ISSN 2250-3153

Residual Life Assessment of 60 MW Steam Turbine Rotor

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Abstract- Design of a component usually involves optimizing its dimensions to meet the operational requirements without failure during the design life. If the operational loads are constant and the operating temperature is not high, a component can be designed for infinite life. However, if the operational loads are fluctuating, they cause fatigue in the component. In addition, if the component operates at high temperatures for very long periods, it may experience creep damage.
With the increase of steam turbines steam parameter and the participation in peak-load adjustment of power grid more and more frequently, the stress of the turbine's rotor is becoming increasingly complex, and the variable thermal stress has became the major factor reducing its life. We used a 60MW supercritical steam turbine rotor and analyzed the variation of thermal stress in the warm starting-up and cold shutdown process. In this project the analysis based on the operating data measured from actual operation and calculated the variations of the temperature field and stress field during the process of warm starting-up and cold shutdown over a period of 400 minutes with the method of thermal-structure direct interaction analysis by ANSYS.

Index Terms- ANSYS, Creep, Fatigue, Life assessment, Pressure Loadings, Thermal Stresses.

I. Introduction

An important characteristic of a steam power plant is its ability to maintain reliability and safety of the plant against frequent start-ups and load changes. The rapid increase of temperature and rotational speed during starts-ups, especially, makes conditions more severe and causes main components' damage and reduction of life span for steam turbine. Thus accurate knowledge of thermal stresses is required for the integrity and lifetime assessment for the turbine rotor. In this project, the Residual life assessment for steam turbine rotor was established by combining effects of thermal stresses due to temperature variation and stresses due to pressure load. This study particularly focused on the time-dependent inelastic behavior (creep) of materials and cyclic loading (fatigue) under non-isothermal conditions. Using this study, Residual life assessment of steam turbine rotor can be obtained. We will validate the results obtained from simulation with experimental values.

II. Problem Definition

Damage produced by mechanisms of deterioration affecting turbine integrity is directly related with times, and are produced after long year turbine operation. These mechanism produce a progressive damage on materials that turbine is manufactured with, reducing its mechanical properties. It also produces deviation and distortion on inner turbine parts, becoming to efficiency deterioration. There are two of these mechanisms that demonstrates to be more significant to assess the life consumption of affected component, not only for its relation with time factor, but for the responsibility of turbine components that they, such as rotors and casings, that are large and expensive and may produce disastrous damage. The essential objective is to show, according with damages produced by these two mechanisms, the aspects involving when assessing and analyze turbine remnant life in order to get life extension and recovery or improvement of efficiency.

Thermal power plant components are subject to both low cycle fatigue damage based on number of start-ups and shut-downs as well as long changes and creep damage based on number of hours of continuous operation at high pressure and temperature. Designing every component for infinite life necessitates reducing the stress level below endurance limit and makes the component heavier and costlier. Hence, components of power plants are usually designed for finite life of about 25 to 30 years, based on assumed load fluctuation and operating parameters.
The fatigue damage and creep damage vary for each power station and for each unit, depending on the number of shut-downs for preventive or breakdown maintenance and also depending on the power demand in the grid, and may not be equal to the design parameters. Considerable reserve strength and longevity could still be expected at the end of design life, because of change in material data and variation of operating conditions from the design conditions, etc.

III. Objective

Residual life assessment (RLA) of components will help in using excess life that can be derived, if necessary, by operating at part-load or below- design condition on a machine- specific basis and is cost effective. Real life case studies in a number of countries have shown that it is possible to retain the power units in service for 50 to 60 years, by periodic inspection and corrective measures. Estimation of residual life and current thermo-fatigue damage of steam turbines Rotor material.
•Quality control of transients.
•Management of start-stop modes.
•Solution of research tasks.
Residual life is estimated by real-modes of loading. It is possible to use individual characteristics of low-cyclic fatigue and strain cycling of certain rotor material. Software can be adapted for

certain type of a turbine. Counters allow determining rotor individual remaining life by thermo-fatigue resistance criterion.
•Software and procedure development.
•Software adaptation for certain equipment.
•Development and implementation of a project of steam-turbines high temperature rotors residual life.
•Calculations of equipment residual life.

3.1 Steam Turbine

Turbine is an engine that converts energy of fluid into mechanical energy. Steam turbines are machines that are used to generate mechanical (rotational motion) power from the pressure energy of steam. 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. Its modern manifestation was invented by Sir Charles Parsons in 1884. Steam turbines are the most popular power generating devices used in the power plant industry primarily because of the high availability of water, moderate boiling point, cheap nature and mild reacting properties. The most widely used and powerful turbines of today are those that run on steam. From nuclear reactors to thermal power plants, the role of the steam turbine is both pivotal and result determining. Because the turbine generates rotary motion, it is particularly suited to be used to drive an electrical generator about 90% of all electricity generation in the United States is by use of steam turbines. The steam turbine is a form of heat engine that derives much of its improvement in thermodynamic efficiency through the use of multiple stages in the expansion of the steam, which results in a closer approach to the ideal reversible process.

IV. MATERIALS

It is generally known that rotors made of high CrMoV steels (customary: 9% up to 12%Cr) show bad running behavior in babbitted bearings. Therefore it is necessary to coat the journal areas of such rotors with materials which prevent the known wire whooping effect and improve the performance. For safety reasons, those materials are normally applied by overlay welding. A low alloy MnCr weld metal with an approximately 0,2 % carbon content was selected as overlay weld material. To reduce the carbon diffusion, butter layers made of a filler metal similar to 16 Mo 3 were deposited on the 12 % Cr steel rotor prior to depositing the MnCr surfacing electrode. In principle all these welds are performed using the submerged arc welding process. The only exception is axial bearing areas where the buffer layers are performed with an automatic gas–shielded welding unit.

i.Saturated steam turbine rotors, normally made of NiCrMoV steel are susceptible to erosion corrosion especially in the area of the shaft seal section. Due to the high steam flow rates, a material which is strongly resistant to erosion corrosion is necessary. The standard rotor material does not fulfill these requirements.
ii. Density = 7.8e-6 kg/mm3
iii.Poisson's ratio Prxy = 0.3
iv.Young's modulus EX = 1.6e5 N/mm2

V. MODELLING AND ANALYSIS

Rotor was modeled using CATIA V5. First line diagram was drawn using commands line, fillet, and constraint in Sketcher shown in fig-1. 3D model was generated in Part modeling using command revolve shown in fig-2. We have modeled the rotor turbine from the industrial drawing of Turbo Machinery Industries PvtLtd-Hyderabad, which is shown in fig- 3. The turbine rotor is axisymmetric so we considered a 2D model.

