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Review Article

Investigation of stresses at a critical location for shape optimization of connecting rod using finite element analysis

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Abstract

A connecting rod is an element that is used to transmit power from the piston to the crankshaft in an IC Engine. The behaviour of connecting rod is affected by the fatigue phenomenon because of its cyclic loading. Fatigue is the primary cause of catastrophic failure of a connecting rod in an IC Engine. In the present work, shape optimization of the connecting rod is carried out by finite element analysis under reversible cyclic loading. In every phase of reversible cyclic loading, the stresses are generated and the critical locations on the connecting rod are located. The modelling of the connecting rod is carried out on CATIA, and ANSYS workbench is used for the FEA. The effects of design parameters are investigated, such as of fillet radius, groove depth, and groove length, based on maximum stresses generated at their critical location. With an increase in fillet radius, and decreasing groove depth and length, the maximum stresses generated were reduced by 15.07%, 6.31%, and 7.55%, respectively, due to a decrease in stress concentration. Finally, the optimized model has reduced the maximum stress at the bigger end of the connecting rod by up to 26.44%. This connecting rod now has better longevity during the operation.

Keywords: connecting rod, shape optimization, cyclic fatigue loading, FEM, FEA

1. Introduction

In an IC engine, a connecting rod is an intermediate link between the piston and the crankshaft, which converts reciprocating motion to rotating motion. The connecting rod is subjected to fatigue phenomenon by its reversible cyclic loading of roughly 10^8 to 10^9 cycles, as these forces are transmitted to the connecting rod by the piston, and significant compressive forces act due to the combustion of fuels and the large tensile forces due to inertia (Agrawal & Srivastava, 2012).

Connecting rods are manufactured by a casting process; however, from fatigue failure and durability point of view, casting can have as downsides some defects, such as blow-holes and porosity (Agrawal & Srivastava, 2012). By forging, blow-holes and porosity can be eliminated, which gives an advantage over the cast rod (Tevatia, Lal, & Srivastava, 2011). Generally, the shape of a connecting rod is designed as an I-section to provide maximum strength with minimum weight. The maximum stresses generated near the piston end of the connecting rod can be reduced by giving it excess material relative to the smaller end of the rod.

Parkash Gupta and Mittal (2013) identified critical locations on connecting rods under static and dynamic analyses of a universal tractor (U650) under fatigue loading. The connecting rod was modeled using CATIA, Pro-E, and analyzed through ANSYS workbench. They optimized the model of connecting rods for weight reduction and for improved life and manufacturability, as well as a better performance.

Fatigue strength is the most important consideration in the shape optimization of connecting rods (Tiwari, Tiwari, & Chandrakar, 2014). Fatigue analysis and life prediction can be performed using three approaches: stress-life theory, strain-life theory, and crack growth (Agrawal & Srivastava, 2012). Since a connecting rod in an engine bears static and dynamic fluctuations under loading, it is one of the most critical components. Kumar and Kumar (2015) improved the strength-

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to-weight ratio and optimized the shape of connecting rods made of forged steel, grey cast iron, aluminum, and titanium, under varying loads, by changing their cross-sectional areas as stress was induced at the smaller end more significantly than at the larger end of the connecting rod (Pathade & Ingoel, 2013). Some researchers analyzed connecting rods made of composite material Al6061 that is more deformable than Al6061+B_4C (Kumar, 2015).

Due to the repetitive tensile and compressive stresses (reversible cyclic loadings) the fatigue phenomenon develops, causing dangerous ruptures and damage to the CR (Agrawal & Srivastava, 2012; Roy, 2012). Agrawal and Srivastava (2012) modeled a forged steel crankshaft on Pro/E, whereas the ANSYS workbench was used for the FEFA under cyclic loading. They investigated the effects of crank-pin fillet radii, crank-pin oil hole diameter, crank-web thickness, inner diameter, and depth of drilled hole at the back of crankshaft, based on maximum von Mises stresses generated at the critical location, and predicted 13.5% lower von Mises stresses compared to the initial design.

