Finite Element Analysis Based Material Selection and Weight Reduction of Connecting Rod

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Abstract: Connecting rod is essential component of internal combustion engine it acts as a linkage between piston and crankshaft. There are three main zones, the piston pin end, the central shank and the big end. The piston pin end is the small end, the crank end is the big end and the central shank is of I-cross section. Connecting rod is a pin jointed strut in which more weight is concentrated towards the big end. In the point of view that location of the CG point of connecting rod lies more towards the big end. Material usually used to manufacture connecting rod in mass is steel, but it can also be made of Aluminum or titanium for high performance engines, or of cast iron. They can be produced either by casting, powder metallurgy or forging. However, connecting rods which are produced by casting have higher possibility of containing blow holes which are adverse from durability and fatigue points of view. Once the manufacturing process are studied design considerations were studied and it was used to reverse calculate the boundary condition for which steel connecting rod was designed. Later steel was replaced by aluminium and further it was replaced with aluminium with titanium inserts. Various results for each material were studied and comparison was made to study the improvement that occurred with reduction in weight.

Keywords: Aluminium, Aluminium with Titanium Inserts, FEM, Reverse Engineering, Weight reduction.

1. INTRODUCTION

1.1 Background

The automobile engine connecting rod is a mass production, critical component. It connects reciprocating piston to rotating crankshaft, transfer the thrust of the piston to the crankshaft. Every vehicle that uses an internal combustion engine needs at least one connecting rod depending upon the number of cylinders in the engine Connecting rod is itself component of internal combustion engine, it acts as a connective linkage between piston and crankshaft. Connecting rod has three main parts. The piston pin end, the central part and the big end. The piston pin end is the small end, the crank end is called as big end and the central portion is of I-cross section. Connecting rod is a pin jointed strut in which more weight is lies towards the big end. In that point of view the location of the CG point of connecting rod lies more towards the big end. This connecting rod is most made of steel for production engines, but can be made of Aluminium or titanium for high output power engines, or of cast iron. They may be produced either by casting, powder metallurgy or forging. However, connecting rods could be produced by casting, the difference between other processes and casting usually, they have blow holes because of inert gases during pouring of metal which are adverse from durability and fatigue points of view. It is true that forgings produce blow hole free and better rods gives them an advantage over casted connecting rods. Blanks which are manufactured by powder metal have the advantage of being near fine net shape, minimize material waste. However, the cost of the blank is more due to the high raw material cost and complicated manufacturing techniques. Automobile industry always requires cost less and high quality product. This gives scope to study design techniques so as to improve and provide industrial needs. The time spends in trial and error analysis in the design process need to be eliminated in order to survive in this fast moving market. Thus, computational method has been used in previous stage of the design. Finite element method is applied for modal analysis and structural analysis of connecting rod. Modal analysis is the process of obtaining the inherent dynamic characteristics of a system in form of natural frequencies, damping factors and mode shapes, and using them to construct a mathematical model for its dynamic behavior. Whereas structural analysis gives idea about stress distribution at loading condition. Mesh determination is very in order to ensure that the best mesh size selection is important to perform the analysis for other parameter involves. As quality is key of stability and convergence of various mesh processing applications, there is frequently a need to improve the quality of the mesh. Reverse engineering (RE) is the process of taking something like a device, a mechanical component or even software a part and recognize its workings in detail, usually with the intention to construct a new device or program could does the same thing without copying anything from the original . In order to boost the quality and efficiency of design, RE is used. It is not just redesign the product but also to make sure that the new component can achieve more than original product.

1.2 Problem Definition

The objective of this work was to optimize the steel connecting rod for its weight. The optimization of steel rod is more intended to work with different material so as to have light weight and as good as necessary strength. Optimization begins with identifying the correct load conditions and magnitudes. Overestimating the loads will simply increase the safety factors. The idea behind optimizing is to retain just as much strength as is needed. In this problem no such change in geometry is allowed. This is because the component is already a part of assembly, by doing reverse engineering same part is to be generated but with sufficient amount of load. The design and weight of the connecting rod have influence on car performance. Hence, it effects on the car manufacture trust. Replacing in the design and material results an important increment in weight and also performance of engine. The structural parameters considered for weight optimization during the analysis include the buckling load factor, stresses due to loads, bending stiffness, and axial stiffness. Therefore, the component can give the more strength, efficient design and lighter in weight that would create a major success in the automotive industry.

