Rajshahi University of Engineering & Technology

Experiment No. : 06
Experiment Name : Fatigue failure analysis and case study.
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Introduction:

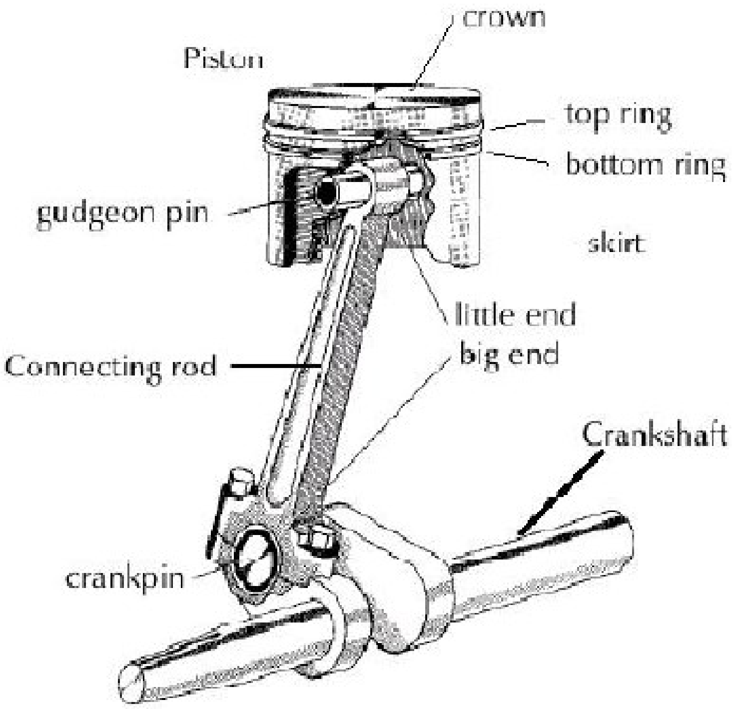
Fatigue is the weakening of a material caused by cyclic loading that results in progressive and localized structural damage and the growth of cracks. Fatigue failure is defined as the brittle fractures occurred while a repeated load or cyclic load is applied. This brittle fracture can be regardless of the material type whether it is a ductile or brittle material. In this experiment we will discuss the theoretical steps to analyze fatigue failure. Next we study a case of failed connecting rod from the article :

Ref : [Fatigue Fracture of Truck Diesel Engine Connecting-Rods
Article *in* Journal of Failure Analysis and Prevention · April 2015
DOI: 10.1007/s11668-015-9934-7]

Further in this experiment we will create our own 3D model of connecting rod in SolidWorks software and simulate the static and fatigue test and finally we discuss how to prevent fatigue failure.

Theory:

A piston is a component of reciprocating engines, reciprocating pumps, gas compressors, hydraulic cylinders etc. A connecting rod, also called a con rod, is the part of a piston engine which connects the piston to the crankshaft. The connecting rod converts the reciprocating motion of the piston into the rotation of the crankshaft. The connecting rod is required to transmit the compressive and tensile forces from the piston, and rotate at both ends.



The early stages of failure analysis:

When a failure occurs in any specimen, firstly we have to investigate the reasons behind it. By investing the actual reasons we could prevent the future failure of those specific specimens. Here, we have to collect some background information of the specific connecting rod of the piston where failure has occurred. At first we have to ensure that, if that connecting rod had any **past failure history** or not. Then we have to know the **timeline history of the failure.**

This means if it was a catastrophic failure or it gave a warning before failing. And the time difference between the warning given & failure occurred. Then we have to consider the **material properties** of the failed specimen. We also have to investigate if that failed connecting rod had any **previous repairing records.** At last, we have to collect some **photographic documentation** for visualizing the failed part of the connecting rod . It would be helpful for the future laboratory testing to analyze the specific fatigue failure.

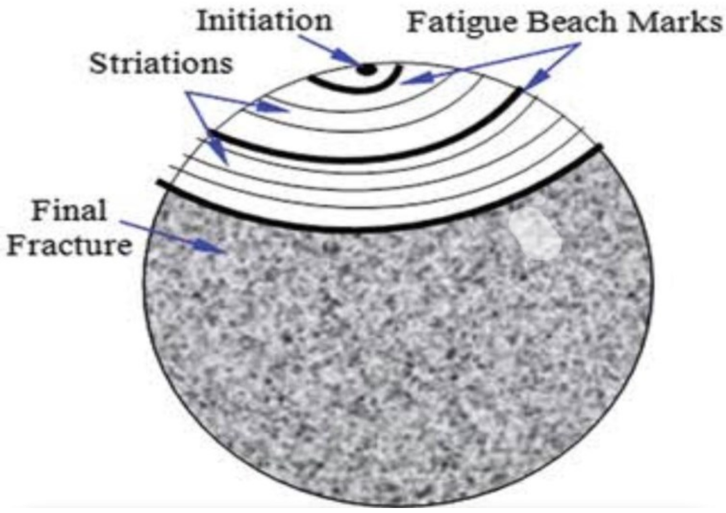
Subsequent stages:

<u>Macroscopic visual examination:</u>

The most important step in any failure analysis is the visual or macroscopic examination of the failed component. This step proceeds all other examination techniques, including those directed at the microscopic level. An integral part of any macroscopic examination is the use of micro etching to reveal the mechanical abuse marks, grinding scorch, decarburization, hardness or structure gradients etc.

