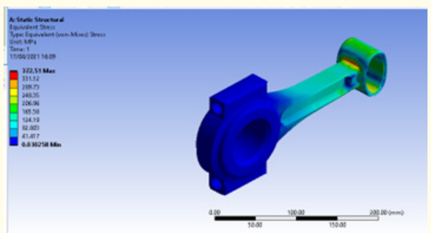

Figure 5: Equivalent (Von Mises) Stress of Titanium Alloy Material.

The maximum equivalent (Von Mises) stress induced in the titanium alloy connecting rod has a magnitude of 372.57 MPa for the given loading condition. The compressive yield strength of titanium alloy is 848 MPa. The stress distribution in the titanium alloy connecting rod was observed to be high at the piston end of the connecting rod and reduces gradually towards the big end of the connecting rod. The big end of the connecting rod was observed to have the minimum induced Von Mises stress as shown in figure 5. The induced stresses in the titanium alloy connecting rod are far lower compared to compressive yield strength of the titanium alloy material. The model can therefore be considered to be fit for purpose since it can withstand the given load imposed on the connecting rod.

The theoritical factor of safety value for connecting rods is 5.5. The Ansys generated factor of safety for titanium alloy connecting rod madel has a maximum and minimun factor of safety range magnitudes of 15 and 2.4966 respectively. The big end of the titanium alloy connecting rod was observed to have a higher factor of safety than the small end of the connecting rod where the load was applied as shown in figure 6. The theoritical factor of safety value of 5.5 was found to be within the range of factor of safety values generated by Ansys. The model is therefore very safe.

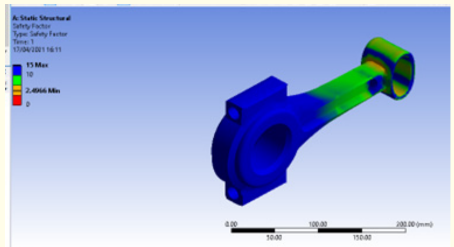

Figure 6: Factor of Safety of Titanium Alloy Material.

Table 4: Summary Results for Titanium Alloy material.

Parameters	Maximum	Minimum
Total deformation	0.46668 mm	0.051854 mm
Equivalent Elastic Strain	0.0039991 mm	5.779×10^{-7} mm
Equivalent Von Mises Stress	372.57 MPa	0.030258 MPa
Factor of Safety	15	2.4966

Table 4 shows a summary of the results obtained when static structural analysis was conducted on the model titanium alloy connecting rod.

Structural Steel material

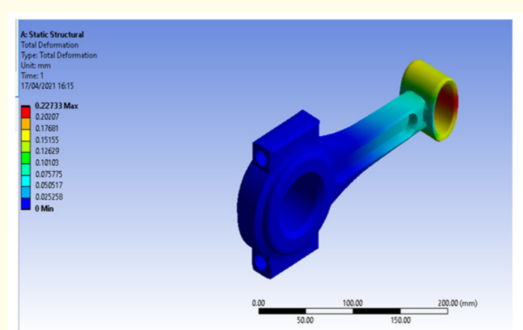

Figure 7: Total Deformation of Structural Steel Material.

The Total maximum deformation induced in the model structural steel connecting rod when a compressive load of 49637.2N was applied at the small end is 0.22733 mm. Structural Steel has a percentage elongation or reduction of 21% which is far greater than the induced deformation of the connecting rod when the compressive load was applied. It was observed from figure 7 that, minimum deformation occurred at the big end of the structural steel connecting rod. The deformation was pronounced at the small end of the structural steel connecting rod where the compressive load was applied. So, the structural steel connecting rod will remain safe with the induced total deformation.

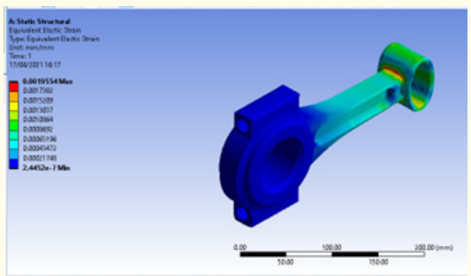

Figure 8: Equivalent Elast Strain of Structural Steel Material.