Bharti, Singh, and Hussain (2013) showed that the maximum stress was generated at the crank end (Desai, Jagtap, & Deshpande, 2014). They reduced by 11.23%, 12.65%, and 10.56% the weight of the I, +, and ellipsoidal sections of the C-70 connecting rod, respectively. Anusha and Reddy (2013) performed finite element analysis on the two-wheeler Hero Honda Splendor's connecting rod and observed that the maximum stresses developed at the piston end of the connecting rod. Tiwari, Tiwari, and Chandrakar (2014) investigated 10% weight and 25% cost reduction by optimization of C-70 steel to replace forged steel connecting rods. The optimized model was efficient in design as the stresses are lesser than in the existing model. A weight reduction of about 3.5% was achieved in the steel material by the optimized design (Shanmugasundar et al., 2021).

Tevatia, Lal, and Srivastava (2011) analyzed I, +(plus), and H sections of connecting rods of equal masses and also investigated the effects of critical dimensions such as f_R, D, and H based on maximum von Mises stresses generated at the critical locations. They concluded from their research that the H section CR is unsuitable against fatigue failure for the entire range of fillet radius, inner diameter, and height of the big end compared to I and + section (Lal, Tevatia, & Srivastava, 2010; Tevatia *et al*., 2011). Saxena and Ambikesh (2021) modeled and analyzed the stresses developed on the Splendor motorbike connecting rod and observed that aluminium alloy 7475 was a superior material to carbon steel or titanium alloy Ti-6Al-4V.

Shenoy and Fatemi (2006) investigated the state of stress at various locations on connecting rods under service operating conditions. Due to the increase in inertial load, the maximum and mean stresses increase with engine speed. The axial stresses are produced in the connecting rod due to gas pressure in the cylinder, whereas bending stresses are developed due to the centrifugal effects (Pathade & Ingoel, 2013). Agrawal, Ali, and Rathore (2022) investigated the effects of design parameters such as fillet radius and addendum on the maximum stresses generated at the fillet radius of the root of spur gear.

2. Problem Formulation

2.1 Failure of connecting rod

There are many causes for the failure of engine components. One of the causes of failure of a connecting rod at the fillet area is the reversible cyclic loading during its service life. Due to the geometry of connecting rod and engine mechanism, the connecting rod fillet has a maximum stress range. Due to the combustion of fuels inside the cylinder, the load is transmitted from the piston to the connecting rod, causing a significant bending moment to develop on the entire geometry of connecting rod. Due to stress concentration at the fillet areas, these locations/points act as a critical locations, where cyclic loads could cause fatigue crack initiation leading to fracture.

For designing and optimizing any engine component, identifying its causes of failure is of critical importance. Fillets behave as stress raisers on the connecting rod surface; therefore, cracks may develop at their surface and grow inward due to combined cyclic bending and torsion loads.

2.2 Finite element modelling

In the finite element parametric modeling phase, design parameters and component dimensions and features are used and develop a relationship that captures the intended product behavior. The accuracy of models plays an important role in the Finite Element Analysis (FEA) of connecting rods to give the closest results. Modeling of any component is based on a set of principles for mathematical and computer modeling of 3D solids. The basic dimensions of the I-section are 58 mm thickness of a connecting rod of 2500 mm length between the big and the small end centers. With the help of the geometry (2D) of the I-section connecting rod, a three-dimensional model of connecting rod was generated using CATIA V5 SOFTWARE, as shown in Figure 1.

