Low Cycle Thermal Fatigue Damage In Steam Turbine Rotor- Analytical Evaluationof Remaining Life - A Case Study

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Abstract:

This paper discusses about a case study for analytical evaluation of low cycle thermal fatigue damage of a high pressure (HP) rotor of 210 MW steam turbine during transient. The thermal strain also has been evaluated analytically.The assessment of the damage has been checked by analytical method namely cyclic life expenditure (CLE), which essentially utilizes the proprietary information of the turbine manufacturer whereas the former method utilizes the accessible published information. In the absence of actual material properties data of the rotor, certain permissible practical assumptions have been made in the study here. The analytical method may help in quick assessment of low cycle fatigue (LCF) damage of a steam turbine rotor during transient.

Keywords: Low cycle fatigue (LCF), Transient, Thermal strain, Steam turbine rotor

1.Introduction

Non-availability of various components of thermal power plants leads to loss of generation. The rotor shaft of a steam turbine is a very important component whose fitness for the purpose is required to be assessed periodically to ensure safe availability.

The shaft is subjected to a low cycle thermal fatigue (TF) stresses during start-up, shut down and load changes due to the temperature gradient across the thick section between bore and the outer surface. Reducing start-up times to improve flexibility leads to an increase in the transient thermal stress levels at the rotor surface and bore. This TF stress field is further aggravated due to the presence of number of steps, grooves of the gland seals, heat relieve grooves etc. As these areas are subjected to high TF stresses, cracks are initiated from here[1, 4]. The crack is initiated after the maximum fatigue damage level is exhausted. Onesuch crack is shown in Fig. 1 [3]. Sizing of such crack by ultrasonic time of flight diffraction (TOFD) method has been reported earlier [4].

Fig. 1 Photo showing T.F. cracking in disc radii and balance hole [3]

The low cycle thermal fatigue damage during transient being the prevailing predominant damage mechanism for crack initiation in case of a turbine rotor, its assessment a priori is very important. The assessment provides the information about the extent of damage the rotor has undergone and thus based on the extent the plant authority may adopt appropriate engineering decision regarding safe running.

Analytical methods for determining the fatigue damage level for crack initiation on a rotor have amply been discussed earlier [2]. Actual field data with respect to start-up curve, geometry, number of cold starts have been adopted in those methods for evaluation of its low cycle fatigue damage (LCF).

In this paper analytical methods for assessing the fatigue life fraction of a real life rotor have been presented. The steps adopted in these methods for a Cr-Mo-V steel HP rotor of a 210 MW steam turbine are presented as a case study. Two methods namely analytical and cyclic life fraction (CLE) have been adopted for evaluating the fatigue life fraction expenditure. The findings from both the methods are inter-compared.

The analyticalmethod discussed here may be useful in faster and reliable assessment of LCF damage in a rotor which will help the plant authority.

2. Low Cycle Fatigue

The problem of low cycle fatigue arises in a rotor primarily during transient condition where, due to the massiveness of the rotor, thermal gradients are set up in the rotor. The surface follows the ambient temperature change more closely than the interior, so that the surface would expand or contract relative to the interior but is prevented from doing so by the bulk of rotor. Thermal strains thus result with every start stop cycle and with load changes [2].

With the admission of steam the surface first tries to expand but is held in check by the bulk of the rotor resulting in compressive stresses at the surface. If the load increase is sufficiently severe, compressive yielding occurs so that a residual tensile stress results when the loading cycle is completed. During steady operation, the residual tensile stress relaxes to a degree that depends on the temperature and time of operation at the steady load. When the load is decreased the rotor surface goes in to the tension. This tensile stress is superimposed on the residual tensile stress. If tensile yielding occurs during load decrease, a residual compressive stress results. This stress will not relax appreciably, however, because temperature has reached a low value by now. The typical cycle of events [7] undergone by material in the critical region of a turbine rotor is illustrated in Fig. 2.