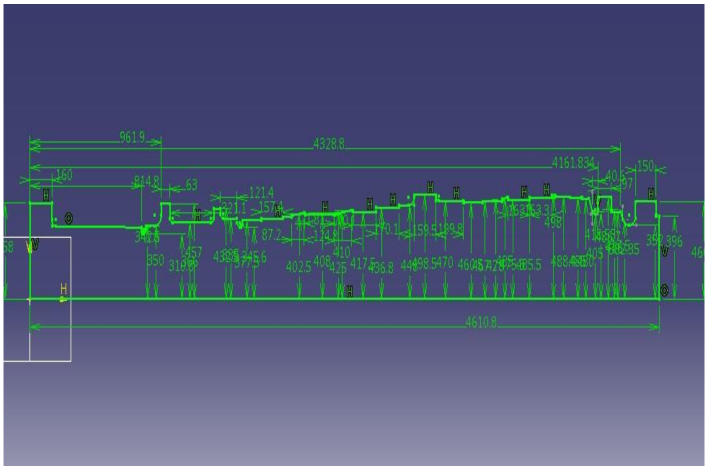

Figure-1 2D sketch of a Rotor.

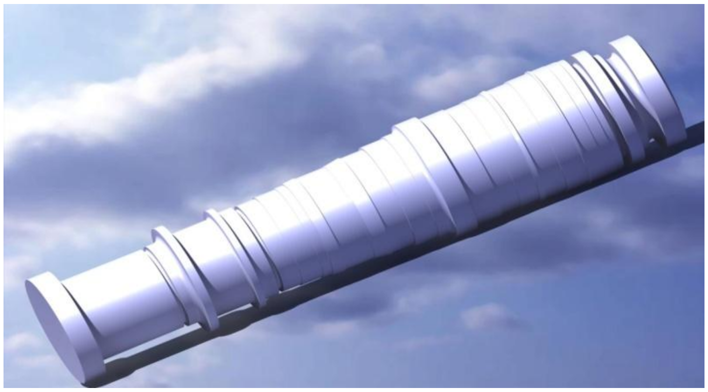

Fig-2 3D model of Rotor.

Fig-3 Turbine rotor-2D Model

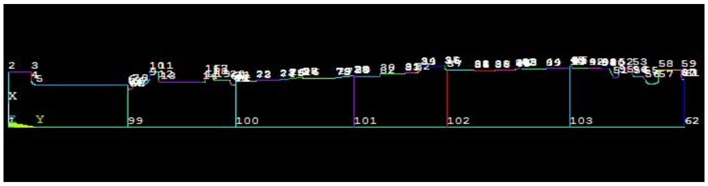

Figure-4 2D wireframe

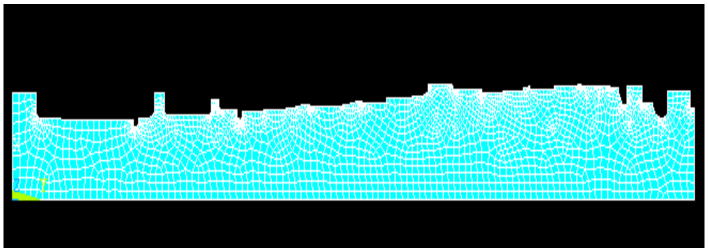

Fig-5 Meshed model

VI. ANALYSIS

6.1 Thermal Analysis

A thermal analysis calculates the temperature distribution and related thermal quantities in a system or component. Typical thermal quantities of interest are:

- •The temperature distributions.
- •The amount of heat lost or gained.
- •Thermal gradients.
- •Thermal fluxes.

Only the ANSYS Multiphysics, ANSYS Mechanical, ANSYS Professional, and ANSYS FLOTRAN programs support thermal analyses. The basis for thermal analysis in ANSYS is a heat balance equation obtained from the principle of conservation of energy. The finite element solution you perform via ANSYS calculates nodal temperatures, and then uses the nodal temperatures to obtain other thermal quantities. The ANSYS program handles all three primary modes of heat transfer: conduction, convection, and radiation.

6.1.1 Types of Thermal Analysis:

ANSYS supports two types of thermal analysis

- ➢ A **steady-state thermal analysis** determines the temperature distribution and other thermal quantities under steady-state loading conditions. A steady-state loading condition is a situation where heat storage effects varying over a period of time can be ignored.
- ➢ A **transient thermal analysis** determines the temperature distribution and other thermal quantities under conditions that vary over a period of time.

6.1.2 Transient Thermal Analysis:

Transient thermal analysis is the thermal analysis where in boundary conditions and properties Change with time. This is to say that the constraints such as ambient temperature, thermal coefficient and material properties etc. are time dependent. Transient thermal analysis is important in analyzing models that are subjected to boundary conditions and material properties that with time and temperature.

Turbine rotors used in aero engines are subjected to high temperature rise as they are subjected to many start and stop cycles. Since the turbine rotor is subjected to large temperature variation, the material properties such as specific heat, enthalpy and young's modulus undergo variations with time. In such conditions there is the probability of failure of the turbine rotor if the turbine rotor is not designed taking into consideration the transient effects.

At the beginning of the cold start, the component is at uniform ambient temperature. When a cold metal component is exposed to a hot fluid medium, thermal gradients set in across the thickness and along the length. During the thermal transient, this temperature gradient changes with time till the metal reaches its steady state temperature distribution. Due to thermal inertia of the metal, it takes more time to reach its steady state value by conduction than the actual duration of fluid temperature change during the transient.

6.2 Structural Analysis

Structural analysis is probably the most common application of the finite element method. The term structural implies not only civil engineering structures such as bridges and buildings, but also naval, aeronautical, and mechanical structures such as ship hulls, aircraft bodies, and machine housings, as well as mechanical components such as pistons, machine parts, and tools.

6.2.1 Types of Structural Analysis:

The seven types of structural analyses available in the ANSYS family of products are explained below. The primary unknowns (nodal degrees of freedom) calculated in a structural analysis are displacements. Other quantities, such as strains, stresses, and reaction forces, are then derived from the nodal displacements. Structural analyses are available in the ANSYS Multiphysics, ANSYS Mechanical, ANSYS Structural, and ANSYS Professional programs only. You can perform the following types of structural analyses. Each of these analysis types are discussed in detail in this manual.

