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Fatigue Life Validation and Analysis of Connecting Rod

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Abstract

The connecting rod in four stroke reciprocating diesel engine is subjected to variable loading when Engine is in operating condition. The design of connecting rod is critical for the engine Performance, fatigue life, linear vibration & durability of engine. The fatigue failure is occurred due to alternating compressive & tensile stresses during its two revolutions. The fuel combustion inside cylinder generates a huge compressive force at power stroke. The 3D model is prepared and CAE analysis is done to predict the maximum Stresses and check whether it is safe for fatigue failure. The modification in design is done to make it safe for fatigue life. The experimental Fatigue testing is carried out to validate the predicted & Actual fatigue life of connecting rod.

Keywords: *Connecting rod, CAE analysis, fatigue testing, fatigue life*

1. Introduction

The basic purpose of connecting rod is to transmit motion and force from piston to the crankshaft pin. It sometimes has a provision of transmitting the lubricating oil between parts. The connecting rod forms a part of 4 bar link mechanism when it functions inside engine. The connecting rod consist two ends, small end that connects to the piston and big end to crankshaft. The intermediate part between this ends is “I Section”, “H Section”, “circular section” or “a rectangular type”. This section depends on the design requirement and the application where it is going to function inside engine. Normally this is optimized based on the loads coming on it and the space availability. The Connecting rod is subjected to alternating stresses of compression to tension stress when the crankshaft rotates two revolutions in four stroke diesel engine. The connecting rod goes under time varying loadings during its service life. The material selection criteria of this connecting rod are critical as it has to undergo alternating load leading to fatigue failure.

The cyclic loading is very important factor in design of connecting rod. The increase in cross section of connecting rod effects the overall balancing of Engine. If the mass of connecting rod increases than the overall crankshaft design will get affected as a rotary mass gets increase the crankshaft balancing requirement also get increases. Now if the balancing requirement of engine gets increase than the Engine overall vibration gets increase which leads to failure of it component. To keep a fine balance between connecting rod weight and the crankshaft design optimization of weight is required. Although crankshaft design is out of the scope of the paper normally the overall design of engine needs to be considered in designing of connecting rod for engine.

In this paper we will be dealing with multi cylinder diesel engine connecting rod for experimental fatigue testing and soft validation of its design. The failure location of connecting rod is identified with the help of CAE analysis and perform fatigue test on first

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prototype sample. The design of connecting rod is modified to make it pass the fatigue life. After the modification of design again an experimental validation is carried out to validate the results from analysis.

2. Literature Review

Yoo *et al.* [1] done an optimization on the part between the two ends of connecting rod using variation equations, material derivative idea of continuum mechanics, and variable technique to calculate shape design sensitivities. The outcome was taken for iterative equation which helped for optimized design. Serag *et al.* [2] established approximate mathematical function showing the connecting rod mass and cost relationship. This mathematical relation shown was used as function and one of the parameter in design. Sarihan and Song [3] work on small end of connecting rod which was optimized for bush and pin interference fit. The optimized surface was updated in iterative function, stresses found was used for analyzing the fatigue load in connecting rod. Pai [4] has optimized based on the loads coming on connecting rod. The section of rod is optimized by minimizing the inertia load from the gas load. A finite element method is used to check the stresses and the total displacement in all direction. The cost reduction was one of the parameter used to optimize the design.

Ishida *et al.* [5] determined the variation of material stress at I section of connecting rod. The displacement of connecting rod was studied. The variation of forces in two revolutions was also studied. Rabb [6] has done FEA on the connecting rod. The main focus was on bolt threads used for cap bolting of connecting rod. The pre bolt load and the torques on the bolt were studied. The effect of stresses developed in bolt and the threads on the connecting rod was analyzed. The gap between the crankshaft pin and the main bearing were studied. The effects of inertia load on the connecting rod, and the gas pressure were taken into consideration. The outcome showed that the minimum thread diameter has the maximum stresses, this was due to the pattern of the threads created while manufacturing of it. At the same location of higher stress the connecting rod has shown the fatigue failure.