<u>Microscopic examination :</u>

We can use an optical stereo microscope at magnifications of 50X or less for a microscopic examination which can help to reveal the fracture surface details. It can also confirm us the fracture initiation locations and mode of failure. By visual fractography we can observe two distinct regions of that failed connecting rod surface: the fatigue crack initiation & propagation region and the final overload region.



Metallographic examination :
We can use an optical light microscopy in the range of 100X to 1000X to identify the microstructure and heat treatment conditions of the material of that following connecting rod specimen. By this process we would also identify any possible defects originating from material processing or heat treatment.

Scanning electron microscopy:
Scanning electron microscopy (SEM) would assist in characterization of the type of the fracture and pinpointing the source of crack initiation. SEM observation found that fatigue striations on that specific connecting rod fracture surface, a micro feature of fatigue crack propagation, in zones A,B,C of the fracture surface.

Chemical Analysis:
We can ensure by this process that if the material of that connecting rod has been heat treated for maximum strength as resistance to fatigue increases with increasing strength.

<u>Energy Dispersive X-Ray Spectroscopy :</u>
Energy dispersive X-ray Spectroscopy (EDS) is a very useful step in elemental analysis. We will be able to identify & quantify the elemental compositions in that specific connecting rod element by this step.

<u>Verification of mechanical properties :</u>
In this process, we would compare the mechanical properties of an ideal component of a connecting rod with the failed one. Tensile test is performed in this if the size of the specimen is sufficient. Otherwise, hardness or micro-hardness method is performed for the small specimen. We will be also able to know if the surface decarburization or carburization is present or not by this process.

Studying the case :

The test was carried out on a dedicated fatigue test machine, which was hydraulically driven. The connecting-rod was tested purely under tensile-compressive forces. The test loads were applied through dummy pins that replace the original crank pin and the gudgeon. A sinusoidal waveform of 5 Hz was applied to the connecting-rod assembly at the load levels from -177.2 kN to +40.50 kN. The requirement was for $5x10^6$ cycle, but the connecting-rod fractured during cycles of 821078.

Fractographic Observation :

The fractured connecting-rod is shown in Fig. A. It can be seen that the transverse fracture occurred at the small head(piston pin end) of the connecting-rod without obvious plastic deformation on the whole connecting-rod. The fracture surface shows silver gray tint (Fig. B. Two smooth zones vertical to the connecting-rod body are on the fracture surface, corresponding to the lower and upper beams of the connecting-rod. Beach marks typical of fatigue fracture were observed on the fracture surface. Tracing the crack-propagation marks, two independent crack origins (marked A and B) were found to be situated at the same side of the connecting-rod. The propagation direction of the initiating cracks is from the ‘‘left side’’ to ‘‘right side’’. In the middle stage of crack propagation of crack A, the direction of crack propagation inclined upward as shown in Fig. A.