- ➢ **Static Analysis** is used to determine displacements, stresses, etc. under static loading conditions. Both linear and nonlinear static analyses. Nonlinearities can include plasticity, stress stiffening, and large deflection, large strain, hyper elasticity, contact surfaces, and creep.
- ➢ **Modal Analysis** is used to calculate the natural frequencies and mode shapes of a structure. Different mode extraction methods are available.
- ➢ **Harmonic Analysis** is used to determine the response of a structure to harmonically time-varying loads.
- ➢ **Transient Dynamic Analysis** is used to determine the response of a structure to arbitrarily time-varying loads all nonlinearities mentioned under Static Analysis above are allowed.

In addition to the above analysis types, several special-purpose features are available

- • Fracture mechanics
- • Composites
- • Fatigue
- • P-Method
- • Beam Analyses

Two solution methods are available for solving structural problems in the ANSYS family of products: the h- method and the p-method. The h-method can be used for any type of analysis, but the p-method can be used only for linear structural static analyses. Depending on the problem to be solved, the h-method usually requires a finer mesh than the p-method. The p-method provides an excellent way to solve a problem to a desired level of accuracy while using a coarse mesh. In general, the discussions in this manual focus on the procedures required for the h-method of solution discusses procedures specific to the p-method.

6.2.2 Structural Static Analysis:

A static analysis calculates the effects of steady loading conditions on a structure, while ignoring inertia and damping effects, such as those caused by time-varying loads. A static analysis can, however, include steady inertia loads (such as gravity and rotational velocity), and time-varying loads that can be approximated as static equivalent loads (such as the static equivalent wind and seismic loads commonly defined in many building codes).

Static analysis determines the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed; that is, the loads and the structure's response are assumed to vary slowly with respect to time.

The types of loading that can be applied in a static analysis include

- Externally applied forces and pressures.
- Steady-state inertial forces (such as gravity or rotational velocity.
- Imposed (nonzero) displacements.
- Temperatures (for thermal strain).
- Fluences (for nuclear swelling).

A static analysis can be either linear or nonlinear. All types of nonlinearities are allowed - large deformations, plasticity, creep, stress stiffening, contact (gap) elements, hyper elastic elements, and so on. This chapter focuses on linear static analyses, with brief references to nonlinearities.

The thermal gradients produce thermal stresses, in transient and steady state conditions, in the component. Stress analysis is carried out on Finite element model of the component at the critical time of transient, when thermal gradient is high. Stresses due to fluid pressure are added to the thermal stresses. These total stresses vary as functions of space and time.

6.2.3 Coupled Thermal Structural Analysis:

A sequentially coupled physics analysis is the combination of analyses from different engineering disciplines which interact to solve a global engineering problem. For convenience, the solutions and procedures associated with a particular engineering discipline [will be referred to as] a physics analysis. When the input of one physics analysis depends on the results from another analysis, the analyses are coupled.

Thus, each different physics environment must be constructed separately so they can be used to determine the coupled physics solution. However, it is important to note that a single set of nodes will exist for the entire model. By creating the geometry in the first physical environment, and using it with any following coupled environments, the geometry is kept constant. For our case, we will create the geometry in the Thermal Environment, where the thermal effects will be applied.

Although the geometry must remain constant, the element types can change. For instance, thermal elements are required for a thermal analysis while structural elements are required to determine the stress in the rotor and casing. It is important to note, however that only certain combinations of elements can be used for a coupled physics analysis.

VII. TECHNICAL AND OPERATIONAL DATA

Turbine operation is normally classified into three categories. Cold start with turbine casing and rotor temperature at room temperature (after shut down for 30-50 hrs) and the turbine takes more than 3 hours to produce rated power; warm start (after down for 16-30 hrs) while the Rotor material is at significantly higher than room temperature, facilitating turbine to produce rated power in about 2 hours and hot start (after shut down for 4-8 hrs) while the Rotor material is very close to steady state temperature, facilitating turbine to produce rated power in less than an hour Each start-up transient indicates variation of different parameters like pressure, temperature, flow rate and load with time from their starting level to the maximum values. Shut down duration and starts up time vary with the rating of the unit. Obviously, cold start will induce maximum stresses due to thermal transient and is crucial for fatigue.

It was commissioned on 21st Aug 1989 and operated for 1, 69,396 hours (till Nov 2010). It is estimated that the casing has been subjected to 518 hot starts, 322 warm starts and 95 cold starts. Turbine rotor was replaced in 2004. Subsequently, it is estimated that the rotor has been subjected to 165 hot starts, 105 warm starts 30 cold starts and operated for 55,116 hours. Steam turbine rotor is subjected to high temperatures and pressures at different sections of the rotor. These temperatures and pressures are different values at various sections of rotor. We considered the actual values of temperature and pressures, these and temperatures and pressures are essential for analysis and we considered these values as inputs for analysis.

ISSN 2250-3153

Time step (min)	Steam Temp (deg C)	Heat transfer coeff. (W/m2 deg K)
Section - 1 HP Inlet		KP Nos 62-90
0.1	535	3,655.16
2	535	3,841.54
10	535	3,948.12
20	535	4,108.67
40	535	4,343.93
70	535	4,458.39
100	535	4,619.78
115	535	4,860.80
140	535	9,645.46
160	535	44,282.94
180	535	59,918.52
215	535	72,930.03
250	535	72,930.03
300	535	72,930.03
350	535	72,930.03
400	535	72,930.03
Section - 2		KP Nos 90-37
0.1	466	287.82
2	466	289.75
10	466	304.87
20	466	315.48
40	466	332.15
70	466	345.94
100	466	369.81
115	466	381.27
140	466	764.01
160	466	3,476.20
180	466	4,685.48
215	466	5,690.04
250	466	5,690.04
300	466	5,690.04
350	466	5,690.04

