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Life Estimation of a Steam Turbine Blade Using Low Cycle Fatigue Analysis

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ABSTRACT:

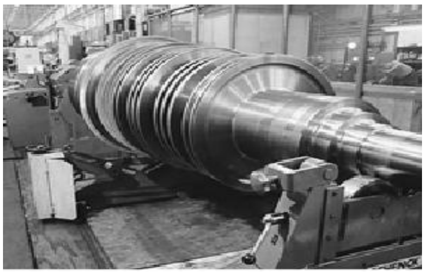
The present work illustrates, 3D finite element analysis (FEA) of low-pressure (LP) steam turbine bladed disk assembly are carried out at a constant speed loading condition. The prime objective is to study structural integrity of bladed disk root with aid of design considerations at design stage. Secondly, design rules are developed for structural integrity of blades and disk considering a factor of safety for material, manufacturing and temperature uncertainties. These design rules are in turn used as design checks with aid of finite element analysis results. Investigations are performed based on Neuber formulae for solving a highly non-linear problem employing linear analysis tool ANSYS 15.0. Local peak stresses at blade and disk root fillet of linear analysis is used to identify the equivalent non-linear stress value by strain energy distribution method for estimating the minimum number of cycles required for crack initiation for low cycle fatigue (LCF) calculations. Design methodology is developed to address the structural integrity of blades at design point and for off-design conditions.

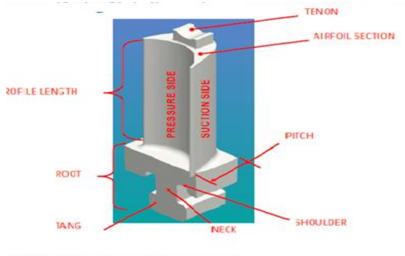
Keywords:

Turbine blade, Failure analysis, Creo Elements, FEM, Ansys.

INTRODUCTION:

In this study, first strain-controlled deformation and fatigue life are calculated for Stem turbine blade and then they are compared with ANSYS results. Various approaches to estimating mean stress effects on strain-life analysis are Morrow method and Smith, Watson, and Topper (SWT) method employed here to estimate the fatigue life of steam turbine blade. Morrow using the true fracture strength is a considerable improvement. However, the Morrow expression employing the fatigue strength coefficient σf'may be grossly non-conservative for metals other than steels. The Smith, Watson, and Topper (SWT) method is a reasonable choice that avoids the difficulties. A steam turbine is a device that extracts thermal energy from pressurized steam and uses it to do mechanical work on a rotating output shaft. In this case, the pressure and flow of steam rapidly turns the rotor. The nozzles and diaphragms in a turbine are designed to direct the steam flow into well-formed, high-speed jets as the steam expands from inlet to exhaust pressure. These jets strike moving rows of blades mounted on the rotor. The blades convert the kinetic energy of the steam into rotation energy of the shaft.





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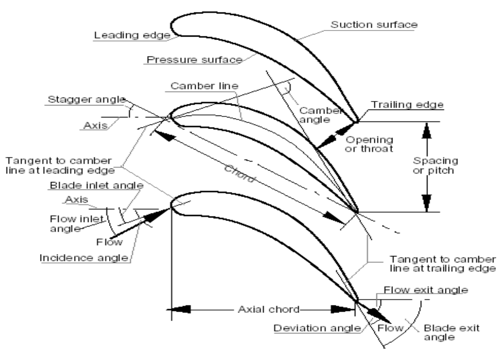

CALCULATION:

Blade design:

Blade design is very difficult and confidential to every turbine designer, So here only outlining the design by just some important dimensions only.

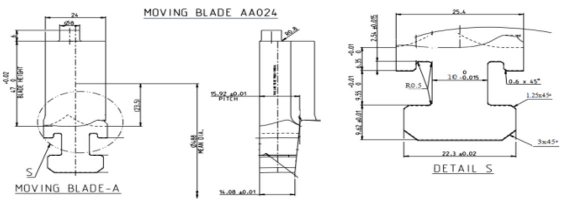

Fig .1 Existing Blade design

Centrifugal force:

Centrifugal force is directed outwards, away from centre of curvature of the path. A simplified 2D figure of the blades under discussion is shown in Figure 5.2.