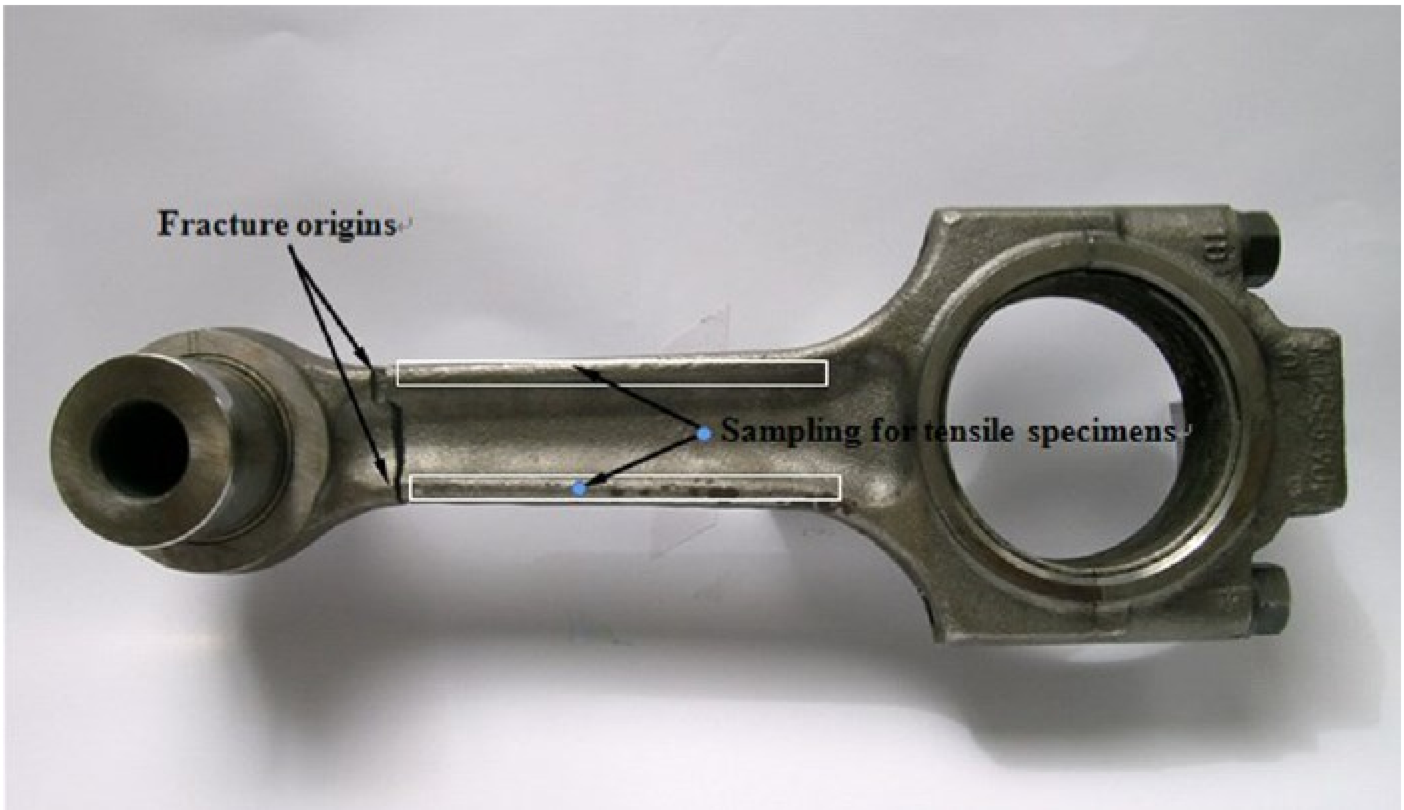


Fig. A : Fractured connecting-rod

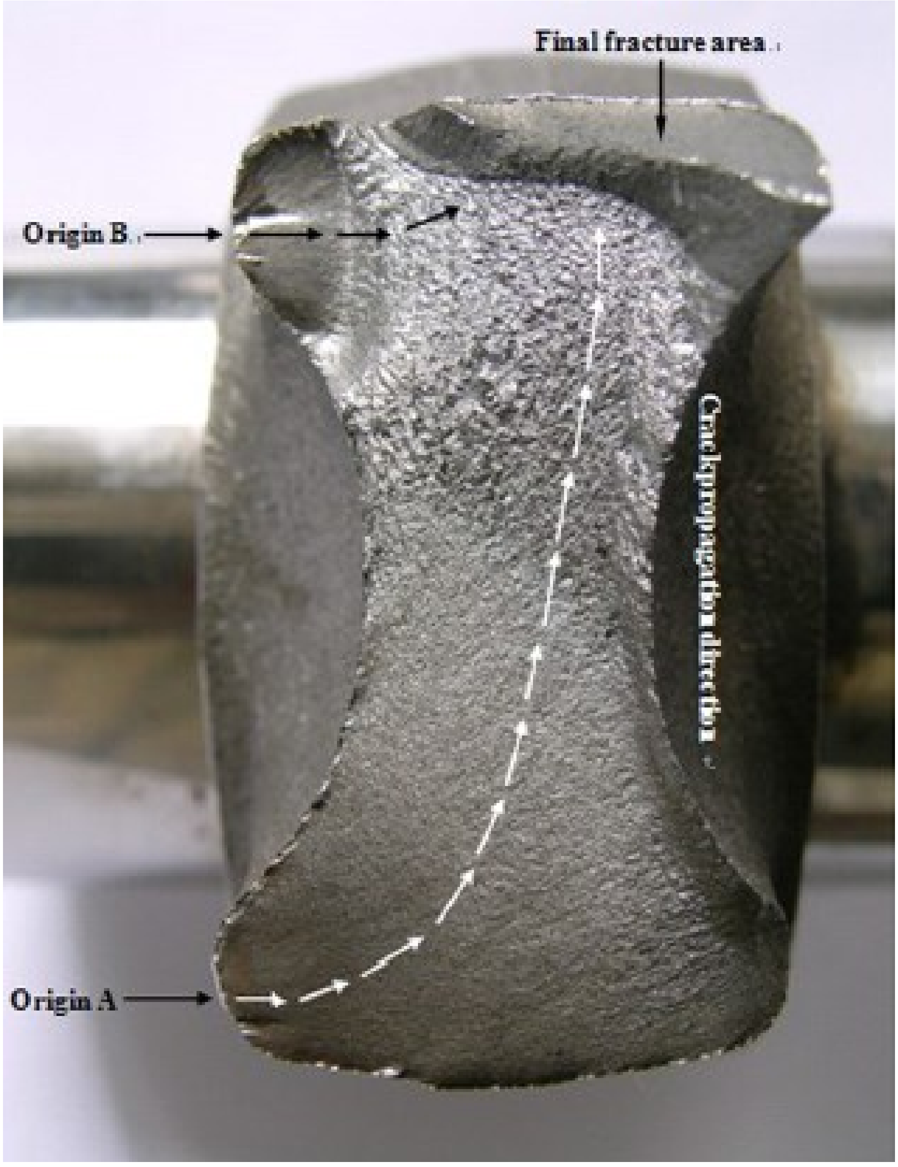


Fig. B : Macro-fracture of connecting-rod

The fracture progressed mainly from the origin A, with origin B playing a secondary role in the failure process. The upper right portion of fracture is final instantaneous overload fracture (as marked in Fig. B)produced when the area of the component which remained uncracked is no longer able to withstand the applied loading.

The smaller instantaneous fracture area indicates
that the applied load on the failed connecting-rod is relatively low. The fatigue striations, micro-features of fatigue fracture, were found in the vicinity of the crack origin and crack propagation zone, coexisting with the secondary cracks (Fig. C). Fractographic observation indicates that fatigue is the main failure mechanism of the connecting-rod. In addition, no obvious damage was found on the rod body close to the fracture. The connecting-rod bolts did not become loose.

