Analysis and Optimization of Connecting Rod With Different Materials

Ramesh B T, Vinayaka Koppad , Hemantha Raju T

Abstract— **Selection of connecting rod for good performance of engine is very difficult. The material used in the connecting rod should be chosen wisely because during manufacturing process it has to undergo various production processes and subsequent heat treatment process, which is very much important for strength and stiffness. Based on which the High Strength Carbon Fiber connecting rod will be compared with connecting rod made up of Stainless Steel and Aluminum Alloy. The results can be used for optimization for weight reduction and for design modification of the connecting rod. Analyses are carried out in ANSYS software**.

Index Terms— **Connecting Rod, FEA, ANSYS Workbench, Crank, Crankshaft, Piston, Stainless Steel, Aluminum Alloy.**

I. INTRODUCTION

A. Piston-Connecting Rod Assembly

A Connecting rod is a member which connecting between piston and crank shaft. Material, such as structural steel, aluminum alloy, titanium, and cast iron are used [1]. The connecting rod package has to be custom tailored to the engine and the customer's needs, says Kerry Novak of Crower [2]. The Small end of the connecting rod is connected to the piston end using a gudgeon pin/ wrist pin by press fit; big end is connected to the crank shaft using fasteners. Stresses on the connecting rod are always high due to the combustion chamber pressure, inertia forces, which induces high value of stresses. According to Vegi [3] "failure of a connecting rod, usually called "throwing a rod" is one of the most common causes for catastrophic engine failure in cars. However, failure of the connecting rod is not common since the big automobile companies try to keep very high factor of safety of 2 or 3 above. To provide warranty, automobile companies should have the robust design and manufacture capability. By having all this factors in consideration, a lot of engines fail or cease due to failure of connecting rod assembly, which leaves the companies to consider that the connecting rod as a very high risk component. For example connecting rod failed for GM 2014 Chevy Malibu's, 2014 Buick Regal GS , 2014 Chevy Impala, 2014Cadillac ATS and 2015 Porsche 911 GT3, which caused millions of dollars to be spent on recall to replace the whole engine and redesign the connecting rod [4]. While designing the connecting rod, Vegi [3] suggested that measures have to be taken to reduce the stresses in the connecting rod. Methods, like grinding the edges to give smooth surface and radius to prevent crack initiation shot peening method, are used which induces compressive surface stress to balance the weight of the connecting rod and piston assembly to reduce the bending stress due to centrifugal action. He suggest us to use high end equipment which zooms in the connecting rod to give minute invisible cracks, which lead to brittle fracture in the ductile material.

Ramesh B T, Mechanical Engineering, VTU/ Jain Institute of Technology, Davanagere, India,
Vinayaka Koppad, Mechanical Engineering, VTU/ STJ Institute of Technology, Ranebennur, India,
Hemath Raju T, His Mechanical Engineering, VTU/ Jain Institute of Technology, Davanagere, India,

B. Connecting Rod Materials

Forged steel is currently Eco boost Mustang material. AA is used mostly in aerospace application; this material is used to handle high stress values. In figure 1 shows Forged steel (FS) - A cosmetic trend has started by using Aluminum alloy as a CR member mainly to reduce the weight, however due to engine design evolving day by day, engineers have moved back to steel. Bryan Neelen [6] of late model Engines (LME) explains, "The weight below the wrist pin is not a big of a concern as the weight above it". He also says that this is one of the biggest reasons for moving back from Aluminum alloy.

Figure 1. Connecting Rod

Aluminum 7075 (AA) - This material is used as CR to reduce the weight and it gives cushion effect between piston head and crank shaft at higher rpm [6-7].AA CRs are generally manufactured by using CNC machines, which has high fatigue life and stronger.AA is used in Aircraft fittings, gears and shafts, fuse parts, meter shafts and gears, missile parts, regulating valve parts, worm gears, keys, aircraft, aerospace and defense applications; bike frames, all-terrain vehicle (ATV) sprockets [8].