Section - 3		KP Nos 37-28
0.1	426.9	326.32
2	426.9	336.19
10	426.9	345.73
20	426.9	370.18
40	426.9	384.76
70	426.9	395.16
100	426.9	418.37
115	426.9	433.04
140	426.9	856.60
160	426.9	3,893.93
180	426.9	5,249.58
215	426.9	6,376.97
250	426.9	6,376.97
300	426.9	6,376.97
350	426.9	6,376.97
400	426.9	6,376.97
Section - 4		KP Nos 28-72
0.1	366.2	440.83
2	366.2	500.09
10	366.2	576.14
20	366.2	654.99
40	366.2	709.09
70	366.2	771.01
100	366.2	842.92
115	366.2	909.21
140	366.2	949.84
160	366.2	4,279.97
180	366.2	5,745.50
215	366.2	6,973.28
250	366.2	6,973.28
300	366.2	6,973.28
350	366.2	6,973.28
400	366.2	6,973.28

ISSN 2250-3153

Section - 5		KP Nos 72-06
0.1	353.4	9.70
2	353.4	10.41
10	353.4	11.91
20	353.4	13.05
40	353.4	14.89
70	353.4	16.71
100	353.4	18.07
115	353.4	20.14
140	353.4	25.86
160	353.4	116.49
180	353.4	156.51
215	353.4	190.06
250	353.4	190.06
300	353.4	190.06
350	353.4	190.06
400	353.4	190.06

Section - 6		KP Nos 06-01
0.1	353.4	7.96
2	353.4	8.04
10	353.4	8.32
20	353.4	8.71
40	353.4	9.09
70	353.4	9.42
100	353.4	9.97
115	353.4	10.51
140	353.4	20.74
160	353.4	97.90
180	353.4	132.07
215	353.4	158.60
250	353.4	158.60
300	353.4	158.60
350	353.4	158.60
400	353.4	158.60

Key point number	Pressure (N/mm2)	Key point number	Pressure (N/mm2)
2	3.068	83	8.949
3	3.068	31	8.949
4	3.068	32	8.949
5	3.068	33	8.949
6	3.068	34	8.949
6	3.068	35	8.949
64	4.792	36	8.949
67	4.792	37	8.949
7	4.792	37	3.068
8	4.792	38	3.068
9	4.792	84	3.068
10	4.792	85	3.068
11	4.792	86	3.068
12	4.792	39	3.068
13	4.792	40	3.068
14	4.792	87	3.068
15	4.792	41	3.068
16	4.792	42	3.068
17	4.792	88	3.068
18	4.792	43	3.068
19	4.792	89	3.068
20	4.792	44	3.068
69	4.792	90	3.068
71	4.792	90	1.392
72	4.792	45	1.392
72	6.617	46	1.392
21	6.617	91	1.392
73	6.617	47	1.392
22	6.617	92	1.392
74	6.617	48	1.392
23	6.617	49	1.392
75	6.617	94	0.431
76	6.617	50	0.431
24	6.617	51	0.431
25	6.617	95	0.431
77	6.617	52	0.431
98	6.617	53	0.431
26	6.617	96	0.152
78	6.617	54	0.152
79	6.617	55	0.152
27	6.617	56	0.152
28	6.617	57	0.152
28	8.949	58	0.152
80	8.949	59	0.0106
81	8.949	97	0.0106
29	8.949	60	0.0106
82	8.949	61	0.0106