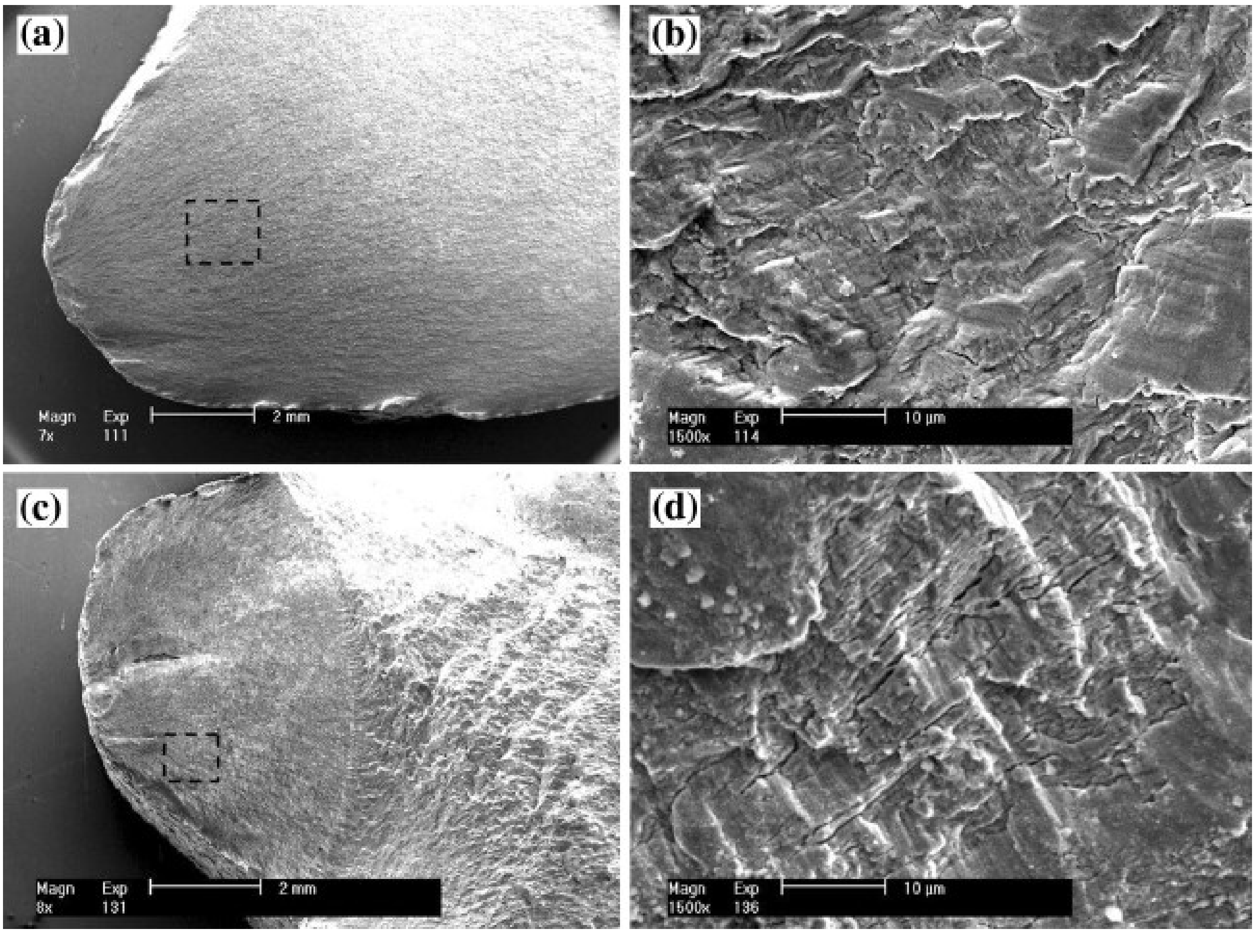


Fig. C : SEM observation on fracture surface: (a) general view on crack origin A, (b) boxed zone in (a) showing fatigue striations and secondary cracks, (c) general view on crack origin B, (d) boxed zone in (c) showing fatigue striations and secondary cracks

Microstructure Observation

Two cross-sectional specimens adjacent to the two crack origins (locations A and B) were prepared to observe the microstructure (Fig. D). Microstructural analysis revealed a ‘‘white layer’’ on the external surface of the connecting rod, mainly composed of ferrite.

