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Failure Analysis of LP Turbine Final Stage Blades of High Capacity Power Plants

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Abstract--- *Main steam turbines in an high capacity thermal power plants are vital and complicated fine aligned, coupled as single tandem high speed rotating mechanical equipment with very fine clearances. Failure analysis cause study on the LP Turbine final stage blades of high capacity Thermal Power Plant in Tamil nadu, india. The LP Turbine blades are made up of X20Cr35 alloy steel with FIR tree root. The study focuses on the LP turbine final stage blade failure for material degradation, Corrosion fatigue, High cycle fatigue and the type of corrosion mechanism which initiates the crack such as corrosion crack, stress corrosion crack, pitting corrosion cracks due to chlorine corrosion etc., Sediments of Silica and Chlorine were identified in Turbine rotor and stator blade trailing edges, Corrosion pitting were identified along the LP Turbine blade trailing edges. The study further focuses on various operating parameters and history of events to arrive optimum solution.*

Keywords--- *Failure Analysis, LP Turbine Blade, Stress Corrosion Crack, Corrosion Fatigue, X20Cr13, FIR Tree Root.*

I. INTRODUCTION

Turbines are the principal elements that convert the thermal energy into kinetic energy. It involves the aerodynamic, thermodynamic, mechanical and material science disciplines. It also reviews design and materials, operation, steam and deposit chemistry. New alloy compositions for turbine blade materials were tried for control over corrosion on turbine blades. The performance of steam turbine reduces mainly due to effects of corrosion which effects flow of high velocity steam passing over the blades. Modern steam turbines must retain a very high reliability throughout their service life of typically 200,000 hours. Among the failure modes which have been observed in steam turbines stress corrosion cracking (SCC) was prominent, corrosion fatigue (CF) has been observed in steam turbine components such as blades and rotors. This paper analysis the causes of failure, mechanism and prevention solutions.

Design factors affecting turbine corrosion

- Mechanical design (stresses, stress concentrations, stress intensity factor, vibration, frictional damping, benefits of over speed and heater box testing) [1]
- Physical shape (stress concentration, crevices, obstacles to flow, surface finish, crevices)
- Material selection (maximum yield strength, corrosion resistance properties, damping, galvanic effects, etc.)
- Heat transfer (surface temperature, evaporation of Moisture, expansion versus stress, flow of moisture, heated crevices)

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- Flow and thermodynamics (flow excitation of blades, incidence angle, stagnation temperature, boundary layer, condensation and moisture, velocity, location of the salt zone, interaction of shock wave with condensation)[2]

Design, improvements in material selection that reduce turbine corrosion include :

- Integral rotors, Welded rotors and discs without keyways—eliminates high stresses in disc keyways.
- Minimising stress and stress concentrations—increasing resistance to SCC and CF.
- Flow path design using computerized flow dynamics and viscous flow—lower flow induced vibration, which reduces susceptibility to CF.
- Flow guides and double-ply expansion bellows— reduces impurity concentration, better SCC resistance.
- Curved (banana) stationary blades that reduce nozzle passing excitation.
- Improved materials for blade pins and bolting—resistant against SCC.
- Alloy Steels to reduce Flow Accelerated Corrosion (FAC) and Moisture extraction to improve efficiency and water droplet erosion.[3]

The main effects of the blade design on corrosion, corrosion fatigue strength, and stress corrosion cracking susceptibility, and pitting resistance include: [4]

- Vibratory stresses and their frequencies.
- Maximum service steady stresses and stress concentrations.
- Flow induced vibration and deposition.
- Mechanical, frictional, and aerodynamic damping.