Folgar *et al.* [7] designed a composite connecting rod with help of finite element analysis. Initially the fatigue failure was not in design consideration. The initial samples were tested for fatigue load. The forces coming on connecting rod were determined for the highest speed of engine. The forces on both small end and big end were considered in design. In the Static tests it was found that the big end and the small end have failed hence this both big end and small end was redesigned to take the loads. Balasubramaniam *et al.* [8] has performed a FEA of connecting rod used in Mercedes-Benz. In their view the 2-D FE simulations can be used to get the initial results and 3-D FE simulations was more nearer to the actual findings. The different forces coming on the connecting rod was considered to do the simulation and actual stress spread over was found. The force under consideration was the inertia forces, the gas forces, the initial pre fitment forces and the bolt loads.

From the Literature review it is seen that the highest forces derived from the inertia of crankshaft, piston pin and the gas force is considered. The changes in load due to rotation of crankshaft and the dynamic relation in between them seem to have no clear idea about it is seen.

It is seen that the maximum overall effect is taken or not is not cleared. Some of them have only considered the effect on big end and some have concentration on the small end failure. The resultant alternating load which leads to fatigue failure is not justified. The practical testing is only done on the highest load condition. The Dynamic stress analysis need to be carried out as the connecting rod is always subjected to tension and compression loads. This cyclic loading of connecting rod also affects the fatigue strength of connecting rod. The exact experimental fatigue life testing and soft validation analysis is not seen.

3. Experimental Program of Connecting Rod Fatigue Test

The connecting rod functions are critical in operation of engine. It has to bear a tensile load and compressive load during its operation in a four stroke cycle. The loads are so varying in nature and in continuous alternating fashion which leads to a major Fatigue failure. For any component design its operating condition is very important and as per that its impact on product life is highly dependent. This needs to check that whether a connecting rod passes to the Fatigue test or needs any improvement on it. This must be validated based on Fatigue testing. Before that some important terms must be seen and known what will be the acceptance criteria for saying that whether the component passes the fatigue life.

3.1. R Ratio

It is a ratio of Compressive load to tensile load denoted by negative sign as compressive load is considered as negative.

3.2. Acceptance Criteria for Connecting Rod

The Connecting rod assembly must past the 10 million cycles without any crack generated on its any part.

3.3. Test Fixture Concept

The Schematic diagram is given for the design of fixture. Refer figure 1 for the fixture design concept. The Big end and small end pins must be made as per the dimensions of crank journal and piston pin diameter with oil groove. Provide the oil grooves at big end and small end of fixture. The Fixture must be made with material having higher strength than the connecting rod. Here the H11 material is used for making the fixture and its components. This material has a greater strength and has a higher shock absorbing property**.**

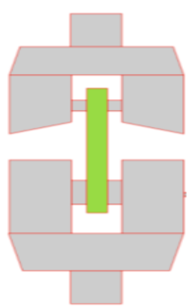

Figure 1. Connecting Rod Fixture Concept

than the material of connecting rod. The design the fixture pins body and fastener is done for two factor of safety, so that it can withstand the applied load. The fixture is given a heat treatment to achieve the surface hardness.

The fixture is inspected with CMM machine as per the drawing. The Fixture is checked in ultrasonic light to confirm if any crack is present while it is manufactured. Periodically it is needed to check every component for fracture and cracks as this fixture also has to undergo severe loads and for continuous operation it has to function.

3.4. Inspection of Connecting Rod

The connecting rod is inspected by Co-coordinate measuring method. The big end journal diameter, small end pin diameter, Centre distance, the bore distortion & circularity of bore is checked as per the designed parameters. The connecting rod bend and twist along the length must be below its design parameter than only the samples can be taken for test.

The induced stress must be relieved from the connecting rod and it should be as per the dimensions considered in design. Check the hardness of material with hardness testing machine. Confirm the prototype material by doing the material test as this is important parameter and can impact overall testing results, if the change in material composition is not as per the material considered in design of the connecting rod.

3.5. Fatigue Testing Procedure of Connecting Rod

Assemble the small end of connecting rod on upper side of fixture as piston also is on the small end of connecting rod and assemble the big end of connecting rod at the lower side of fixture as crankshaft is at big end or bearing end of connecting rod. Tighten the bolt of Connecting rod in steps first with 20Nm and then by 40Nm torque. Give the external oil supply to the fixture. Check if the fasteners of fixture and the connecting rod are torqued as per requirement.

A simple up-down test process is used as connecting rod is subjected to the alternating load of tensile and compressive nature when it is functioning inside a four stroke diesel engine. Increase the load at a 10% incremental load of the resultant alternating load. The R ratio of -2.80 is used with incremental of 1000lbf for testing.

