Design & Shape Optimization of Connecting Rod using FEA: A review

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***Abstract*— The automobile engine connecting rod is a high volume production and critical component. Every vehicle that uses an internal combustion engine requires at least one connecting rod depending upon the number of cylinders in the engine. It connects reciprocating piston to rotating crankshaft, transmitting the thrust of the piston to the crankshaft. As the purpose of the connecting rod is to transfer the reciprocating motion of the piston into rotary motion of the crankshaft. In automotive engines, the connecting rod is subjected to high cyclic loads. These are represented by high compressive loads due to combustion, and high tensile loads due to the connecting rod mass of inertia. The main objective of this study is to optimize the shape of a connecting rod in an automobile engine. A model of the connecting rod has numerically been built and has been solved by the Finite Element Method (FEM) using the ANSYS package to determine the stresses distribution over the entire rod. The aim of the optimization has been to minimize the respective Von Mises stresses which occur at connected rod in both cases, i. e. compressive loads coming from the gas pressure at maximum engine output and the bending loads resulting from the inertia force at the maximum engine power. The weight of the connecting rod should be maintained to prevent increasing of the inertia force**

***Index Terms*—cyclic load, optimization, Von misses stresses, Compressive Load**

I. INTRODUCTION

In modern automotive internal combustion engines, the connecting rods are most usually made of steel for production engines as shown in fig-1. but can be made of T6-2024 and T651-7075 aluminum alloys(for lightness and the ability to absorb high impact at the expense of durability) or titanium (for a combination of lightness with strength, at higher cost) for high performance engines, or of cast iron for applications such as motor scooters. They are not rigidly fixed at either end, so that the angle between the connecting rod and the piston can change as the rod moves up and down and rotates around the crankshaft. Connecting rods, especially in racing engines, may be called "billet" rods, if they are machined out of a solid billet of metal, rather than being cast or forged.

Fig:1- connecting rod

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Fig-2 shows the various parts of connecting rod. The small end of connecting rod attaches to the piston pin, gudgeon pin or wrist pin, which is currently most often press fit into the connecting rod but can swivel in the piston, a "floating wrist pin" design. The big end connects to the bearing journal on the crank throw, in most engines running on replaceable bearing shells accessible via the connecting rod bolts which hold the bearing "cap" onto the big end. Typically there is a pinhole bored through the bearing and the big end of the connecting rod so that pressurized lubricating motor oil squirts out onto the thrust side of the cylinder wall to lubricate the travel of the pistons and piston rings. Most small two-stroke engines and some single cylinder four-stroke engines avoid the need for a pumped lubrication system by using a rolling-element bearing instead, however this requires the crankshaft to be pressed apart and then back together in order to replace a connecting rod.

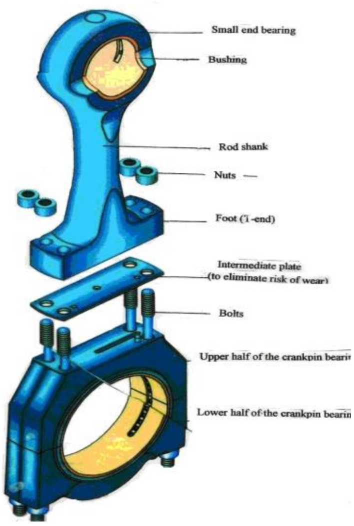


Fig:2- Parts of connecting rod

A major source of engine wear is the sideways force exerted on the piston through the connecting rod by the crankshaft, which typically wears the cylinder into an oval cross-section rather than circular, making it impossible for piston rings to correctly seal against the cylinder walls. Geometrically, it can be seen that longer connecting rods will reduce the amount of this sideways force, and therefore lead to longer engine life. However, for a given engine block, the sum of the length of the connecting rod plus the piston stroke is a fixed number, determined by the fixed distance between the crankshaft axis and the top of the cylinder block where the cylinder head fastens; thus, for a given cylinder block longer stroke, giving greater engine displacement and power, requires a shorter connecting rod (or a piston with smaller compression height), resulting in accelerated cylinder wear.

