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Buckling Analysis and Shape Optimization of Connecting Rod using FEA

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Abstract

In a reciprocating engine, the connecting rod is a one of the most dynamic component of a vehicle that are bear static and dynamic fluctuation of various loads. In operation, the connecting rod is subjected to various complex loads of periodic changes: power thrust from piston pin, high tensile load due to inertia and high compression load due to compression of fuel, whereas bending stress caused by the thrust and by centrifugal effects. In the present investigation, a buckling analysis of connecting rod made up of forged steel used in SUZUKI SPRINT1.0L engine is conducted. This connecting rod is available for import, domestic and vintage. After measuring all dimension of connecting rod, the geometric models were developed using CATIA V5 for buckling analysis and it was analyzed in ANSYS 15 workbench that provides a highly interactive and visual environment to analyze product design performance. Therefore, this study has dealt with gradually changing the cross-sectional area of the connecting rod to perform buckling analysis at varying load and stress conditions. For this analysis, drawing the conclusion that the stress induced at the bigger end of the connecting rod is greater than the smaller end. Therefore, the shifting the stress from the smaller cross sectional area to the middle of the connecting rod by gradually reducing the cross-sectional area of the shank. The topology is used to achieve the objective of optimization in order to improve the shape of the connecting rod.

Keywords: ANSYS 15, Connecting rod, forged steel, modeling, stress analysis, weight reduction.

1. Introduction

Cconnecting rod is a dynamic component of internal combustion engine, and it is subjected to time-varying axial and bending loads. The working principle of connecting rod is very much complex, that it is often subjected to complex loads such as power thrust from piston pin, inertia force, and high compression loads. The connecting rod has to be designed in such a way so that it should withstand these various complex and cyclic loading conditions. Hence, the connecting rod must have good mechanical properties like strength and rigidity as well as should be light in weight. The basic function of connecting rod is to transmit the thrust of a piston to the crankshaft, by translating the reciprocating motion to rotational motion. In an internal combustion engine, connecting rod forms a part of 4 bar mechanism when it functions inside the engine. It consists of two ends, bigger end which connects the crankshaft and the small end which connects the piston. In every stroke connecting rod undertake a different alternating load. The main components of connecting rod are a shank, the small end, and the big end. The cross section of the shank may be circular, rectangular, tubular, I-section, H-section, ellipsoidal section etc. I-section is generally used in high-speed engines whereas the circular section is used in low-speed engines[1]. The selected materials for the forging process should possess excellent mechanical properties such as hardness, rigidity, tensile and fatigue strength. The load applied being cyclic in nature, the main cause of failure of the connecting rod is due to fatigue. Poor design, improper material selection or fabrication defects are the major contributors to the failure of connecting rod. Thus, damage occurs mostly in certain parts of the connecting rod such as the crank pin, smaller end of the connecting rod, roller bearing and the connecting rod bolt[2] . These processes provide various advantages to the product such as improved product quality, efficiency, a significant reduction in cost and energy[3], and some of the studies were also focused on fatigue failure and yielding of connecting rod since it should be able to withstand a large repetitive compressive and tensile load[4]. Stresses of higher magnitudes are generated from the cyclic loading exerted by the piston which extends and compresses in every rotation. The effect increases with increase in load and increasing the speed of engine. Therefore, the component requires thorough designing under static, dynamic and reciprocating loadings[5]. In connecting rod, an only specific section was optimized by reducing the cross-sectional area of the shank, which left the necessity of modeling with actual boundary conditions and the mechanical properties such as stiffness, durability, and resistance which can be numerically analyzed with varying loads and stress conditions. The number of factors influenced the fatigue life of a connecting rod in service, such that complex stress cycle; engineering design, service condition, manufacturing, and material of construction [6]. The finite element analysis approach was adopted in structural analysis to overcome the geometry and all boundary conditions. In the finite element optimization of structure performed the cumulative damage analysis including the cyclic loading for fatigue life calculation [7]. The shape optimization approach of connecting rod subjected to a load cycle consisting of dynamic loads such as compressive load and tensile load, through its stresses at all sections of connecting rod and displacements observed by finite element analysis and fatigue life constrained based on fracture mechanics [8]. While the yielding and fatigue were concerned the significance of buckling was mostly observed in the optimal design of connecting rod and the issue of buckling became substantial in weight reduction of shank part and optimization included the simple linear buckling analysis [9]. The buckling evaluation of connecting rod progressively attracted the attention of automakers, in finite element analysis buckling analysis for the optimal shank; it effectively generated the model of connecting rod. The connecting rod can be considered as a column, subjected to buckling, which has considerable length in proportion to its width, depth and diameter. The critical buckling load of the elastic/plastic beam-column was studied by V. B. Bhandari [10]. The Rankine formula was used to describe the conventional closed-form solution for the critical buckling load of connecting rod, which is the harmonic mean of the yield strength and Euler equation [11]. In case of buckling in connecting rod, there is no such lateral deflection till the load reaches the critical load. The important parameter affecting the critical load is the slenderness ratio. In Finite Element analysis, an enhanced formula is proposed for buckling evaluation in the gradually changing the cross-sectional area of the shank and modify the shape of connecting rod. Reference buckling stress solutions are obtained by performing optimization technique in ANSYS Workbench. We examine the stresses being distributed all over the sections of connecting rod and shank in lights of yield, fatigue, and buckling. The boundary conditions in the front-rear direction were different from those in left and right side direction of connecting as rod shown in Fig. 1. These dissimilar boundary conditions limit the application of Euler equations. There are two practical buckling modes of connecting rod, first mode called “side buckling” occurs in the direction parallel to the rotational axis of the connecting rod and other mode called “front-rear buckling” occurs in the direction perpendicular to side buckling.