Test the first proto sample on initial load which is equal to the mean fatigue strength. Now if the first sample fails to meet the acceptance criteria than go to next sample with reduced initial load. This will help us to know at what load it will pass the fatigue life acceptance criteria. If the first sample passes the acceptance criteria than in second new sample needs to increase the incremental load to next higher level, check if that meets the acceptance criteria. After one sample pass the acceptance criteria than in next sample increase the load to the desired intended max load.

Now when the sample passes at this intended max test load than the next three samples should show the consistency in results. This will helps out in making sure that at what load the connecting rod design will pass the fatigue life acceptance criteria. If we directly go to the max load than we might not be able to know that whether it is on border case or still has some margin for meeting the acceptance criteria.

Figure 2. Sample 'A1' Prototype Failed at Big End

4. Result and Discussion

Table 1. Fatigue Test Results

Sr No	Sample No.	Acceptance cycles	Cycles Competed	Remarks
1	A1	10 million	6 million	FAIL

From the above Table 1 & Figure 1 it is seen that the first prototype sample has failed to meet the acceptance criteria of fatigue life as it has a cracked at 6 million cycles. This result shows that even before the initial mean load condition the connecting rod is not meeting the acceptance criteria. Due to above result it is clear that the current design cannot meet the fatigue life of connecting rod. Further testing of samples is not necessary as the design has failed below its maximum alternating load.

With the help of CAE analysis, the connecting rod needs to be analysed for failure at the location near big end bearing. If the results also shows the high stresses near the failure location than it can be seen that the actual fatigue testing results and the soft validation done on analysis matches. If this is done within acceptable margin than only the modifications can be done in the design of connecting rod that can meet the fatigue life acceptance criteria.

5. Analysis of Connecting Rod

The Connecting rod has a very different type of motion than rest of the parts in engine. The

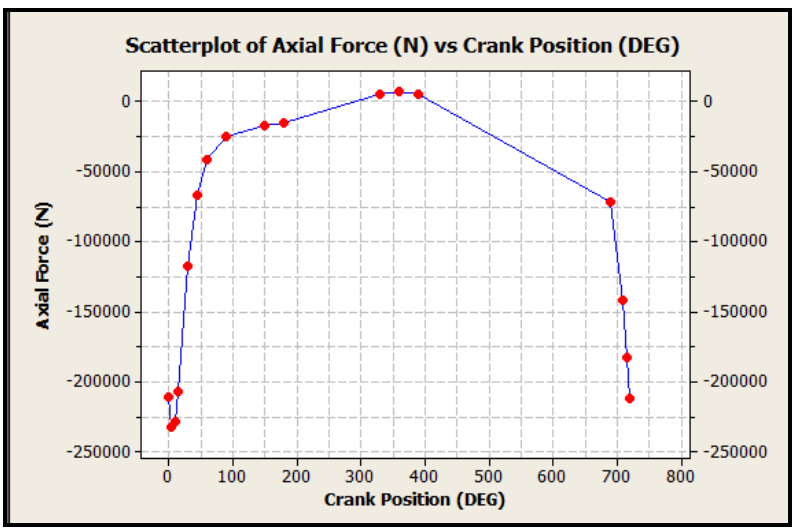

Figure 3. Graph of Axial force V/s Crank Position

motion has a time factor, axial and bending load. The forces acting on the connecting rod needs to be found. Since this being a low speed engine (1500. rpm), the forces causing the bending movement due to inertia load has to be found out. Based on the amount of load it has to decide whether it needs to be taken in account or not. For fatigue life of connecting rod it is necessary to know the compressive force and tensile forces coming on the connecting rod