The connecting rod is under tremendous stress from the reciprocating load represented by the piston, actually stretching and being compressed with every rotation, and the load increases to the square of the engine speed increase. Failure of a connecting rod, usually called throwing a rod, is one of the most common causes of catastrophic engine failure in cars, frequently putting the broken rod through the side of the crankcase and thereby rendering the engine irreparable; it can result from fatigue near a physical defect in the rod, lubrication failure in a bearing due to faulty maintenance, or from failure of the rod bolts from a defect, improper tightening or over-revving of the engine. Re-use of rod bolts is a common practice as long as the bolts meet manufacturer specifications. Despite their frequent occurrence on televised competitive automobile events, such failures are quite rare on production cars during normal daily driving. This is because production auto parts have a much larger factor of safety, and often more systematic quality control.

Finally, a shape optimization for connecting rod reduces the stresses over the entire rod. Due to its large volume production, it is only logical that optimization of the connecting rod for its weight or volume will result in large-scale savings. It can also achieve the objective of reducing the weight of the engine component, thus reducing inertia loads, reducing engine weight and improving engine performance and fuel economy.

II. LITERATURE REVIEW:

There is a vast amount of literature related to Finite Element Analysis of shape optimization of connecting rod. Many research publications, journals, reference manuals, newspaper articles, handbooks; books are available of national and international editions dealing with basic concepts of FEA. The literature review presented here considers the major development in implementation of FEA.

Pravardhan S. Shenoy and Ali Fatemi (2005) [2] carried out the dynamic load analysis and optimization of connecting rod. The main objective of this study was to explore weight and cost reduction opportunities for a production forged steel connecting rod. Typically, an optimum solution is the minimum or maximum possible value the objective function could achieve under a defined set of constraints. The weight of the connecting rod has little influence on the cost of the final component. Change in the material, resulting in a significant reduction in machining cost, was the key factor in cost reduction. As a result, in this optimization problem the cost and the weight were dealt with separately. The structural factors considered for weight reduction during the optimization include the buckling load factor, stresses under the loads, bending stiffness, and axial stiffness. Cost reduction is achieved by using C-70 steel, which is fracture crackable. It eliminates sawing and machining of the rod and cap mating faces and is believed to reduce the production cost by 25%.

Fig- 3 shows the actual and the digitized connecting rods.

Fig- 3: The actual and the digitized connecting rods.

The weight difference between the two when corrected for bolt head weight was less than 1%. This is an indication of the accuracy of the solid model. The engine configuration considered is tabulated in Table I.

I: Configuration of the engine to which the connecting rod belongs.

Crankshaft radius	48.5 mm
Piston diameter	86 mm
Mass of the connecting rod	0.439 kg
Mass of the piston assembly	0.434 kg
Connecting rod length	141 mm
Izz about the center of gravity	0.00144 kg m^2
Distance of C.G. from crank end center	36.4 mm
Maximum gas pressure	37.3 Bar

For cyclic loading, used a safety factor of 1.66 on the endurable load amplitude for connecting rod. The same factor was used for the allowable stress amplitude here, and corresponds to a FI of 0.60. Similar to the case for axial loading, this assumed FI of 0.60 or the FI in the existing component, whichever was higher, was used for obtaining the allowable stress amplitude at a given location or region of the connecting rod. Fig 4 shows the FI distribution for the existing geometry with respect to the endurance limit of the existing material under cyclic load.

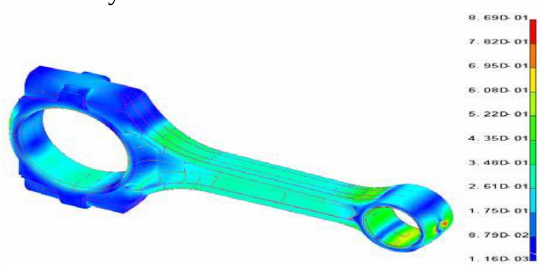


Fig- 4: Failure Index (FI), defined as the ratio of equivalent stress amplitude at R = -1 to the endurance limit of 423 MPa, for the existing connecting rod and material.