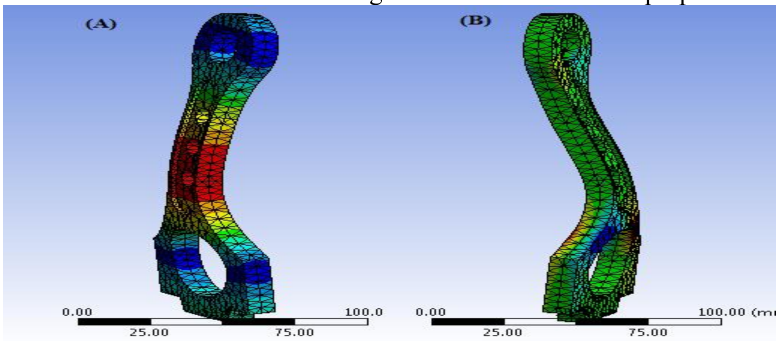

Fig. 1. Buckling modes of the connecting rod: (a) side buckling and (b) front-rear buckling

2. Literature review

Folgar et al. [12] did Fabrication and Performance of Fiber FP/Metal Matrix Composite Connecting Rods. In this, the connecting rod was developed for high-performance automotive applications by using different materials like aluminum and magnesium reinforced with fiber FP. The connecting rod had being selected as the model to develop a design, fabrication technology and the value of these reinforced casting. They were studied to predict the structural behavior of connecting rod using two or three-dimensional FEA modeling and the result of analysis were matched well and closely with static and fatigue testing of FP/Aluminium and FP/Magnesium cast of connecting rod. R. K. Gupta [13] did Recent Developments in Materials and Processes for Automotive Connecting rods. In this, the connecting rod was made up ferrous alloys and it was made by casting and drop forging with reduced the automobile weight, more power intensive and with well-balanced components. They were also a reduction manufacturing and finished processes, reducing the loss of material as chips, and also reducing the labor requirements. S. Shenoy and A. Fatima [14] did Dynamic analysis of loads and stresses in connecting rods. In this, performed loading analysis under the service loading condition was performed for a connecting rod and followed by quasi-dynamic to captured stress variations and operation using finite element analysis. On the basis of variation of stress ratio, resulting stress time histories, bending stresses and multi-axiality of stress state in overall part of the connecting rod under the service operating condition was investigated. Finally, it was found that even through connecting rod was analyzed under axial loading, bending stress was significant and multiaxial stresses were obtained using finite element analysis. A comparison was also made between the stresses using quasi-dynamic finite element analysis and stress obtained using static finite element analysis which is commonly performed. S. Peak et al. [15] had worked on the Application of high-performance power metal connecting rod in the V6 Engine. In this, the connecting rod was taken from HYUNDAI motor, which was made up of two materials, instead of conventional hot forged and powder metal forged connecting rod, market available connecting rod was selected for the investigation, to obtained low product cost, improve characteristic, bearing reliability and optimized design with high quality. The result, the mass of a powder metal forged steel connecting rod was 17.7% lighter than the conventional hot forged type connecting rod and also the mass of the crank end 22.5% lighter than conventional type connecting rod. So that the mass of moving parts can be reduced, with this mass reduction, NVH characteristic and bearing reliability can be enhanced. And also, HMC conducted for stiffness tests, fatigue test and real engine endurance tests for both conventional