A plastic stress intensity factor approach to turbine disk structural integrity assessment

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ABSTRACT. This study based on a new fracture mechanics parameter is concerned with assessing the integrity of cracked steam turbine disk which operate under startup-shutdown cyclic loading conditions. Damage accumulation and growth in service have occurred on the inner surface of slot fillet of key. In order to determine elastic-plastic fracture mechanics parameters full-size stress-strain state analysis of turbine disk was performed for a quote-elliptical part-through cracks under considering loading conditions. As a result distributions of elastic and plastic stress intensity factors along crack front in slot fillet of key of turbine disk depending on surface crack form are defined. An engineering approach to the prediction of carrying capacity of cracked turbine disk which is sensitive to the loading history at maintenance is proposed. The predictions of the rate of crack growth and residual lifetime of steam turbine disk are compared for elastic and elastic-plastic solutions. It is shown that the previously proposed elastic crack growth models provide overestimate the lifetime with respect to the present one. An advantage to use the plastic stress intensity factor to characterize the fracture resistance as the self-dependent unified parameter for a variety of turbine disk configurations rather than the magnitude of the elastic stress intensity factors alone is discussed.

KEYWORDS. Structural integrity; Turbine disk; Plastic stress intensity factor; Quote-elliptical part-through crack.

INTRODUCTION

In power steam turbine components there is the possible occurrence of undetected defects that can propagate at each startup-shutdown cycle, and sequence, damage accumulation and growth acceptance criteria have to be defined for the turbine critical zones. The successful lifetime prediction for power engineering turbines required application of fracture mechanics methodology with knowledge of loading history at operation, local stress/strain in concentration zones, static and fatigue material properties, the stress intensity factors for the appropriate crack geometry and crack growth rate characterization for the material. Accumulated experience with respect to turbine discs and blades based on the deterministic and probabilistic approaches has shown [1-6] that advance in fracture technology proceeds best through mutual interaction between analysis and experimental observations.

Very few investigations devoted to the nonlinear fracture mechanics analysis exist which refer to structural integrity turbine disc assessment. The typical operation damages in such stress concentration zones are part-through thickness corner cracks. The most approaches to the corner crack growth prediction in the turbine disc under cyclic loading contains simplified models of stress-strain state in the nonlinear region at the crack tip. From this disadvantage is free a nonlinear stress intensity factors introduced by Shlyannikov et al. [7-10] for the conditions of plasticity and creep-fatigue interaction. These studies have focused on the background for the characterization of static and cyclic fracture resistance

materials and structures using one unified parameter in the form of the plastic and creep SIF's, which take into account both in-plane and out-of-plane constraint effects at fracture.

The present work provide an appropriate theoretical and numerical investigations based on the limited experimental data substantially assist fracture mechanics technology in application especially to part-through surface cracks fatigue life predictions for rotating components of power steam turbines. The paper also concentrates on the residual life assessment aspect in greater detail of nonlinear fracture mechanics using power steam turbine disc as a case study.

SUBJECT FOR STUDY AND MATERIAL PROPERTIES

Rotor in power steam turbine experience both cyclic and sustained centrifugal and thermal loads due to the nature of the rotor operating cycles. The methodology describing in the present study is applied to a 100 MW steam turbine rotor shown in Fig.1a. The turbine disc is loaded, in general, by thermal and mechanical stresses because it is operated at c.a. 550ºC and 3000 rpm. Subject for analysis is the disk of 22nd stage turbine rotor with central bore and through-thickness key (Fig.1b). Operation damage in the form of corner crack with length on the free surface a =12 mm and depth along shaft thickness b = 23mm was detected in the slot fillet of key in the disc of 22nd stage (Fig.1c). This stage is operated at about 140°C therefore the influence of temperature is not take into account. For the lifetime calculations, the following operating data were assumed: total operation time is 236607 hours, number of starts is 204. The material of turbine disc is Steel 34XH3MA which main mechanical properties are listed in Tab. 1.
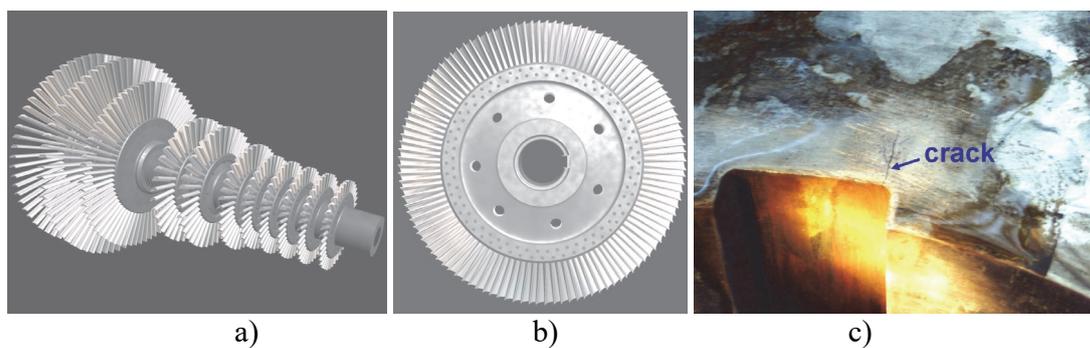