Any physical system vibrates. The frequencies where vibration naturally occurs, and the model shapes which the vibrating system assumes are properties of the system which can be calculated analytically using modal analysis. Analysis of vibration modes is a critical component of a design, but it is not observed. Fixed vibration modes in structural components can shorten connecting rod life, and causes premature failure, resulting in hazardous situations. Detailed modal analysis gives the basic vibration, modes shapes and related frequencies. This can be relatively simple for basic components of a system, end very complicated when eligible for a complex mechanical device or a complicated structure exposed to time based wind loading. This system needs accurate recognition of natural frequencies and mode shape using techniques such as Finite Element Analysis. Using Finite Element method to predict the dynamic properties of structures becomes important in advance mechanical industries, like automobile industries.

1.3 Scope Of Project

1. The model of connecting rod will be developed using available modeling software CATIA V5.

2. FEA method will be used to study different behavior of model under various loads.

3. Connecting rod is modeled as rigid bodies and are fixed at different positions.

4. Static linear and contact non-linear analysis will be done.

5. By using FEA method dynamic characteristics of a system such as natural frequencies and mode shapes are found out.

6. Optimization of the model will be done by having multiple iteration over different material.

2. LITERATURE REVIEW

2.1 Venu gopal Vegi[1] — This paper include design and analysis of connecting rod. Connecting rod is manufactured by carbon steel. Model of connecting rod is developed in CATIA software and analysis is done in ANSYS 13.0. Deformation, von misses stress strain, Factor of safety and weight reduction of two wheeler piston was done. By minimizing factor of safety weight of connecting rod can be reduced it also increase the stiffness than carbon steel, reduce stress. After fatigue analysis, define the life of connecting rod.

2.2 Vikas Gupta [2] — Objective of this work is to re-optimize the existing connecting rod of by changing some parameters. The critical regions are identified by static and fatigue analysis. The material is same C-70 alloy steel is used. The change was seen in von misses stress, 9.4% less stress is observed at critical point under static load. 5 gram of weight is reduced which very low. For material optimization only design parameters are not so important but if different materials are considered then it are effective material optimization will occur.

2.3 Ramanpreet Singh [3] — This paper includes the study of connecting rod of single cylinder four stroke engine. Objective of this paper is to develop a true nature of composite material in connecting rod. Comparison of conventional and composite material connecting rod is compared with the help of ANSYS. Analysis is carried out by mesh TET4 to obtain different stresses by keeping same boundary condition for both materials. There is a scope for this analysis by changing the mesh type that is mesh TET10 and compared.

2.4 Kuldeep B [4] - replaced the material of connecting rod by aluminium based composite material structured with silicon carbide and fly ash. And it also gives idea of the modeling and analysis of connecting rod. FEA analysis was performed by considering two materials. The parameter like von misses stress, von misses strain and displacement was got from ANSYS software. Compared to the old material the new material found to have lesser in weight and more stiff. It resulted in reduction of 43.48% of weight, with 75% reduction in deformation

2.5 Adila Afzal [5] - this study investigates and compares fatigue behavior of forged steel and powder metal connecting rods. The experiments contain strain-controlled specimen testing, with specimens got from the connecting rods, as well as connecting rod bench testing based on load-control. Monotonic and cyclic deformation behavior, as well as strain-controlled fatigue properties of the both materials are analyzed and compared. S-N curves (Experimental) of the two connecting rods from the bench tests got under R = -1.25 constant amplitude loading conditions are also calculated and compared. Fatigue properties got from specimen testing are then used in life cycle of the connecting rods, using the S-N approach. The observed lives are compared with bench test results and it contain the effects of stress concentration, surface finish, and average stress. The stress concentration factors were obtained from Finite element analysis, and the slightly changed Goodman equation was used, to calculate for the average stress effect.

2.6 Fanil Desai [6] - The main function of connecting rod is to convert reciprocating motion of piston to rotary motion of crankshaft. It is the combined component of internal combustion (IC) engine. It is the more stressed part of IC engine. During its operation various stresses are acting on connecting rod. The effect of compressive stress is more in connecting rod due to gas pressure and whipping stress. The aim of this paper is to investigate the compressive stress acting on connecting rod at different loading condition. There are two samples of connecting rods are taken for experimental analysis. Structural analysis performed using ANSYS. Experimental analysis was performed on connecting rod made up of forged steel. The purpose of this study is to execute the performance of connecting rod under different loading condition. Experimental results will be verified with the numerical results.

2.7 G.M. Sayeed Ahmed [8] - The present work has been undertaken to replace the existing connecting rod manufactured by forged steel which is broken for LML Freedom with the aluminium connecting rod. The spare parts of the LML scooter are not available as the production has stopped by company. This thesis, the connecting rod is modeled in Pro/Engineer, forces are calculated, analysis is done on the connecting rod using materials aluminium 6061, aluminium 7075, aluminium 2014carbon fiber 280 gsm bi-directional, and Analysis is also performed for the assembly of piston, connecting rod and crankshaft. The prototype of the connecting rod is manufacturing using direct machining for aluminium alloy and hand layup method for carbon fiber connecting rod.