hot forged and powder metal forged connecting rod used in a new V6 engine. A. Mirehei et al. [16] did Fatigue analysis of connecting rod of the universal tractor through finite element method (ANSYS). In this, the connecting rod was taken from the universal tractor (U650) for the investigation through ANSYS and its lifespan was estimated. The main cause for the performing this research showed the behavior affected by fatigue phenomenon due to cyclic loadings and consider the result of more saving in cost and time, as two very significant parameter relevant for the manufacturing. In the result, the load applied to fully reversed loading and also verified the critical point on the connecting rod for the crack growth initiation from. Finally, the allowable number of load cycle for fully reversed loading was gained 10^8 cycles and the result can be useful to bring about modifications in the process of manufacturing. L. Figiel, B. L. and M. Kaminski [17] did Sensitivity Analysis in a Fatigue Delamination Problem of an Elastic Two-Layer Composite. In this, various parameters affected the fatigue delamination growth in laminates, material properties, and composite shape. The better understanding about the effecting parameters lead to the fatigue delamination behavior and also gave the path for optimal composite design. These effects can be elucidated for appropriate sensitivity analysis. A Finite element analysis, the computational approach for sensitivity analysis was proposed. In this analysis, the study for composite parameter effects for fatigue delamination problem in the elastic two-layer composites and used to observed sensitivity gradients of the fracture parameter and fatigue cycle number for layer elastic constants. Finally, it was observed that sensitivities computed from this approach were numerically sensed and stable results were verified by another computational approach.

3. Problem Formulation

For buckling in connecting rod, there are three most critical areas which are considered. Four different sections are considered for buckling analysis calculation in Fig.2. The main objective of present work is shaped optimization and buckling analysis of connecting rod made of forged steel. The load, taken here for analysis purpose, as a constraint, depends on the engine specification. The obtained dimensions by measuring the dimension of the connecting rod by using the micro meter, vernier caliper, and ruler. According to this dimension, the model of connecting rod is generated by using CATIA V5. The Forged steel connecting rod is selected for analysis, with the total effective volume and mass respectively $5.717e^{-5}$ m^3 and 0.44886 kg. The configuration of the connecting rod is provided in the Table 1.

Table 1: Dimensions of the connecting rod

Parameter	Value
Thickness of Shank	10 mm
Length of connecting rod	195 mm
Outer diameter of Big end	88 mm
Inner diameter of Big end	44 mm
Outer diameter of small end	44 mm
Inner diameter of small end	22 mm

The different section of the connecting rod was developed using CATIA V5 are shown in Fig. 2.