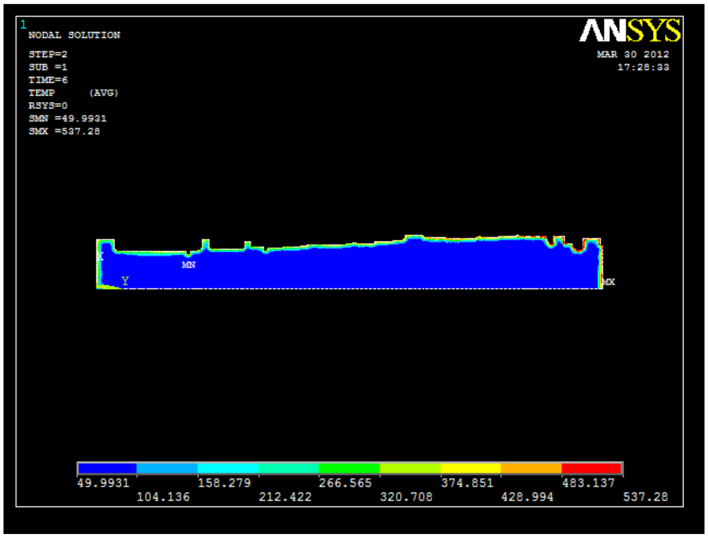

Figure-6 Temperature distribution at 0.1 minutes

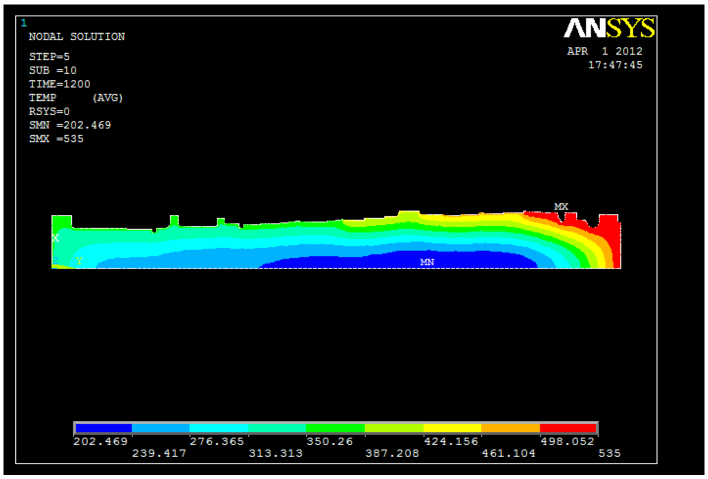

Figure-7 Temperature distribution at 20 minutes

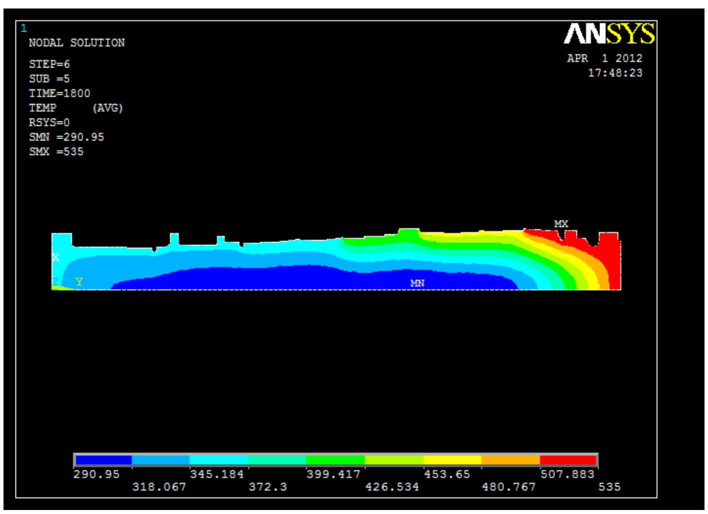

Fig-8 Temperature distribution at 30 minutes

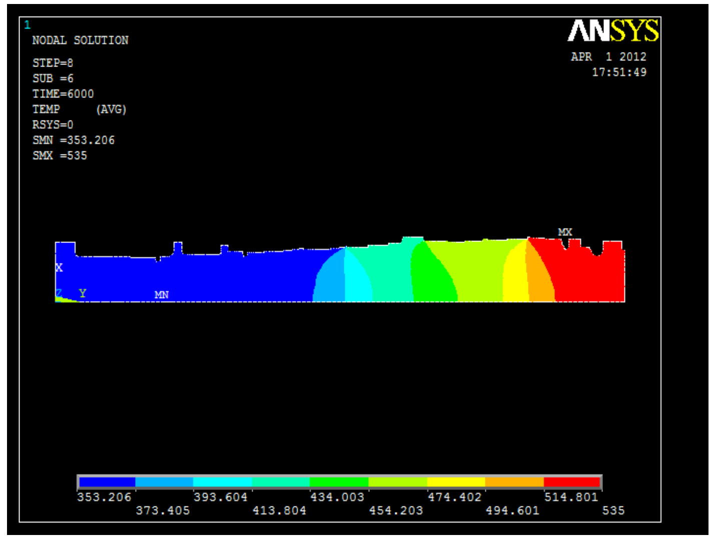

Fig-9 Temperature distribution at 100 minutes.

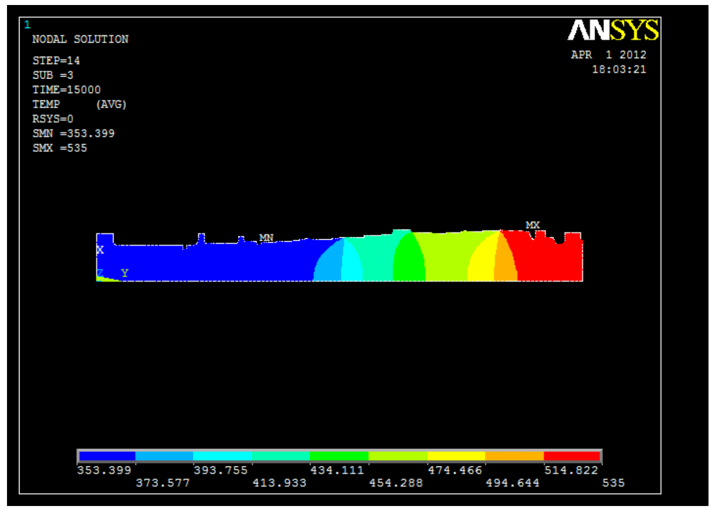

Fig-10 Temperature distribution at 250 minutes.

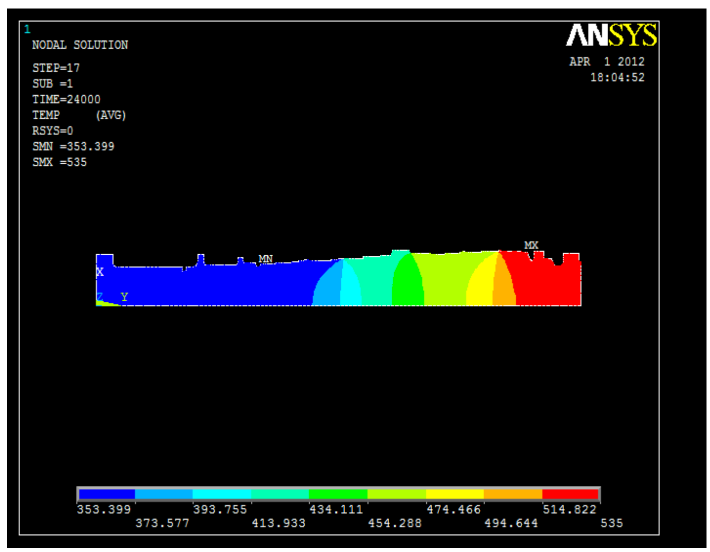

Fig-11 Temperature distribution at 400 minutes.

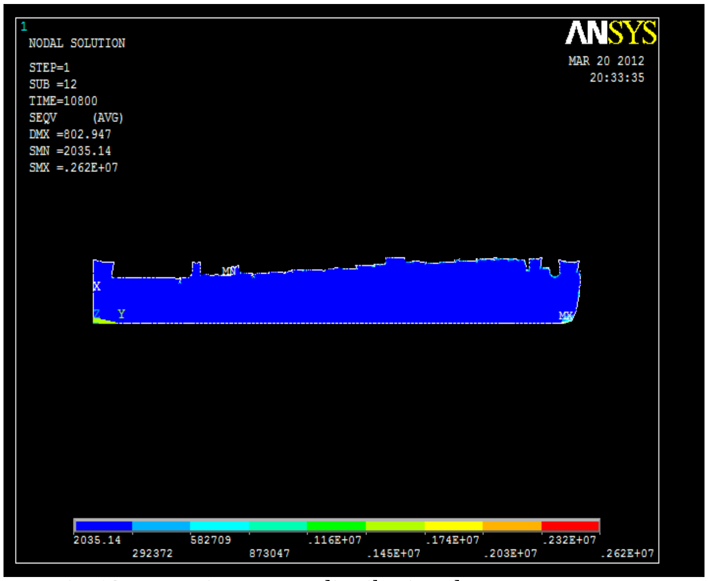

Fig-12 Von Mises stress distribution due to temperature at180minutes.