The corrosiveness of the steam turbine environment is caused by one or more of the following:

- Concentration of impurities from low ppb levels in steam to percent levels in steam condensates (and other deposits) resulting in the formation of concentrated aqueous solutions
- Insufficient pH control and buffering of impurities by water treatment additives such as ammonia
- High velocity and high turbulence flow of low-pH moisture droplets (FAC)

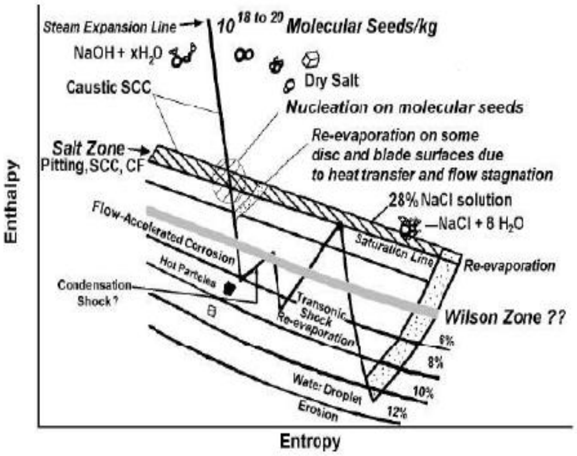


Figure: Mollier Diagram with LP Steam Expansion Line and Thermodynamic Regions for Impurity Concentration and Corrosion Mechanisms

Mollier diagram of the LP turbine steam expansion line and thermodynamic impurity concentrations regions (NaOH, salts, etc.) and resulting corrosion. Low volatility impurities in the salt zone are present as concentrated aqueous solutions. The NaCl concentration can be as high as 28 percent. Note that the conditions at the hot turbine surfaces (in relation to the steam saturation temperature) can shift from the wet steam region into the salt zone and above. [5]

Thus disc stress corrosion cracking often occurs in the wet steam regions. The surfaces may be hot because of heat transfer through the metal or because of the stagnation temperature effect (zero flow velocity at the surface and change of kinetic energy of steam into heat).

Design-related root causes include high surface tensile stresses and stress concentrations, and use of high strength materials. Sources of stresses that contribute to SCC of discs include:

- Basic centrifugal load caused by rotor rotation. Locally high concentration of centrifugal loads caused by variation in the gaps (gauging) between blade and disc rim attachment.
- Residual machining stresses.
- Vibratory stresses—interaction of SCC and corrosion fatigue. Also, vibratory stresses reduce the life of the cracked disc when the flaws reach a sufficient size that fatigue becomes a dominant mechanism. Steam chemistry root causes of SCC and CF cracking include: [6]
- Improperly operated condensate polisher (operating beyond ammonia breakthrough, poor rinse, etc.).
- Operating outside of recommended steam purity limits for long periods of time; sometimes caused by organic acids from decomposition of organic water treatment chemicals. Condenser leaks—minor but occurring over a long period of time.
- Water treatment plant or condensate polisher regeneration chemicals (NaOH or H2SO4) leak downstream.
- Condenser leaks—major ingress, generally one serious event, and the system and turbine not subsequently cleaned.
- Shutdown environment: poor layup practices plus corrosive deposits.

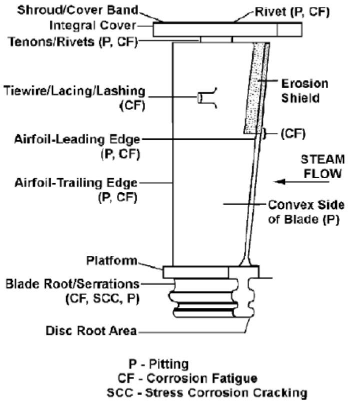


Figure: Locations of Cracking and Localized Corrosion on LP Turbine Rotating Blades. There Has Also Been SCC and CF Cracking in the Tiewire Holes