The magnitudes of maximum and minimum equivalent elastic strain induced in the model structural steel connecting rod are 0.001955 and respectively for the given loading condition. It was observed that the equivalent elastic strain was more pronounced at the small end of the connecting rod. The big end of the structural steel connecting rod was observed to have suffered the least equivalent elastic strain as shown in figure 8.

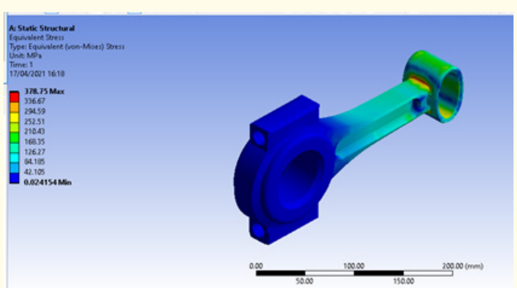

Figure 9: Equivalent (Von Mises) Stress of Structural Steel Material.

The maximum equivalent (Von Mises) stress induced in the structural steel connecting rod has a maximum magnitude of 378.75 MPa for the given loading condition. The compressive yield strength of Structural Steel is 920 MPa. The stress distribution in the structural steel connecting rod was lower at the big end of the connecting rod. It was observed that the maximum stress occurred at the small end of the connecting rod where the compressive load was applied as shown in figure 9. The induced Von Mises stress is lower compared to the compressive yield strength of the Structural Steel material. For material optimisation, material can be removed from the big end of the structural steel connecting rod for improve weight and cost reduction. The model can therefore be considered to be fit for purpose since it can withstand the given loading condition.

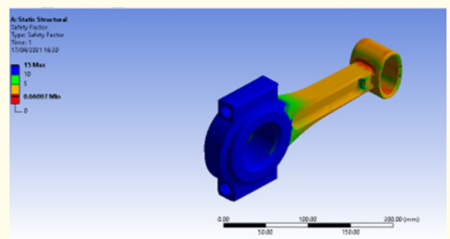

Figure 10: Safety Factor of Structural Steel Material.

Generally, the theoritical factor of safety value for connecting rod is 5.5. The Ansys generated factor of safety of the structural steel connecting rod madel has a maximum and minimun factor of safety magnitudes of 15 and 0.66007 respectively. The maximum factor of safety was observed to be more pronounced at the big end of the connecting rod as shown in figure 10. The theoritical factor of safety value of 5.5 is within the range of factor of safeties of the model structure steel connecting rod generated by the Ansys. The model is therefore very safe.

Table 5 shows a summary of the results obtained when static structural analysis was conducted on the model structural steel connecting rod.

Table 5: Results for Structural Steel material.

Parameters	Maximum	Minimum
Total deformation	0.22733 mm	0.025258 mm
Equivalent Elastic Strain	0.001955 mm	2.4452×10^{-7} mm
Equivalent Von Mises Stress	378.75 MPa	0.024153 MPa
Factor of Safety	15	0.66007

Gray cast iron material

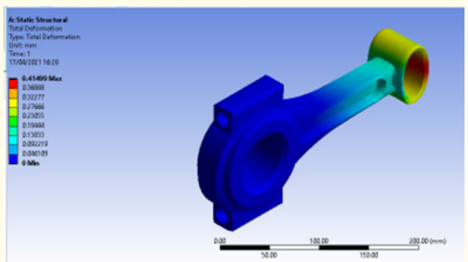

Figure 11: Total Deformation of Gray Cast Iron Material.

The total maximum deformation induced in the gray cast iron connecting rod when a compressive load of 49637.2N was applied is 0.41499 mm. Gray cast iron has a percentage reduction of 15% which is greater than the induced total deformation when the compressive load was applied. So, the model gray cast iron connecting rod will remain safe with the induced total deformation in the connecting rod. The maximum deformation was observed to have occurred at the small end of the gray cast iron connecting rod where the compressive load was applied. The big end of the gray cast iron connecting rod suffered the least deformation as shown in figure 11.