II. LITERATURE REVIEW

Axial stresses and bending stress are acted on the connecting rod inside the combustion chamber. **According to Yogesh N Dupare** [5], He also says that axial stress is due to combustion chamber pressure and inertia forces and bending stress is due to centrifugal action of the connecting rod when connected to the crank shaft. Tony George Thomas [6] adds that fatigue failure is very high due to the fluctuation of these loads. **Yogesh [5] says** that 50-90% of the failure of the connecting rod are due to fatigue failure, thus it is very important to consider fatigue failure in the connecting rod design and great care must be taken by the Computer aided Engineering (CAE) team in a company to perform analysis on fatigue and come up with the redesign proposal, if necessary. **2016 Ford Eco Boost Mustang** uses forged steel as a connecting rod member. There is always been a thug of war in automobile industry to choose the type of connecting rod material. In this thesis forged steel and aluminum 7075 material is used as a connecting rod material. CAE analysis is carried out to pick the better material. Computer aided Engineering (CAE) team in a company performs analysis on all the real world problems using many different software by applying real world constraints to get solutions. Every company is equipped with a CAE team, which performs a detailed analysis on the connecting rod in every automobile companies by applying combustion chamber constraints like pressure, inertia forces, suppress the linear motion of the connecting rod were ever necessary. This team comes up with a real time results after the analysis is carried out and suggestions are made to redesign, if necessary. Once the CAE team approves the design then the actual production of the part kicks off. The connecting rod selected in this analysis is under investigation to validate the stresses and fatigue life of the component. Furthermore, if the connecting rod fails the design requirement, a new design proposal is given where ever necessary. **VelivelaLakshmikanth, and Dr. Amar NageswaraRao** - says that the temperature generated inside the CC is around 300 C for a 4 stroke IC, which is taken by the piston head. As we see in the picture the temperature effects are very high on the piston head and the temperature reduces to 50 C at the skirt of the piston (Piston skirt is the side portion of the piston which is in contact with the piston ring). By the time temperature effects reach CR, it continues to reduces, which is the reason temperature effects are neglected.

2.1Temperature Effects

Since most of the heat inside the CC is taken by the piston head, we do not see temperature effects as a major issue on the connecting rod which is show in figure.2. Bending stress are neglected since the crankshaft design is unavailable-Bending stresses are very important to consider since it causes lot of damages like fracture growth, failure due to wear. However, in this analysis due to the unavailability of the crankshaft design, the bending stresses which are caused due to rotational action of the CR are neglected.

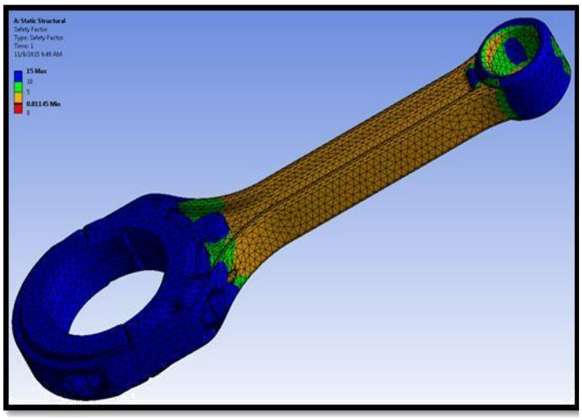

Figure 2.Piston head thermal stress plots [11].

Bending stresses can only be calculated using crankshaft design. Basic connecting rod design requirements-

- Max. Stress developed in connecting rod must be lower than the yield limit of the material.
- FOS must be 2 or above.
- Infinite fatigue life is preferred & FOS is 2

III. BOUNDARY CONDITIONS

Axial stress developed and fixed constraints on the CR are the real time boundary conditions which are seen in Eco Boost Mustang Engine.

Axial Stress- Axial stresses are developed due to the

- Combustion Chamber pressure (CC)
- Inertia Force

Combustion chamber pressure (CC) - High value of axial stresses is developed due to compressive pressure developed inside the combustion chamber due to the combustion of fuel [5].

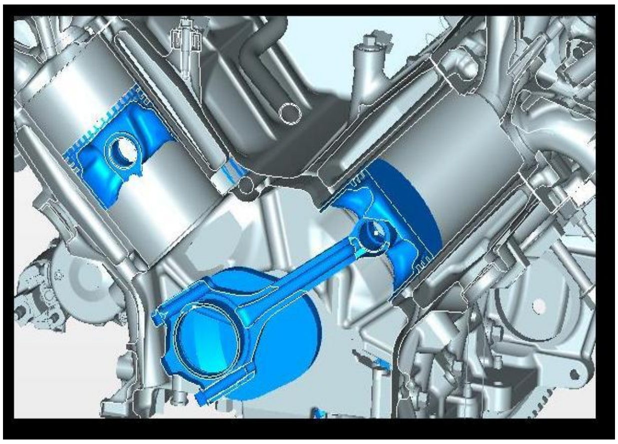

Figure 3. Piston- Combustion chamber and piston connecting rod.