Analytical Modeling – General There has been a continuing progress in the analytical modelling for the determination of natural frequencies of the system comprising of a set of blades mounted on the bladed disk. The early attempts to model the blade as a beam element have progressively led to a more comprehensive finite element representation. This finite element representation of real blade profile becomes necessary especially when plate or shell type of vibratory modes is induced. Estimate the dynamic stresses in last stage steam turbine blades under reverse flow conditions, last stage steam turbine blades are known to suffer high alternating stresses under low volumetric flows of steam. The low volumetric flows results in a reverse flow condition and the resulting response is unstable vibration that occurs predominantly at fundamental mode of the blade. Besides the high alternating stresses, the last stage blades are also subjected to severe centrifugal load stress that when combined with the alternating stress is responsible for fatigue failures. cracks were analyzed at the root of the third blade row of low-pressure steam turbine blades of different natural frequencies. The root cause of the fatigue crack initiation was pitting corrosion of the forged ferritic/martensitic X20Cr13 material. Metallographic investigations, finite element analysis and fracture mechanics analysis combined with experimental data from the literature are used to evaluate crack propagating stresses to discuss the operating conditions. The calculations show that corrosion pits at the root of the turbine blade increase the local stresses above yield strength. Excitation of natural frequencies by changing the rotor speed is not responsible for the crack propagation. The centrifugal load and superimposed bending load caused by unsteady steam forces are responsible for the crack propagation. [7]

The comparative study of the model analysis of steam turbine blade with the analytical method. In any steam turbine the last stage blades are most prone for the failure due to severe dynamic conditions of loading. First the modal analysis of last stage blade is carried out with the help of FEM techniques and the natural frequency calculated. Finally the variation in natural frequency and mode shapes for cracked and un-cracked blade is studied.

Blade Excitation and Response: The major source of blade excitation arises out of the interaction between the moving blade rows and the stationary blade row. A logical approach towards the design of turbo machine blade is to study the nature of these excitation forces and analyze the dynamic stresses. Many researchers have worked to develop the basic theories of isolated aerofoil and have studied the flow interference in a turbo machinery stage. Find the variation in vibration response of blades with the crack size of fir tree root free standing blades. Generation of crack in blade root causes the loss of stiffness in the vicinity of blade root. It results in shifting of natural frequencies and redistribution of dynamic and static stress in the blade root which may cause failure of the blade. A 3D finite element model of a blade and its fir-tree roots has been analyzed. Results of FEM study are validated by experimental results of cracked blades. Finally the variation in natural frequency and mode shapes for different sizes cracked blades are studied. A suitability of the bladed disk design regarding the possibility of the resonant vibration excitation can be assessed on the basis of several approaches. Most information concerning the evaluation of the bladed disk design suitability is provided in the SAFE diagram but the possibility of exciting the action wheel resonant vibration can also be evaluated from the Campbell diagram. Further criterion is the assessment of the design suitability on the basis of a critical speed of the bladed disk. It especially causes breakdowns of relatively flexible disks.[8] The investigation included a metallographic analysis of the cracked blades, natural frequency test and analysis, blade stress analysis, unit's operation parameters and history of events analysis, fracture mechanics and crack propagation analysis. This paper provides an overview of this failure investigation, which led to the identification of the blades torsional vibrations near 120Hz and some operation periods with low load low vacuum as the primary contribution to the observed failure.

Experimental Evaluation: Rotating blades have been recognized as one major cause of failure in many turbines and jet engines. They are, usually rotating at high speeds, interacting with the erosive environment, have complicated shapes, and undergo severe dynamic and thermal loadings. These operating conditions expose blades to many vibration excitation mechanisms and at the same time make the vibration measurement process of blades a very complicated task. Experiments are done to evaluate the frequencies of blades. The model analysis of steam turbine blade Experimental Method. In any steam turbine the last stage blades are most prone for the failure due to severe dynamic conditions of loading. NFT of these blades in lab conditions is mandatory to detune these blades. First the modal analysis of last stage blade is carried out with the help of FEM techniques then the blade is tested in NFT lab and the natural frequency calculated by both the methods is compared. After the validation of model through experimental results the similar study is also carried out for a cracked blade. Finally the variation in natural frequency and mode shapes for cracked and un cracked blade is studied. Blade failure is a common problem of a steam turbine and its failure in-service results in safety risks, repair cost and nonoperational revenue losses. Thus, there liability of these blades is very important for the successful operation of a steam turbine. Dynamic analysis of a steam turbine blade in computational environment is carried out in the present work. In order to gain physical insight into the flexural dynamics of such turbine blades with the inclusion of the rotor dynamic effect, the turbine blade was approximated as a twisted cantilever beam with an asymmetric aerofoil cross-section fixed on a rigid rotor disk. Methods to validate the computational procedures for cantilever beam were established. Similar computational procedures were leveraged for the turbine blade. Critical speeds were obtained for different excitations.