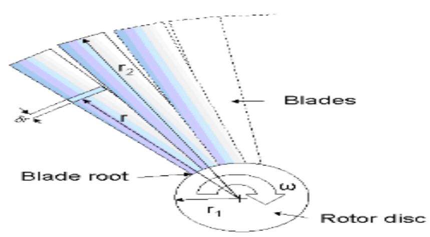

Fig .2 Simplified blade dimensions

The general equation for centrifugal force is

$$F = mr\omega^2 \text{ ----- (1)},$$

Where m is the mass of the moving object, r is the distance of the object from the centre of rotation (the radius of curvature) and ω is the angular velocity of the object. In the case under consideration, we need to account for the fact that the mass of the blade is distributed over its length and the radius of curvature also changes along the length of the blade.

Consider a small segment of mass δm, of length having width δr at a distance r from the centre. Then the equation for the centripetal force δF on this small segment is given by:

$$\delta F = \quad \delta m r\omega^2 \text{----(2)}$$

The blades have a cross sectional area A (mm^2) and material density ρ (kg/mm¬3). Then we can write the mass of the element ¬ rAmδρδ =δm = ρAδr

Equation (2) can be write as δF= (ρAδr)rω2 or

Formally it can be writing as dF= ρAω 2rdr Let be the radius of the rotor disc and be the distance between the centre of the rotor disc and tip of the blade. Then, integrating equation (3) along the total length of the blade, the total centrifugal force acting on the blade is given by We can convert the angular velocity from revolutions per minute (rpm) to radians per second using the following relationship:

NUMERICAL:

Calculation of Centrifugal Force: The following data is considered for design and centrifugal force estimation. Blade speed

N= 8000 rpm Blade cross-sectional area

A=165.161mm2

Material densityρ=7850x10-6kg/mm3

Blade tip radius r2 = 267.5 mm Blade root radius

r1 = 220.5 mm Blade length

r2-r1 =47mm

So we can calculate the angular velocity in radians per second as ω= 8000 x 2 π/60,ω= 837.75 rad/sec Substituting the all above values in equation (4)

F=7850x10-6x165.161x837.752x

(267.52-220.52)/2x1000

F=10,436.2N

Hence the magnitude if the centrifugal force acting on the blade due to high angular velocity is 10,436N. Fatigue life calculation: There are many methods to calculate the Fatigue life. Based on the available data, accuracy and ease Smith, Watson and Topper (SWT) Mean Stress Correction for Strain Life method used

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for the present work. SWT equation for Fatigue Analysis is given below
Where
σmax=Maximum stress
Δε/2=Total strain applitude
σ' failure=Fatigue Strength Coefficient or Effective strength
ε' failure =Fatigue ductility coefficient
E=ModulusofElasticity
2Nfailure=Number of reversals
b=Fatigue strength exponent
c= Fatigue ductility exponent
Intensity of this work is to estimate the fatigue life of the turbine blade. But here number of cycles ”N” in the emperical formula is with different powers, which is difficult to calculate directly. So let us go for trial and error method by assuming some values for
“Nf”.σmean = (σ1+σ2)/2
σa =(σ1-σ2)/2
σmax = σmean+σa

S.No	σ1	σ2	σmean	σa	σmax
1	540	0	270	270	540
2	540	0	270	270	540
3	540	0	270	270	540
4	540	0	270	270	540
5	540	0	270	270	540
6	540	0	270	270	540
7	540	0	270	270	540
8	540	0	270	270	540
9	540	0	270	270	540
10	540	0	270	270	540
11	540	0	270	270	540

ε1	ε2	εa/2	Life “Nf”	Error
0.00266	0	0.00133	1000000	-31571.8
0.00266	0	0.00133	10000000	38278.82
0.00266	0	0.00133	5000000	21009.25
0.00266	0	0.00133	2500000	795.1888
0.00266	0	0.00133	2300000	-1863.37
0.00266	0	0.00133	2350000	-1172.64
0.00266	0	0.00133	2450000	155.8311
0.00266	0	0.00133	2420000	-235.573
0.00266	0	0.00133	2440000	26.02422
0.00266	0	0.00133	2435000	-39.126

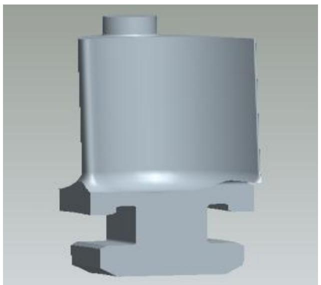

Fig.3 HP turbine blade creo in proe model

Pre-processer for blade analysis

Step1: Geometry creation

First step of Ansys is creating the geometry. This can be directly done in design module or else we can import the geometry from other location also. But it should in the format which can be read by ANSYS. Some of that type of formats is IGES, STEP. Here for this analysis geometry file is imported in “STEP” which is exported from the Creo 1.0 (it is modeling software also known as PROE).