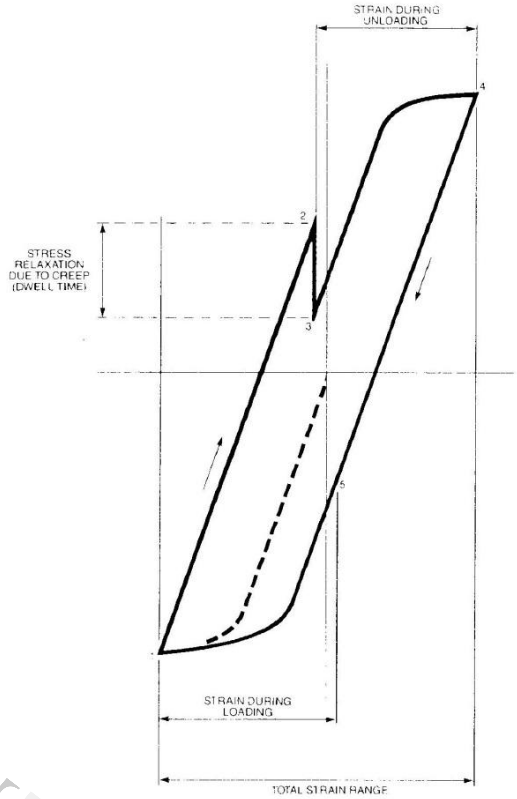

Fig. 2 Typical stress-strain cycle at rotor surface (7)

During repetition of this simple cycle at least three damage mechanisms can be operative: (1) fatigue due to repeated cycle imposed by the strain range (2) creep damage during stress relaxation at high temperature and (3) creep damage under steady operative loads. If the load changes are not severe and thermally induced strains do not exceed the yield strain, the relaxation of residual stresses (item 2 above) does not become important.

As the thermal strain is found to be less than the yield strain, the creep damage during stress relaxation is not considered here. Moreover, the creep damage under steady operative loads is also not considered here. In this paper purely LCF damage during transient is discussed.

3.Analytical Evaluation

The objective of the analytical evaluation being determining the fatigue life fraction expenditure of the steam turbine rotor it is very important to determine the number of cycles required for initiation of fatigue crack in the rotor. In its normal operation the rotor undergoes transient condition during start-up and shutdown cycles. The information on the number of such cycles is precisely available from the plant records. The rotor experiences thermal strain during these start-up and shutdown cycles.

A generic relation between a given thermal strain experienced and the number of cycles to cracking at the temperature of interest like 540 °C (utility power steam turbine) for Cr-Mo-V rotor steel is available in literature [2]. The thermal strain itself is obtained by analytical method using guidelines available in literature [2]. This enables the determination of cycles to initiate fatigue cracking.

A case study is presented here bringing out the analytical evaluation. In the present case, the rotor is made of Cr-Mo-V steel and works at a nominal temperature of 540°C. It has experienced 15 cold starts since commissioning. Its geometrical details with respect to diameter, surface grooves and the cold start-up curve were obtained from the plant records. The thermal strain was required to be evaluated for determining the cycles to cracking under this present condition. In the subsections to follow, the steps for evaluating the thermal strain and the fatigue life fraction expenditure are detailed.

3.1 Evaluation of thermal strain

In assessing the fatigue damage, the thermal strain corresponding to the various transients, as well as the strain concentration factors corresponding to the stress concentration factors at the critical regions need to be determined. The principles adopted here for analytically determining the thermal strain based on the guidelines available in literature [2] are described below.

i) Determine the material properties:

The following typical material properties are determined from the published literature - thermal expansion coefficient (α), thermal diffusivity ($\frac{k}{\gamma c}$), cyclic yield strain (ε_y), where,

k = metal conductivity; γ = density; c = specific heat.The heat transfer condition is represented by Biot number ($\frac{hR}{k}$) to be equal to 100 [2] where, h = surface heat transfer coefficient; R = rotor outer radius.

Determination of the exact values of these properties requires extraction of samples from the actual rotor and subsequent destructive testing. Sampling and destructive tests were not carried out here. The appropriate calculation may be performed by suggested values [2] given in Table 1.

Table 1 Material Properties

Material properties	Value
Thermal-expansion coefficient (α)	8.5×10^{-6} in/in °F
Thermal diffusivity ($\frac{k}{\gamma c}$)	0.3 ft^2 /h
Cyclic yield strain (ε_y)	2×10^{-3} in/in
Biot number ($\frac{hR}{k}$)	100

ii) Determine dimensionless ramp time:

The dimensionless ramp time ($\Delta\tau$) defined as [2]

$$\Delta\tau = \frac{k}{\gamma c} \cdot \frac{\Delta t}{R^2} \quad \text{.........................(1)}$$

Where, $\frac{k}{\gamma c}$ = thermal diffusivity; Δt = ramp time;

R = rotor outer radius

The ramp time (Δt) is obtained from the start-up curve, the present rotor is subjected to. The curve obtained from the plant records is illustrated in Fig. 3. The ramp time therein for the rotor was considered from the point 'ESV opens for warm-up' (135 minute) at 237 °C to 'reach 210 MW' (345 minute) at 540 °C. Thus the ramp time was found to be (345-135) minute = 210 minute = 3.5 hour over a temperature change (ΔT) = (540-237) °C = 303 °C (577 °F).