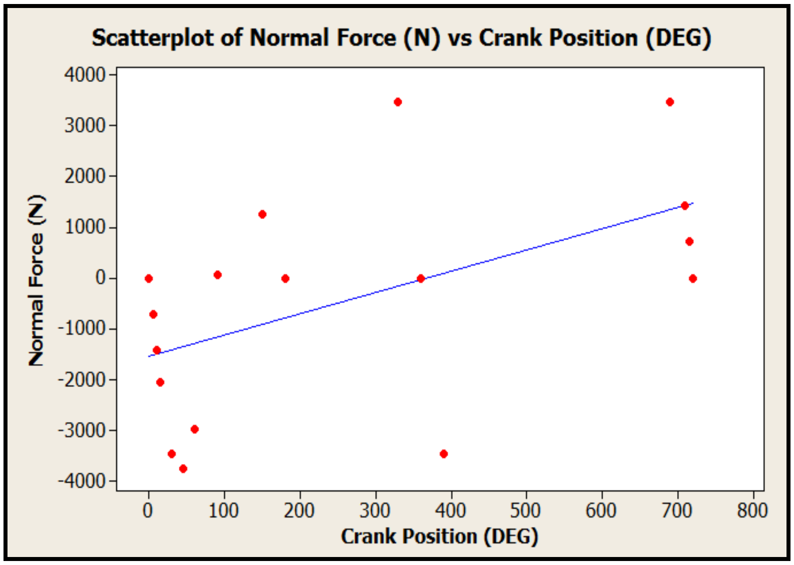

Figure 4. Graph of Normal Force V/s Crank Position

when crankshaft is rotating in engine. A connecting rod is subjected to dynamic loading when it is working in four stoke of Engine. This load at each degree of rotation has different load cases. Table 2 shows the material and its material properties used to apply in analysis. The engine type and power produced is given. Here it is considered that inertia load and its reactions are

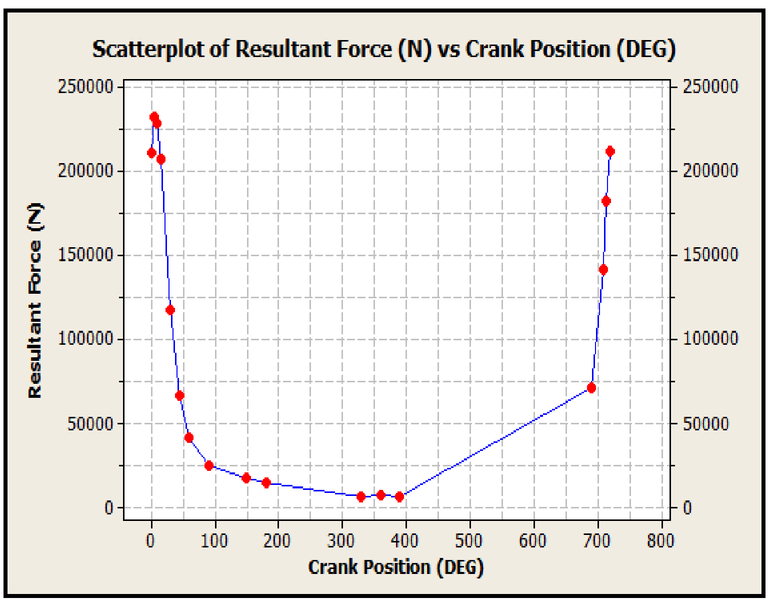

Figure 5. Graph of Resultant force V/s Crank Position

based on the engine speed at each degree of crankshaft rotation. The analysis has to be conducted for fatigue life of the component as this is one of the major components in Engine and has a very high effect to the engine function if it fails.

Table 2. Connecting Rod and Engine Specification

Engine type	V-type, stationary
Power	1250 HP
Material of connecting rod	42CrMoS4N
Ultimate strength	890 MPa
Yield strength	640 MPa
Module of Elasticity	21e4 MPa
Poisson's ratio	3e-1
Density	7850 kg/m3
Weight	5.270 kg

Normally it is seen that there maximum gas force is considered and a direct force is considered and tested, but this is not the true case as the connecting rod has a movement and it is not a stationary component in Engine. The bending stresses are derived from the moment of connecting when the crankshaft rotates at each stroke of engine. The power stroke is only one in two revolution of crankshaft hence the load varies once in two revolution of four stroke diesel cycle.

The forces are calculated by considering the engine cycle as a four bar link mechanism. The Axial forces and normal force are calculated on each degree of crankshaft rotation. The resultant of these forces is calculated per degree rotation of crankshaft. The Minitab 16 statistical software is used to plot the graphs as shown in Figure 3. The axial forces on Piston are not constant or nearly equal at each degree of crankshaft rotation. This shows that in four stroke engine the connecting rod has to go under variable loading condition. The figure 4 is of Graph of Normal force on piston per degree of rotation shows that the forces are near to zero or symmetric in nature. The resultant of Axial and normal force per degree of crankshaft is calculated and plotted as shown in figure 5. The graph of resultant force acting on piston graph shows that the forces are varying in nature as the crankshaft rotates from zero to two revolution of crankshaft rotation.

