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Structural integrity assessment of turbine disk on a plastic stress intensity factor basis

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ABSTRACT

Based on a new fracture mechanics parameter, this study is concerned with assessing the integrity of a cracked steam turbine disk operating under startup-shutdown cyclic loading conditions. Damage accumulation and growth in service occurred on the inner surface of the key slot. To determine the elastic-plastic fracture mechanics parameters, full-size stress-strain state analysis of the turbine disk was performed for semi-elliptical cracks under startup loading conditions. As a result, the distributions of the elastic and plastic stress intensity factors along the crack front in the key slot of the turbine disk were defined according to the surface crack form. An engineering approach for predicting the lifetime of cracked turbine disks is proposed. The predictions of the crack growth rate and residual lifetime of the steam turbine disk are compared for elastic and elastic-plastic solutions. It is shown that the previously proposed elastic crack growth models overestimate the lifetime with respect to the model presented in this research. The expediency of using 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 also discussed.

1. Introduction

Fatigue life prediction for steam turbine rotors has traditionally involved two interconnected structural integrity problems: probabilistic analysis of real structures to assess LCF/HCF and crack growth modeling to determine the residual lifetime based on the theoretical relationship and experimental data. There are a number of investigations devoted to both life assessment and failure analyses of turbine discs in the literature. Most are based on probabilistic concepts for material properties and variable loading conditions that provide specified failure probabilities [1–6]. In service, aging turbine components are often re-analyzed using the safe-life method of Corran and Williams [7] according to the damage tolerance and given reliability. Shlyannikov et al. [8] developed a deterministic approach for predicting the residual lifetime of turbine disks on the basis of the critical zone concept, which is sensitive to both the degradation of the main mechanical properties and the loading history at maintenance. Recently, Banaszkiewicz [9] proposed a generalization of this methodology for a steam turbine lifetime assessment, which included a deterministic damage calculation, probabilistic simulation and consideration of the fracture mechanics.

In the power steam turbine components, there is the possible occurrence of undetected defects that can propagate during each startup-shutdown cycle, and as a result, damage accumulation and growth acceptance criteria should be defined for the turbine critical zones. Bell et al. [10] support the notion that the possibility of safely using the remaining 99.9% of the lifetime of turbine discs has led to the consideration of special procedures when steam turbine components are inspected and returned to operation if defect free. A successful lifetime prediction for power engineering turbines requires the application of fracture mechanics methodology with knowledge of the loading history at operation, local stress/strain in concentration zones, static and fatigue material properties, 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 deterministic and probabilistic approaches has shown [11–16] that advances in fracture technology proceed best through the mutual interaction between analysis and experimental observations.

Very few investigations have been devoted to nonlinear fracture mechanics despite their importance in structural integrity turbine disc assessment. In general, the common failure locations for turbine discs under operation conditions are often at the critical zones, such as the central and bolt holes, disc/blade attachment area, and key slots [8,11]. The typical operation damage in such

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Nomenclature

a	crack length
b	crack depth
c	distance from the inner surface of the key slot in the depth direction
d	slot depth
E	Young's modulus
I_n	governing parameter of the crack-tip stress-strain field
K_1	elastic stress intensity factor of a mode-I crack
K_p	plastic stress intensity factor
n'	cyclic strain hardening exponent
N	number of cycles
r	crack tip distance
R_0, R_1	inner and outer disk radius
r_c	fracture process zone size
s_{ij}	deviatoric stresses
$\bar{S}_1$	elastic strain energy density factor
$\bar{S}_P$	plastic strain energy density factor
$\Delta\bar{S}_{th}$	threshold strain energy density factor
t	hub thickness
w	hub width
ΔW	strain energy density range
$\tilde{\alpha}, n$	the Ramberg-Osgood elastic-plastic constant and exponent
n'	cyclic strain hardening exponent
$\tilde{\sigma}_e$	the Mises equivalent normalized stress
$\tilde{\sigma}_{ij}, \tilde{u}_i$	normalized stress and displacement
$\tilde{\sigma}_{ij}^{FEM}$	dimensionless angular stress functions directly determined from the FEA distributions
σ_b	nominal ultimate tensile strength
σ_{yn}	nominal stress
σ_0	monotonic tensile yield strength
σ_u	true ultimate tensile strength
σ'_f	fatigue strength coefficient
$\sigma_{\theta\theta}$	hoop stress
ε'_f	fatigue ductility coefficient
ψ	reduction of area
θ	polar angle
ϕ	elliptical crack angle
ρ	blunted crack tip radius
η	nominal stress biaxiality ratio
SIF	stress intensity factor
SED	strain energy density
LCF	low-cycle fatigue
HCF	high-cycle fatigue