The outer radius (R) of the rotor was measured to be 0.98 ft. The thermal diffusivity ($\frac{k}{\gamma c}$) as discussed in 3.1 *(i)*is 0.3 ft^2/h.

With the above values, the dimensionless ramp time ($\Delta\tau$) from Eq. (1) is determined to be 1.

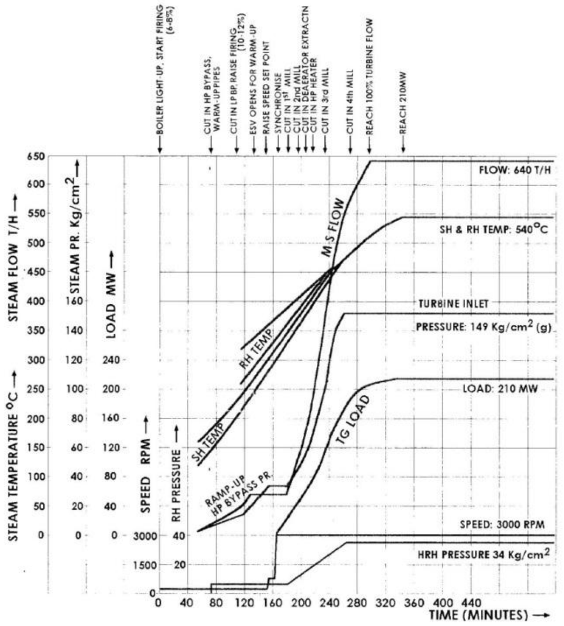

Fig. 3 Boiler start-up curves after 160 hours shutdown

(iii) Determine dimensionless surface strain range:

The dimensionless surface strain range (x) defined as [2],

$$x = \frac{\Delta\varepsilon_{TS}}{2\alpha\Delta T} \quad \text{......................................} \quad (2)$$

Where, $\Delta\varepsilon_{TS}$ = surface strain range; α = thermal expansion coefficient;ΔT = temperature change;

The dimensionless surface strain-range can be determined knowing the heat transfer condition represented by Biot number ($\frac{hR}{k}$) and ramp time ($\Delta\tau$). For the present rotor case wherein the Biot number is equal to 100 and $\Delta\tau$ = 1, the dimensionless surface strain range (x) can be read as equal to 0.1 from Fig. 4.

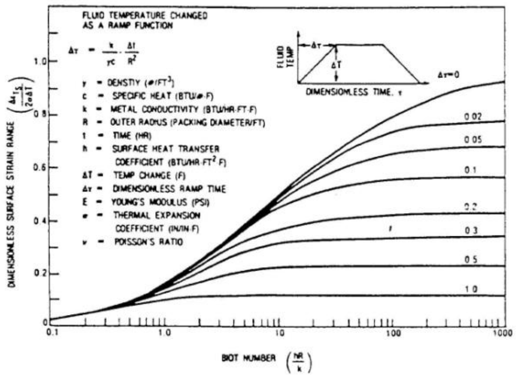

Fig. 4 Dimensionless nominal cylinder-surface thermal strain, used for calculating nominal thermal strain range on surfaces of turbine rotors (2)

(iv)Determinesurface strain range:

At this stage, the dimensionless surface strain range being known, if the values of thermal expansion coefficient (α) and the temperature change (ΔT) are substituted in Eq. 2, the surface strain range ($\Delta\varepsilon_{TS}$) can be obtained.

For the present case, the surface strain range ($\Delta\varepsilon_{TS}$), thus calculated as 980.9 x 10^{-6} in/in.

(v) Determine effective strain:

The effective strain is defined as $\Delta\varepsilon_{TS}K_{\varepsilon}$ where, K_{ε} is the plastic strain concentration factor. The plastic strain concentration factor can be determined knowing the normalized nominal strain range ($\frac{\Delta\varepsilon_{TS}}{2\varepsilon_y}$) and stress concentration factor (K_T).