A. MESH AND MESH SENSITIVITY

Solving a complex body to find the results of stress and fatigue life without using Finite element analysis is tedious and takes a lot of man hours and often results in human errors in solving complex equations. In 1943 an efficient way to solve complex problems related to a component was introduced by R. Courant [13]. He discretized the whole component into small elements, this process of breaking down the body is called meshing. This small elements are solved individually for solutions. Then solution of each individual element is summed up to get a final solution. One should understand that the obtained solution are not exact, but are approximate solutions which Engineers can trust.

Mesh- A very fine mesh was created at the critical areas like fillet region and edges of the CR. These are the sections in the CR where there is probability of max. stress concentration. Mesh connections are created in the assembly for connectivity while mesh operation is performed and make assembly a single model for analysis results.

B. Mesh sensitivity analysis

The purpose of conducting this analysis is to get accurate output solution. In this thesis, it is carried out to fin exact stress and fatigue plots. The relationship between input value and output values are understood using mesh sensitivity analysis. Output results were studied for different input element sizes from 8mm to 2 mm (element size).

IV. CAE ANALYSIS FOR FS AND AA

Static structural and fatigue analysis are carried out on the connecting rod. Here the analysis is done for FS and AA. BCs are applied, as inputs, to get stress and fatigue plots.

A. CAE analysis on a Forged steel connecting rod:

Boundary Conditions (BC) - These are the conditions or constraints, which are applied on the connecting rod, which is present inside the engine block of the Ford Eco Boost Mustang. BC is the pressure inside the CC, Inertia force due to the reciprocating action and fixed constraints on the CR.

Static structural analysis - This type of analysis deals with steady loading conditions only and ignores effects of loads which changes over time, for example inertia and damping effects. However, inertia loading which are caused due to self-weight, reciprocating and rotational motion, can be considered.Von misses stress, deformation, and factor of safety plots are obtained by conducting static structural analysis. Von misses stress plots are used in this analysis since they give detailed stress plots versus the yield limit and also often used since it give a detailed plot for all ductile materials in theory of plasticity. Maximum stress developed is at the fillet region of the CR for (–Y) direction axial loading. Maximum stress is 770 MPa at the fillet section which is higher than the yield of the material 625 MPa.

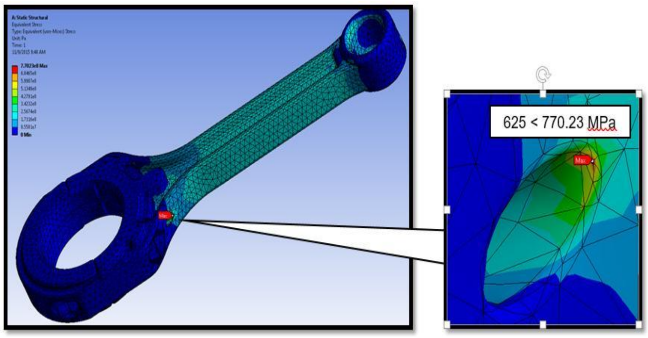

Figure 4.Von misses stress plot for –Y directional axial loading.

Maximum deformation, which occurs in the CR, is at the piston end [16]. We can see maximum deformation at the piston end because the area is very small for pressure distribution. Factor of safety (FOS) plots- It is the ratio of the yield to the maximum stress developed. In general, practicing Engineers try to have FOS of 2 or above for connecting rod.

Fatigue analysis: - When the connecting rod is applied repeated cyclic loads, like pressure and inertia force, the material begins to weaken, this is known as fatigue. When the material is subjected to repeat cyclic loading there will be progressive and localized structural damage . The stress developed will be always less than the yield stress and ultimate stress, however due to repeated loading; the material will fail from generations of crack to brittle material like failure. This type of failure generation is very hard to identify since the connecting rod is not visible to naked eyes and it is inside the engine cylinder. This type of failure is called "throwing a rod" and the whole engine ceases, which leads to irreparable engine. According to survey it says 90% of the connecting rod failure is due to the fatigue. In this thesis, fatigue analysis is carried out to see if the connecting rod fulfills infinite life requirement, also if the connecting rod fails, further analysis is carried out to find value of the stress for which the life of the CR increases to infinite and giving FOS of value 2.