Figure 1: 100 MW steam turbine rotor and disk of 22nd stage with operation damage.

Material	Young modulus E, (MPa)	Poisson's ratio ν	Yield stress σ_0, (MPa)	Ultimate stress σ_f, (MPa)	Strain hardening exponent n	Strain hardening coefficient $\overline{\alpha}$
Steel 34XH3MA	196363	0.3	790	992	7.49	2.39

Table 1: Main mechanical properties.

ELASTIC-PLASTIC STRESS FIELDS IN TURBINE DISK

Prior to lifetime predictions, a 3D FE model of the 22nd stage turbine disc section generated was available and used for the purpose of this study. As shown in Fig.2, the turbine disc and blades, as well as the rivets incorporated in the orignal 3D model. The startup power conditions was chosen in stress analysis as it represents the most severe combination of temperature and rotor speed in the operation profile. Due to the planting disc onto the turbine shaft with a tightness, on the inner surface of the disc bore occur radial stresses with the magnitude of 50MPa, which are also taken into account in the calculations.
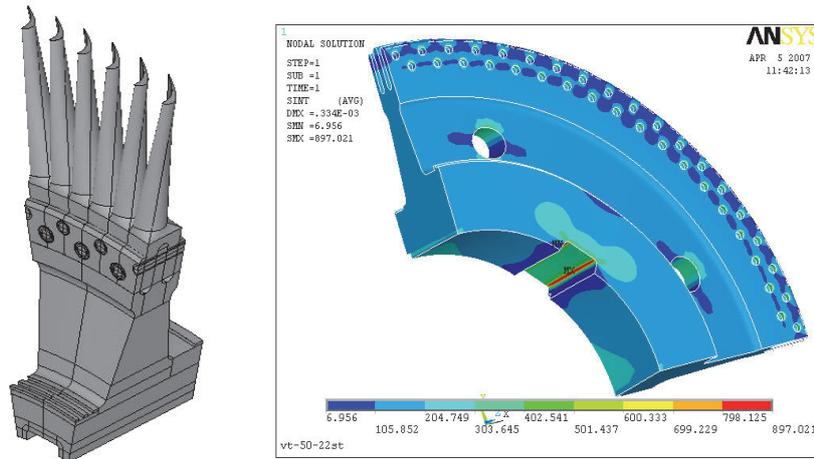
Figure 2: Equivalent stress distribution for turbine disk.
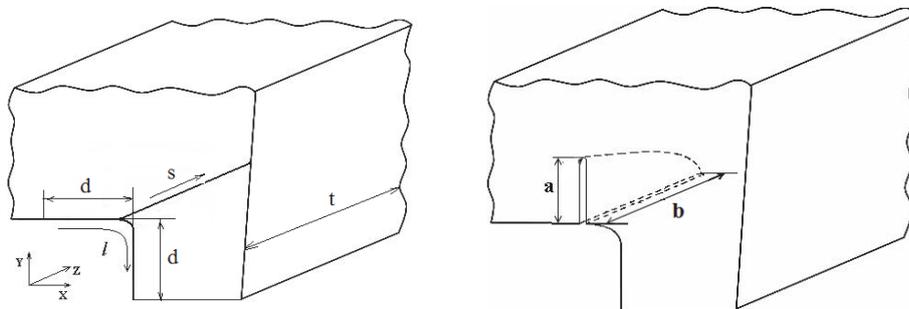

Figure 3: Coordinate systems at slot fillet.