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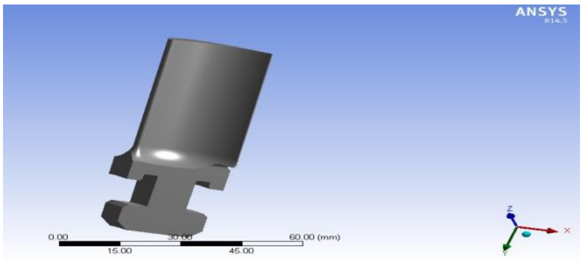

Fig-4 Imported Blade model

Step 2:

Material assignment is the second step for analysis. Because based on the type of material same geometry will give different results even for same working conditions. So after importing the model, It should be assigned the material properties.

Properties of Outline Row 3: Structural Steel

	A	B	C	D	E
1	Property	Value	Unit		
2	Density	7850	kg m^-3		
3	Isotropic Secant Coefficient of Thermal Expansion				
6	Isotropic Elasticity				
12	Alternating Stress Mean Stress	Tabular			
16	Strain-Life Parameters				
17	Display Curve Type	Strain-Life			
18	Strength Coefficient	1945	MPa		
19	Strength Exponent	-0.106			
20	Ductility Coefficient	2.58			
21	Ductility Exponent	-0.777			
22	Cyclic Strength Coefficient	1E+09	Pa		
23	Cyclic Strain Hardening Exponent	0.2			
24	Tensile Yield Strength	2.5E+08	Pa		
25	Compressive Yield Strength	2.5E+08	Pa		
26	Tensile Ultimate Strength	4.6E+08	Pa		
27	Compressive Ultimate Strength	0	Pa		

Fig -5 Material properties of steel

Pre-processer for blade analysis

Step 1: Mesh Generation or Ansys model generation. Mesh generation means discritising the model into small element. Finite element itself explains that dividing a complex element into small well known shape. Once model is assigned with material then meshing of the geometry will be done. Then onwards geometry can be named as ansys model. Here tetrahedron mesh is used to generate the meshed model with element size 1mm.

Details of "Mesh"

Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Patch Conforming Options	
Triangle Surface Mesher	Program Controlled
Advanced	
Shape Checking	Standard Mechanical
Element Midside Nodes	Program Controlled
Straight Sided Elements	No
Number of Retries	Default (4)
Extra Retries For Assembly	Yes
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Defeaturing	
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Automatic Mesh Based Def...	On
Defeaturing Tolerance	Default
Statistics	
Nodes	194769
Elements	134892
Mesh Metric	None

Fig.6 Meshed structure of Blade

Step 2: Constraining the element

The main aim of any analysis is to get some results by applying some forces on it. So geometry should not be allowed to free moment due to the force application. Hence it need some constrains. Constrain means arresting the motion at some location. That may be fixed, displaced constrain.Here blade is constrained by fixed supports at side of the blade tang. This is due to locking of blade in rotor disk.

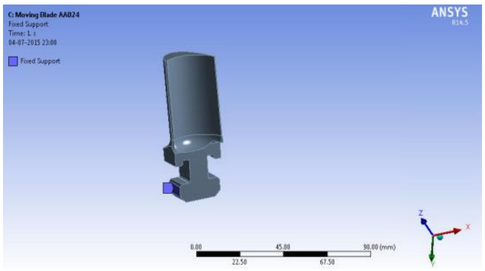

Fig-7 Constrains applied to Blade

Step 3: Application of loads

Centrifugal force is the major force acting on blades. When compared magnitudes of all other forces acting on blade with centrifugal force magnitude they can be negligible. So in this analysis centrifugal force only considered as load of application.