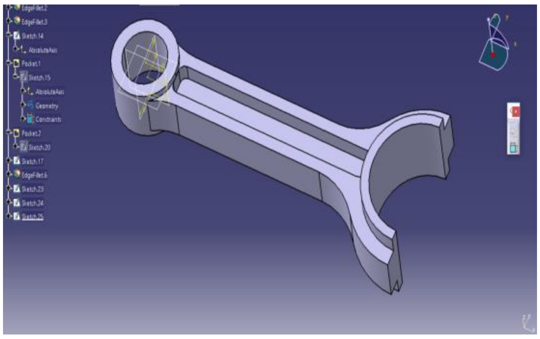

Figure 1. 3D solid model of a connecting rod

2.3 Finite element analysis

In this study, the finite element analysis of connecting rod was carried out on ANSYS workbench software. Convergence was achieved for the entire range of elemental lengths, using ten–node tetragonal elements, having 3-DOF at each node, which were used for meshing the 3D model. A higher-order 3D element, having fine mesh, is used to model irregular shape components such as connecting rods. These fine-meshed 3D elements give more authentic results at critical locations. The 3D model of connecting rod was meshed with 122,351 elements, with element lengths varying from 6 mm to 2 mm in a step of 1 mm. For an element size of less than 4 mm, the variations in the magnitude of maximum stresses generated at the critical location became negligibly small. The meshed model of connecting rods with element sizes at different locations is shown in Figure 2.

Boundary conditions in the FE model are based on the engine configuration. Figure 3 shows the boundary conditions applied in the FE model of the connecting rod. Boundary conditions change according to the direction of the load applied. At first, the connecting rod is assumed to exert a tensile force, and corresponding stresses at each node are calculated; after that, the compressive stresses are determined by replacing the tensile force with a compressive force precisely of the same magnitude but opposite in direction. Figure 4 and Figure 5 show the defined loading conditions in the FE model of the connecting rod. In every phase of reversible cyclic loading, the von Mises stresses are generated and located at the critical locations on the connecting rod, where the maximum stresses generated exceed the allowable limit.

To analyze the stresses on the connecting rod, various boundary conditions were run with the connecting rod model. In the FEM analysis, the smaller end of the connecting rod was fixed, and the tensile and compressive load of 9500 N was applied on the big end.

The material properties of connecting rod used in linear elastic finite element analysis were obtained from Lal *et al*. (2010) and Tevatia *et al*. (2011) are listed in Table 1.