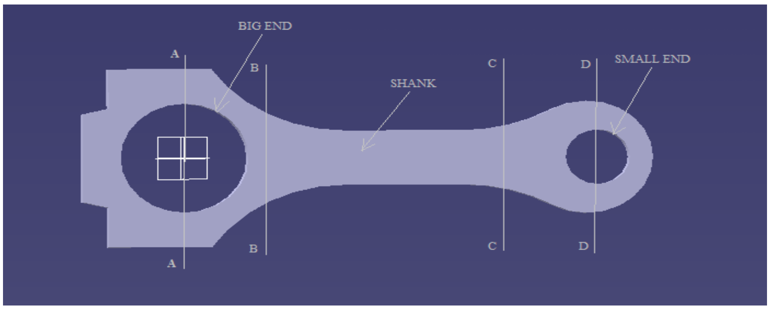

Fig. 2. Different section of connecting rod

4. Materials and methods

Forged steel is widely used in construction, manufacturing, and other application because of their good mechanical properties like high tensile, compressive strength and low cost. The methodology includes fulfilling safety norms and a design of connecting rod under the loading conditions. The buckling phenomenon with connecting rods was performed for finite element analysis and the cross-sectional areas of the shank for several connecting rods were ground to provide components with different slenderness ratios. The slenderness ratio (S=L//r) with shank thickness is 10mm of the integral connecting rod was 19.5 (medium size connecting rod). When the slenderness ratio increases to 32.5 by reducing shank thickness from 10 mm to 6 mm, in these connecting rod both the buckling and as well as direct stress are of significant values. The three specimen are prepared with a different cross-section of the shank are for the finite element analysis. The main basis of taking the three models of connecting rod is, to gradually reduce the stress from first model to the final model. The compressive load of 1.9 KN at 4000 rpm, depending upon the engine specifications and material type, is applied to all the three models of the connecting rod and stress values were obtained. Mechanical properties of forged steel used in the connecting rod are shown in Table 2.

Table 2: Properties of Forged Steel (material used to make the connecting rod)

Material properties	Value
Young's Modulus (E)	221 GPa
Density (ρ)	7850 kg/m^3
Poisson's ratio(μ)	0.3
Yield Strength (Y_s)	556 MPa
Ultimate Tensile Strength (S_u)	827 MPa

5. Finite element analysis

The shape optimization of connecting rod consists of distribution of stresses in places of the model where the stresses were highest. Fig. 3. shows the meshed model of the present connecting rod using finite element analysis. A tetrahedral element was used for the solid mesh. Thus after meshing the connecting rod load and boundary conditions are applied.

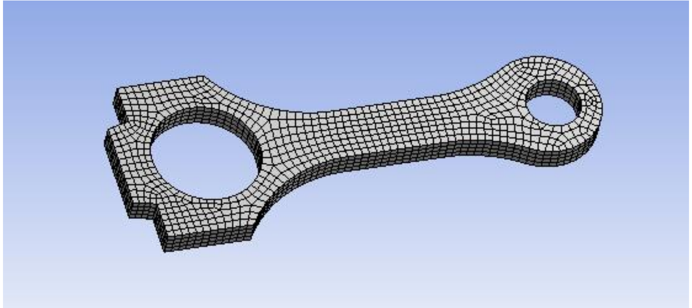

Fig. 3. Meshed model of Connecting rod

5.1 The compressive force is applied both end (opposite in direction) and there are four fixed support, two fixed support at the smaller end and bigger end respectively. The compressive gas load applied at the power strokes was 1.9 kN for linear buckling. Fig. 4 Indicate the equivalent stress distribution in the forged steel connecting rod for the given loading conditions. The maximum and minimum stress was observed to be 457.04 MPa and 0.016076 MPa respectively.

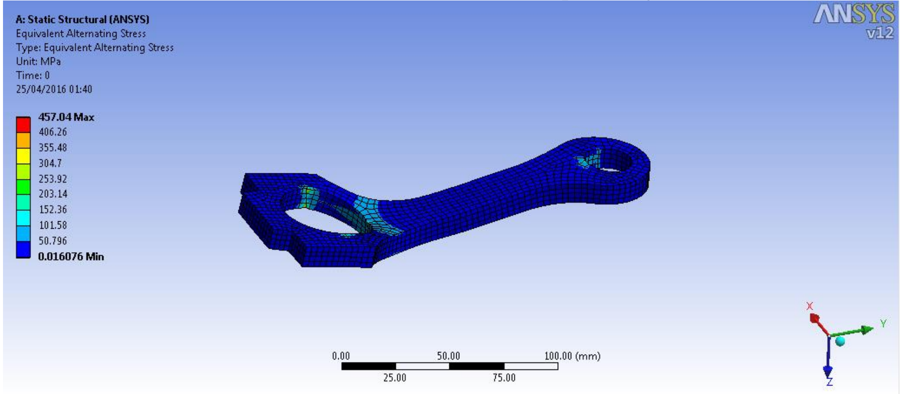

Fig. 4: Load application to the model of connecting rod of 1.9 kN

5.2. For the same model, material has been removed from the cross-sectional area of the shank in order to reduce the resulting inertial and centrifugal force which definitely improves static and buckling results. With the total effective volume and mass reduction is respectively 5.4823e^{-5} m^3 and 0.43036Kg, 1.9 kN of force is applied after meshing it with same value as in first case and output is recorded. The Fig. 5 indicates the static analysis of connecting rod conducted in order to understand the buckling failure location for the same model and material has been removed from the cross-sectional area of the shank in order to reduce the mass of the rod. The maximum and minimum stress was observed to be 525.22MPa and 0.011215 MPa respectively.