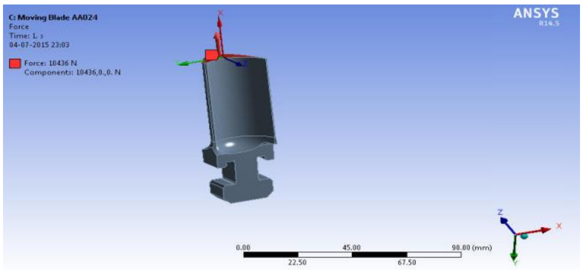

Fig.-8 Load application to steam turbine blade

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6.4 Post processor for blade analysis

Step1: Solving the model, it means allowing the system to run all given conditions like application of constrains and loads.

Step 2: Generating the results after proper solving Analyst can able to get the required results. Here Stress developed within the blade and fatigue life estimation is major criteria of project. So get the results by selecting the required options like equivalent stress and Fatigue tool.

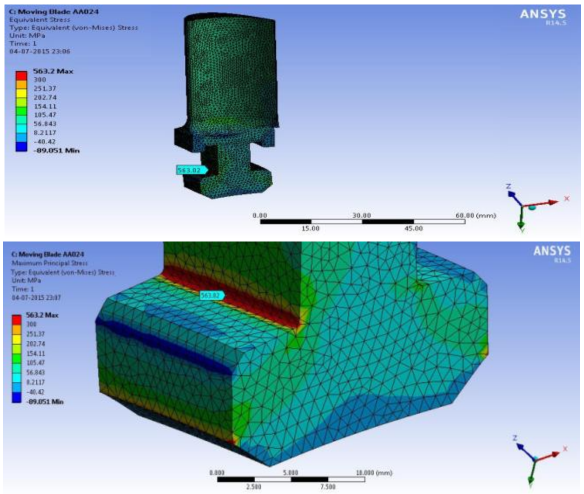

Fig.-9 Equivalent stress of the steam turbine blade

Equivalent von mises stresses observed (563 MPa) on the fillet region of the blade as depicted in the figure f.

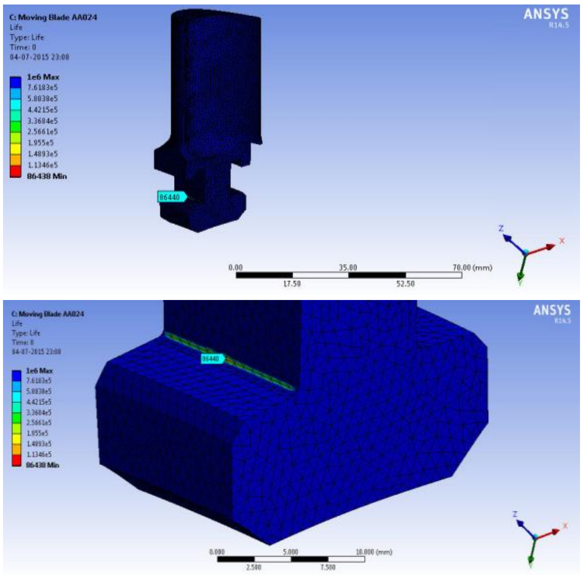

Fig 10.Fatigue life of the steam turbine blade

Minimum Fatigue life observed at the fillet region is 866438 as depicted in the figure .

MODIFICATIONS SUGGESTED:

Existing blade design is good enough for fatigue life in theoretical calculation. But there is a problem in finite element analysis. In theoretical calculation blade model is getting infinite life (2.438e6). By running ANSYS software existing blade design is getting only 86436 is number of cycles as fatigue life. Modified design of steam turbine blade Here failure of blade mostly occurs in T root. So it requires some modifications to get the infinite life (1e6). By doing some trial and error methods in changing the dimensions of T root. Finial a modification is suggested to turbine designer as below.

1. Neck width of the blade is increased by 1mm. i.e. Neck width is modified to 11mm from 10mm
2. Fillet radius of the root is modified to 0.8 mm from 0.5mm
3. Chamfer dimensions of the tang (bottom part of the root) is changed to1x45oand 2.77x45o from 1.25x45oand 3x45o respectively.

