NUMERICAL MODELLING OF CREEP-FATIGUE DAMAGE DEVELOPMENT IN STEAM TURBINE ROTORS USING INELASTIC MATERIAL MODELS

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1. Introduction

The increasing steam parameters and requirements for high operational flexibility of power plants are a reason of intensive creep-fatigue damage of steam turbine components operating at elevated temperatures. Typical operation cycle consists of a start-up, steady state, load change, shutdown and natural cooling [1]. During transient phases, the low-cycle fatigue damage is generated, while steady-state operation brings about the creep wear. In order to accurately evaluate the creep-fatigue life exhaustion, inelastic material models and proper approach to multiple cycles consideration have to be applied.

The paper presents the results of investigations performed for a steam turbine rotor showing significant differences in predicted strain accumulation and damage depending on the material model and cycles analysis method used.

2. Constitutive equations

The physics of creep-fatigue interaction involves two types of strain accumulation, namely the time-dependent inelastic strain due to creep and time-independent plastic strain due to fatigue. The characteristic strain model is adopted for describing the accumulation of creep strain ε_{cr} expressed as [2]:

$$\varepsilon_{cr} = \frac{\varepsilon_{\chi}}{(\sigma_R/\sigma - 1)} \quad (1)$$

where ε_{χ} is the characteristic strain, σ_R is the creep rupture strength and σ is the current stress.

Time-independent plasticity is modelled using the Huber-Mises-Hencky yield criterion, a linear kinematic hardening model and the associated plastic flow rule [3]

$$\dot{\varepsilon}_{ij}^{pl} = \dot{\lambda}\left(s_{ij} - \alpha_{ij}^{d}\right) \quad (2)$$

where $\dot{\varepsilon}_{ij}^{pl}$ is the plastic flow rate, $\dot{\lambda}$ is the plastic work, s_{ij} is the deviatoric part of the stress tensor and α_{ij}^{d} the deviatoric part of the backstress tensor whose evolution in time is described by Ziegler's linear hardening law.

3. Results and discussion

Numerical calculations of stress/strain field development in a steam turbine rotor during cyclic operation were performed using the finite element method. As an example, three operation cycles were analyzed each consisting of the same start-up, steady state, shutdown and natural cooling. Creep was considered in steady-state phase, while plastic strain accumulation was enabled at all phases of the cycle. For comparison purposes, also visco-elastic material behavior was considered in the analyses.

Figure 1 presents the equivalent plastic strain distribution in the rotor together with the development of the plastic strain zone in the area of highest strain (heat groove) for subsequent cycles. As it is seen, the size and magnitude of the plastic strain zone increases during cycling and the fatigue damage development advances. However, the plasticity zone is highly localized.

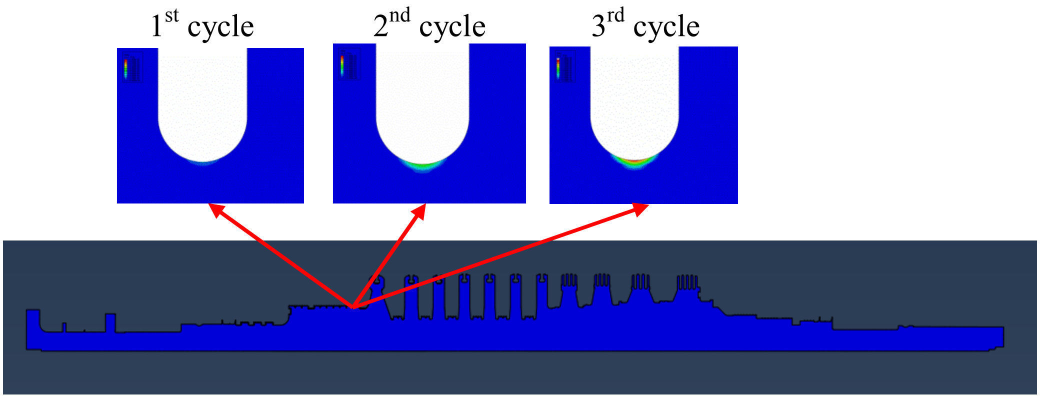

Figure 1. Plastic strain accumulation in the rotor heat groove during cyclic operation.

The evolution of creep strains in this area during cycling calculated using different methods is shown in Figure 2. The time of creep strain accumulation in each cycle is equal to 100 hours (steady-state phase). It is seen that three quantitatively different creep strain curves are predicted using various models. The full visco-elasto-plastic material model predicts the largest creep strains (red line) with strain rates decreasing within each cycle and increasing between subsequent cycles. When only one cycle is computed (purple line) using the visco-elasto-plastic model with steady-state creep phase extended to 300 hours, the creep strain curves diverge after the first cycle and the model significantly underestimates the creep damage (creep strain c.a. 60% lower after 300 hours). When plastic behavior is neglected and only visco-elastic material model applied, creep strain accumulation (blue line) and creep damage are from the beginning even more underestimated comparing with the full visco-elasto-plastic model predictions. The differences can be attributed to compressive plasticity reversed by tensile creep which occur in the real operation cycles. The visco-elasto-plastic model is thus best suited for creep-fatigue damage evaluation in steam turbine rotors.

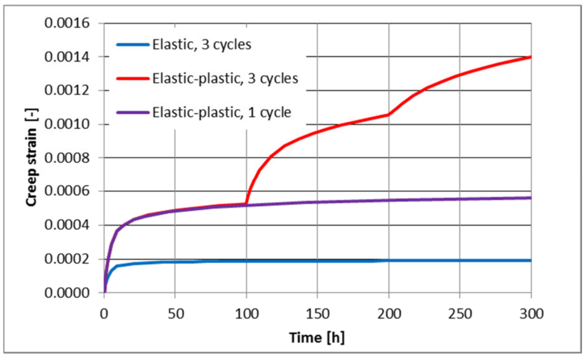

Figure 2. Creep strain accumulation in the rotor heat groove during cyclic operation.

6. References

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