2.8 S. Vijaya Kumar [10] - Existing connecting rod is manufactured by using iron. This project gives the idea of prototype model and analysis of connecting rod. In this connecting rod is replaced by chrome steel and titanium for Yamaha Fz-s bike. A two dimensional drawing is drafted from the hand calculations. A parametric model of connecting rod is modeled by creo parametric 2.0 software. Analysis is performed by using ansys software. Connecting rod can be designed for weight and reduction in cost also to increase the life time of connecting rod. Up to some level of extent the weight of the connecting rod is light in weight and more strength as compared to the original design. The maximum stress is within the designed stress limit for chrome steel and titanium.

2.9 Boundary Condition

Forces Acting on Connecting Rod

Following are the forces acting on connecting rod.

1. Force on the piston due to gas pressure and inertia of the reciprocating part.
2. Force due to inertia of the connecting rod or inertia of the bending forces.
3. Force due to friction of the piston rings and the piston.
4. Force due to friction of the piston pin bearing and the crankpin bearing.

2.10Tetrahedron Element

As per the knowledge of boundary condition given earlier we can see that connecting rod is subjected to repeated tensile and compressive force, for which corresponding stress are to be determine. In order to get correct value of stress proper element size is calculated by applying a constant load of 10,000 N. it was applied for both compression and tension.

In this analysis value of force is not important because

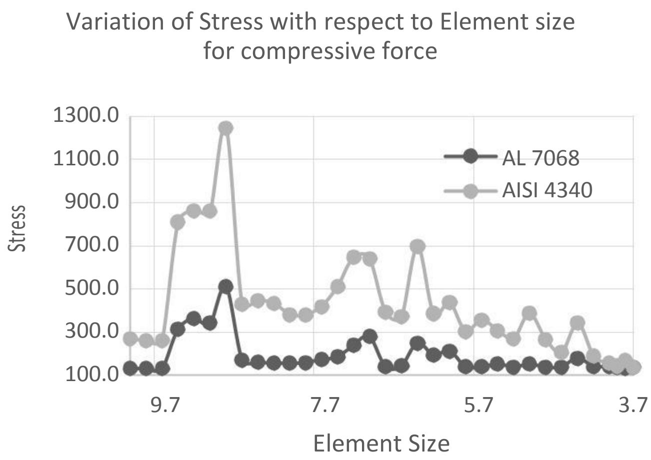

Fig.1 stress vs. element size (tetra element)

We are concern with the element size which was changed from 10mm to 3.7mm. Variation of stress to element size is shown in graph Fig. 1 This graph contains the study of element for same connecting rod but with different material.

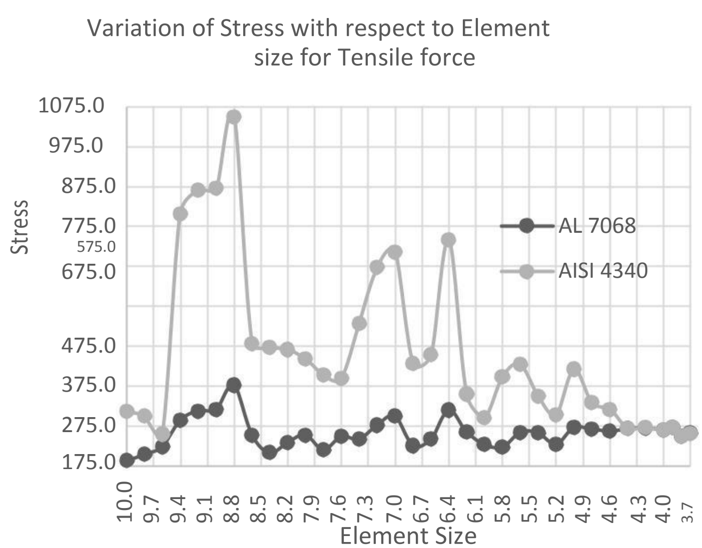

Fig.2 stress vs. element size (tetra element)

Our main objective of this project was to reduce the weight of connecting rod without any changes in the shape of connecting rod. Our main objective of this project was to reduce the weight of Connecting rod without any changes in the shape of connecting rod. Thus in order to achieve the objective material change was the only option. As we are looking for an element size which is suitable for both material, each of them were analyzed for both compression and tension. When a constant load is applied to same con-rod stress generated in it must be same irrespective of the material it is made up of. When this condition is obtained at that point the element size is checked and it will be used for further detail analysis. In above graph which is a plot for compression of steel and aluminium connecting rod we can see that after an element size of 4.2mm value of stress starts to converge at same point. At 3.7mm values are almost equal and thus for any further analysis related to compression element size of 3.7mm will be used.