Natural Frequency and Mode Shape : Natural frequency is the frequency at which an object vibrates when excited by a force, such as a sharp blow from a hammer. At this frequency, the structure offers the least resistance to a force and if left uncontrolled, failure can occur. Mode shape is the way in which the object deflects at this frequency. An example of natural frequency and mode shape is given in the case of a guitar string. When struck, the string vibrates at a certain frequency and attains deflection shape. The frequency can be noted by the pitch coming from the string. Different string geometries lead to different natural frequencies or notes. By nature of its structure, a turbine blade has many natural frequencies and mode shapes. These frequencies and mode shapes are somewhat further complicated by the use of shroud to connect group of blades together.

Vibratory Forces: Some alternating forces must exist to excite a structure to vibrate. These forces have inherent frequencies and shapes just as bladed disk do. In a steam turbine, the most common sources of excitation are nozzle passing frequencies and running speed harmonics. Running speed harmonics occur due to interruptions in the fluid flow path. Frequencies of running speed are multiples of rotor operating speed. For example, the tenth harmonic of running speed would be a force that occurs ten times for every revolution of the wheel. For example, a turbine rotor running at a speed of 3000 RPM (50 cycles/sec or Hz) would have running speed harmonics occurring at 120HZ, 180Hz, 240HZ

Resonance: Each blade on a rotating turbine disk experiences a dynamic force when it rotates through a non-uniform flow from stationary vanes. The dynamic response (e.g. stress, displacements, etc.) levels experienced by the bladed depend on:

1) The natural frequencies of the bladed disk and tier associated mode shapes.

2) The frequency, the shape and the magnitude of the dynamic force which are ion of the turbine speed, number of stationary vanes and their location around the annulus and/or the number of interruptions in the flow passage e.g. struts and their location around the annulus. [4]

3) The energy dissipating properties called damping – provided by blade material, frictional slip between joints, aerodynamic damping from steam, etc. A turbine bladed disk may get into a state of vibration where the energy build up is a maxima in its response (stress, displacement, etc.) and minima in its resistance to the exciting force. This condition is called a state of 'RESONANCE'. There are two simultaneous for the energy built up per cycle of vibration to be a maximum. These conditions are Thus for a resonance to occur, both of the above conditions must be met. [9]

Results of Poor Water Treatment: In the ideal situation, water would be feed to a boiler free of any impurities. Unfortunately, this is not the case. Water cleanup is always required. The following items are the most problematic to steam turbines:

1. Calcium (Ca) scale– Calcium forms

2. With sulphates (SO4) and other compounds to form calcium sulphate, calcium bicarbonate, calcium carbonate, calcium chloride, and calcium nitrate.

3. Chemicals adhere to boiler tube walls forming scale during evaporation. Its formation increases with the rate of evaporation so these deposits will be heaviest where the gas temperatures are highest. Scale is a non-conductor of heat which leads to a decreased heat transfer of the boiler tubes, and can result in tube failure due to higher tube metal temperatures. Build-up of scale also clogs piping systems and can cause control valves and safety valves to stick.