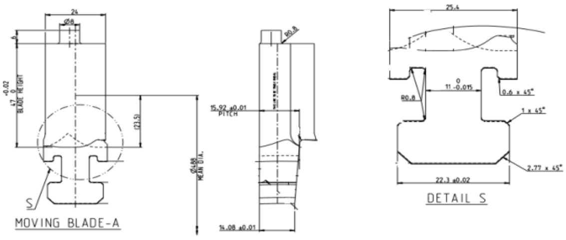

Fig.11 Modified blade design

FE Analysis of Modified blade

Step1: Geometry creation

First step of Ansys is creating the geometry. This can be directly done in design module or else we can import the geometry from other location also. But it should in the format which can be read by ANSYS. Some of that type of formates is IGES, STEP. Here for this analysis geometry file is imported in "STEP" which is exported from the Creo 1.0 (it is modeling software also known as PROE).

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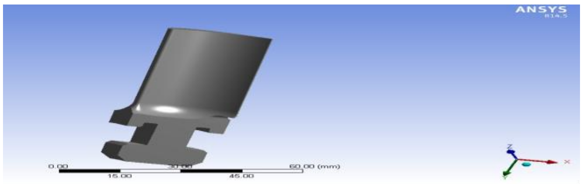
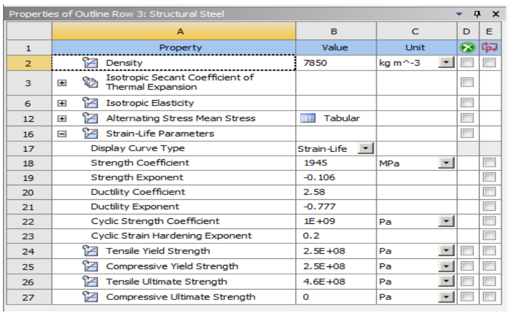


Fig.12- Modified Steam turbine blade model

Step 2:
Material assignment is the second step for analysis. Because based on the type of material same geometry will give different results even for same working conditions. So after importing the model, It should be assigned the material properties.



Properties of Outline Row 3: Structural Steel

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6	Isotropic Elasticity				
12	Alternating Stress Mean Stress	Tabular			
16	Strain-Life Parameters				
17	Display Curve Type	Strain-Life			
18	Strength Coefficient	1945	MPa		
19	Strength Exponent	-0.106			
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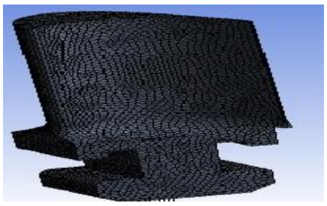
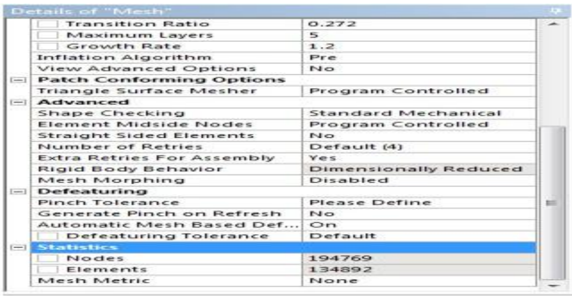
25	Compressive Yield Strength	2.5E+08	Pa		
26	Tensile Ultimate Strength	4.6E+08	Pa		
27	Compressive Ultimate Strength	0	Pa		

Fig 13- Material Properties

Processor for modified blade analysis

Step 1: Mesh Generation or Ansys model generation
Mesh generation means discritising the model into small element. Finite element itself explains that dividing a complex element into small well known shape. Once model is asigned with material then meshing of the geometry will be done. Then onwards geometry can be named as ansys model. Here tetrahedron mesh is used to generate the meshed model with element is





Details of "Mesh"

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Inflation Algorithm	Pre
View Advanced Options	No
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Number of Retries	Default (4)
Extra Retries For Assembly	Yes
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Defeaturing	
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Automatic Mesh Based Def...	On
Defeaturing Tolerance	Default
Statistics	
Nodes	194769
Elements	134892
Mesh Metric	None

Fig.14- Meshing of modified steam turbine blade

Step 2: Constraining the element
The main aim of any analysis is to get some results by applying some forces on it. So geometry should not be allowed to free moment due to the force application. Hence it need some constrains. Constrain means arresting the motion at some location. That may be fixed, displaced constrain. Here blade is constrained by fixed supports at side of the blade tang. This is due to locking of blade in rotor disk.