After several iterations, which involved determining the loads and performing FEA for the resulting geometry of each iteration step, an optimized geometry was obtained. Mass of the optimized connecting rod is 396 grams, which is lower than the mass of the original connecting rod by 10%. This geometry was found to satisfy the aforementioned design constraints. Fig 5 shows the FI distribution for the optimized connecting rod, for cyclic loading

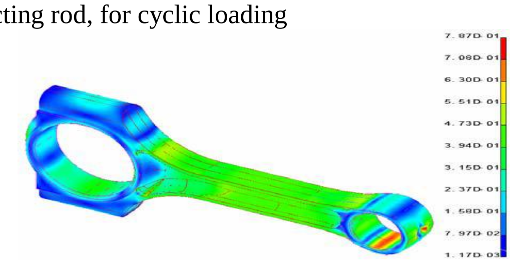


Fig 5: Failure Index (FI) distribution for the optimized connecting rod.

The maximum von Misses stress is at the outer corners of rod-cap interface in Fig 6. Of the many nodes on the inner cap edge (at the rod-cap interface), the node with minimum radial displacement had a radial displacement value of 0.077 mm. This displacement is towards the center of the connecting rod bore. However, the clearance between the crank end bearing and the crankshaft is of the order of 0.026 mm for connecting rods in this size range.

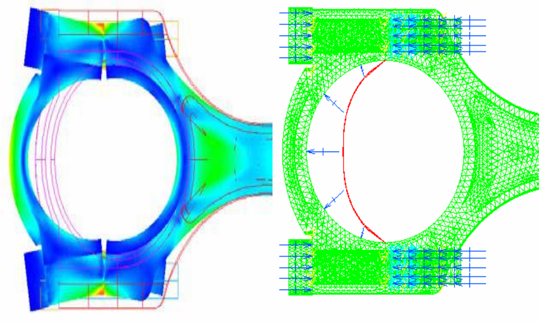


Fig-6: von Misses stress variation and displacements (magnified 20 times) of the connecting rod and cap under tensile load. The FE model is shown on the right.

The following conclusions can be drawn from the results of this study:

a) Fatigue strength was the most significant factor (i.e. design driving factor) in the design and optimization of the connecting rod.

b) Stresses and displacements were observed to be significantly lower under conditions of assembly (with bearings, crankshaft and piston pin and bushing), when compared to stresses obtained from unassembled connecting rod subjected to cosine loading.

c) The section modulus of the connecting rod should be high enough to prevent high bending stresses due to inertia forces, eccentricities, as well as crankshaft and case wall deformations.

d) The optimized geometry is 10% lighter than the current connecting rod for the same fatigue strength, in spite of lower yield strength and endurance limit of C-70 steel compared to the existing forged steel.

1N. Y. Kumari, 2Dr. B V R Gupta[3] carried out the Dynamic Analysis & Optimization of Connecting Rod Using FEM, The main objective of this study was to explore weight and cost Reduction opportunities for a production forged steel connecting rod. This study has dealt with two subjects, first, dynamic load of the connecting rod, and second, optimization for weight and cost. In the first part, the relations for obtaining the loads and accelerations for the connecting rod at a given constant speed of the crankshaft were also determined. Quasi dynamic finite element analysis was performed at several crank angles. After that the component was optimized for weight and cost subject, and space constraints and manufacturability.

While performing quasi-dynamic FEA of the connecting rod as shown in fig-7, external loads computed from the load analysis were applied to both the crank end and the piston pin end of the connecting rod. Many FE models were solved, each model with the applied loads obtained from the load analysis at the crank angle of interest. Therefore, such analysis is different from a static analysis as the time-varying dynamic nature of the loading represented by load variation at different crank angles is accounted for. It should also be noted that the dynamic load analysis step was required as a separate step, as input to the stress analysis step using IDEAS.

Fig. 7: Quasi-Dynamic FEA Result

Quasi-dynamic FEA results differ from the static FEA results because of the time-varying inertia load of the connecting rod, which is responsible for inducing bending stresses and varying axial load along the length, as available on the fig. 8.