1. Minimum life of the CR is 504 cycles only.
2. CR is at high risk of failure as the min. life of the component is 504 cycles only.
3. It is the responsibility of the Engineer to redesign the CR to give fatigue life of 10E6 cycles.

In general practice for steel material, CR is designed for infinite cycles. Fatigue redesign for forged steel connecting rod

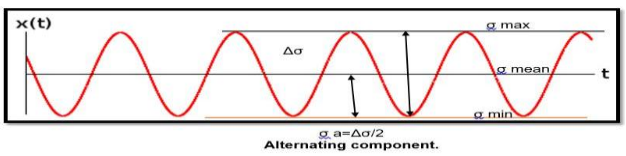

Figure. 5 fully reversed case

Fully Reversed case. A case where there is tensile and compressive loading on the connecting rod are the same. According to Yogesh, CR will undergo a fully reversed case and further analysis is carried out considering the CR is under tension and compression loading [5].

- σ max- Maximum alternating stress developed= +770.23 MPa
- σ min – Minimum alternating stress developed= -770.23 MPa
- σ mean- mean of σ min and σ max= 0 MPa.
- Δσ = Total value of stress developed= 770.23 + 770.23= 1.54 E3 MPa
- σ a=Δσ/2= 770.23 MPa.
- Alternating component= σ a= 770.23 MPa (max stress developed)
- Assuming the CR has maximum stress value of 770.23 MPa throughout its life cycle (Worst possible case).

According to Shigleys Mechanical engineering design hand book - it is very unrealistic to consider the specimen to have an endurance limit same as the one calculated for lab specimen. These factors vary in real life compared to lab specimen. Varies actors which affects are like heat treatment, fretting corrosion, surface condition, stress concentration, Size, shape, life, stress state, speed, fatigue, galling.

This imperfection in the real world scenario is calculated using-

Correction Factors= C load X C size X C temp X C reliability X C surface finish

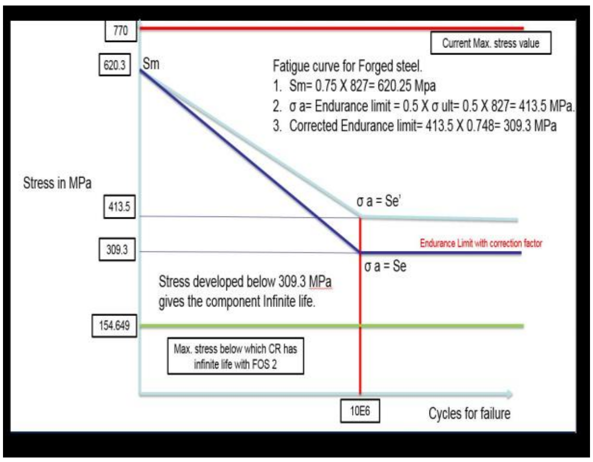

Figure. 6 Stress vs time graph (S-N graph)

Stress versus cycles to failure graph is plotted. Sm, endurance limit, and corrected endurance limit is plugged in the graph. Stress value below 309.3 MPa gives the material infinite life. The above stress value gives the CR infinite life and FOS of 2 and infinite fatigue life.This satisfies the design guide requirement. Conclusion and Validation

1. Maximum working stress is 154.6 MPa, which is less than yield stress, which is 625 MPa.
2. FOS is 4 for static structural axial loading; meets the design guide requirement.
3. Working stress at fatigue is 154.6 MPa which is less than endurance limit, with correction factor is 309.3 MPa.
4. Safety Factor at fatigue is 2; meets the design guide requirement.
5. Maximum stress and poor fatigue cycles occurs at the fillet section of the CR, redesign at this area, by either deleting the fillet section or increase the thickness at that particular site, is highly recommended to reduce stress concentration.
6. CR life is now designed for Infinite cycles and meet the design guide requirement.

By considering all the above factors, a robust CR design can be designed.

B. CAE analysis for ALUMINUM 7075 connecting rod

Boundary conditions are applied on the ALUMINUM 7075 connecting rod to get the output stress and fatigue plots Piston connecting rod assembly- Aluminum alloy

- Pressure on piston head 17.7MPa (-Y direction axial loading).
- Force due to Inertia 1000 N (-Y direction axial loading).
- Z direction is fixed.
- X direction free for rotational
- Y direction free for reciprocating.