Similarly Fig. 2 shows the graph for element size vs. stress for tensile loading. Same procedure is to be followed to get a proper size. From graph we can clearly see that once element size is 4.4 or less stress value for both materials are nearly same. As we know solution time increases as number of node increases hence 4.3mm element size is selected. This size gives result with less deviation, computing time and with minimum number of nodes.

2.13 Hex domain Element

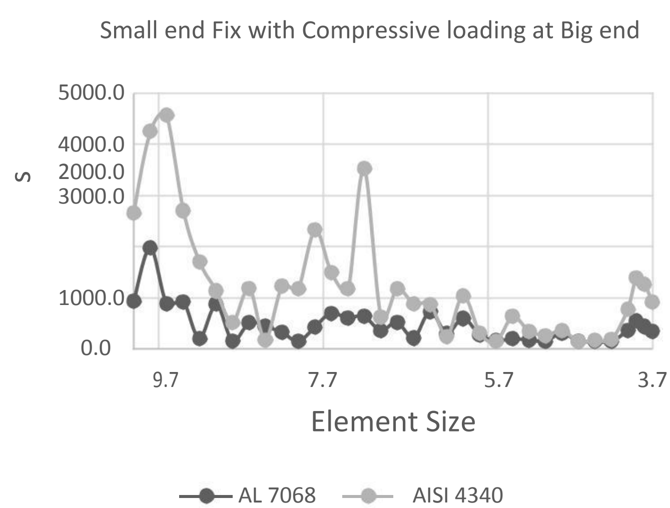

Fig 3 stress vs. element size (Hex element)

Selection of size for hex element is quite difficult if we go through above mentioned method. For this component is analyzed two time for same nature and magnitude of force. First Degree of Freedom (DOF) at big end is constrained and force is applied to small end, later, small end is constrained and big end is applied with compressive force. Theoretically if boundary conditions are exchanged between big end and small end stress produced must be same. Therefore, a particular size must be selected which will give same stress even if boundary condition is exchanged.

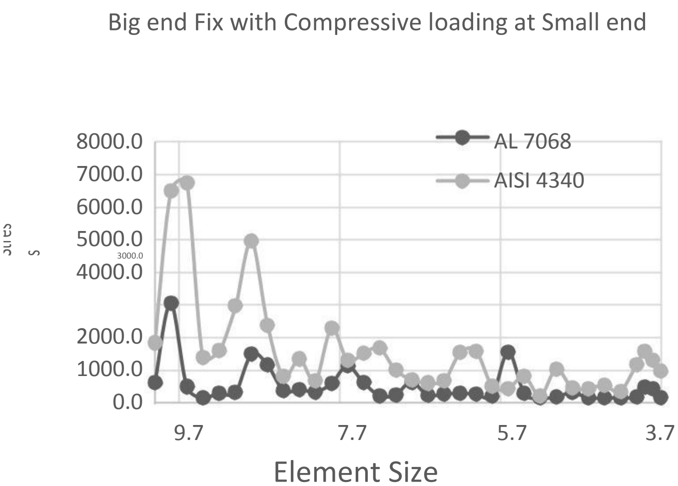

Fig. 4 Stress vs. Element size (HEX Element)

In the order to select element size two graph are studied which are for compressive load but at different end. In above graph we can see the region from 4.7 has three points (4.6, 4.4 & 4.2) are the one which coincide with each other. This graph is the plot of stress when big end is fixed and compressive load is applied for both materials. As said earlier even if the fix end and load end is exchanged between big end and small end stress value must be same, thus a second graph for various size was plot in which small end is big end is applied with load. The above three point were studied in this second graph Fig. 3. From this we can see that element size 4.6mm is the best suitable element size when it is compared with other two size. 4.6mm size will be used for any study related to compression with hex element is concern. Detail values for each element

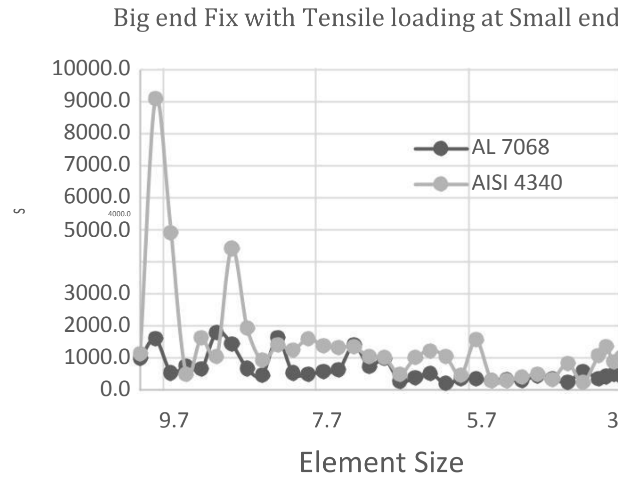

Fig 5. Stress vs Element size (Hex element)

size for every case are available in Appendix. Element size for compression was selected, on same method element for tension is selected. First the graph fig 4 was studied.