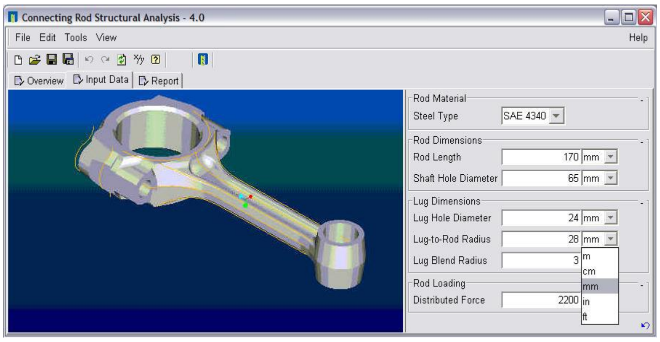


Fig.8: Connection Rod Structural Analysis

Static analysis of a connecting rod that is typically performed can yield unrealistic stresses, whereas quasi-dynamic analysis provides more accurate results better suited for fatigue design and optimization analysis of this high volume production component. Maximum and mean stresses increase with increasing engine speed because of the increase in the inertia load. The stress range (or amplitude), however, is independent of the engine speed.

Dr.B.K.Roy [1] carried out the research on Design Analysis and Optimization of Various Parameters of Connecting Rod using CAE Softwares. Various designs of connecting rod have been analyzed in this report and finally an optimal design has been selected for Finite Element Analysis. Using ANSYS-12.0 Workbench and CATIA V5R19, Various results are found out and compared with the existing results. It has been found out that the study presented here has came up with better results as well as safe design of connecting rod under permissible limits of various parameters and safe stresses.Fig-9 shows the dimension of new suggested design of connecting rod.

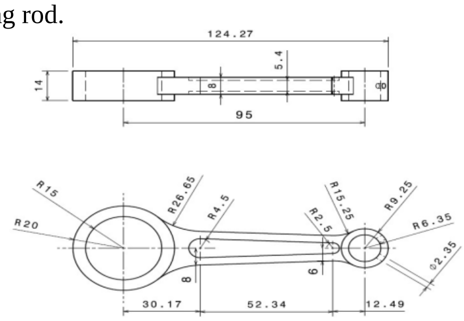


Fig.9 – New Suggested Design

After selecting Material as a stainless steel, Next step in methodology is Mesh Generation. Meshed Generated model of connecting rod is shown in fig. 10.

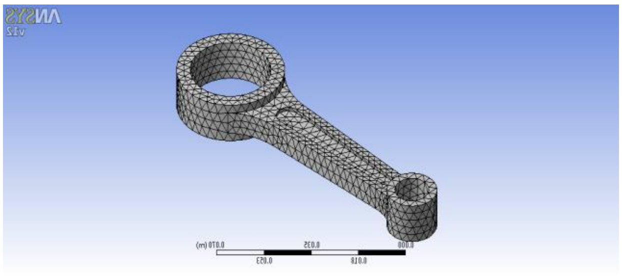


Fig 10 - Meshed model of connecting rod

After preparing the model ready for analysis, various constraints, supports and loads are applied, keeping in mind various boundary conditions. A Fixed Support is applied at crank end and a static load of 4319N is applied. In between loading and applying fixed support on connecting rod, various parameters like sizing, shaping, view angles, transition and smoothing of design is studied and analyzed to get optimized results in which proper care is needed as any error can cause variation of results in pre-processing phase of Finite Element Method.

Current work has concluded up with the fact that slight and careful variation in design parameters can give a good design which can be made feasible by a number of analysis using CAE tools and Softwares.

• Static and Fatigue, both analysis are important as both showed up different aspects of factors on which care should be taken before finalizing any part design.

• Stress, Strain, Deformation, Life, Damage, Biaxiality Indication etc. have been studied and analyzed to get the good design parameters with taking into account the safe permissible stresses and factors which would have affect the design if not taken into account.