The magnitudes of maximum and minimum equivalent elastic strain induced in the model gray cast iron connecting rod are 0.003579 and respectively for the given loading condition. It was observed that the equivalent elastic strain in the model connecting rod was lower at the big end of the gray cast iron connecting rod. The piston pin end of the connecting rod was observed to have suffered the greatest equivalent elastic strain as shown in figure 12.

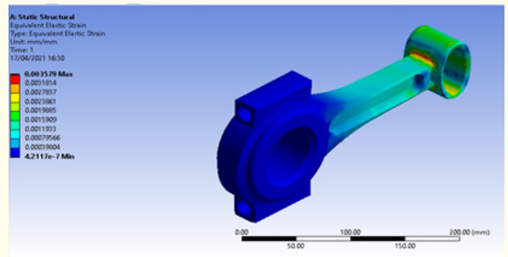

Figure 12: Equivalent Elastic Strain of Gray Cast Iron material.

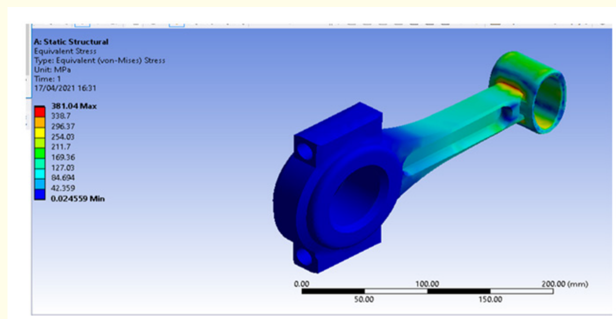

Figure 13: Equivalent (Von Mises) Stress of Gray Cast Iron Material.

The maximum equivalent (Von Mises) stress induced in the gray cast iron connecting rod has a maximum magnitude of 381.04 MPa for the given loading condition. The average compressive yield strength of gray cast iron is 943 MPa. The induced Von Mises stress in the gray cast iron connecting rod is lower compared to the average compressive yield strength of the gray cast iron material. It was also observed that the induce Von Mises stress was maximum at the piston pin end while the big end of the connecting rod suffered the least inducement of Von Mises stress as shown in figure 13. The big end of the gray cast iron connecting rod was not greatly affected by the compressive load imposed on the connecting rod. For material optimisation, material can be removed from the big end of the gray cast iron connecting rod for improve weight and cost reduction. The model can therefore be considered to be fit for purpose since it can withstand the given loading condition.

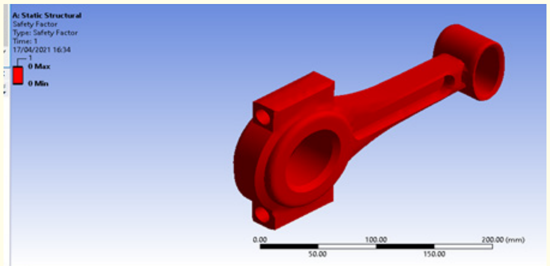

Figure 14: Safety Factor of Gray Cast Iron Material.

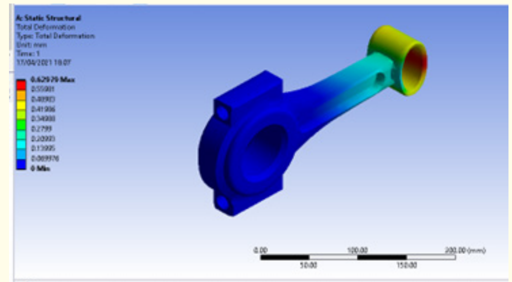

Figure 15: Total Deformation of Aluminium 7075 T6 Alloy.

Connecting rods are designed to have a theoritical factor of safety value of 5.5. The Ansys generated factor of safety of the modal gray cast iron connecting rod has a maximum and minimun factor of safety magnitudes of 0 and 0 respectively. It was obseverd that, the entired connecting rod has no factor of safety as shown in figure 14. The theoritical factor of safety value of connecting rod of 5.5 is greater than the range of factor of safety generated by Ansys. The model is therefore not safe if the factor of safety of the model gray cast iron connecting were to be considered.