From this graph we can see that once element size is smaller than 5.7 values of stress for both materials converges. Thus all the element size lower than 5.7 were considered and they were studied in the next graph as in fig. 5 When this point was studied in second

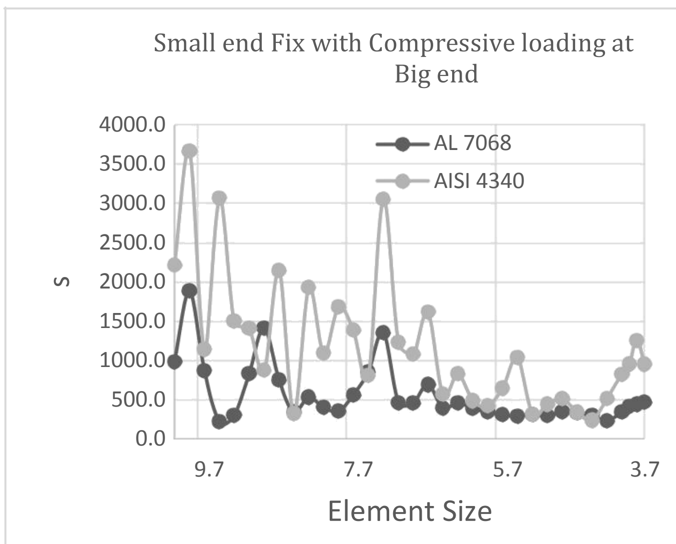

Fig. 6 Stress vs. Element size (Hex Element)

graph we can see that only element size 4.6mm coincide in both the graph. Therefore, for tensile analysis for hex element size of 4.6 will be used.

3 Calculation of Tensile Load of Aluminium connecting Rod

$$F_I = \text{force on bolt} = \frac{\pi}{4}\, d^{2} * \sigma_t * N$$

F_I = Inertia force due to reciprocating part

d = diameter of bolt = 8 mm

σ_t = allowable tensile stress = 125 N/mm^2

N = number of bolts = 2

Using cad model of connecting rod diameter of bolt was measured and it came out to be of 8mm.

$$F_I = \frac{\pi}{4} * 8^2 * 125 * 2$$

$$F_I = 12566.37 \text{ N} \approx 12570 \text{ N}$$

4 Experimental validation

Mechanical testing plays a vital role for determining fundamental properties of engineering materials as well as in developing new materials and in maintaining the quality of materials for use in design and construction. If a material is used to a engineering structure that will be subjected to different loads, it is important to know that the material is able to take a load and withstand on that load when it is in working. Therefore the material is subjected to different loads like compression, tension, bending or torsion and it is tested for same. The most common type of test used to determine the mechanical properties of a material is the Tension Test. Tension test is widely used to provide basic design data on the strength of materials and is an acceptance test for the specification of materials. The major parameters which gives the stress-strain curve obtained during the tension test are the ultimate tensile strength yield strength or yield point, modulus of elasticity, % elongation and the reduction in area, Toughness, Resilience, Poisson's ratio can also be determined by the use of this testing technique. In this test, a specimen is prepared suitable for attach into the jaws of the testing machine type that will be used. The specimen used is approximately uniform over a gage length (the length within which elongation measurements are done**)**.

Study of different tests are carried out in laboratory on universal testing machine

1. Tension test on ductile material
2. Compression test on brittle material
3. Shear test on metals
4. Bending test
5. Deflection test on wood material
6. Hardness test
7. Impact test

Here tensile test on connecting rod is performed to check % of elongation.

Fig.7 Deformation Test on UTM

The test is carried out as per IS 1139-1966

Total deformation at 13100 N load is 0.16784 mm.