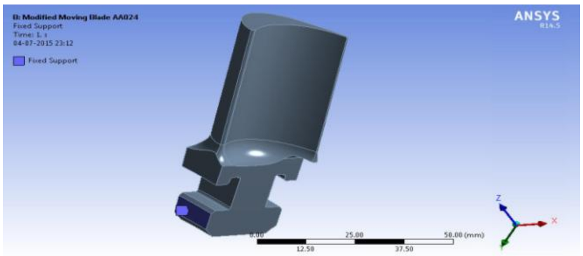

Fig15. Constrains applied to modified steam turbine blade

Step 3: Application of loads
As discussed in literature survey under chapter 2 centrifugal forces is the major force acting on blades. When compared magnitudes of all other forces acting on blade with centrifugal force magnitude they can be negligible. So in this analysis centrifugal force only considered as load of application.

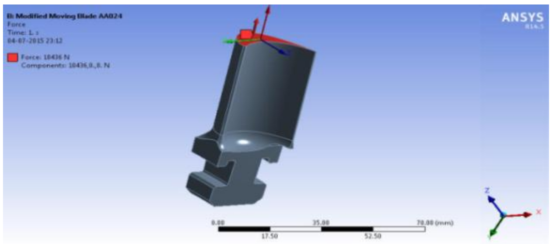

Fig16 Load application to modified steam turbine blade

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Post processor for modified blade

Step1: Solving the model, it means allowing the system to run all given conditions like application of constrains and loads.

Step 2: Generating the results

After proper solving Analyst can able to get the required results. Here Stress developed with in the blade and fatigue life estimation is major criteria of project. So get the results by selecting the required options like equivalent stress and Fatigue tool.

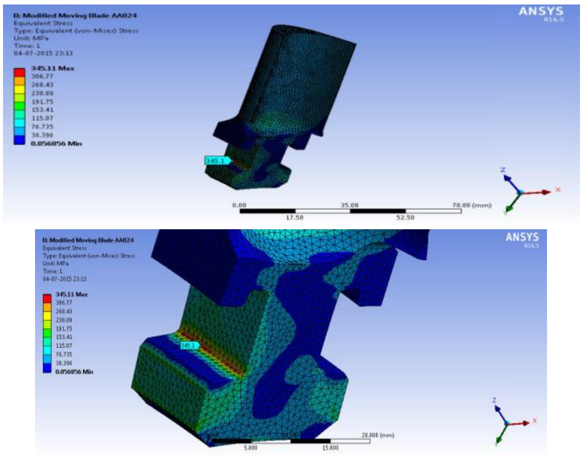

Fig .17 Equivalent stress of modified steam turbine blade

With the implementation of design modification, the Equivalent von mises stresses observed (345 MPa) on the fillet region of the blade as depicted in the fig above. The stress levels reduced from 563MPa to 345 MPa which will helps in improving the fatigue life.

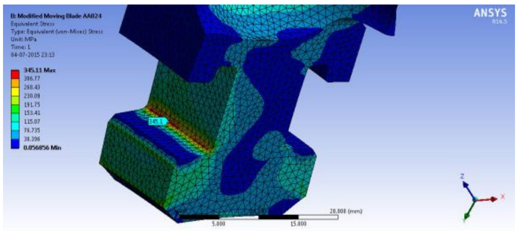

Fig.18- Fatigue life of modified steam turbine blade

Minimum Fatigue life observed 1e6 and the entire blade is meeting the requirement as depicted in the fig g

RESULTS:

From the ANSYS results of existing blade and modified blade design following comparisons are made for better understanding of improvement in the blade life.

Table 7.4 Comparison of results

S.No.	Parameter	Existing Blade	Modified blade
1	Equivalent stress (Mpa)	560	345.1
2	Fatigue life "N"	86438	1000000

CONCLUSION:

This project has attempted to investigate the fatigue response of the steam turbine blade in terms of high cycle fatigue. The goal of the research was to establish the technique of the high cycle fatigue assessment of the HP turbine blade equipped with the T root and to determine the number of startups to the crack initiation of the particular LP blade. Existing blade design is good enough for fatigue life in theoretical calculation. But there is a problem in finite element analysis. In theoretical calculation blade model is getting infinite life (2.438e6). But during run of ANSYS software existing blade design is getting only 86436 is number of cycles as fatigue life. Here failure of blade occurs in T root of blade. So it requires some modifications to get the infinite life (1e6). By doing some trial and error methods in changing the dimensions for T root of the blade Finial a modification is suggested to turbine designer which is able to achieve the life of 1e6 cycles as fatigue life.

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