The groove width-depth ratio is measured to be 1.3 and the relevant stress direction which the rotor experiences in its operation leads to stress concentration factor (K_T) equal to 1 + 2 x (width-depth ratio) i.e. 3.6.

For the present case, where the normalized nominal strain range ($\frac{\Delta\varepsilon_{TS}}{2\varepsilon_y}$) = 0.245 and stress concentration factor (K_T) = 3.6, the plastic strain concentration factor (K_{ε}) can be read by interpolation between K_T = 3 and K_T = 4 from Fig. 5. The value so read is equal to, K_{ε} = 3.6.

Thus, the effective strain ($\Delta\varepsilon_{TS} K_{\varepsilon}$) = 0.0035.

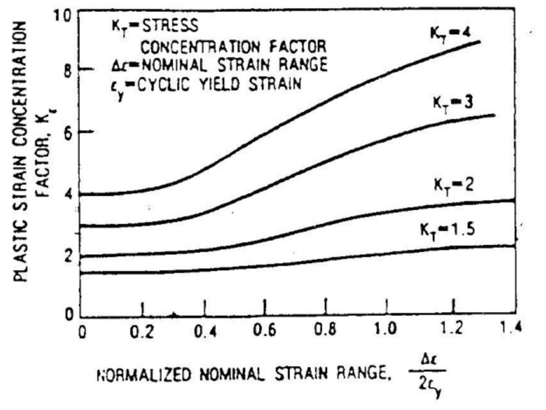

Fig. 5 Plastic strain-concentration factors for low alloy steels (2)

3.2 Determination of fatigue-life fraction expended

The fatigue life fraction expenditure of a rotor can be calculated by dividing the total number of cycles it has experienced by the number of cycles to cracking.

In the present case the Cr-Mo-V steel rotor has been in service for 1,35,847 hours at a nominal temperature of 540°C and experienced 15 cold start-ups.

Step-wise calculation of the life expended of the rotor is described below.

Step-1: Determine the cycle to cracking (N_f):

The low cycle fatigue curves correlating the number of cycles and effective strain at fatigue cracking for Cr-Mo-V rotor steels working at approximately 540 °C are shown in Fig. 6 [2].

For the present case, where the effective strain is equal to 0.0035, the cycles to cracking (N_f) can be read as 10^4 from Fig. 6.

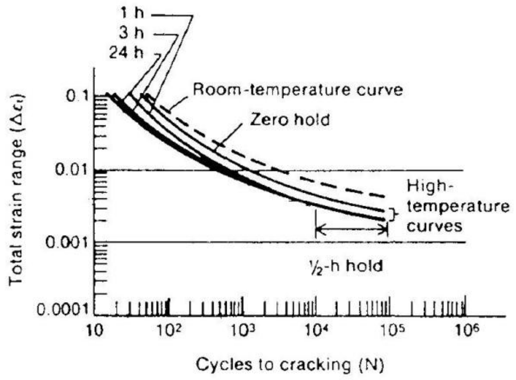

Fig. 6 Low cycle curves for Cr-Mo-V rotor steels at approximately 540°C (1000°F) (2)

Step-2: Calculate fatigue-life fraction expended:

The rotorhas experienced 15 numbers of cold start-ups since its commissioning.

Thus the fatigue-life fraction expended = $15/10^4$ = 0.0015

4. Validation of the result by alternative method of cyclic life expenditure (CLE)

The results obtained above by analytical evaluation are validated by comparing the life fraction expended evaluated by another method namely cyclic life expenditure (CLE) method. The CLE curves, generally given by turbine manufacturers represent the percent life expended per cycle as a function of rate of steam temperature change or ramp rate and magnitude of temperature change for any given rotor diameter and surface stress concentration factor, K_T .

Some typical CLE curves for a set of 'D' and 'K_T' are illustrated in Fig. 7 [2]. The cyclic life expenditure for other rotors having different values of 'D' and 'K_T', can be obtained by interpolation or extrapolation. These curves are valid only for symmetrical temperature transients in both up and down ramp.