5 RESULTS AND DISSCUSSION

Element size selection, with respect to the study

Fig. 8 Meshing of connecting rod

element size was used and solid model of connecting rod is meshed. Fig. 8 shows the mesh model of connecting rod. Tensile analysis was performed with element size of 3.7 mm, the values of force was

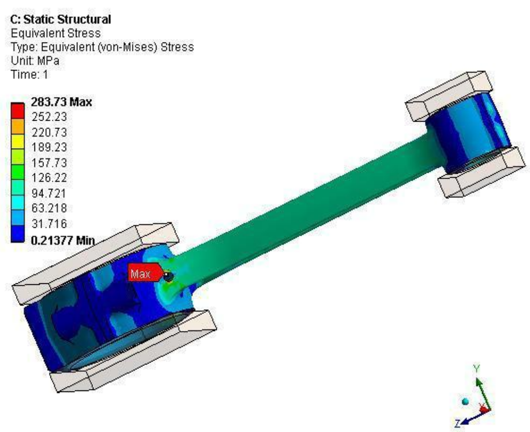

Fig. 9 Variation of stress for tensile loading

increased until the stress in connecting rod crosses to allowable tensile strength. Total no. of node that was found after meshing was 67856 nodes. When the of 13500 N load was applied stress was 283 MPa. Nature of force and stress along the rod is presented in fig. 9 Total deformation at this particular load was about 0.18391mm.

In same way maximum compressive strength was obtained. Element size of 3.7 is used and analysis was carried out. Total number of 75000 nodes were obtained and used for analysis. Variation of stress for compression is in Fig. 10 stress concentration point can be found at base of I section where I beam and big end coalesce. It is found out of max stress bit at same time it is also the point for stress riser. Thus the stress at that point will be always predicted higher than the actual value. To find actual stress, variation of stress around the stressed point is studied and it was found that at about 50000 N load, component reaches its allowable

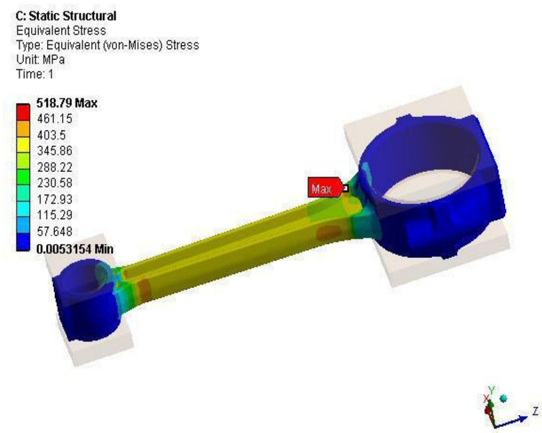

Fig. 10 Variation of stress for compressive loading

compressive stress. Now same analysis will be carried out using hex element.

Value of load will be found in same way as mentioned

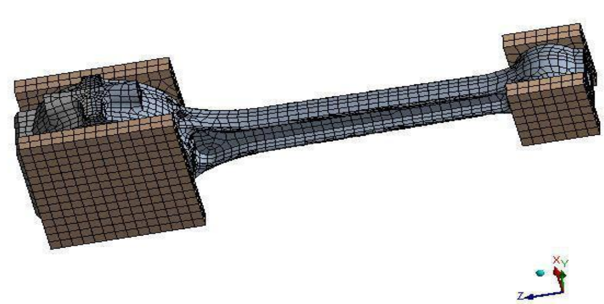

Fig. 11 AISI 4340 with hex mesh

in previous analysis. Element size of 4.6mm will be used for both compressive as well as tensile test. Total number of nodes found out 54332. Analysis was carried out and they are tabulated in Table. Not only axial loads were calculated but buckling load, and weight were obtained all this of them are tabulated in table. **TABLE 2** Comparison of Tetra over hex element

Item	AISI 4340	
	Tetra	Hex
Compressive strength	50000 N	49600 N
Tensile strength	13500 N	13500 N
Buckling load	37220 N 144590 N	37190 N 144600 N
weight	0.67028 Kg	