SILICA (SiO2): Silica can formed scale at low pressures below 40 bars. Above 40 bars, silica starts to volatize, passing over with steam to potentially form deposits on the steam turbine diaphragms and blades. These deposits change the steam path components profiles resulting in energy losses and wheel chamber pressure of turbine rise. The degree of loss depends upon the amount of the deposits, their thickness and their degree of roughness. For example, if the nozzle area of the first stage flow path was reduced by 10%, the output of the steam turbine would be approximately 3% less. A similar loss could occur if the turbine received steam for power augmentation purposes. For same power of output steam quantity is more required. [10]

SODIUM (Na): Sodium can combine with hydroxide ions creating sodium hydroxide (caustic). Highly stressed areas of steam turbines can be attacked by sodium hydroxide and cause stress-corrosion cracks to occur.

CHLORIDE (Cl): Chlorides of calcium, magnesium, and sodium, and other metals are normally found in natural water supplies. All of these chlorides are very soluble in water and therefore, can carry over with steam to the steam turbine. Chlorides are frequently found in turbine deposits and will cause corrosion of austenitic stainless steel and pitting of steel. Corrosion resistant materials protect themselves by forming a protective oxide layer on their surface. [11]

IRON (Fe): High iron is not found in raw water but high concentrations can come from rusted piping and exfoliation of boiler tubes. Iron is found in condensate return in a particle form as it does not dissolve in water. The detrimental aspect of iron is called steam turbine solid particle erosion, which causes significant erosion of steam turbine steam path components.

II. RESULTS AND DISCUSSION

- **To avoid corrosion due to chlorine:** Turbine wet steam washing can be introduced to clean the cl scales.

Turbine Washing Procedure

After Compressor Stopped Condensate export Pump (P-27) taken in line, make up valve open, KS(live steam) valve closed and vent valve to be opened. Oil circulation and barring to be taken in line. When the line temperature came down to 2500 C then washing started as per following steps. [12]

1) KS(very high pressure steam) steam (live steam) all isolation valves closed and bypass valve closed,

2) Lube oil pump running.

3) Condensate pumps running, it may be stopped after 4-5 hrs. Make up valve closed. And open drain valve.

4) CO2 suction line I / V open interlock to be bypassed from Instrumentation maintenance.

5) Reset the compressor.

6) Keep 1st I/valve full open and 2nd I/V slightly open on the line connecting 15 ata motive steam and adjust the condensate so as to maintain the line temperature at 165°C to 175°C and pressure about 10-11 ata.

7) Follow the normal Compressor start up procedure.

8) After opening of HP/LP valves adjust the rpm of turbine to 800 to 1000 by adjusting the inlet steam.

9) Analyse the condensate for Phosphate, silica, PH and conductivity after every two hours.

10) Washing to be carried out till the two consecutive readings are same.

11) The mixed steam is refilled to carry out purging for 10～30 min. During the purging via steam, the condensate and impurities are drained through open drain line when the filled condensate reaches 80% , and the condensate is refilled and the vacuumizing is conducted after the drainage; the cylinder drain and the inlet nipple are connected after the condensate is drained from the cylinder, meanwhile, the main steam pipe is heated. The procedure may be shortened according to the cleaning time or the purging may not be conducted, but the condensate must be drained.

12) The steam washing line with proper connections and support of the steam lines to the turbine are important as well as the steam drains with PG & TG arrangement and at least two drains line provided, If the steam supply lines are putting a load on the turbine, it is likely to cause the turbine to vibrate and will cause mechanical distress to the attachment locations. Similarly, when steam turbines are started, there is a warm-up time to heat the turbine to

the proper temperature level before admitting full starting steam. The heating rate must be slowly up to 100 0C and then rate should be 3-4 0 per minutes

- **To avoid Major blade failure at run time**: NFT and MPI Tests to be conducted during every capital overhauling on all the LP turbine final stage blades.