Table 6: Results for Grey Cast Iron Material.

Parameters	Maximum	Minimum
Total deformation	0.41499 mm	0.046109 mm
Equivalent Elastic Strain	0.003579 mm	4.2117×10^{-7} mm
Equivalent Von Mises Stress	381.04 MPa	0.024559 MPa
Factor of Safety	0	0

Table 6 shows a summary of the results obtained when static structural analysis was conducted on the model gray cast iron connecting rod of a Nissan pick up engine.

Aluminium 7075 T6 alloy material

The total maximum deformation induced in the aluminium 7075 T6 alloy connecting rod when a compressive load of 49637.2N was applied is 0.62979 mm. Aluminium 7075 T6 alloy material has a maximum percentage reduction of 25% which is far greater than the induced deformation in the connecting rod when the compressive load was applied. Figure 15 shows that the induced deformation was maximum at the piston pin end of the connecting rod. The big end of the aluminium 7075 T6 alloy connecting rod suffered the minimum deformation as shown in figure 15. The total deformation suffered by the connecting rod when the compressive load was applied was less than the percentage reduction of aluminium 7075 T6 alloy material. Hence, the model will remain safe with the induced total deformation in the aluminium 7075 T6 alloy connecting rod.

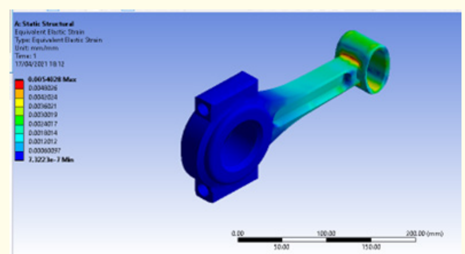

Figure 16: Equivalent Elastic Strain of Aluminium 7075 T6 Alloy.

The magnitudes of maximum and minimum equivalent elastic strain induced in the model aluminium 7075 T6 alloy connecting rod are 0.0054028 and respectively for the given loading condition. It was observed that the equivalent elastic strain in the model aluminium 7075 T6 alloy connecting rod was maximum at the piston pin end of the connecting rod as shown in figure 16. This was anticipated since it was the piston pin end that suffered the maximum deformation. The big end of the connecting rod suffered the minimum equivalent elastic strain as shown in figure 16.

The maximum equivalent (Von Mises) stress induced in the aluminium 7075 T6 alloy connecting rod has a maximum magnitude

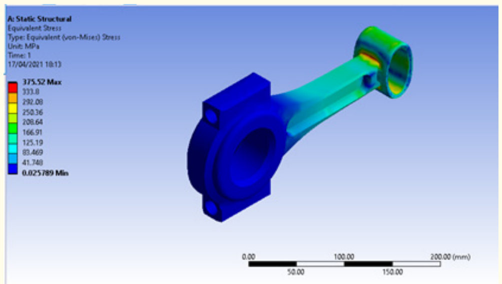

Figure 17: Equivalent Stress of Aluminium 7075 T6 Alloy Material.

of 375.52 MPa for the given loading condition. The compressive yield strength of aluminium 7075 T6 alloy material is 607.9 MPa. The induced Von Mises stress is lower compared to the compressive yield strength of the aluminium 7075 T6 alloy material. It was also observed that the induce Von Mises stress was only experience at the small end where the compressive load was applied through to the shank of aluminium 7075 T6 alloy connecting rod. The big end of the connecting rod was not greatly affected by the compressive load imposed on the connecting rod as shown in figure 17. For material optimisation, material can be removed from the big end of the aluminium 7075 T6 alloy connecting rod for improve weight and cost reduction. The model aluminium 7075 T6 alloy connecting rod can therefore be considered to be safe since it can withstand the given loading condition.