5.1 Aluminium 7068

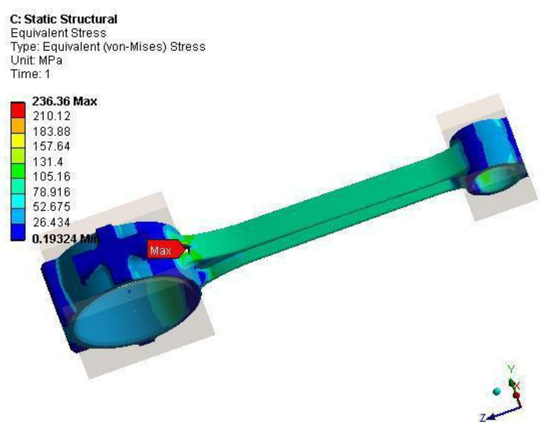

Fig. 12 Changes of stress for tensile loading

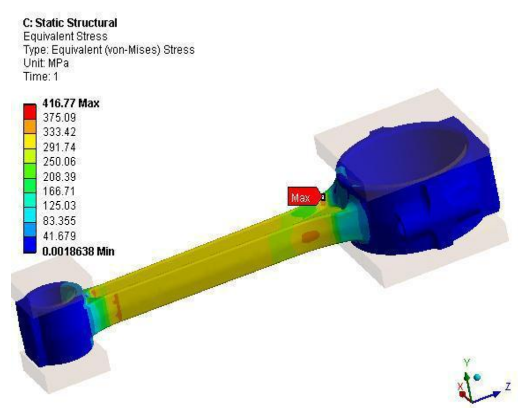

Fig.13 Changes of stress for compressive condition

FOS of 2.5 is given thus the allowable tensile strength was found out to be as 236 MPa and allowable compressive stress is 378 MPa. By using same element As per hand calculation the value of tensile strength for aluminium is 12570N . this show that connecting rod will fail at oil hole that is present near big end for repeated tensile loading. This is the plot that will be used to identify the correct stress in a stress riser point.

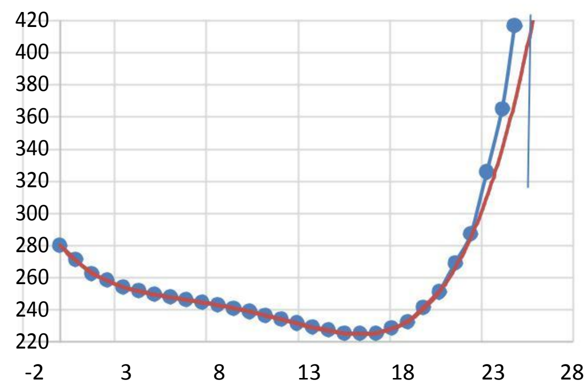

Fig. 14 stress along the path

When we are encountered with a stress converging point the surrounding element around that point and some points little away from that point which will act like a base to study that point. This intersection point will be the point which will give the actual value of stress for given load. At a compressive load of 39700 N stress reach its allowable stress. This little difference in strength of rod and require strength of rod leaves a scope for further work in material. For this we would look for some kind of composite work since we know that composite are light in weight but still have high strength.

Table 2 Comparison of Tetra over hex element

Item	AL 7068	
	Tetra	Hex
Compressive strength	39700 N	39300 N
Tensile strength	12000 N	12100 N
Buckling load	12957 N	12944 N
weight	0.24335 Kg	

5.2 Aluminium with titanium insert

In previous section connecting rod made of only Aluminium does not have sufficient strength to withstand the boundary conditions. For tensile loading we have seen that maximum stress will occur at oil hole which is present at the interface of big end and I section. This stress concentration occurs because of extracting of material. As we know whenever there is a minimizing of material at some region stress at that region will extensively increase. Same goes in our case, in order to provide lubrication this hole is placed but that result in reduction in strength. To increase the stiffness of the oil hole material is added which will

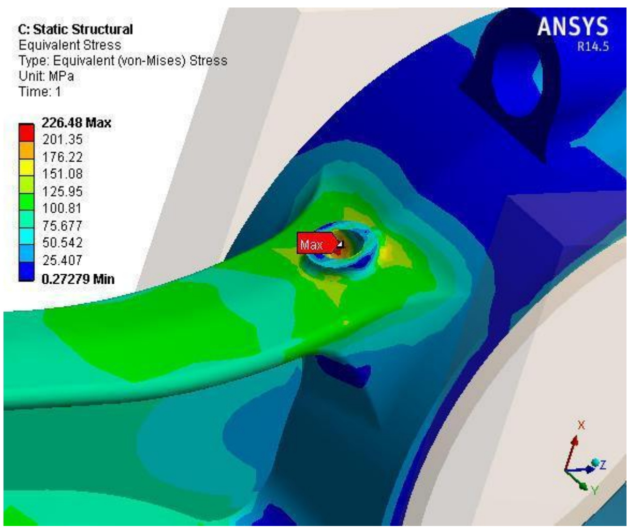

Fig 15. Variation of stress for tensile condition

help the stress to get distributed. This material is placed as an extruding part from oil hole which then give a fillet radius which will distribute the stress over entire surface. This extruded part have an outer radius of 10mm and the oil is a kept unchanged, as per the instruction any dimension cannot be changed but slight modification that will help in increasing strength will be accepted. Fig.16 shows the modification that was made. After this modification of adding material stiffness of oil hole have changed drastically, at a load of 13300 N s value have reached up to 226 MPa which is still low then allowable stress. Compressive strength can be improved by only if the stress at the point of maximum stress is reduced. This reduction is possible is some support material is present or else by changing the fillet radius that is given at interface of I beam and big end. But we are not allowed to change any original dimension which keeps the task difficult. Maximum stress point is also an stress riser point which makes it difficult to study the effect of any changes. After every iteration stress value is to be found out and some stress riser nodes are to be eliminated . Once this element are discard remaining elements are used for prediction of stress value. Following Fig.16 show the position of insets, dimension of insert are width 1.5mm