From Fig.4, it was observed that the peak stresses mainly occur on the surface of the slot fillets of key (web and disc bore). In order to compare the parameter distributions along slot fillet on the free surface of the disk as well as along the disc hub in the thickness direction (Fig.4) is convenient to introduce the dimensionless coordinates in the following form: $\bar{l} = l/(2d)$, $\bar{b} = s/t$ where l and s are current coordinates, t is hub thickness equal 180 mm, d is slot depth equal 15 mm. In such representation of numerical results, we will use variables and changing in the range from 0 to 1. It should be noted, as it follows from Fig.4, that the stresses on the free surface and in the slot along hub thickness are higher than the yield stress of Steel 34XH3MA.
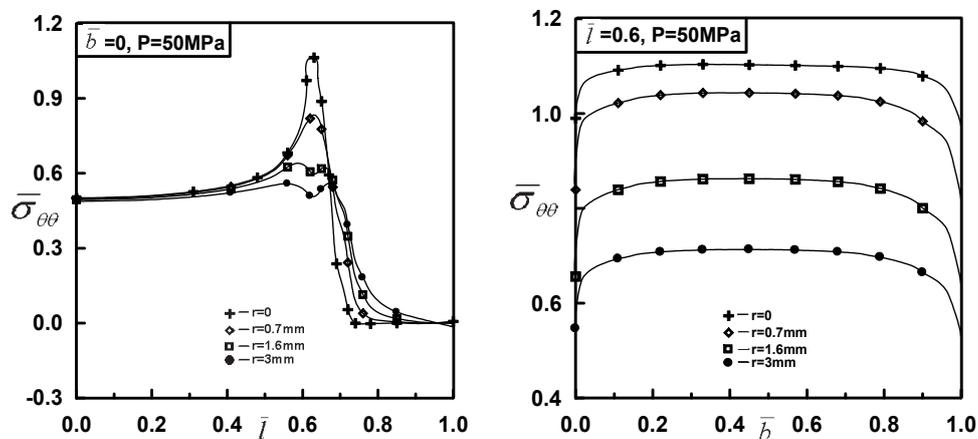

Figure 4: Hoop stress distributions along fillet and hub.

ELASTIC-PLASTIC STRESS INTENSITY FACTORS

Full-field elastic-plastic FEA are performed using ANSYS finite element (FE) code to determine the stress-strain parameter distributions along of the crack-front for turbine disc of considered configuration. The elastic stress intensity factor (SIF) K_1 distribution around the corner crack is calculated for each of front profile and the results superimposed according to the desired hoop stress distribution in the uncracked disc σ_{yn} defined by the polynomial in the following form

$$K_1 = \sigma_{yn}\sqrt{\pi l}\, f_1(\varphi)\, f_2\!\left(\frac{a}{b}\right) f_3\!\left(\frac{a}{w}\right) f_4\!\left(\frac{b}{t}\right) \tag{1}$$

where a is the crack length, b is the crack depth, φ is the elliptical crack angle, w is the hub width. Fig. 5 shows the dependencies of elastic SIF on the crack sizes for turbine disc considered configuration for two main points of the crack front, i.e. the free surface of hub and the slot surface of key.

The special kind of nonlinear calculations accounting for the plastic material properties were performed to determine plastic stress intensity factors $\overline{K}_P$ for the same crack front profiles in turbine disc after corresponding loading history at operation

$$\overline{K}_P = \left[\left(\frac{\sigma_{yn}}{\sigma_0}\right)^2 \frac{\pi\left(\overline{K}_1^2\right)}{\bar{\alpha} I_n}\left(\frac{a}{w}\right)\right]^{1/(n+1)} \tag{2}$$

where I_n is the governing parameter of elastic-plastic stress-strain field at the crack tip. Fig. 6 represents the plastic SIF distributions along the initial and final crack front profiles in the turbine disc. These results of elastic and elastic-plastic numerical solutions for the SIF were employed to residual fatigue life prediction of turbine disc with operation damages.
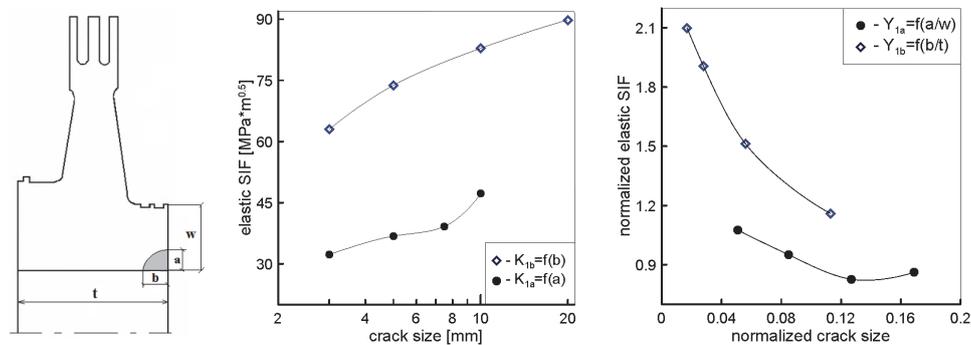