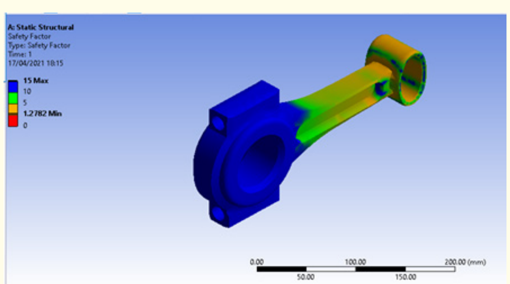

Figure 18: Safety Factor of Aluminium 7075 T6 Alloy Material.

Theoritical value of factor of safety for Connecting rods design is 5.5. The Ansys generated factor of safety of the modal aluminium 7075 T6 alloy connecting rod has a maximum and minimun factor of safety magnitudes of 15 and 1.2782 respectively. It was observed that the maximum factor of safety occurred at the big end of the connecting rod while the small end and the shank of the connecting rod was observed to have lower factor of safety as shown in figure 18. The theoritical factor of safety value of connecting rod of 5.5 falls within the range of factor of safety values generated by Ansys. The model aluminium 7075 T6 alloy connecting rod is therefore safe if the factor of safety of the material were to be considered.

Table 7: Results for Aluminium 7075 T6 Material.

Parameters	Maximum	Minimum
Total deformation	0.62979 mm	0.069976 mm
Equivalent Elastic Strain	0.0054028 mm	7.3223×10^{-7} mm
Equivalent Von Mises Stress	375.52 MPa	0.025789 MPa
Factor of Safety	15	1.2782

Table 7 shows a summary of the results obtained when static structural analysis was conducted on the model Al 7075 T6 alloy connecting rod of a Nissan pick up engine.

Comparison of static structural analysis results

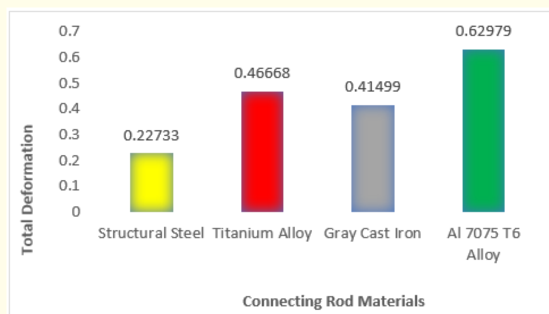

Figure 19: Summarised Results for Total Deformation.

The total deformation results of the static structural analysis of the connecting rods of the four different materials are as shown in figure 19. The static structural results presented in figure 19 shows a total deformation for Structural Steel connecting rod as 0.22733 mm, Titanium alloy connecting rod 0.46668 mm, gray cast iron connecting rod 0.41499 mm and aluminium 7075 T6 alloy connecting rod 0.62979 mm. It was observed that, structural steel connecting rod deformed less compared to the other three connecting rods of the four different materials. Aluminium 7075 T6 alloy (implementing material) connecting rod was observed to have deformed more than all the other connecting rods of the three different materials and in all cases as shown in figure 19, it was also observed that minimum deformation occurred at the big end of the connecting rods. Maximum deformation was observed to be more pronounced at the piston end of the connecting rods where the compressive load was applied in all cases.

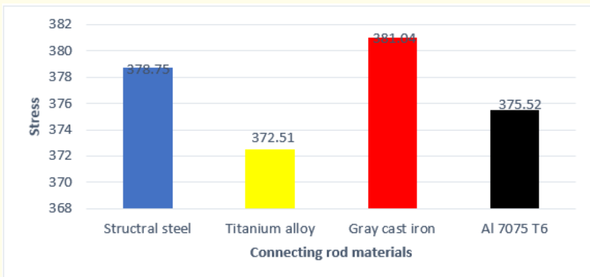

Figure 20: Summarised Results for Von Mise Stresses.