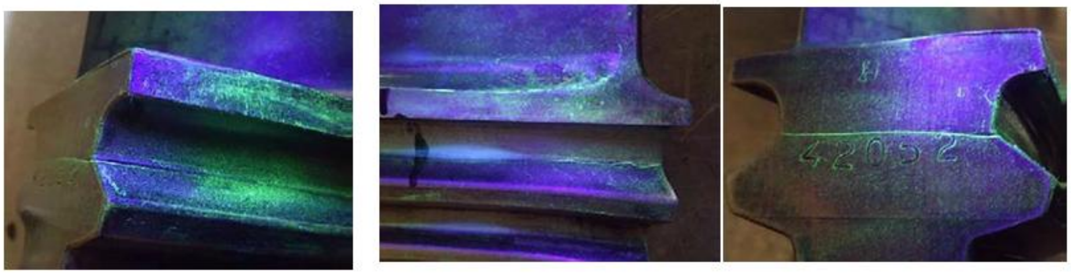
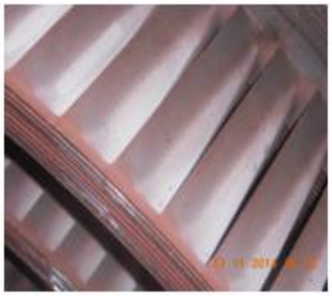


Figure: Cracks identified at the FIR tree root of final stage LP blades during the Magnetic Particle Test (MPI)

LP Turbine dismantling for Inspection

Pitting corrosion



chlorine scale formation

Blade crack at Root

Failed Turbine blade Root

Turbine Rotor after Alumina Blasting

Damaged LP Rotor Final Stage Blades

HP Turbine dismantling

IP Turbine Dismantling

LP Turbine Bottom Fixed Blades

Both LP1 & LP2 turbine rotors placed condition

III. CONCLUSION

In most cases where material yield strength is <130 ksi (895 MPa), the solution to disc SCC is a design change to reduce stresses at critical locations. This has been achieved by eliminating keyways or even disc bores (welded rotors) and by larger radii in the blade attachments. Higher yield strength (>130 ksi, 895 MPa) low alloy steel discs should be replaced with lower strength materials. The goal is to keep the ratio of the local operating stress to yield stress as low as possible, ideally aiming for the ratios to be less than 0.6. Minimizing applied stresses in this manner is most beneficial in preventing initiation of stress corrosion cracks. Once cracks begin to propagate, a reduction in stress may be only marginally effective unless the stress intensity can be kept below ~10 to 20 ksi-in1/2 (11 to 22MPa-m1/2). This is because of the relative independence of the crack growth rate over a broad range of stress intensities. For many rim attachment designs, such levels of applied stress intensity are impossible to achieve once an initial pit or stress concentration has formed. An emerging solution to disc rim stress corrosion cracking is a weld repair with 13%Cr stainless steel. For high capacity thermal power plants the LP turbine blades made of superior **X10Cr13 alloy steel** is recommended in stud of X20Cr13. Further from the various surface enhancement processes the **laser peening process** have greater advantage to increase the resistance of turbine blades to foreign object damage (FOD) and improve high cycle fatigue (HCF) life. The process creates residual compressive stresses deep into part surfaces – typically five to ten times deeper than conventional metal shot peening. Another solution has been to shot peen the blade attachments to place the hook fit region into compression using **clamping pieces**. Good control of the steam purity of the environment can help to prevent or delay the SCC. Maintaining the recommended levels of impurities during operation by providing **Effective Condensate Polishing Unit** (CPU) at the CEP discharge and providing adequate protection during shutdown can help minimize the formation of deposits and corrosive liquid films, and lengthen the period before stress corrosion cracks initiate. **NFT and MPI tests** on every capital Overhauling help to identify the crack if any before the major run time break down which cause very high damages to the TG set. **Wet steam washing for the LP turbine** during every annual overhauling and **Alumina blasting** during every capital overhauling can reduce the chloride scale on the turbine blades which is the prime factor initiate the crack failure. The operating period(s), events, or transients that are causing excursions in water and steam chemistry should be identified using the monitoring locations and instrumentation recommended in the independent water chemistry guidelines.

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