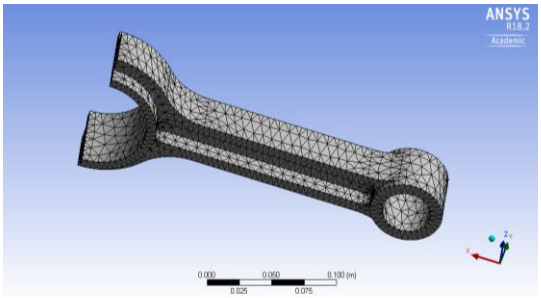

Figure 2. 3D meshed model of a connecting rod

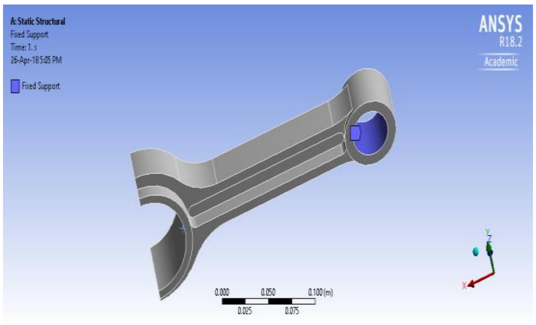

Figure 3. Boundary conditions on the connecting rod

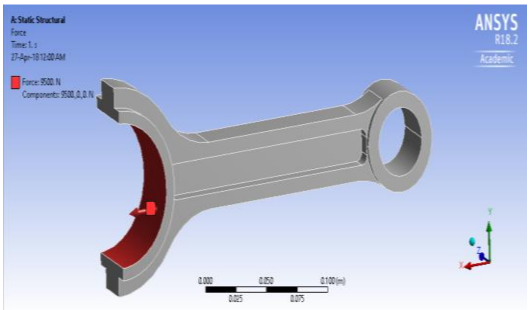

Figure 4. Tensile loading of the connecting rod

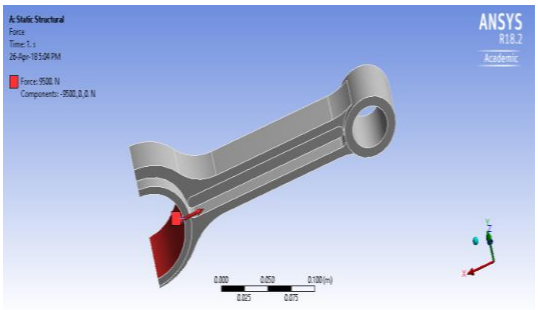

Figure 5. Compressive loading of the connecting rod

Table 1. Properties of the connecting rod material (Tevatia *et al*., 2011; Lal *et al*., 2010)

Material property	C-70 alloy steel
Tensile strength	621 MPa
Yield strength	483 MPa
Young’s modulus	207 GPa
Density	7700 Kg/m^3
Poisson ratio	0.30

In the present study, it was found that the fillet radius at the big end of connecting rod experienced the highest von Mises stress of 3.1112e7 Pa; therefore, this was selected as the critical location, and the FEA underestimated by 7.32% maximum stress generated relative to the FEA in Tevatia *et al.* (2011). Therefore, the results obtained from the FEA of a connecting rod model can be assumed to be satisfactory and the accuracy of the FE model used is established.

3. Shape Optimization of Connecting Rod

The present work aimed to optimize the shape of the connecting rod to achieve a high strength tolerant of high tensile and compressive loads. In this approach of shape optimization, the overall shape of the connecting is not changed; only the size is modified by varying some design parameters. Geometrical parameters are used as design variables in the size optimization. In this approach, the design variables such as fillet radius, groove thickness, and groove length of connecting rod are varied.

In the process of optimizing the shape of the connecting rod, various parameters such as the total length, radius, and thickness of the connecting rod are held fixed. The parameters that change in the optimization are known as design variables. The present work used as design parameters fillet radius, groove thickness, and groove length for the shape optimization.

4. Result and Discussion

The finite element analysis investigated and analyzed the effects of critical dimensions, namely fillet radius, groove thickness, and groove length of the connecting rod, based on maximum von Mises stresses generated at the critical location under reversible cyclic loading. The original model was analyzed by assuming the critical dimensions of connecting rod as fillet radius = 48 mm, groove thickness = 11.5 mm, and groove length = 165 mm. The von Mises stresses at the critical location have been determined, and the effects of design parameters were analyzed by taking the same masses of connecting rod.

4.1 Effect of fillet radius on the big end

The overall decrease in stresses generated with an increase in fillet radius is due to a decrease in stress concentration at the big end fillet. It is concluded that for both tensile and compressive loadings along the axis, a larger fillet radius of 50 mm may be preferred at the optimum level. Increasing the fillet radius from 47 mm to 50 mm reduces the stresses generated by 15.07% from that in the original model. Table 2 shows the magnitude of stress generated as function of the fillet radius at the big end of the connecting rod. Figure 6 shows the optimized connecting rod model with a fillet radius of 50 mm.

4.2 Effect of groove depth (Thickness)

Another step in the shape optimization was the variation of groove depth of the connecting rod. The stresses at the critical location were obtained by assuming equal mass for all design alternatives of the connecting rod. Table 3 shows the effects of groove depth on maximum stresses generated at the critical location in the connecting rod. Also, Figure 7 shows the optimized model in which the magnitude of stress is generated at a groove depth of 10.0 mm on connecting rod. Therefore, this may be considered a safe value for both tensile and compressive loading. Moreover, the stress level at the critical location is also reduced by 6.31%, compared with the stresses generated during optimization of the big end fillet radius to 50 mm.