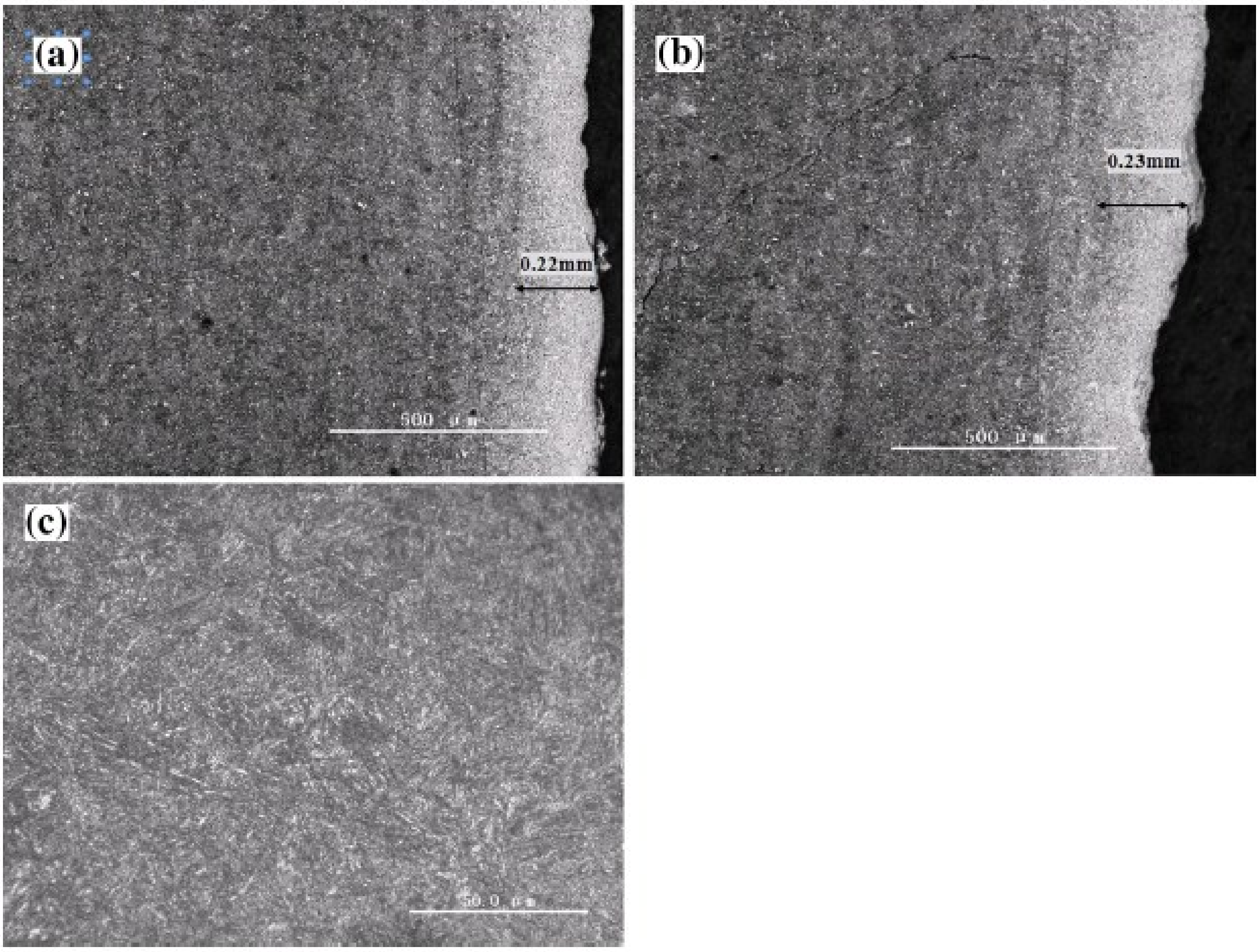


Fig. D: Cross-sectional microstructures of connecting-rod: (a) region A, (b) region B, (c) core

Chemical Properties Evaluation:

The chemical composition of the failed connecting-rod material indicates that it was fabricated from 42CrMo steel:

Table 1: Chemical composition of connecting-rod material

	C	Si	Mn	P	S	Cr	Mo	Fe
Analyzed	0.40	0.29	0.72	0.010	0.001	1.14	0.16	Bal.
Specified	0.38–0.45	0.20–0.40	0.50–0.80	≤0.04	≤0.04	0.90–1.20	0.15–0.25	Bal.

Mechanical Properties Evaluation:

Two flat-tensile samples were prepared to evaluate the tensile properties of connecting-rod material, and the results are shown in Table 2, along with the specified values.
It can be seen that tensile properties are within the range of the specification.

Table 2: Examination results of mechanical properties of connecting-rod material

Reading	Ultimate strength (MPa)	Yiels strength (MPa)	Elongation (%)	Hardness (HBS)
1	995	878	14.2	290, 290, 291, 291, 290
2	997	874	15.2	
Specified	850–1000	≥650	≥12	250-310