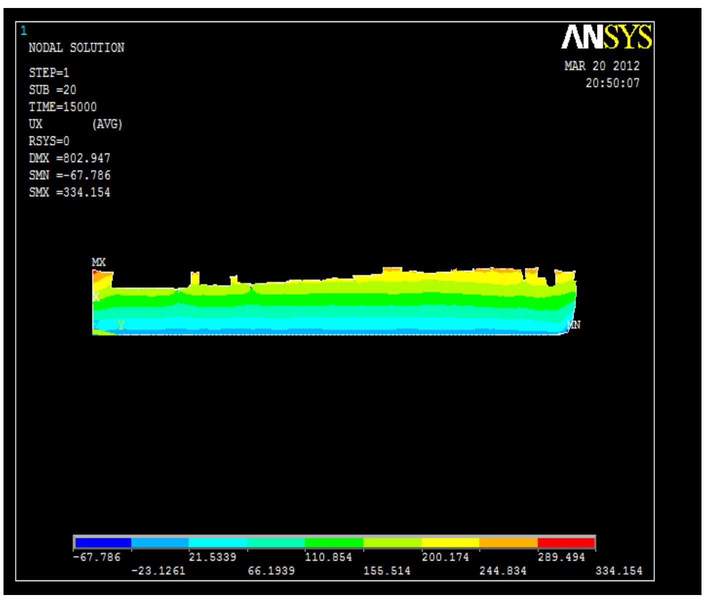

Fig-13 Radial displacement due to temperature at 180 minutes.

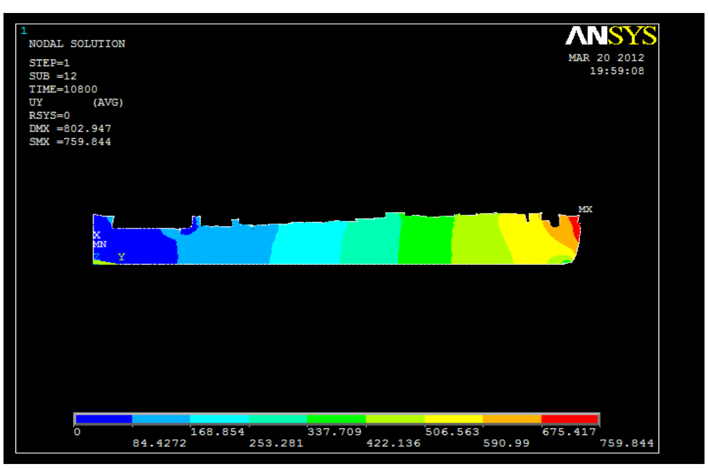

Fig-14 Axial displacement due to temperature at 180 minutes

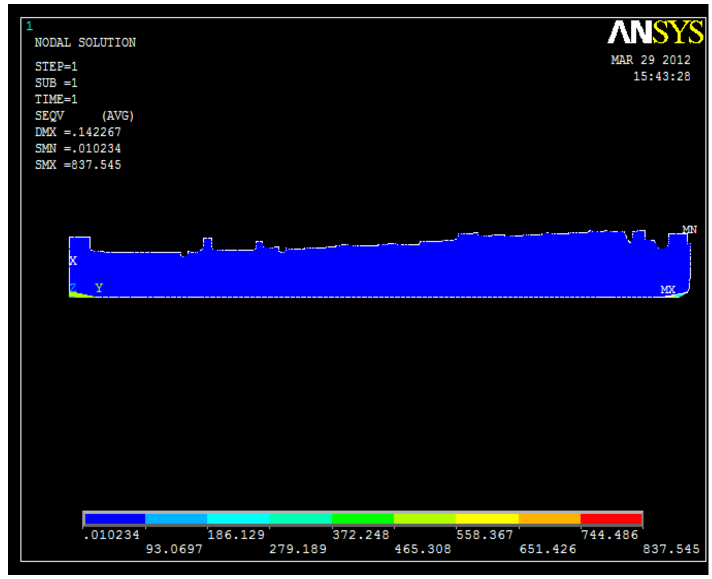

Fig-15 Von Mises stress distribution due to pressure load.

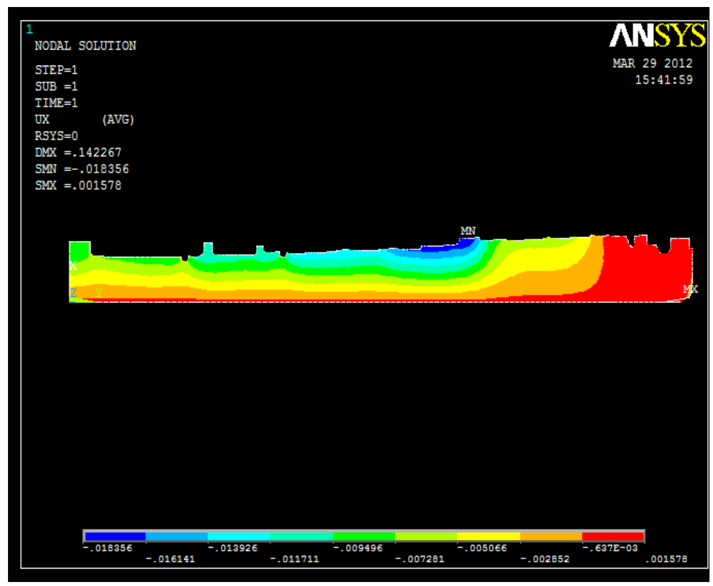

Fig-16 Radial displacement due to pressure load.