4.3 Effect of groove length

Reducing the groove length is another way to optimize the connecting rod. The increase in stresses is due to a stress concentration at this location, which depends not only on the big end fillet radius and the groove depth but also on the groove length, which can be reduced in this optimization. Table 4 shows the magnitude of stress generated by various groove lengths of the connecting rod. Figure 8 shows the optimized connecting rod model with a groove length of 135 mm. Moreover, the stress level at the critical location was also reduced by 7.55 % compared to the stresses generated during the optimization of groove depth to 10.0 mm.

Table 2. Effect of big end fillet radius on the stress generated

Fillet radius (mm)	Max. stress (Pa)	Min. stress (Pa)	Status
47	3.6679e7	2199.8	
48	3.1112e7	3710.8	Original
49	2.6715e7	4267.8	
50	2.6422e7	4569.1	Optimized

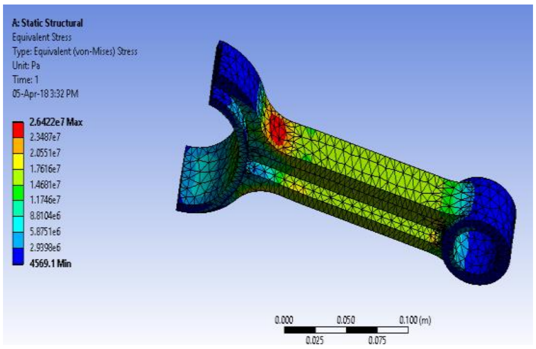

Figure 6. Stress generated at 50 mm fillet radius of connecting rod

Table 3. Effects of groove depth on the stress generated

Groove depth (mm)	Max. stress (Pa)	Min. stress (Pa)	Status
10.0	2.4754e7	2823.4	Optimized
10.5	2.4985e7	2803.7	
11.0	2.5723e7	4362.5	
11.5	2.6422e7	4569.1	Original

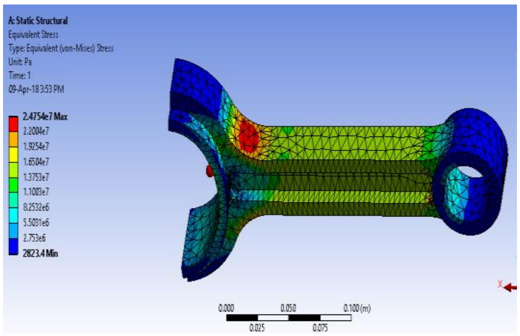

Figure 7. Stress generated at 10 mm groove depth of connecting rod

Table 4. Effect of groove length on the stress generated

Groove length (mm)	Max. stress (Pa)	Min. stress (Pa)	Status
165.00	2.4754e7	2823.4	Original
155.00	2.3022e7	2685.9	
145.00	2.2978e7	2414.4	
135.00	2.2884e7	2302.3	Optimized

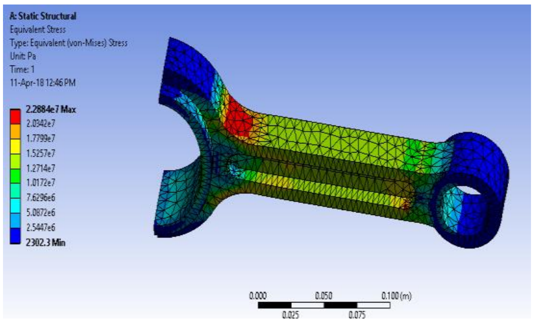

Figure 8. Stress generated at 135 mm groove length of the connecting rod

4.4 Comparison of optimized and original connecting rod

Local geometry optimization was applied separately to the different design parameters of a connecting rod, based on dynamic loading and stress analysis. Table 5 shows a comparison of the optimized design parameters with the original connecting rod as regards reducing the von Mises stresses at the critical locations. Since the stresses are higher in the fillet area due to a stress concentration, the first local optimization was increasing the fillet radius from 47 mm to 50 mm, and after that variation of groove depth (thickness) from 11.5 mm to 10.0 mm. Reducing the groove length from 165 to 135 mm was the next step in geometry optimization. The von Mises stresses generated were reduced by such optimizing of the connecting rod.