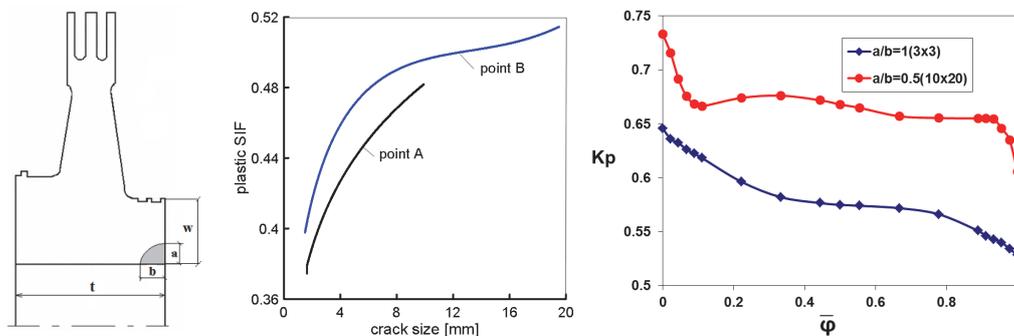Figure 5: Elastic SIF versus crack size in depth and length direction.

Figure 6: Plastic SIF as a function of crack size and front profile.

STRUCTURAL INTEGRITY ASSESSMENT

Application of the strain energy density (SED) function for analyzing fatigue fracture has been made in work [11]. To extend the response to unloading, reloading and cyclic loading, making use of the cyclic stress and strain curves, a critical state of elastic-plastic hysteresis loop can be written in terms of the strain energy density as

$$\left(\frac{dW}{dV}\right)_c^* = 4\sigma_f^* \varepsilon_f^* \left(2N_f\right)^{-m} \tag{3}$$

Substituting into the left part of formula (3) the total SED we have got

$$\left(\frac{\sigma_{yn}^2}{E}\right)\left[\frac{1}{\overline{\delta}}\left(\overline{S}_\Sigma\right)\right] = 4\sigma_f^* \varepsilon_f^* \left(2N_f\right)^{-m} \quad \text{where} \quad \overline{S}_\Sigma = \frac{(1+\nu)}{2}\left[a_{11}\overline{K}_1^2\right] + \frac{n\left(\overline{K}_1^2\right)}{(n+1)}\left(\frac{a}{w}\right)\frac{\pi}{I_n}\tilde{\sigma}_e^{n+1} \tag{4}$$

The crack growth rate per cycle, da/dN, is given by

$$\frac{da}{dN} = 2\overline{\delta}\, a \left(\frac{\sigma_n^2 \overline{S}_\Sigma - \sigma_{th}^2 \Delta\overline{S}_{th}}{4\sigma_f^* \varepsilon_f^* E\overline{\delta}}\right)^{\frac{1}{m}} \tag{5}$$

The above rate of crack propagation law contains the mechanical properties of the material, E, cyclic properties σ^*, ε^*, n', the governing parameters of elastic-plastic stress-strain field In and a length parameter $\overline{\delta}_c$ associated with the fracture process zone size. More details to determine the SED functions $\overline{S}_\Sigma$, $\Delta\overline{S}_{th}$, the In-factor and equivalent stress $\tilde{\sigma}_e$ for cracked body different configurations are given by Refs. [7-11].

We have paid our attention on the combined method including the numerical stress-strain distribution in the parts and components of power steam turbine by using finite element analyses and limited experimental data related to elastic-plastic material properties under uniaxial tension. Within the current investigation a fatigue life estimation approach (Eq.5) based on the FEA results and experimental data is applied to predict residual durability of power steam turbine disk with take into account of operating time.

The fatigue crack growth analysis was performed under harmonic loading using the elastic and elastic-plastic SIF's distributions along different crack front profiles. An initial circumferential edge crack at the highest elastic-plastic stress location was chosen to be 1.6 mm in the depth and length direction, which is much smaller than the observed crack size at operation. It is found that the crack growth in the depth direction is much faster than that in the length direction as it shown in Figs. 7 and 8. Also it should be noticed that the two ends of the crack tend to place in the radial direction and this is believed to be due to the influence of the hoop stress.
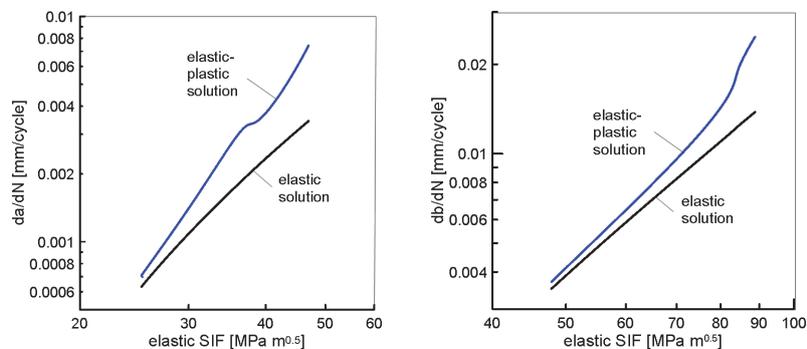