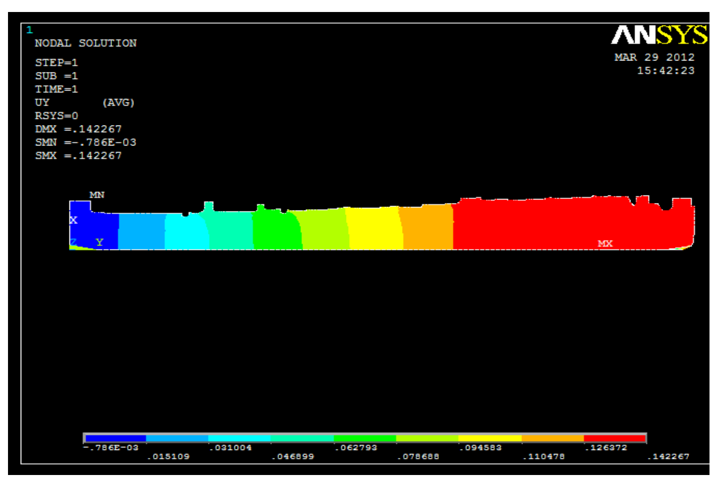

Fig-17 Axial displacement due to pressure load

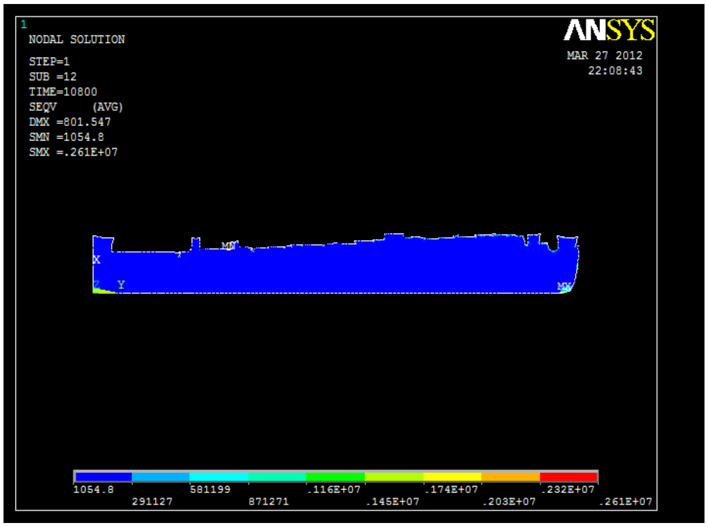

Fig-18 Von Mises stress distribution due to combined load at 180 minutes

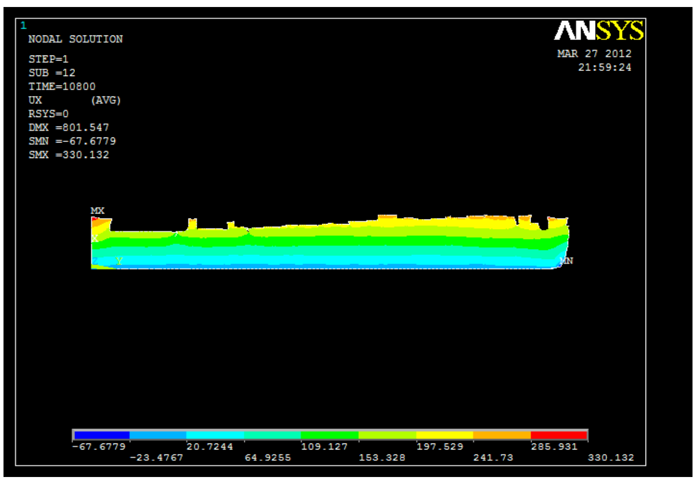

Figure-19 Radial displacement due to combinedLoad at 180minutes.

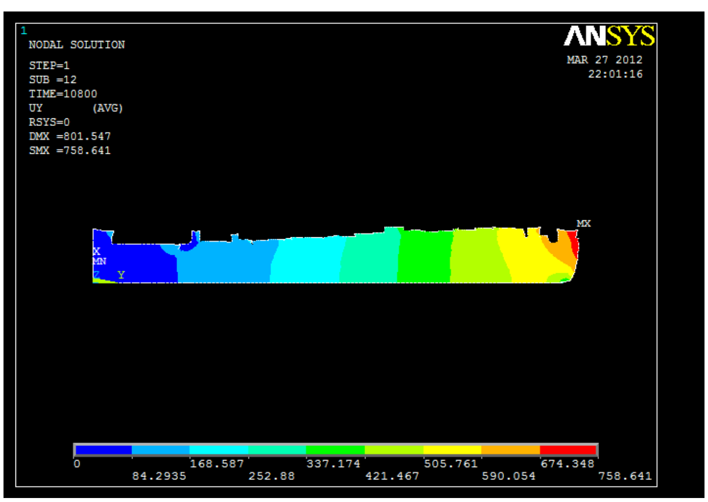

Figure-20 Axial displacement due to combined load at 180 minutes.

VIII. RESULTS AND DISCUSSIONS

8.1 Transient Temperature Distribution and Thermal stress:

At the beginning of the cold start, the component is at uniform ambient temperature. When a cold metal component is exposed to a hot fluid medium, thermal gradients set in across the thickness and along the length. During the thermal transient, this temperature gradient changes with time till the metal reaches its steady state temperature distribution. Due to thermal inertia of the metal, it takes more time to reach its steady state value by conduction than the actual duration of fluid temperature change during the transient.

8.2 Thermal Stress Analysis:

The thermal gradients produce thermal stresses, in transient and steady state conditions, in the component. Stress analysis is carried out on Finite element model of the component at the critical time of transient, when thermal gradient is high.

8.3 Static Analysis:

The fluid pressure produces static stresses, in steady state conditions, in the component. Stress analysis is carried out on Finite element model of the component at different pressure loads.

8.4 Static Transient Thermal Analysis:

Stresses due to fluid pressure are added to the thermal stresses. These total stresses vary as functions of space and time. Pressure loads and Thermal gradients are applied at a time to find out the stresses.

IX. VALIDATION

The experimental stresses and computational stresses obtained from our analysis at some nodes are as shown be

Static Transient thermal analysis		
Experimental stress	**Computational stress**	**% Error**
21587.49	21041	2.53
41658.72	40852	1.93
44007.19	43034	2.21
47905.75	47702	0.42
74021.33	73777	0.33
Experimental X-displacement	**Computational X-displacement**	**% Error**
252.52	231.53	8.31
61.73	58.076	5.91
194.55	183.59	5.63
141.78	134.4	5.2
133.27	125.91	5.52
Experimental Y-displacement	**Computational Y-displacement**	**% Error**
509.72	496.28	2.63
373.43	346.59	7.18
258.71	249.91	3.4
156.99	151.52	3.48
95.48	87.468	8.39

Transient thermal analysis		
Experimental stress	**Computational stress**	**% Error**
42942.75	40855	4.86
43555.33	43037	1.19
44009.72	44793	1.77
48901.16	47705	2.44
50196.58	48713	2.95

Experimental X-displacement	Computational X-displacement	% Error
26.09	24.438	6.33
234.57	231.53	1.29
18.96	18.814	0.77
20.42	18.99	7.01
20.96	19.81	5.48
Experimental Y-displacement	Computational Y-displacement	% Error
501.06	496.25	0.95
374.52	346.55	7.46
259.48	249.88	3.69
157.69	151.5	3.92
90.85	87.459	3.73

Table-1 Comparison between experimental and computational data.