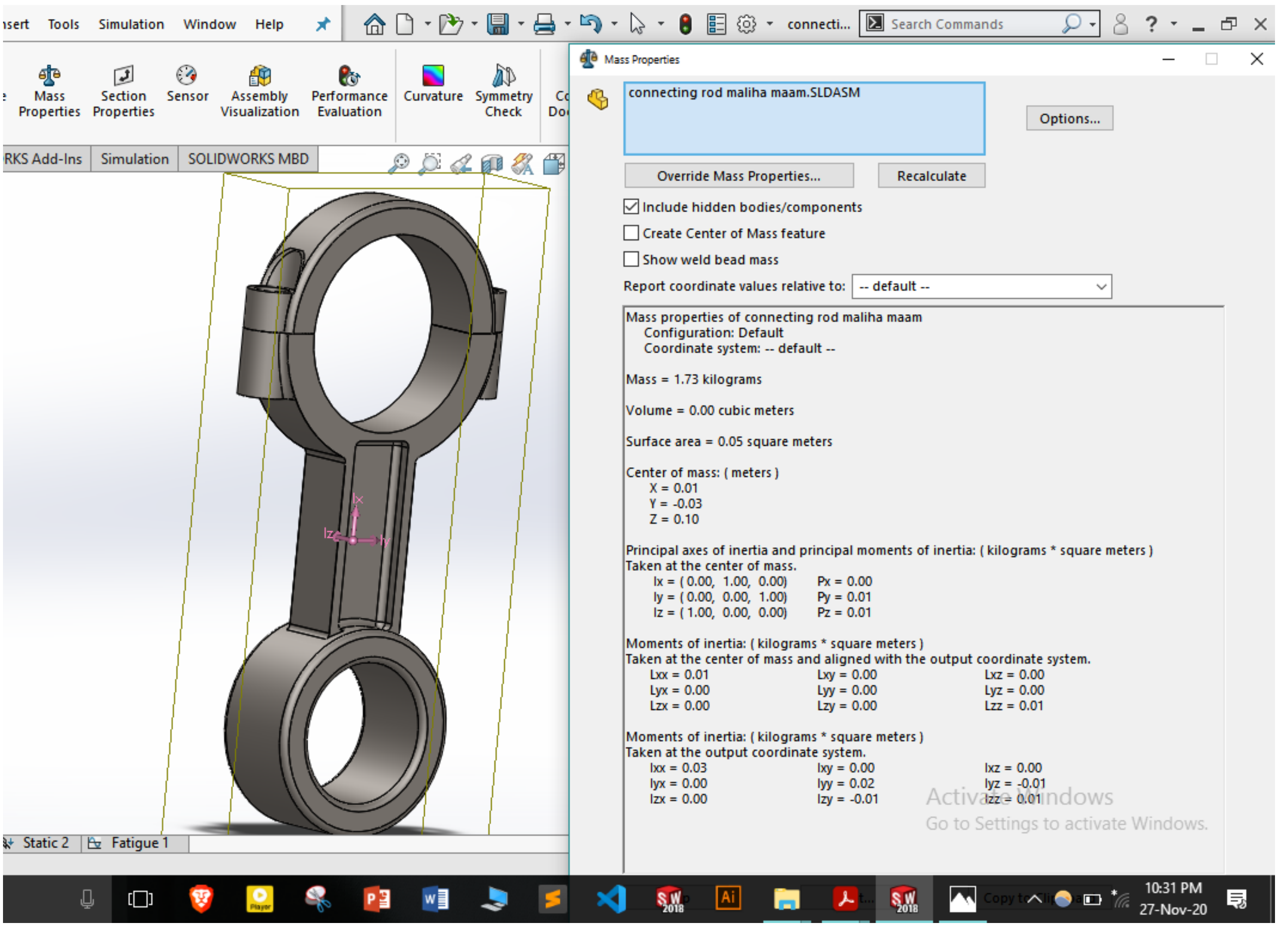
Observations :

The above case studies show that fatigue failure is an important failure mechanism in connecting-rod. This problem can be addressed by strict control on heat-treatment process to ensure metallurgical quality of the connecting-rod. Also careful assembly of various components of the engine and close attention to the abnormal running condition of engine will help to avoid the occurrence of abnormal loads.

FEM analysis:

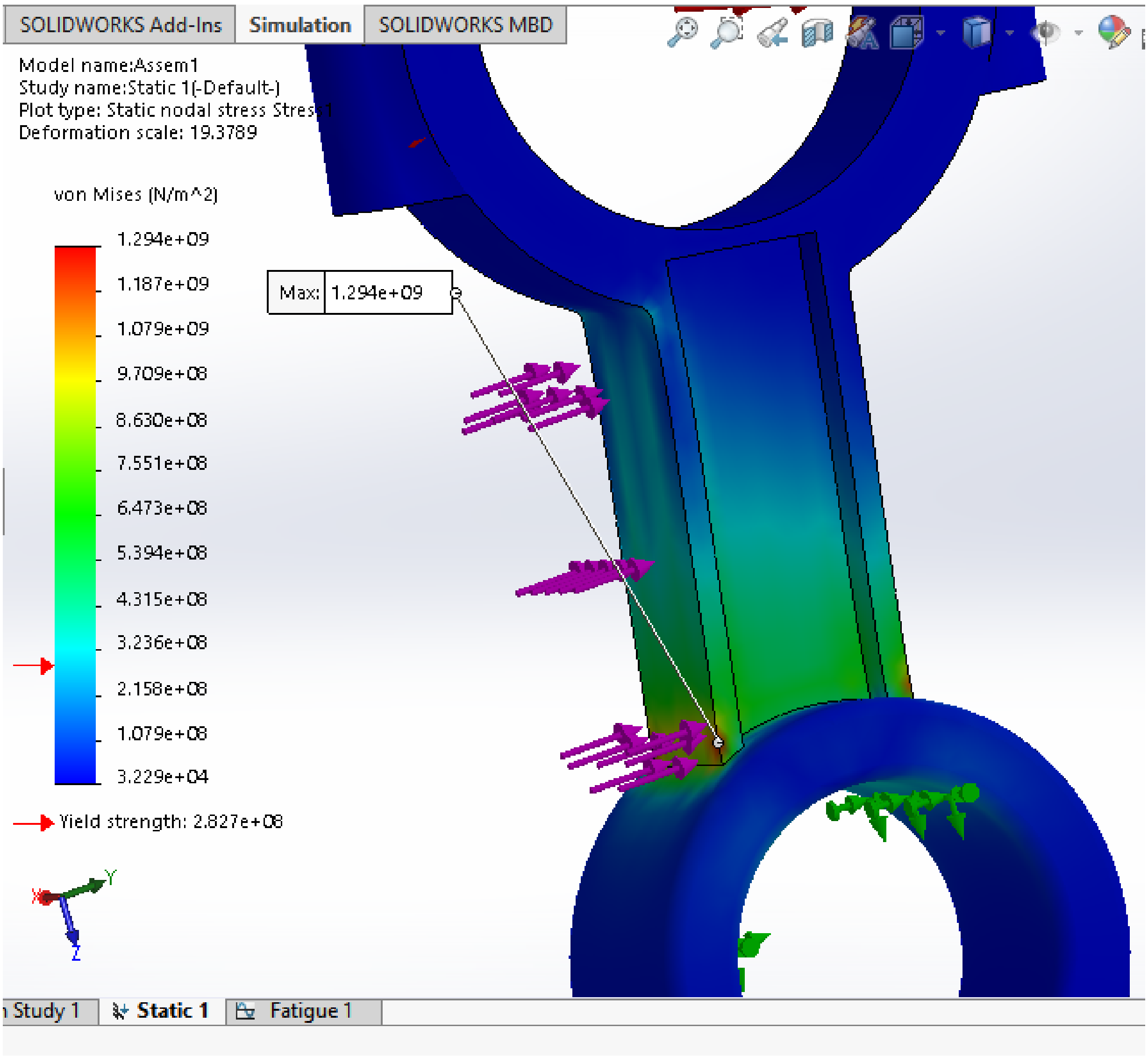
Finite element method (FEM) is defined as a new method used for analyzing fatigue and estimating the component durability which is more advantageous than other techniques. By the finite element analysis method and SolidWorks software, It is possible to analyze the different components from varied aspects such as fatigue and consequently save the time and the cost. The way that defined loadings was effective on the results achieved. So, they should fit as much as possible the real conditions. Stress concentration factors indicated the difference between the real and the working condition. Thus, by using this technique, it is possible to access the distribution of the stresses/strains over the entire component to obtain the accurate critical points by using SolidWorks software .