Figure 20 presents the results of the equivalent Von Mise stresses of the model connecting rods of the four different materials. One of the most critical parameters for this study is the Von Mise stress. This is one of the parameters that was used to determine whether the connecting rods will either fail or not when compared with the yield strengths of the materials. When the induced equivalent (Von Mises) stress is equal or more than the yield strength of the material, then the connecting rod of that material cannot withstand the loading condition, hence the design will fail. From figure 20, when the Von Mise stresses induced in the connecting rods of the four different materials were compared, the figure show that the induced stresses in the connecting rods are: Structural steel connecting rod yielded 378.75 MPa of stress, Titanium alloy connecting rod yielded 372.51 MPa of stress, Gray cast iron connecting rod yielded 381.04 MPa of stress and Aluminium 7075 T6 alloy connecting rod yielded 375.52 MPa of stress. The compressive yield strengths of the materials are: structural steel 920 MPa, titanium alloy 848 MPa, gray cast iron 943 MPa and aluminium 7075 T6 alloy 607.9 MPa. In terms of ranking, the results show that, Titanium alloy connecting rod has the least induced equivalent Von Mise stress of 372.51 MPa followed closely by Aluminium 7075 T6 alloy connecting rod of 375.52 MPa, Structural steel connecting rod of 378.75 MPa and Gray cast iron connecting of 381.04 MPa respectively. Titanium alloy and aluminium 7075 T6 alloy connecting rods were observed to have the best Von Mise stresses than the connecting rods of the two other materials because, titanium and Aluminium alloys are very elastic in nature and has the tendency to distribute the effects of the load evenly in the connecting rod thereby distributing the induced stresses as well, hence their abilities to endure or resist stresses than the other two materials. All the connecting rods of the four materials were observed to have their induced Von Mise stresses to be far lower than their yield strengths.

Table 8: Factor of Safeties for the Connecting Rods of Four Different Materials.

Materials	Safety Factor	
	Maximum	Minimum
Structural Steel		
Titanium Alloy		
Gray Cast Iron		
Aluminium 7075 T6 Alloy		

Table 8 revealed that, the range of factor of safety values for the connecting rods of the four different materials are: Structural steel connecting rod has the best factor of safety values ranging from 0.66007 to 15 followed by Aluminium 7075 T6 alloy connecting rod which also have factor of safety values ranging from 1.2782 to 15 compared to Titanium alloy which also have very safe factor of safety values ranging from 2.4966 to 15. In terms of factor of safety, gray cast iron is the most dangerous material. The material has zero factor of safety values.

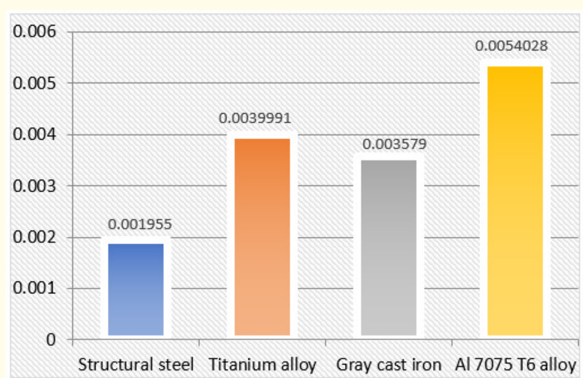

Figure 21: Summarised Results for Equivalent Elastic Strains.

The results of the equivalent elastic strains of the connecting rod of the four different materials were presented in the graph as shown in figure 21. When the equivalent elastic strains of the connecting rods of the four different materials were compared in figure 21, the results show that, the equivalent elastic strain for the connecting rods of Structural steel is 0.001955 representing 13% of the total elastic strain of the connecting rod for the four materials, Titanium alloy is 0.0039991 representing 27% of the total elastic strain of the connecting rod for the four materials, Gray cast iron is 0.003579 representing 24% of the total elastic strain of the connecting rod for the four materials and aluminium 7075 T6 alloy is 0.0054028 representing 36% of the total elastic strain of the connecting rod for the four materials. It was also observed from Figure 21 that, Structural steel connecting rod has the least equivalent strain followed by Gray cast iron connecting rod, titanium alloy and aluminium 7075 T6 connecting rods respectively. Gray cast iron connecting rod came close to structural steel because the material is brittle and under the given loading condition its deformation and strain will not be visible enough. Since aluminium 7075 T6 alloy connecting rod was the worst affected in terms of deformation, it was therefore obvious that it will have the largest strain since strain and deformation are very closely related or strain depends on the extent of deformation.