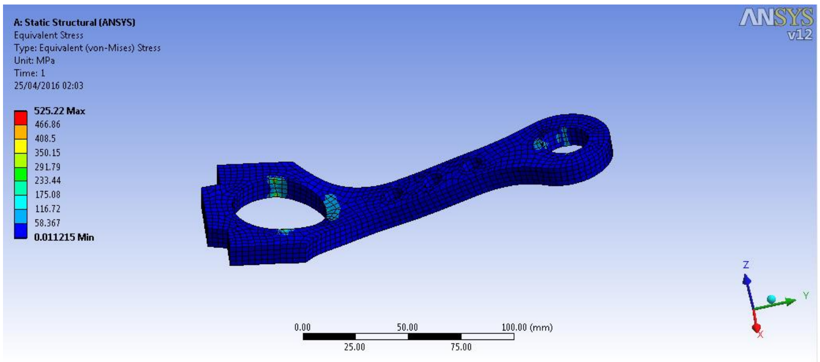

Fig. 5: Stress analysis after removal of material

5.3. For the above model, material has been removed from the shank in order to reduce the weight of the rod. At the I-section area, the pocketing has been done over the cross-sectional area of the shank at 0.2 mm of material is removed from each side and chamfer entire corner of connecting rod at 1mm length at 45 degree and the final model of connecting rod were generated. With the total effective volume and mass reduction is respectively $4.9501e^{-5}$ m^3 and 0.3885 kg. Then further research the important parameters were determined and applicable on the optimized design. The final model of connecting rod after complete in the above three steps is shown in fig.6.

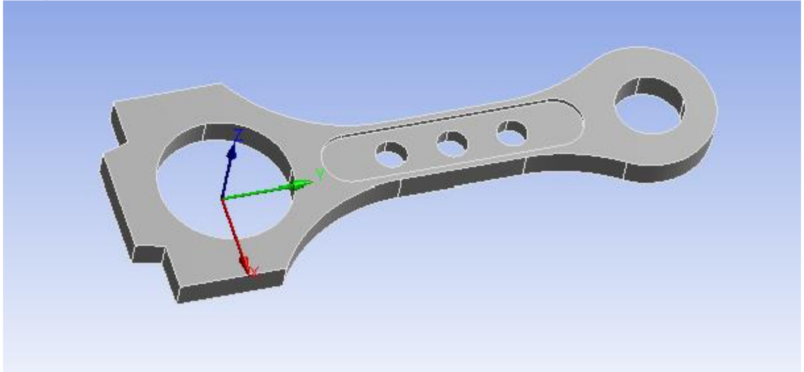

Fig.6. the final model of connecting rod.

5.4. Fig.7 show the meshing has been done on the final model of connecting rod using ANSYS 12. A tetrahedral element was used for the solid mesh. Total number of elements and node was generated 8541 and 4298 respectively.

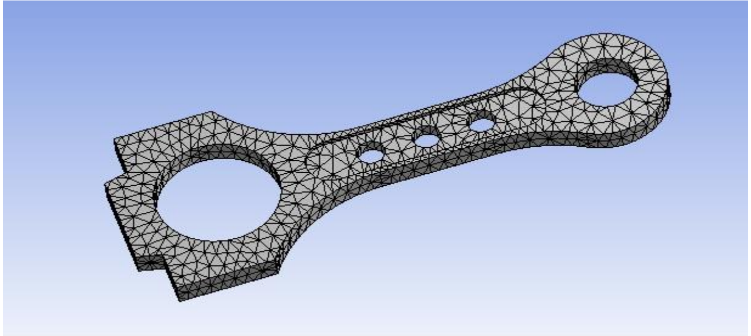

Fig 7. Meshed final model of Connecting rod

5.5 For the above final model material has been removed from the shank in order to reduce the weight of the rod. At the I-section area make three holes with pocketing at the shank area of connecting rod. With the total effective volume and the mass reduction were $4.9501e^{-5}$ mm^3 and 0.38858 kg respectively, 1.9 kN load is applied after meshing it with the same value as in the first case and output is recorded. The maximum and minimum values of equivalent stresses were observed 462.99 MPa and 0.0036147 MPa respectively.