stress concentration zones is in the form of corner cracks. The most complete evaluation of elastic stress intensity factors for corner-cracked turbine discs is given by Bell et al. in a parametrical 3D FE study [10]. However, more frequently, surface defects grow in turbine discs that are subjected to cyclic loading in a low cycle fatigue regime in critical zones where high plastic strain is present. Under these conditions, a key component of the steam turbine component life analysis is knowledge of the nonlinear fracture mechanics parameters for corner cracks with regard to the three-dimensional geometry under complex stress loadings. In his early work, Dowling [17] modified Rice's J-integral to the cyclic nonlinear deformation by replacing the elastic stress intensity factor range ΔK with ΔJ. Following up his work, several approaches [18–21] were elaborated for describing crack growth rates under LCF conditions. To predict corner crack growth from bolt holes in a gas turbine compressor disc, Zhuang [22] developed a numerical method to account for both the plastic zone and loading biaxiality effects. The special case of fatigue surface flaw lifetime prediction in turbine discs with forging-induced initial cracks was investigated by Hou et al. [23].

The aforementioned approaches to corner crack growth prediction in a turbine disc under cyclic loading include simplified models of the stress-strain state in the nonlinear region at the crack tip. A disadvantage is the nonlinear stress intensity factors, introduced by Shlyannikov et al. [24–27], for the conditions of plasticity and creep-fatigue interaction. In [24], a plastic stress intensity factor was introduced as a material fracture resistance characterization parameter based on the analytical form of the elastic-plastic stress and strain fields in the vicinity of the crack tip. The authors [25] extended the concept of the plastic SIF to the mixed mode crack growth rate under biaxial cyclic loading. It should be noted that during power steam turbine operation, rotating discs are frequently subjected to biaxial or multiaxial loading conditions in the presence of plastic strain in the critical zones. With recent advances in 3D-full field finite element methods [25,26], the plastic SIF has provided more accurate fracture toughness and crack growth rate predictions than the relatively new two-parametrical theories and criteria. In general, studies [24–27] have focused on the background for characterizing static and cyclic fracture resistance materials and structures using one unified parameter in the form of plastic and creep SIFs, which take into account both in-plane and out-of-plane constraint effects at fracture.

This paper provides an appropriate theoretical and numerical investigation to substantially assist fracture mechanics technology in application to partial surface cracks and fatigue life predictions for rotating components of power steam turbines. This paper also investigates the residual life assessment of nonlinear fracture mechanics using a power steam turbine disc as a case study. The present work, in a theoretical sense, follows the approach found in [24,25], which allow a more general plastic SIF expression to be obtained for a corner-cracked turbine disc in the presence of plastic strain in critical regions. Based on the numerical results of the governing parameter of the elastic-plastic stress field in the form of the I_n-integral and dimensionless equivalent stress $\tilde{\sigma}_e$ distributions along the corner crack front, a new formulation for the plastic stress intensity factor is given for the considered cracked turbine disc configuration and operation loading conditions. The crack growth rate and remaining lifetime predictions of the steam turbine disc are evaluated and compared using elastic and elastic-plastic solutions. It is found that the situation is oversimplified under LEFM, as the assessment is based only on the elastic SIF corresponding to the standard elastic material properties. Finally, the application of the new plastic fracture resistance parameter for the power engineering turbine component structural integrity assessment is discussed.

2. Subject for study and material properties

The rotor in the power steam turbine experienced both cyclic and sustained centrifugal and thermal loads due to the nature of the rotor operating cycles. The turbine rotor is loaded, in general, by thermal and mechanical stresses because it is operated at 550 °C and 3000 rpm. The methodology described in the present study is applied to a 100 MW steam turbine rotor, as shown in Fig. 1a. Power steam turbine T-100-130 is a single-shaft three-cylinder unit, which has 27 stages and consists of cylinders of high,