Conclusions

The parameters that were considered under the static structural analysis were: total deformation, equivalent elastic strain, equivalent Von Mises stress and the factor of safety of the four connecting rods made with titanium alloy, gray cast iron, structural steel and aluminium 7075 T6 alloy respectively. Both compressive and tensile loads act on the connecting rod but the compressive loads are much greater than the tensile loads, therefore the connecting rod was designed for the compressive load. Since, the connecting rod is hinged at both ends by piston pin and crank pin and experiences compressive load, therefore it can be said that it behaves like a strut. The main objective of this project was to determine the possibility of using local aluminium alloy material to design and manufacture a connecting rod for weight optimisation without losing the strength of the connecting rod. The connecting rod was modelled using Autodesk inventor 2017 software using the calculated dimensions. The dimensioning of the connecting rod was obtained through systematic and rigorous calculations based on theoretically empirical formulars for connecting rod design. The drawing interface of the Autodesk inventor was lunched and the connecting rod was modelled based on the dimensions generated in a 2D format and later converted through extrusion into a 3D format. The 3D connecting rod was save in an imported stp (step) format for easy importation into Ansys. The analysis of the connecting rod was done using Ansys 2020R2 student's software. The connecting rod in the Ansys was subjected to a compressive calculated load of 49637.2 N. Then Finite Element Analysis technique was used to determine the total deformation, directional deformation, equivalent elastic strain, equivalent Von Mises stress, maximum and minimum principal stress and factor of safety of the connecting rod of the four different materials and compared. The results of the analysis showed that, the stresses induced in the four connecting rods which were made of different materials were far below the yield strengths of the materials. Hence, it can be concluded that all the connecting rods of the four different materials can withstand the compressive gas loads that was imposed on them. It was also found that, Al 7075 T6 connecting rod has the highest deformation of 0.62979 mm representing 36% which was more than all the other connecting rods. Structural steel connecting rod was found to have the lowest deformation of 0.22733 mm representing 13%. The results were validated by using the implementing material (Al 7075 T6 alloy) to fabricate a connecting rod and were tested using tensile test machine to determine the strength of the connecting rod. The test result was then compared to an existing connecting rod made with steel and it showed that both connecting rods are strong. The weights of the connecting rods were also compared and the result showed that the weight of aluminium 7075 T6 alloy connecting rod is 48% lower than the connecting rod made with steel. The total cost of manufacturing the connecting rod made with aluminium 7075 T6 material was GH₵ 65 which is lower compared to steel connecting rod which cost GH₵120 on the market. There is a cost savings of GH₵55 when the connecting rod of aluminium 7075 T6 material is considered.

Data Availability Statement

The numerical model simulations of the modified connecting rod upon which this study was based on are too large to or transfer. Therefore, the authors wish to provide all the necessary information which will make it possible for the replication of the simulations. The design specifications of the connecting rod were generated from empirical formulas and outline in Table 3. Based on the specifications, the connecting rod was modelled in an Autodesk inventor version 2017 and saved in CAD format step (stp) file extension. The modelled connecting rod was imported into Ansys software version 2020R2 to determine the parameters set for this study considering the boundary conditions as shown in Figures 2. The connecting rod was meshed in the Ansys software as shown in Figure 1 with a defeature size of 3mm and a resolution of 5. The data upon which the analyses of this study was based on can be accessed by following the above outlined procedure.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