K. Sudershn Kumar1, Dr. K. Tirupathi Reddy2, Syed Altaf Hussain3[4] carried out their research on Modeling and Analysis of Two Wheeler Connecting Rod.Existing connecting rod is manufactured by using Carbon steel. This paper describes modeling and analysis of connecting rod. In this ,connecting rod is replaced by Aluminum reinforced with Boron carbide for Suzuki GS150R motorbike. A 2D drawing is drafted from the calculations. A parametric model of connecting rod is modeled using PRO-E 4.0 software. Analysis is carried out by using ANSYS software. Finite element analysis of connecting rod is done by considering two materials ,viz.. Aluminum Reinforced with Boron Carbide and Aluminum 360. The best combination of parameters like Von misses stress and strain, Deformation, Factor of safety and weight reduction for two wheeler piston were done in ANSYS software. Compared to carbon steel, aluminum boron carbide and aluminum 360, Aluminum boron carbide is found to have working factor of safety is nearer to theoretical factor of safety, 33.17% to reduce the weight, to increase the stiffness by 48.55% and to reduce the stress by10.35% and most stiffer.

For the structural analysis of connecting rod, Dimensions of Width and height of the connecting rod is For C.S = 12.8mm and For AL 360 = 16.4 mm. The loading conditions are assumed to be static. Analysis done with pressure load applied at the piston end and restrained at the crank end or other load applied at the crank end and restrained at the piston end. The element choosen is SOLID 187, it was used with the tetrahedral option, making it a 10-node element with 3 degrees of freedom at each node. The finite element analysis is carried out on carbon steel connecting rod as well as on three different materials of carbon steel, aluminum boron carbide and aluminum 360. From the analysis the equivalent stress (Von-mises stress),displacements were determined and are shown in fig 11-12. Table 2 shows the comparative of factor of safety for three different materials.

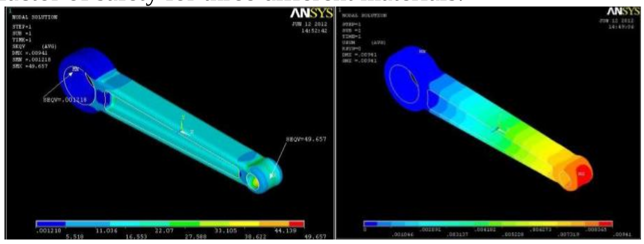


Fig 11: von misses stress & Displacement of carbon steel.

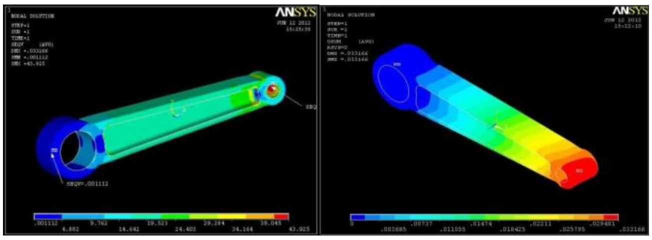


Figure12: von misses stress & Displacement of aluminum 360.

Result for Stiffness of connecting rod:

a) Carbon steel

Weight of connecting rod =0.727Kg
Deformation =0.00941mm
Stiffness =Weight/Deformation
=0.727/0.0094 =77.34 kg/mm

b) Aluminum360

Weight of connecting rod =0.48581Kg
Deformation =0.0033166mm
Stiffness =Weight/Deformation
=0.48581/0.00331 =146.77 kg/mm

c) Aluminum boron carbide

Weight of connecting rod =0.48581Kg
Deformation =0.012219mm
Stiffness=Weight/Deformation
= 0.48581/0.012219 = 39.7585 kg/m

Result for percentage of increase in stiffness:

a) Aluminum 360 =77.34-146.77/77.34 = -0.8977
b) Aluminum boron carbide = 77.34-39.7585/77.34
= 0.4855

Result for percentage of stress reduction:

a) Aluminum 360 =49.625-43.925/49.625 =0.1035
b) Aluminum boron carbide =49-43.925/49 =0.1035

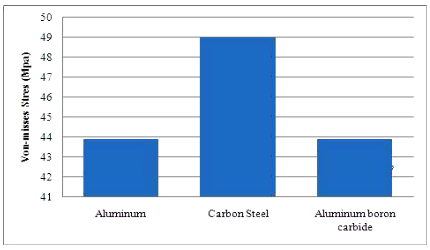


Fig 13: Von-Misses Stress for three materials.

Fig-13,14,15 shows the corresponding von misses stress ,deformation and working factor of safety for three materials.