Figure 7: Crack growth rate comparison for elastic and elastic-plastic solutions.
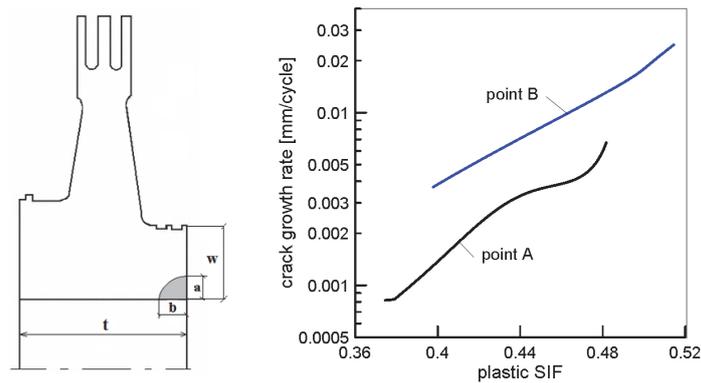
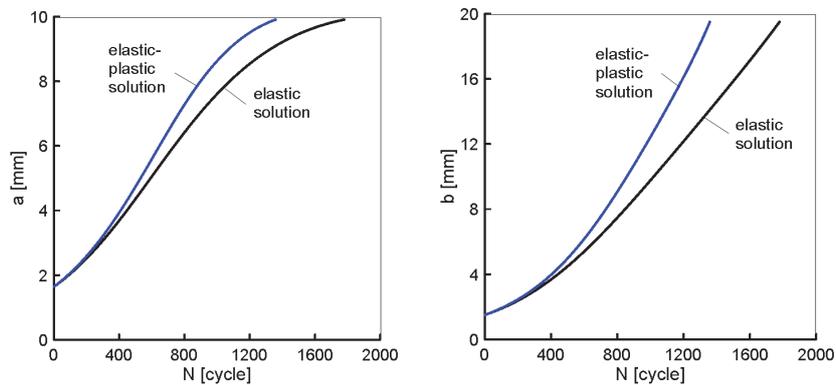Figure 8: Crack growth rate as a function of plastic SIF.

Figure 9: Lifetime prediction based on elastic and elastic-plastic solutions.

Fig. 9 represents the comparison between the predicted change in crack length a on the free surface of disc and the crack depth b along the slot of key as a function of fatigue load cycles for both type of solutions. The elastic-plastic solution on based on the plastic SIF's show that the crack would grow on the free surface from 1.6 mm to 10 mm and in the depth direction from 1.6 mm to 20 mm in about 1,300 cycles. At the same time the elastic solution using the elastic SIF's gives overestimate the lifetime in about 1,700 cycles.

As the predicted crack growth rate according to nonlinear fracture mechanics approach is much faster that elastic modeling, this indicates that the plastic material properties have a significant effect on the damage accumulation and growth in an critical zone of turbine disc. It should be pointed out that the elastic solution is not accounted for the stress-strain state redistributions at the plastic zone close to the crack tip. The implications due to this limitation may give non-conservative predictions of crack growth rate for this case as the actual stress and strain may be higher than predicted by elastic solution. As the purpose for analyzing the edge crack in the turbine disc considered at the operation was to estimate the crack growth rate under extreme situation, the residual fatigue life should be determined based on the elastic-plastic solution.

SUMMARY

A study on residual life assessment of disc with initial flaws in a power plant steam turbine was carried using full-size 3D analyses and fatigue crack growth predictions. The predictions of the rate of crack growth and residual lifetime of steam turbine disk are compared for elastic and elastic-plastic solutions. It is shown that the previously proposed elastic crack growth models provide overestimate the lifetime with respect to the present one. An advantage to use the plastic stress intensity factor to characterize the fracture resistance as the self-dependent unified parameter for a variety of turbine disk configurations rather than the magnitude of the elastic stress intensity factors alone is shown.

The methodology of the lifetime assessment of steam turbine components presented in this study has considerable practical importance. The approach described in the present work is implemented in practical engineering tools, and its usefulness was illustrated with an example of its practical application to a steam turbine rotor.

ACKNOWLEDGMENT

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