Static stress analysisBy conducting static stress analysis, von misses plots, deformation plots, FOS and fatigue plots are obtained. Max. stress developed is at the fillet region of the CR for (–Y) direction axial loading. Maximum stress is 795.7 MPa at the fillet section, which is higher than yield of the material 503 MPa.

C. Deformation plots

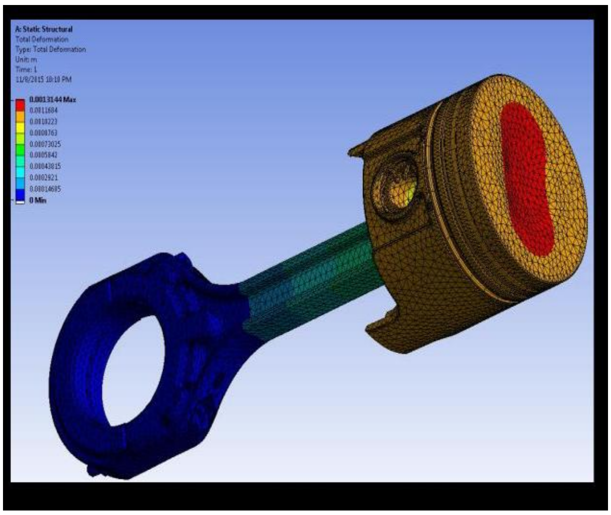

Figure .7 Deformation plot on piston head for –Y directional axial loading. Maximum deformation occurs at the piston head since cross section area is less.

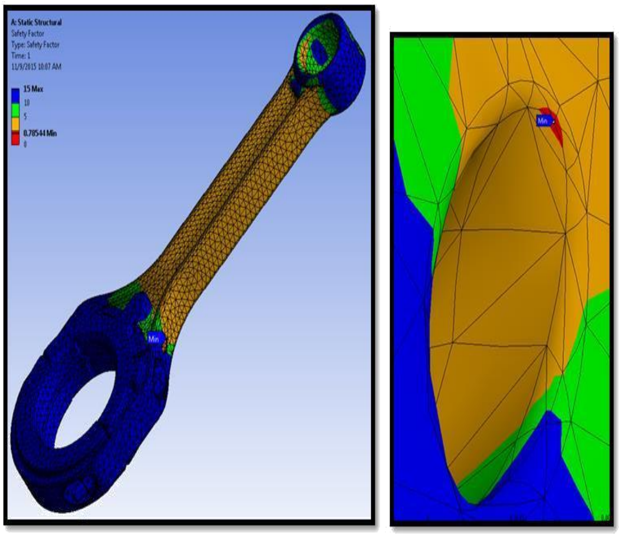

Figure .8 FOS plot for –Y directional axial loading

Maximum deformation occurs in the CR, is at the piston end [16]. One can see maximum deformation at the piston end because the cross section area is very small.Factor of safety (FOS) plots- It is the ratio of the yield to the maximum stress developed. In general practice Engineers try to have FOS of 2 or above for connecting rod.

Minimum FOS occurs at the fillet section of the CR assembly, desired FOS is 2 or above.

Fatigue analysis for Aluminum 7075Objective of the analysis is to maintain fatigue life of 10E8 and FOS of 2.

- CR is at high risk of failure as the min. life of the component is 286 cycles only.
- It is the responsibility of the Engineer to redesign the CR to give fatigue life of 10E8 for aluminum alloy.
- In general practice, CR is designed for a minimum of 10e8 cycles or infinite cycles.

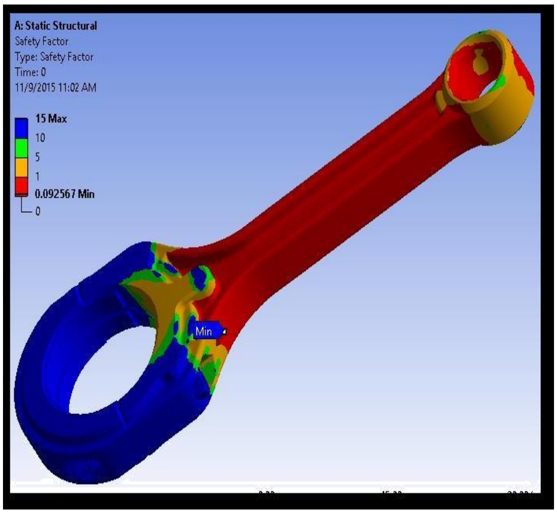

Figure. 9 Deformation plot on piston

1. Safety factor for fatigue is 0.09 which is less than 1, risk of failure is very high.
2. General practice is to have safety factor of 2 or above.
3. Further analysis is carried out to increase the CR life to 10E8 and safety factor to 2 or above.