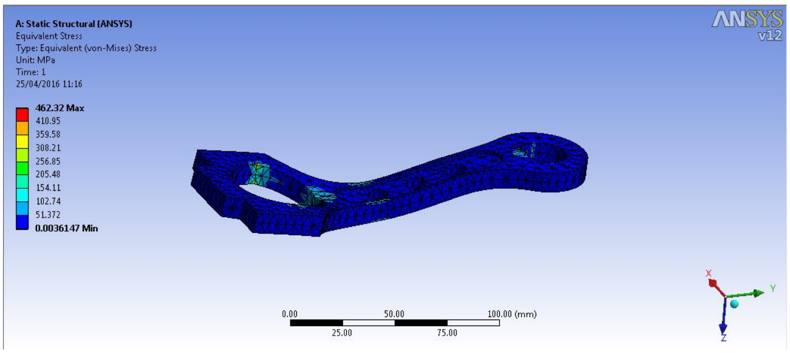

Fig 3. Load application to the final model of connecting rod.

5.6. The load is applied on the model with the reduction of material from the shank area of about 0.06028 kg mass. And output result is recorded. Following are the comparative chart of all 3 output values of the different mass condition as shown in table 3.

Table 3. Geometric and mechanical properties after three steps

Model	volume	mass	Max. stress	Min. stress
First model	$5.717e^{-5}$	0.4488	457.04 MPa	0.16076 MPa
Second model	$5.482e^{-5}$	0.43036	525.22 MPa	0.011215 MPa
Third model	$4.9501e^{-5}$	0.38858	462.32 MPa	0.0036147 MPa

5.7. The buckling analysis result for the given loading conditions to the connecting rod made with the different model of connecting rod is as follows. The fig. 4 shows equivalent stresses behavior under the given loading condition with the reduction of the mass of connecting rod.

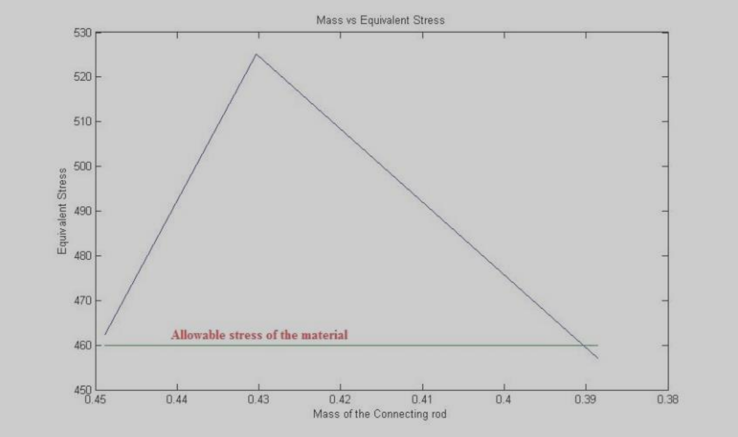

Fig 4. Graph between the mass of the forged steel and the obtained value of equivalent stress.

6. Finite element model optimization

Optimization of the design indicates that the maximum stress for any material should never exceed the yield stress of the material. The connecting rod should resist high compressive load due to explosive pressure inside the engine cylinder. The limit load of connecting rod depends on both geometry and yield strength. For the buckling analysis, the objective was to optimally minimize the mass of the connecting rod under the effect of equivalent stress by reducing the cross-sectional area of shank within the limit of allowable stress. The critical value (458, 0.392) depicts the optimized values of equivalent stress and mass of the connecting rod. And if the critical thickness is below the allowable stress, then the connecting rod would fail. The weight reduction if the connecting rod is 12.5 % of total mass of the connecting rod. The manufacturing cost of the connecting rod is also to be minimized.

7. Conclusion

From buckling analysis, the stresses in each loading conditions were studied and the cross-sectional area where excess material can be removed were decided. The optimization carried out in buckling analysis gives deep insight by considering optimum parameter for shape modification in the existing connecting rod. The material removed to reduce the weight of connecting rod so as to improve the efficiency. The maximum equivalent stress comes out to be 458 MPa which is less then allowable stress of material that 460 MPa hence the design is safe. Optimization was performed to reduced weight by 12.5 %, than the initial model of connecting rod. The forged steel connecting rod exhibits higher fatigue strength and longer life. The forged connecting rod mainly fails in the transition to the bigger end (crank end) region.

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