To simulate the static and fatigue study we made a solid 3D model of a connecting rod of ideal dimension in SolidWorks software :



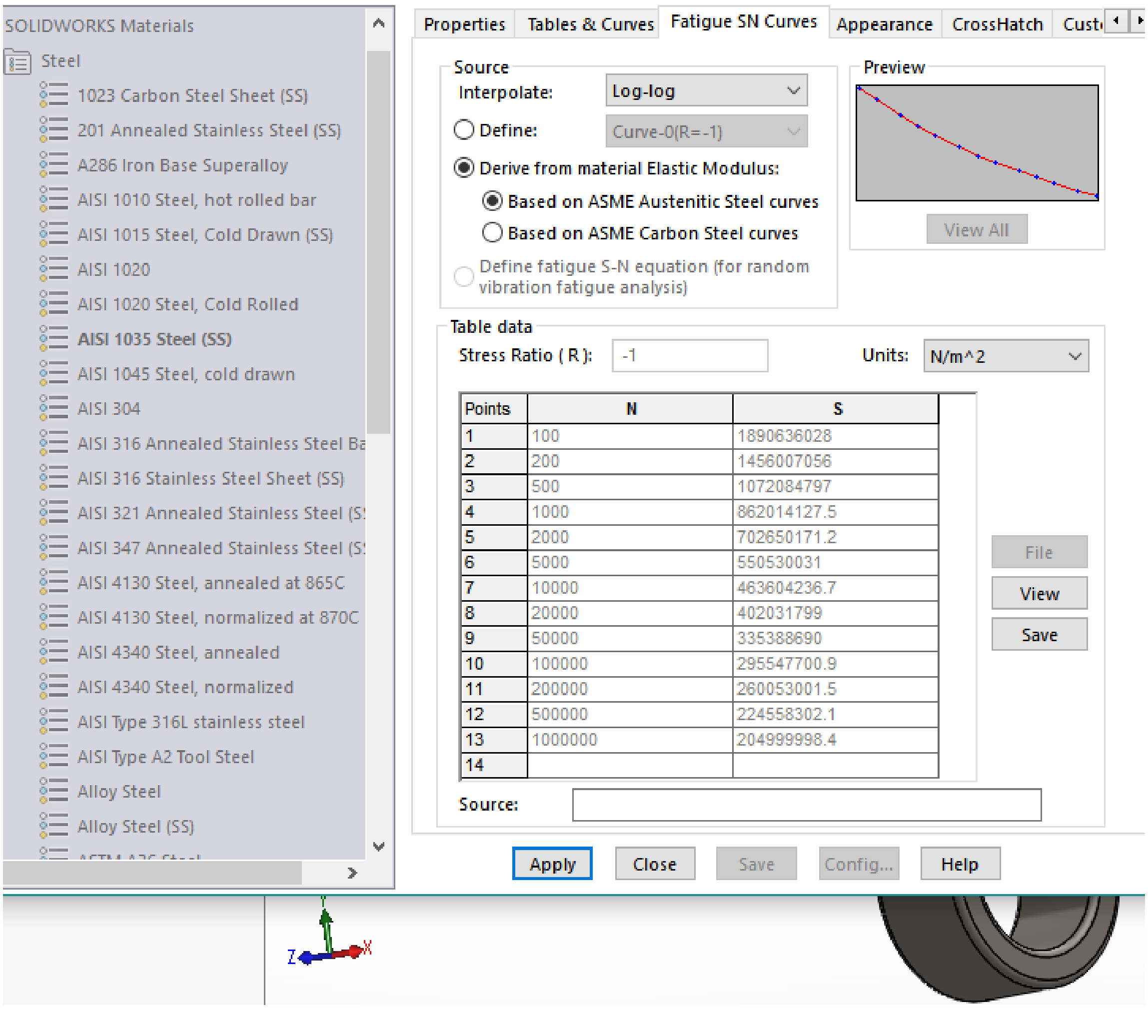
Next we selected material for our connecting rod. We used structural steel (AISI-1035).