D. Fatigue redesign for forged steel connecting rod

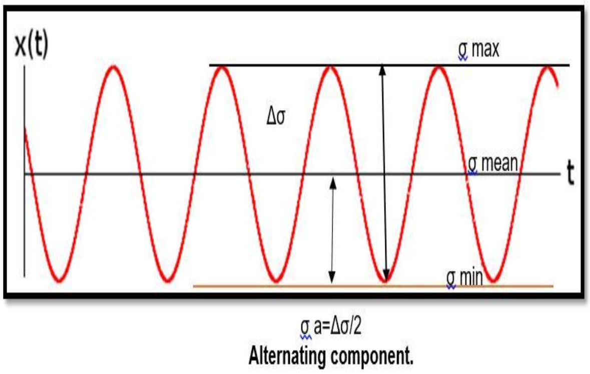

Figure .10 Fully reversed case

Fully Reversed case- A case where there is tensile and compressive loading on the connecting rod are the same. According to Yogesh, CR will undergo fully reversed case and further analysis is carried out considering the CR is under tension and compression loading [5].

- σ max- Maximum alternating stress developed= +795.7 MPa
- σ min – Minimum alternating stress developed= - 795.7 MPa
- σ mean- mean of σ min and σ max= 0 MPa.
- Δσ = Total value of stress developed= 770.23 + 770.23= 1.59 E3 MPa
- σ a=Δσ/2= 795.7 MPa.
- Alternating component= σ a= 795.7 MPa (max stress developed)
- Assuming the CR has maximum stress value of 795.7 MPa throughout its life cycle (Worst possible case) & FOS of 2.

In real life scenario, the material will have lot of manufacturing defects so the corrected endurance limit has to be found out by finding out what are the possible errors that can be found. According to Shigleys Mechanical engineering design hand book- it is very unrealistic to consider the specimen to have an endurance limit same as the one calculated for lab specimen. These factors vary in real life compared to lab specimen. Varies actors which affects are like heat treatment, fretting corrosion, surface condition, stress concentration, Size, shape, life, stress state, speed, fatigue, galling.Draw Stress vs Time (S-N) diagram

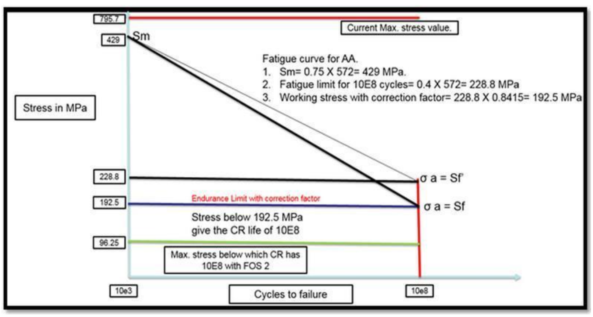

Figure .11 Stress vs time graph (S-N graph)

Stress versus cycles to failure graph is plotted. Sm, endurance limit and corrected endurance limit is plugged in the graph. Stress value below 192.5 MPa gives the material 10E8 life. The stress value gives the CR 10E8 cycles of life and FOS of 2 and infinite fatigue life.This satisfies the design guide requirement.

Conclusion and validation

1. Maximum working stress is 96.25 MPa, which is less than yield stress, which is 503 MPa.
2. FOS is 5.2 for static structural axial loading, meets the design guide requirement.
3. Maximum working stress at fatigue is 96.3 MPa which is less than the fatigue Limit with correction factor is 192 MPa.
4. Safety Factor at fatigue is 2, meets the design guide requirement.
5. Maximum stress and poor fatigue cycles occurs at the fillet section of the CR, redesign at this area, by either deleting the fillet section or increase the thickness at that particular site, is highly recommended to reduce stress concentration.

6. CR life is now designed for 10E8 cycles and meets design guide requirements. By considering all the above factors a robust CR design can be designed.