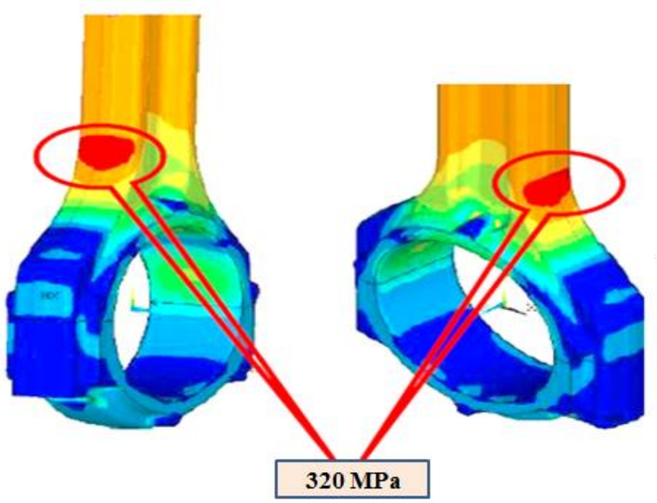

Figure 6. Highest Stress Location at Big End of Connecting Rod

The 3D CAD model of the connecting rod is prepared on the Wildfire software. After development of model the CG is found out. Parametric design approach is used of modelling of connecting rod. The extra flashes along the entire connecting rod length, the chamfers at bolt hole are removed in order to reduce the model meshing problems & size. It can be expected that these simplification would lead to great amount of savings in the solution time, without compromising on the accuracy of the solution. The connecting rod mass as measured on a weighing & actual 3D model matches within than 1%, indicating the accuracy of the model used for analysis.

5.1. Identification of Fatigue Failure Location on Connecting Rod

After developing the 3D model meshing is done by using Hyper Mesh software. The meshing is done by treating the connecting rod as a single part. The Von Mises stresses are checked at different locations. While analysing the stresses under the tensile and compressive loading, two different cases were considered, one in which the force were applied at big end and the small end was fixed. The second case in which the force was applied on small end and big end was kept fixed. The axial compressive force was assumed to be acting on the connecting rod. The force are applied as a uniformly distributed load over 120◦ of contact area, on the piston end, and all the nodes of 120◦ of contact area of the crank were treated as fixed, *i.e.* all their degrees of freedom were set to zero. The compressive, forces on big end with small end fixed, maximum Von Mises stress = 320MPa. As shown in figure 6. It is seen that high stress location is near the both side of big end on the connecting rod shown in Red colour. The stresses at this location is highest than compared to the other region of connecting rod. Even if Material homogeneity, heat treatment and the overall sizes matches and the connecting rod is free from micro crack, the failure may occur at the predicted location.

Thus to overcome this high stress location it is needed to modify the cross section area at that failure location, so that it can meet the fatigue life acceptance criteria.

6. Fatigue Test on Modified Connecting Rod

The modification of cross section at the big end location is applied to the tooling of connecting rod. The fresh samples are procured for fatigue testing. The earlier described procedure is followed to conduct the fatigue testing on these samples. After the first same number A2 has passed the acceptance criteria than the next step is done with Incremental load. The A3 sample is tested with desired max load which is meeting the acceptance criteria. To check the consistency of the result A4 & A5 are tested to check whether it meets the acceptance criteria.

Table 3. Modified Samples Fatigue Test Results

Sr No	Sample No.	Acceptance cycles	Cycles Competed	Remarks
1	A2	10 million	10 million	PASS
2	A3	10 million	10 million	PASS
3	A4	10 million	10 million	PASS
4	A5	10 million	10 million	PASS

8. Conclusion

The Sample A1 has failed in fatigue testing at the big end of connecting rod. The validation of connecting rod max stress region is same where actual fatigue failure of connecting rod has occurred. The actual failure location and soft validation failure location which enabled to take the corrective action for design modifications of connecting rod. The connecting rod goes under variable loading condition at each degree of rotation hence fatigue testing is important parameter for any design of connecting rod.

After the design modification the new samples are satisfactorily meeting the acceptance criteria of fatigue life and the three samples test results are showing us the consistency in meeting the acceptance criteria. From this it is concluded that the fatigue failure predicted in CAE Analysis and actual experimental testing work carried out co-relates with each other and the design of connecting rod is safe as it passes the 10 million cycle's acceptance criteria. Thus experimental fatigue life validation and analysis of connecting rod correlates with each other.

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