Bibliography

1. Aluworks Ghana. "Chairman's Statement of Address" (2019).
2. Biradar A., *et al*. "Analysis and Optimisation of Connecting Rod used in Heavy Commercial Vehicles". *International Journal of Engineering Development and Research (IJEDR)* 5.3 (2017).
3. Davis JR. "Alloying: Understanding the Basics" (2019).
4. Khurmi R S and Gupta J K. "Theory of Machine, First Edition". Eurasia Publishing House (PVT) Ltd. Ram Nagar, New Delhi (2005).
5. Khurmi R S and Gupta J K. "Textbook of Machine Design, First Multi-Colour Edition". Eurasia Publishing House (PVT) Ltd. Ram Nagar, New Delhi.
6. Leela Krishna V and Venu G V. "Design and Analysis of Connecting Rod using Forged Steel". *International Journal of Scientific and Engineering Research* 4.6 (2013).
7. Malleshwara NR. "Design optimisation and analysis of a Connecting Rod using ANSYS". *International Journal of Science and Research (IJSR),* India (2013).
8. Ministry of Trade and Industry. The Ghana Automotive Development Policy.www.Moti.gov.gh. (2019).
9. Ministry of Trade and Industry. Ghana Beyond Aid. 7beyond-aid-agenda. (2019).
10. Mohankumar D and Rakesh L. "Design and Analysis of Connecting Rod". I*nternational Journal of Pure and Applied Mathematics* (2017): 105-109.
11. Mohamed AH., *et al*. "Design and Analysis of Connecting rod using Aluminium Alloy 7068 T6, T6 511". *International Journal of Mechanical Engineering and Technology (IJMET)* 5.10 (2014): 57-69.
12. Nachimuthu A. K., *et al*. "Analysis and Optimising Connecting Rod for Weight and Cost Reduction". *International Journal of Research and Innovation in Engineering Technology* (2014): 1-7.
13. Nitturkar HD., *et al*. "Design and Analysis Connecting Rod Using Different Materials". *International Research Journal of Engineering and Technology (IRJET)* (2020).
14. Nilam P., *et al*. "Design and Analysis of Connecting Rod for Weight Reduction in Case of CI Engine". *International Journal of Engineering Sciences and Research Technology* (2017).
15. Noor MM., *et al*. "Analysis of Connecting Rod Based on Finite Element Approach. Malaysia Technical Universities Conference on Engineering and Technology". Putra Palace (2008).
16. OmPrakash S., *et al*. "Optimisation of Connecting Rod for Weight Reduction by Finite Element Analysis". *International Research Journal of Automotive Technology (IRJAT)* (2018): 80-87.
17. Palamisamy S., *et al*. "Improvement of Various Parameters in Different Application of Connecting Rod". *Journal of Applied Sciences Research* (2015): 30-33.
18. Pravardhan S and Ali Fatemi. "Connecting Rod Optimisation for Weight and Cost Reduction". SAE International, the University of Toledo (2015): 01-0987.
19. Prof. Doshi N P and Prof. Ingole NK. "Analysis of Connecting Rod using Analytical and Finite Element Method". *International Journal of Modern Engineering Research (IJMER)* 3.1 (2013): 65-68.
20. Raviraj Y T and Abhay A U. "Analysis of connecting Rod used in Two-Wheeler Under Static Loading by FEA". *International Journal of Engineering Trends and Technology (IJETT)* 20.1 (2015): 27-34.

21. Sumit D and Ankit C. "Weight Optimisation of Connecting Rod of Internal Combustion Engine Using Finite Element Analysis". *International Journal for Research Trends and Innovation (IJRTI)* (2019).

22. Srihersha B and Sudhakar Rao P. "Design Consideration for Connecting Rod". *International Journal of Engineering and Advance Technology (IJEAT)* (2020).

23. Tanya Buddi., *et al*. "Fabrication and finite element analysis of two-wheeler connecting rod using reinforced aluminium matrix composites Al7068 and Si3N4". *Materials Today: Proceedings* 44 (2021): 2471-2477.

24. The aluminium Association, Inc. Aluminium Selection and Applications. Washington D. C. 20006, 900 19th Street, N. W. Suite 300 (1998).

25. Venkatesh S., *et al*. "Design and Analysis of Connecting Rod with Modified Materials and FEA Analysis". *International Journal of Engineering Research and Technology (IJERT)* (2014).