To find out where the stresses concentrate we executed a static study in SolidWorks which showed us where the maximum stress concentrate. Usually this is where the fatigue failure occurs



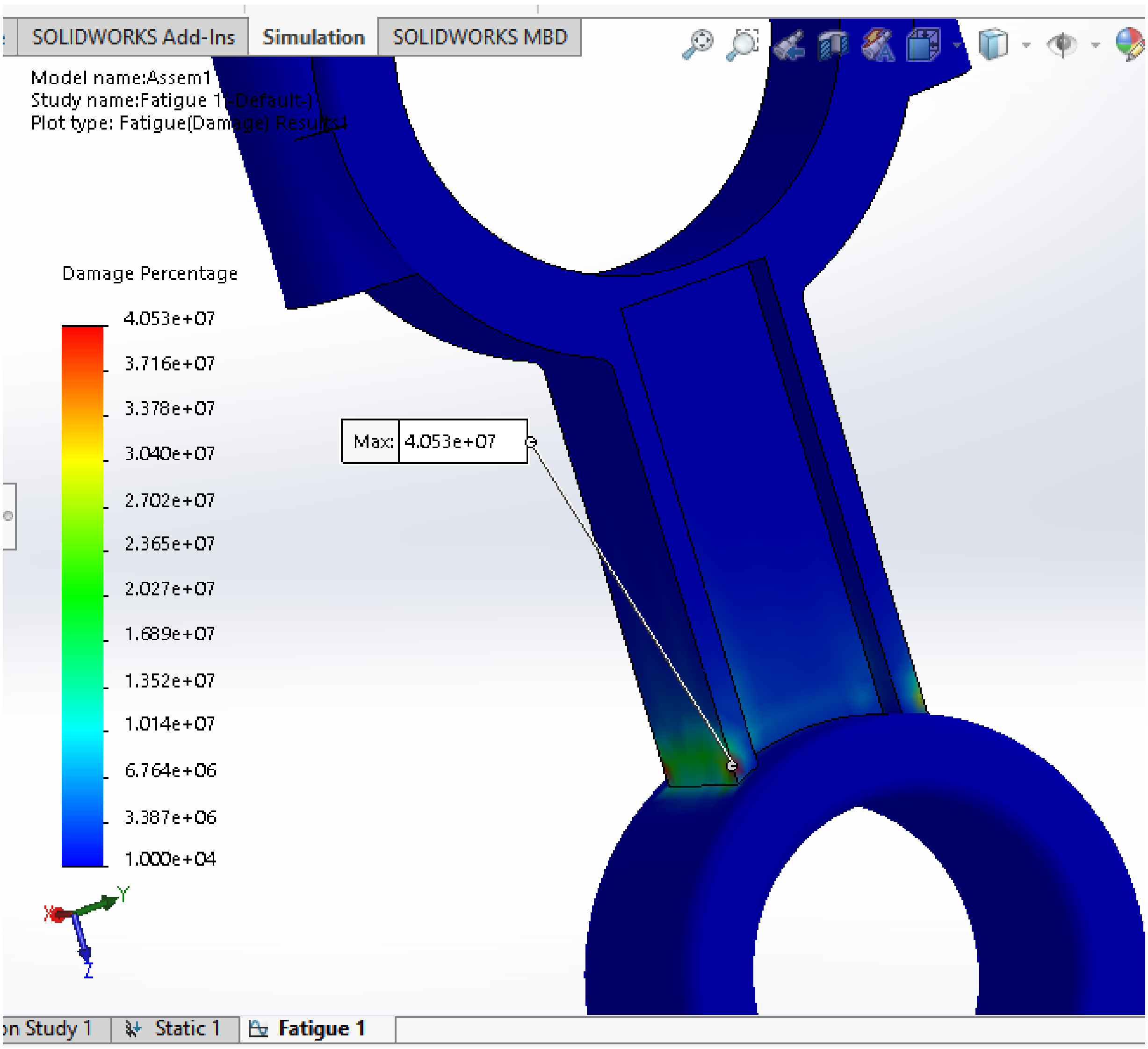
The fillet corners developed the maximum stress so fatigue failure will start form this red area, also note there are some green areas around middle of the extruded cut. These are sharp edges and theoretically we know these points to be stress raisers.

To find out how many cycles the connecting rod made of structural steel of that specific dimension we simulated the fatigue study. The end where the the piston head is connected was made rigid and tension and compressive load of $1x10^{05}$ Nm^{-2} was applied on the connecting rod. For this we applied the fatigue data of AISI-1035 in our 3D model:



From this fatigue data we were able to simulate how many cycles our connecting rod can withstand

Our connecting rod survived 4.053×10^{07} cycles prior fatigue failure. And failure occurred from the fillet corners as we predicted from our static stress simulation results.



Later in this analysis we will develop a 3D model better than this to show that fatigue life can be extended by creating a better design for connecting rods.

Prevention of fatigue failure:

Fatigue failure can occur due to inclusions or porosities which are due to manufacturing faults, better manufacturing process can help the fatigue life to increase. Better heat treatment process can also extend the fatigue life. And better designs can also extend fatigue life.

To show how better designs can prevent fatigue failure we customized our previous model a little bit. We increased the fillet radius to 5mm and we got rid of the extruded cut which is used in connecting rods to reduce the material usage. Our new model survived 3.53×10^{06} cycles more than our previous model.