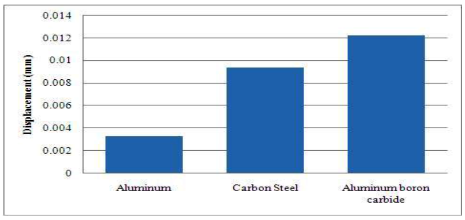


Fig 14: Displacement for three materials.

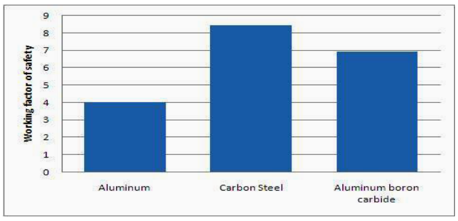


Fig 15: working factor of safety for three materials.

For considering the parameters, the working factor of safety is nearer to theoretical factor of safety in aluminum boron carbide. Percentage of reduction in weight is same in Aluminum 360 and aluminum boron carbide. Percentage of increase in stiffness in aluminum boron carbide is more. Percentage of reducing in stress Aluminium boron carbide and Aluminum is same than Carbon steel.

M.S.Shaari1,M.M. Rahman1,2,M.M. Noor1, K. Kadirgama1 and A.K. Amirruddin1[5] carried out their work on design of connecting rod of internal combustion engine:a topology optimization approach. The objectives of this paper are to develop structural modeling ,finite element analyze and the optimization of the connecting rod for robust design. The structure of connecting rod was modeled utilized SOLIDWORKS software. Finite element modeling and analysis were performed using MSC/PATRAN and MSC/NASTRAN software. Linear static analysis was carried out to obtain the stress/strain state results. The mesh convergence analysis was performed to select the best mesh for the analysis. The topology optimization technique is used to achieve the objectives of optimization which is to reduce the weight of the connecting rod. From the FEA analysis results, TET10 predicted higher maximum stress than TET4 and maximum principal stress captured the maximum stress. The crank end is suggested to be redesign based on the topology optimization results. The optimized connecting rod is 11.7% lighter and predicted low maximum stress compare to initial design. For future research, the optimization should cover on material optimization to increase the strength of the connecting rod.

The objective of optimization technique is to minimize the mass of the connecting rod and reduce the cost of production. The connecting rod subjected to tensile load at crank end, while using factor of safety 3 as recommended by Shenoy(2004). The maximum stress of the connecting rod monitored and make sure it is not over the allowable stress. The load of the connecting rod optimized is comprised of the tensile load of 26.7 kN at crank end. Linear buckling analysis was performed on the connecting is 26.7 kN. The buckling load factor is considered also 3. The optimization technique methodology flowchart is shown in Fig 16.

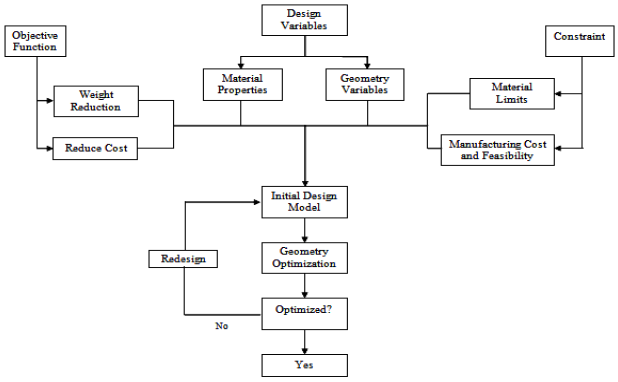
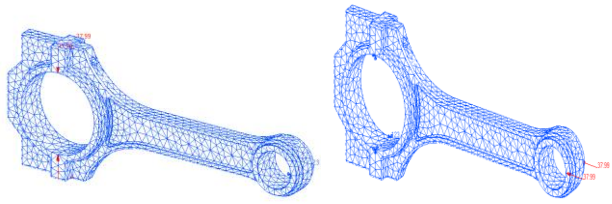


Fig 16: Flowchart of optimization approach

The uniformly distributed tensile load 180^{o} on the inner surfaces of the crank end while the other part, pin end is restrain as in Fig 17. It is just same when load uniformly distributed on pin end surfaces, the crank end will restrain in all direction.



(a) *(b)*

Fig17: (a) Tensile load at crank end and fixed at pin end; (b) Tensile load at pin end and fixed at crank end.