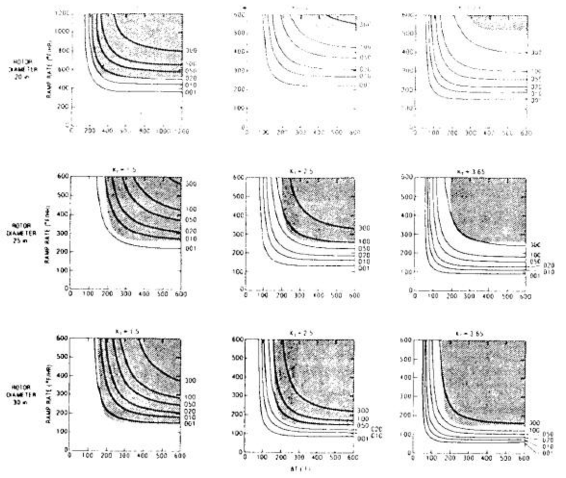

Fig. 7 Cyclic life expenditure curves [2]

In the CLE method, the fatigue life fraction expended is directly calculated by multiplying the cyclic life expenditure with number of cycles.

For the present case, the step-wise calculation of fatigue life fraction expenditure is described below.

(i) Identification of the relevant CLE curves:

Diameter (D) of the rotor is 23.6 inch and stress concentration factor (K_T) is 3.6. The value of K_T was approximated as 3.65. CLE curves are available for D at 20 and 25 inches. Thus CLE curves identified are at K_T = 3.65, D = 20 inch and D = 25 inch.

(ii) Determine the ramp rate and magnitude of temperature change:

From the start-up curve in Fig. 3, the ramp time (Δt) and the temperature change (ΔT) were determined in previous subsections as 3.5 hours and 577 °F respectively. Thus the ramp rate is 577/3.5 °F/hr = 165 °F/hr and the magnitude is 577 °F.

(iii) Determine cyclic life expenditure:

First, from the identified set of CLE curves for D = 20 inch, ramp rate of 165 °F/hr and temperature change (ΔT) of 577 °F, the value of CLE is in between 0.001 to 0.01%. By linear interpolation the value of CLE is determined as 0.04%.

Secondly, from the identified set of CLE curves for D = 25 inch, ramp rate of 165 °F/hr and temperature change (ΔT) of 577 °F, the value of CLE is in between 0.05 to 0.10%. By linear interpolation the value of CLE is determined as 0.067 %.

Adopting the method of linear interpolation, for D = 23.6 inch, the value of CLE is obtained as 0.05%.

(iv) Determine fatigue life fraction expenditure:

The rotor has already undergone 15 cycles. Thus for CLE being 0.05%, the total fatigue life fraction or cyclic life expenditure is (0.05 x 15)% = 0.75% = 0.0075.

5.Discussion

The low cycle thermal fatigue damage in a real life turbine rotor has been evaluated analytically. The extent of damage has further been verified by another method namely life cycle expenditure (CLE). The fatigue damage assessment by analytical method is 0.0015 whereas the CLE method has yielded the value as 0.0075. Apparently both the values are very low as far as the extent of damage is concerned.

It is felt that for assessing the fatigue life fraction expenditure, the analytical method is more convenient to implement as compared to the CLE method. The reason being, the inputs required in analytical method are likely to be available in the published literature for public domain. Whereas, in CLE method, the CLE curves may be a classified document available only in the domain of the turbine manufacturers and their customers and hence pose a serious limitation in damage assessment by this method.

Certain assumptions with respect to the various material properties have been made for the steam turbine rotor under the present study. The other assumptions namely evaluation of plastic strain concentration factor from Fig. 5, low cycle fatigue curves for determining the cycles to cracking from Fig. 6, CLE curves from Fig. 7 for the present rotor material have been made. Material properties data specific to a given rotor as in the present case requires destructive sampling and subsequent testing. Actual material property data is most likely to yield more rational assessment of the low cycle thermal fatigue damage. However, drawing the samples to get at the material properties is not always feasible. Hence in real life situation, the analytical evaluation method as explained in the case study is a practical solution for damage assessment.

The analytical method discussed in the paper for assessing LCF damage prima facie provides satisfactory result. The method may be adopted where a quick decision on run/replace based on fitness for the purposes is required to be taken.

6.Conclusion

The analytical method discussed in this paper can help in assessing the fatigue life fraction expenditure of an aged steam turbine rotor. The steps discussed in the method are easy to adopt. The assessment will help the concerned plant authority in taking an appropriate decision regarding safe running of the turbine rotor.

Acknowledgement:

The authorsare thankful to the management of CPRI for kind permission to publish this paper. Sincere thanks are also due to the eminent authors of the publications, indicated in the references, whose works have given valuable inputs for preparation this text.

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