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Multilevel approach to lifetime assessment of steam turbines

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ABSTRACT

This paper presents a multilevel methodology for a steam turbine lifetime assessment based on the damage calculation, probabilistic analysis and fracture mechanics considerations. Creep-fatigue damage calculations serve as a basis for evaluating the current lifetime expenditure and for defining additional steps of analysis. The need for the use of probabilistic analysis results from the inherent uncertainty in estimating the lifetime expenditure primarily caused by scatter in material properties. Fracture mechanics considerations are helpful in determining additional safety margins for components containing cracks. This methodology has been illustrated using an example of the lifetime calculations of a high-temperature steam turbine rotor. The calculations were based on the results of 2D numerical simulations performed for steady state and transient operating conditions.

1. Introduction

Steam turbine components operating at high and highly variable temperatures are exposed to degradation because of creep and thermo-mechanical fatigue processes [1]. These components' lifetime is already limited at the design stage and results from the creep and fatigue characteristics of the material used. The operational wear of these steam turbine components causes the loss of lifetime and decreases the reliability of turbine components, which manifests itself by their increased failure frequency and lower availability.

The problems of lifetime and reliability are essential from the viewpoint of not only avoiding the premature failure of a component before its design life has expired but also extending the service life of power plant equipment beyond its design life [2]. The lifetime extension is driven by economics; nevertheless, it must always be technically sound to ensure the safe operation of turbo-sets.

The basis for any efforts aimed at extending the service life of power turbo-sets is the assessment of the current degree of damage of their components, including the main components of steam turbines. These assessments are performed with the use of metallographic tests and theoretical analyses, which are the necessary elements of a comprehensive assessment of the material state [3]. Theoretical analyses resolve themselves by determining the so-called lifetime fractions and are based on deterministic models in spite of the large scatter and uncertainty of operation and the material data used for the calculations. This means that the lifetime assessment performed with this method is not definitive and, therefore, requires complementing by using additional analyses such as probabilistic simulations or fracture mechanics calculations.

A lifetime assessment of power plant components operating at creep-fatigue conditions is usually performed using the life fraction rule introduced by Robinson [4] and Taira [5] and recommended by industrial standards, *e.g.* ASME Code [6] or TRD 508 [7]. In this method, fatigue damage is determined by a cyclic fraction and creep damage is determined by a time fraction, which after summation result in total creep-fatigue damage. Instead of a time fraction, a ductility exhaustion rule is also used for the creep damage calculation [8]. An extensive investigation of both rules was conducted by Colombo [9], who performed thermo-mechanical fatigue experiments on plane, notched and component feature specimens and compared damage results with the predictions of the time fraction and ductility exhaustion rule. The outcome was that both methods resulted in safe predictions for all thermal fatigue tests. Recently, Cui and Wang [10] introduced two lifetime estimation models for steam turbine components under thermo-mechanical creep-fatigue loading. The first model is a phenomenological model developed as an extension of the generalized damage accumulation rule, while the second model is derived from a unified visco-plastic model with incorporated isotropic damage. Both models predicted the creep-fatigue lives within a scatter band of factor two, but the first model resulted in significantly better predictions, resting on the conservative side. Carragher *et al.* [11] presented a lifetime assessment methodology for power plant headers consisting of a

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cyclic visco-plasticity material model and a multi-axial critical-plane implementation of the Ostergren fatigue indicator parameter. Cracking directions predicted by this model are consistent with reported in-service cracking.

The purpose of this paper is to present a methodology for a steam turbine lifetime assessment based on the deterministic damage calculation, probabilistic simulations and fracture mechanics considerations. The advantage of this method is its ability to estimate the probability of creep-fatigue crack initiation when lifetime predictions are based on minimum material property data. This approach is commonly used in engineering practice and is characterized by a high level of conservatism. Moreover, the method enables damage assessment and residual life prediction to be performed based on not only creep-fatigue calculations but also two additional factors: the probability of crack initiation and microstructural damage. As an illustration, lifetime calculations for a high-temperature steam turbine rotor performed with both deterministic and probabilistic methods are presented.