From the results, it can be found that the TET10 mesh predicted higher von Mises stresses than that TET4 meshes. For the same mesh size, TET10 is expected to be able to capture the high stress concentration associated with the bolt holes. Fig 18 and 19 show the variation of stress and displacement over the global edge length and it can be seen that the TET10 is always captured the higher values.

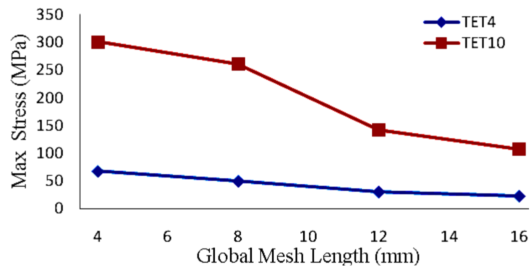


Fig 18: Comparison between TET4 and TET10 on von-Mises stress

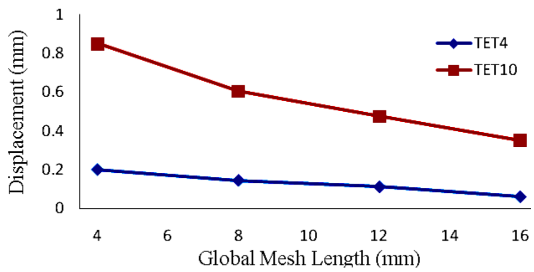


Fig 19: Comparison between TET4 and TET10 displacement

The implementation of these optimizations is to find out the best design and topology of the connecting rod to improve the performance and the strength especially at the critical location.The modeling of connecting rod and FE Analysis has been presented. Topology optimization were analyzed to the connecting rod and according to the results, it can be concluded that the weight of optimized design is 11.7% lighter and maximum stress also predicted lower than the initial design of connecting rod. The results clearly indicate that the new design much lighter and has more strength than initial design of connecting rod. Material optimization approach will be considered for future research.

III. CAE TOOLS AND SOFTWARE

Computer-Aided Engineering (CAE) is the broad usage of computer software to aid in engineering tasks. It includes computer aided design (CAD), computer aided analysis (CAA), computer integrated manufacturing (CIM), computer aided manufacturing (CAM), material requirements planning (MRP) and computer-aided planning (CAP).CAE embraces the application of computers from preliminary design (CAD) through production (CAM). Computer Aided Analysis includes finite element and finite difference method for solving the partial differential equations governing solid mechanics, fluid mechanics and heat transfer, but it also includes diverse program for specialized analyses such as rigid body dynamics and control system modeling. Recently, manufactures have been asked to design their products for eventual recycling, and this aspect of engineering will undoubtedly fall under the umbrella of CAE, but as of yet it doesn't have its own acronym. CAE tools are being used, for example, to analyze the robustness and performance of components and assemblies. The term encompasses simulation, validation, and optimization of products and manufacturing tools. In the future, CAE systems will be major providers of information to help support design teams in decision making.CAE areas covered include:

1. Stress analysis on components and assemblies using FEA (Finite Element Analysis);
2. Thermal and fluid flow analysis Computational fluid dynamics (CFD);
3. Kinematics;
4. Mechanical event simulation (MES).
5. Analysis tools for process simulation for operations such as casting, molding, and die press forming.
6. Optimization of the product or process.

IV. CONCLUSION

Above all researchers gives the idea about designing of the connecting rod. It explains about the various stresses to be considered while designing the connecting rod and different materials used and comparing the result of all material. Also most of the researchers used the CATIA software for the modeling and ANSYS software for analysis. These can be used for designing the any connecting rod in Automobile. Connecting rod can be designed for weight and cost reduction also to increase the life time of connecting rod. Upto some level of extent the weight of the connecting rod is lighter and having more strength as compared to the original design.

ACKNOWLEDGMENT

I sincerely thanks to all the authors who worked on design and analysis of Shape and weight optimization of connecting rod.

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2) "Design Of Air Booster For 1200 Ton Mechanical Press" Volume 14 Issue 1 Version 1.0 Year 2014, Online ISSN: 2249-4596 Print ISSN:0975-5861.