Table 6 compares the von Mises stresses of the optimized connecting rod with an original connecting rod of C-70 Alloy Steel. This optimization reduces the stresses in reversible cyclic loading from 3.1112e7 Pa to 2.2884e7 Pa. Therefore, the result of the geometry optimization process was von Mises stress reduction by 26.44% compared with the original connecting rod at its critical location.

Table 5. Comparison of optimized design with the original connecting rod

Sr. No.	Parameters	Original connecting rod (mm)	Optimized connecting rod (mm)
1.	Fillet radius	48	50
2.	Groove depth	11.5	10.0
3.	Groove length	165	135

Table 6. Comparison of stresses in the optimized and original connecting rods at their critical locations

Stresses generated in original connecting rod		Stresses generated in optimized connecting rod		Percentage reduction in stresses generated
Max. stress (Pa)	Min. stress (Pa)	Max. stress (Pa)	Min. stress (Pa)	
3.1112e7	3710.8	2.2884e7	2302.3	26.44

When the thickness of connecting rod at this critical location becomes less than the thickness of the remaining circular part of the big end, this section of the connecting rod becomes the weak link. This leads to a drastic increase in the stress at the critical point. Figure 9 shows the final optimized model of the connecting rod. This model of the connecting rod will have more durability. This can also be employed in some more stressful conditions.

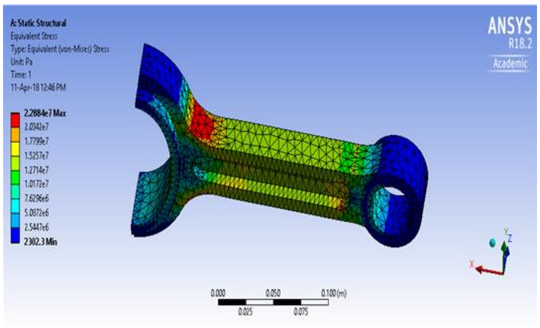

Figure 9. Optimized model of a connecting rod

5. Conclusions

The finite element analysis is a very effective way to identify the stress distribution and makes it easy to simulate realistic complicated loading conditions and to locate the critical sections. The effects of critical dimensions, such as fillet radius, groove thickness, and groove length of the connecting rod, were investigated based on the maximum stresses at critical locations under fully reversible cyclic loading. The following conclusions are drawn from the analysis:

1) The area near the fillet of the big end of the connecting rod is found to be a critical (i.e., failure) location because it experiences the highest von Mises stresses, with high stress concentration factors.
2) Comparative performance of critical dimensions of the connecting rod under fully reversible cyclic loading are:
    - With an increase in fillet radius, the maximum stresses generated decrease due to a decrease in stress concentration near the big end fillet on connecting rod. Increasing the fillet radius from 47 mm to 50 mm reduced the stresses by 15.07 % compared to the original model of the connecting rod.
    - With decreasing groove depth (thickness) on connecting rod from 11.5 mm to 10.0 mm, the stress level at the critical location was further reduced by 6.31 %, compared with the stresses generated during the optimization of the big end fillet radius to 50 mm.
    - By reducing the groove length from 165 mm to 135 mm, the magnitude of stress generated on the critical location of connecting rod was further reduced by

7.55 %, compared with the stresses generated during the optimization of groove depth to 10.0 mm.

Therefore, the optimized connecting rod model is predicted to have a 26.44 % lower von Mises stress, compared to the initial design, at the critical location of maximal stress. This will provide more strength, and will increase the longevity of the connecting rod.

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