E. Results

Obtained results are tabulated below Table 6.1 Forged Steel v/s Aluminum 7075

ANALYSIS RESULTS	FORGED STEEL	ALUMINUM 7075
Max design pressure	17.73 MPa	17.73 MPa
Max Inertia Force	1000N	1000N
Material Yield limit	625 MPa	503MPa
Max. stress developed	770.23 MPa	795.3 MPa
Max deformation	0.000165 m	0.00017 m
FOS	0.81	0.7
Min. fatigue life	504 cycles	286 cycles
Safety factor	0.1	0.09
Endurance limit with correction factors	413.5 MPa	228.8 MPa
Max working stress proposal	154.6	96.25
Safety Factor	2	2
Design guide requirement	Met	Met

V. CONCLUSION

- Aluminum7075 weights three times less than Forged Steel; this material Connecting Rod is mainly used in aerospace application.
- Forged Steel has very high stress handling capacity without yielding.
- Deformation is Forged Steel is less compared to Aluminum7075.
- Also with application of 17.7 MPa pressure and 1000 N inertia force, Forged Steel has better values of stress, deformation, FOS, and fatigue life, which is better than Aluminum7075.
- Aluminum7075 has no infinite life and fails at 10E8 cycles; Forged Steel has infinite fatigue life.
- Also from manufacturing point of view- Manufacturing Forged Steel is easier when compared to CNC manufacturing of . Material thickness for Aluminum7075 is thicker when compared to Forged Steel, for same value of Boundary Condition.As the thickness of the Connecting Rod increases, Connecting Rod comes in contact with the engine block and crankshaft.
- By considering all the above factors, one can conclude that Forged Steel is better material than Aluminum7075 in terms of stress handling, manufacturability and cost.
- Forged Steel is the best material to be used as a Connecting Rod material for Ford Eco Boost Mustang.

REFERENCES

[1] A. Fatemi, J. Williama, and F. Montazersadgh, "Fatigue Performance Evaluation of Forged Steel versus Ductile Cast Iron Crankshaft:
a. AComparative Study." in FIERF, August 2007, pp 1-31.

[2] L. K. Vegi, and V.G. Vegi, "Design and Analysis of Connecting Rod using Forged steel," in International Journal of Scientific & Engineering Research, Volume 1, Issue 6, June 2013, pp. 2081-2090.

[3] Y.B. Dupare, R. B. Tirpude, and A. Y. Bharadbhunje, "Fatigue Analysis in Connecting rod using ANSYS," in Scientific Journal Impact Factor, Volume 4, Issue 711, 2014, pp. 215-220.

[4] T.G. Thomas, S. Srikari, and M. L. J. Suman, "Design of Connecting Rod for Heavy Duty Applications Produced By Different Processes for Enhanced Fatigue Life," in SAS Tech Journal, Volume 10, Issue 1, May 2011, pp. 1-7.

[5] V. Lakshmikanth, and A. N. Rao, "Modelling and Analysis of I.C. Engine Piston Crown Using FEM Package Ansys," in IJRMET, Volume 5, Issue 1,November 2014 ;Dec 2015 PP 51-59.

[6] S. pal, and S. Kumar, "Design Evaluation and Optimization of Connecting Rod Parameters using FEM," in IJEMR, Volume 2, Issue 6, December 2012, pp. 21-25.

[7] R. G. Budynas, and J. K. Nisbett. (2015). Shigley's Mechanical Engineering
a. Design, Tenth Edition. New York, NY: McGraw-Hill Education

[8] Leela Krishna Vegi ,Venugopalvegi " Design And Analysis of Connecting Rod using Forged Steel" International journal of scientific & Engineering Reserch, Volume 4,Issue 6,June-2013.

1.RAMESH B T:

Assistant Professor at Mechanical Engineering Department, Jain Institute of Technology, Davangere, Did master Degree in Machine design, presently pursuing Ph.D in VTU, life Menmber of ISTE, more than ten international journal published in various site, having 08 years of teaching Experience including PG & UG.

2.VINAYAK KOPPAD:

Assistant Professor at Mechanical Engineering Department, STJ Institute of Technology, Ranebennur, Did master Degree in Machine design, , having 07 years of teaching Experince including PG & UG.

3.HEMANTHA RAJU T:

Assistant Professor at Mechanical Engineering Department, Jain Institute of Technology, Davangere, did master degree in Product design and manufacturing, presently pursuing Ph.D in VTU, life Menmber of ISTE, having 07 years of teaching Experince including PG & UG.