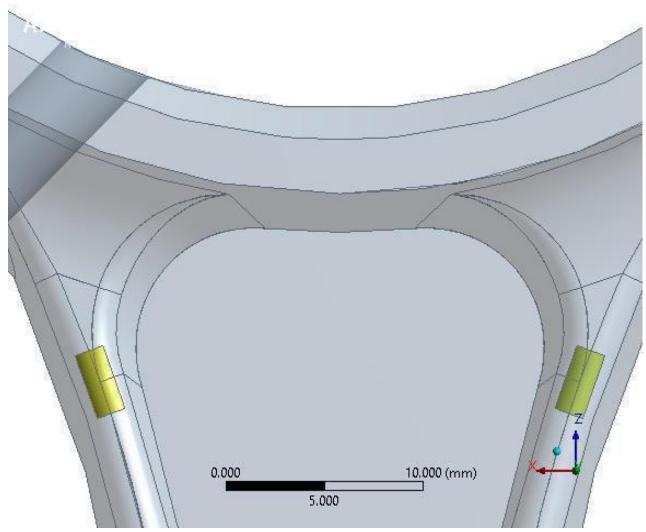

Fig.16 Inserts of Titanium

and height 3.3mm. As we can see in below picture we can see stress at titanium insert is slightly different and values are also low. This shows that there is the transfer of load and this load is reduced by some faction. This results in increase in strength and load carrying capacity is increased. At the load of 41500 N the maximum stress will reach to its allowable compressive strength of aluminium.

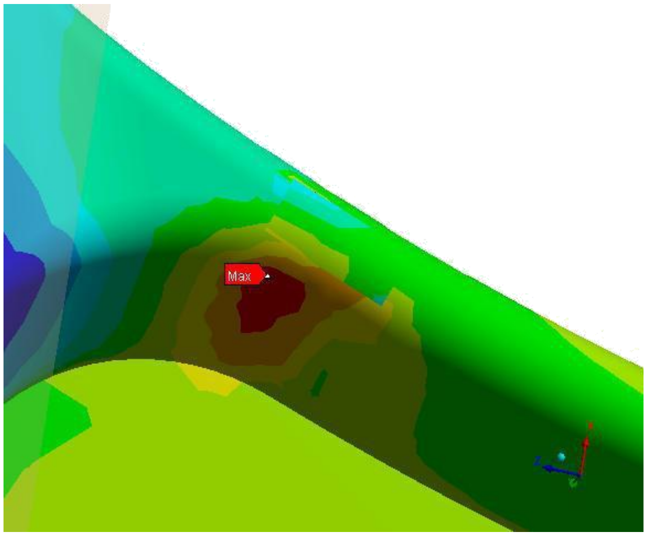

Fig .17 Stress concentration point by compressive load

Table 4 Result of connecting rod after adding titanium with aluminium

Item	AL 7068 with titanium	
	Tetra	Hex
Compressive strength	41500 N	41300 N
Tensile strength	13200 N	13100 N
Buckling load	13079 N	13050 N
weight	0.24376 kg	

Comparison of FEA and Experimental results

Table 5. comparison of Experimental and FEA Results

Experimental Result	FEA Result	% Error
0.16784 mm	0.18381 mm	8.68%

6 Conclusions

63.70 % in optimization in weight

10.38 % in tensile strength

65.20 % minimizes buckling load

It can conclude that from analysis as material changes from Steel to aluminium strength of connecting rod decreases. But as AL 7068 has high tensile strength compared to other aluminium alloy we find that the tensile strength is equivalent to Steel. Buckling load is reduced up to 65 % this shows that AL 7068 connecting rod can be used in engine by having some minor modification in material like use of titanium inserts at high stress concentration point. Weight optimization was of 63.69% thus in high rpm work environment inertia load will be minimized, this helps in reduction of vibration that is produce and weight of engine.

This new connecting rod has a higher reduction in weight but the concept of using inserts is quite difficult. As we can see inserts have sharp edges increases stress concentration. Furthermore placing inserts in mould at proper position for manufacturing purpose is also a problem. While doing sintering process and heat treatment process bonding between titanium and aluminium must have sufficient strength, this bonding between materials is itself a vast field of study in powder metallurgy process. Manufacturing of such connecting rod will have great impact on assembly line.

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