2. Lifetime assessment methodology

The general chart of the lifetime assessment process used in practice is shown in Fig. 1. The process starts with two nearly independent routes: theoretical calculations and material testing [12]. Theoretical calculations aim at evaluating creep-fatigue damage, assuming minimum material properties and calculating failure probability based on the damage computed with the deterministic model and material property data scatter. Material testing aims at revealing surface and volumetric cracks and at determining microstructure damage by using replica or microscopic tests. While crack existence testing on the component surface is performed on all accessible surfaces, the microstructure damage and volumetric crack tests are performed at most critical locations known from theoretical calculations. Damage calculations are used not only to determine critical areas for testing but also to provide very important information on:

- damage mechanism domination at a given location,
- current damage for the worst material properties, and
- the rate of damage accumulation.

This information is useful when defining recommendations regarding the component repair, inspection intervals or modification of operating conditions. The contribution of creep and fatigue damage in total damage is also important from the point of view of failure probability. For a given total damage, the contribution of creep and fatigue damage influences failure probability.

When cracks are not found, a component assessment is performed on the basis of the damage calculation, failure probability and microstructure damage, and the residual lifetime is determined. In case cracks are found in the component, fracture mechanics assessment can be performed to determine safe operation time with propagating crack. Such assessment is not always possible and depends on the damage mechanism and component type. Fracture mechanics calculations are only useful when failure is crack propagation-controlled [13].

For initiation-controlled failures, when the time to crack initiation is considerably longer than the time required for the crack to grow to a critical size or a critical crack size is below the limit of detection, fracture mechanics analyses and conventional non-destructive examination techniques serve no useful purpose. In these circumstances, the existence of a macroscopic crack is, in most cases, a sign of useful life exhaustion, and the crack has to be removed or the component retired.

Failure is initiation controlled when the material is very brittle and when the critical crack size so small, it is below the limit of detection for conventional non-destructive examination techniques. Additionally, high stresses may reduce the critical crack size below the level of detection. If a component has a thin cross section, the remaining ligament can be so small that the crack propagation is of no importance. Moreover, the crack propagation rate can be so high that even with a large critical crack size, once the cracks initiates, it reaches the critical size rapidly. Thus, it is very important to perform an investigation by calculation and material analysis whether the failure is initiation or propagation controlled and to evaluate properly the critical crack size.

The existence of cracks is not always considered as a sort of damage that is dangerous for component safety because the crack growth rate may decrease with an increase in crack size, and crack propagation may stop. This phenomenon is known as crack arrest and can occur, for example, in turbine casings where thermal

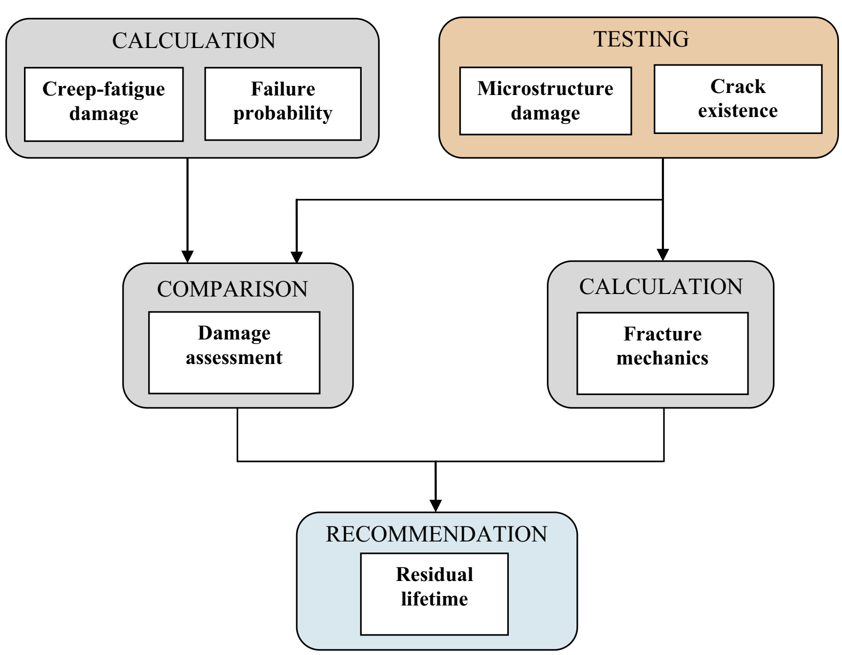

Fig. 1. General chart of lifetime assessment process.