9.1 Fatigue Usage Fraction:

Using the maximum stress due to thermal and pressure load during the transient as the alternating stress range (S range), with the lower limit being zero in the shut down condition, fatigue life usage fraction is obtained from S-N curve

	No. of cycles	Stress	No. of cycles	Stress
		computational		Experimental
	66.007	73777	63.80803	75021.33
	30682	47702	28848.25	48905.75
Avg value	52469.2	45281.2	47475.1	46836.1
	72694	43034	63935.29	45007.19
	92332	40852	85071.52	42658.72
	9063100	21041	8571259	22587.49

The figure below shows S-N curve taking N on X axis and S on Y axis.

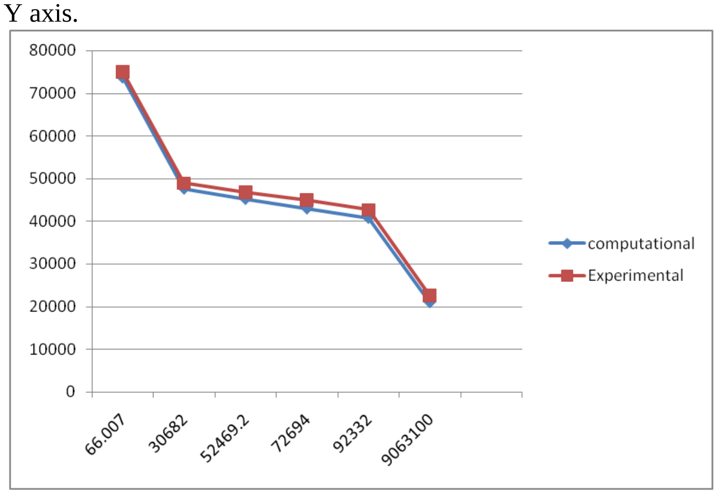

Fig-21 Stress–No. of cycles curve

Uf= n/N

Where, S is the alternating stress range (= S range /2)

n is the actual number of stress cycles experienced by the component, and

N is the maximum number of stress cycles that the component can withstand from S-N curve.

Fatigue usage fraction Uf= $\sum_{i=1}^{m}(\frac{ni}{Ni})$

Based on the experience with thermal stresses during different start-ups, many simplifying assumptions are made. In general, 100 hot starts are considered as equivalent to 1 cold start and 10 warm starts are considered as equivalent to 1 cold start.

9.2 Fatigue Life Usage Fraction:

Total number (n) of stress cycles considered for calculating fatigue life usage fraction (Ref: Aspects of remnant life assessment in old turbines equals (165 hot starts + 105 warm starts)/3 + 30 cold starts = 120 cold starts

Fatigue life usage fraction –(Uf) is given by the ratio n/N where, N equals 10^6 cycles from fatigue (S-N) curve of a typical rotor material corresponding to the alternating stress (S) at a point of 52.1 N/mm 2 during cold start, adjusted for the reference material used In S-N curve.

Fatigue factor			
Uf=	120/52469.2	Uf=0.002287	

This fraction (Uf) for the rotor is obtained as 0.002287

9.3 Creep Usage Fraction:

Using the maximum stress due to thermal and pressure load in the steady state operating condition, creep life usage fraction (Uc) is obtained from creep curve (S – T curve) of the material at the operating temperature.

	Time	Stress	Time	Stress
		computational		Experimental
	264350	48713	190171	50196.58
	314750	47705	254942	48901.16
Avg value	448970	45020.6	403944.5	45921.11
	460350	44793	499514	44009.72
	548150	43037	522233.5	43555.33
	657250	40855	552862.5	42942.75

The figure below shows S-T curve taking T on X axis and S on Y axis.

ISSN 2250-3153

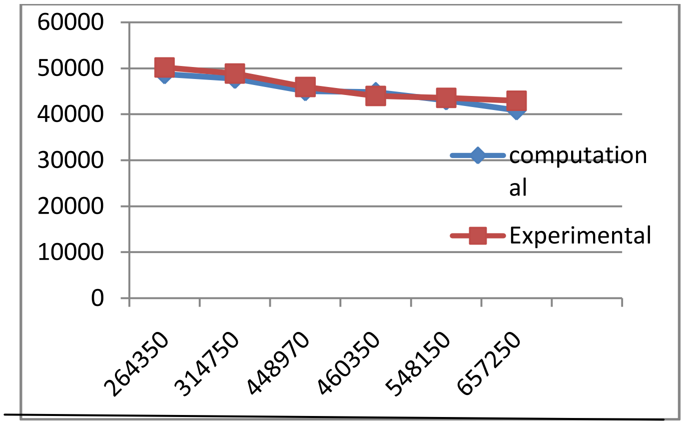

Fig-22 Stress-Time to Rupture Curve

9.4 Creep Life Usage Fraction:

Total duration (t) of operation for this rotor is given as 55,116 hours. Creep life usage fraction is given by the ratio t/tr, where tr equals 3*10 5 hours time from creep (S – tr) curve of the rotor material at the operating temperature corresponding to the total steady state stress (S) of 54.65 N/mm2, due to pressure and thermal loads.

Creep factor				
Uc=	55116/448970		Uc=0.122761	

This fraction (Uc) for the rotor is obtained as 0.122761

X. RESIDUAL LIFE ASSESSMENT

Theoretically, residual life fraction of component is given by
RLF = {1 – Uf – Uc}*10^5.
However, due to many factors influencing fatigue and creep such as deviations from design during manufacture and operation, notches, surface finish, size of component and creep-fatigue interaction, which are not theoretically estimated,
Residual life fraction of component is normally taken as
RLF = {(½) – Uf – Uc.}*10^5

10.1 Residual Life Fraction:

Residual life fraction of turbine rotor is thus given by
RLF = (1/2) – Uf – Uc = 0.5 – 0.002287 – 0.122761 = 0.37

Residual Life					
Residual life=	0.5-0.002287-0.122760986				
	Residual Life=0.374952*10^5		Residual Life is 37495.2 hours		

Residual Life of the Turbine Rotor is 37495.2 hours.

XI. CONCLUSION

- Maximum displacement of turbine rotor is 801.51 mm which is in safe limit.
- Maximum vonmises stress of turbine rotor is 73780 N/mm^2, which is less than designed limit.
- Maximum displacement and maximum obtained stresses of turbine rotor is within the designed limit so our component is safe at the given operating conditions.
- There is a good agreement between computational values and experimental values.
- Residual life of turbine rotor has a minimum life of 8 years, 37495.2 hours which needs to be validated by non-destructive examination after 4 years for identifying surface cracks and material degradation.

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