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Thermo-Mechanical Analysis of a Steam Turbine rotor

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In power plants, high temperatures prevail during long holding times. Furthermore, power plants are often started and shutdown in order to account for gaps or oversupplies in energy production. These loading conditions induce both creep and fatigue loads. Due to their excellent thermo-mechanical properties, such as high tensile strength and elevated corrosion resistance, heat-resistant steels are established materials for power plant components. Nevertheless, these steels tend to soften under deformation, which should be accounted for by a constitutive model.

The contribution at hand analyses the thermo-mechanical behavior of a steam turbine rotor. For this purpose, a unified phase mixture model is introduced. This constitutive model accounts for rate-dependent inelasticity, hardening, as well as softening by employing an iso-strain approach with a soft and a hard constituent. While the soft constituent represents areas with a low dislocation density, such as the interior of subgrains, the hard constituent refers to regions with a high dislocation density, i.e. the subgrain boundaries. Furthermore, two internal variables are introduced: a backstress tensor of Armstrong-Frederick type and a scalar softening variable. The model results in a coupled system of three evolution equations with respect to the inelastic strain, the backstress, and the softening variable.

To allow for the analysis of real power plant components, the model is implemented into the finite element method such that the evolution equations are integrated based on the backward EULER method. The applicability of the model is demonstrated by conducting a thermo-mechanical analysis of a steam turbine rotor with complex geometry under realistic boundary conditions. In a first step, the instationary temperature field in the rotor is computed in a heat transfer analysis. Thereby, typical steam temperatures in power plants and the corresponding heat transfer coefficients are prescribed. As a next step, the structural analysis is conducted based on the phase mixture model and the obtained temperature field as input. In addition, the time-dependent rotational frequency and steam pressure are taken into account. Note that the influence of different start-up procedures such as a cold or a hot start is examined in detail. As a result, the structural analysis provides the stress-strain hystereses, which constitute the basis for further fatigue and damage assessment.

1 Mixture Model

The current contribution briefly presents selected results of a thermo-mechanical analysis of a steam turbine rotor. Due to the prevailing high temperatures ($\approx 873\,\mathrm{K}$) in power plants, the components are subjected to creep deformation [1]. In addition, power plants are often started and shutdown to account for the intermittent energy demand such that cyclic loads act on the components as well. Heat-resistant martensitic steels are commonly used for power plant components since they offer elevated mechanical and chemical properties. Nevertheless, microstructural processes such as the coarsening of subgrains induce softening under creep-fatigue loads [1, 2]. In order to account for the complex material behavior of these alloys, the contribution at hand makes use of a mixture model [1]. By deploying the iso-strain concept for a mixture of two constituents, this approach describes rate-dependent inelasticity, hardening, and softening as well. Note that this model is able to describe the mechanical behavior of heat-resistant steels with respect to wide ranges of stresses and temperatures, although only a moderate number of material parameters is involved, cf. [3, 4].

In the following, we will briefly introduce the principal equations of the constitutive model. Note that further details on the derivation can be found in [3–5]. The strains are splitted additively into the elastic and inelastic parts, whereas HOOKE's law for linear isotropic elasticity is applied to describe the identical elastic behavior of both phases. Furthermore, a backstress tensor $\boldsymbol{\beta}$ of ARMSTRONG-FREDERICK type and a dimensionless scalar softening variable $\mathit{\Gamma}$ are introduced,which results in the following three evolution equations with respect to the stress tensor $\boldsymbol{\sigma}$, the backstress, and the softening variable:

$$\dot{\boldsymbol{\sigma}} = K(T)\,\mathrm{tr}(\dot{\boldsymbol{\varepsilon}})\,\boldsymbol{I} + 2G(T)\left(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{\mathrm{in}}\right) + \left(\frac{\mathrm{d}K(T)}{\mathrm{d}T} + \frac{2}{3}\frac{\mathrm{d}G(T)}{\mathrm{d}T}\right)\dot{T}\,\frac{\mathrm{tr}(\boldsymbol{\sigma})}{3K(T)}\boldsymbol{I} + \frac{1}{G(T)}\frac{\mathrm{d}G(T)}{\mathrm{d}T}\dot{T}\boldsymbol{\sigma}', \tag{1}$$

$$\dot{\boldsymbol{\beta}} = \frac{1}{G(T)}\frac{\mathrm{d}G(T)}{\mathrm{d}T}\dot{T}\boldsymbol{\beta} + 2G(T)\,\frac{\eta_{\mathrm{h}_0}}{1-\eta_{\mathrm{h}_0}}\left[\dot{\boldsymbol{\varepsilon}}^{\mathrm{in}} - \frac{3}{2}\frac{\dot{\varepsilon}^{\mathrm{in}}_{\mathrm{vM}}}{\beta_{\mathrm{vM}_\star}(\sigma_{\mathrm{vM}})}\boldsymbol{\beta}\right], \tag{2}$$

$$\dot{\mathit{\Gamma}} = C_{\mathit{\Gamma}}\left[\mathit{\Gamma}_\star(\sigma_{\mathrm{vM}}) - \mathit{\Gamma}\right]\dot{\varepsilon}^{\mathrm{in}}_{\mathrm{vM}} \tag{3}$$

with the bulk and shear moduli K and G, the temperature T, the material parameter η_{h_0}, the VON MISES variables with index $\square_{\mathrm{vM}}$, the parameter $C_{\mathit{\Gamma}}$, the saturation softening variable $\mathit{\Gamma}_\star$, and the inelastic strain rate of the mixture $\dot{\boldsymbol{\varepsilon}}^{\mathrm{in}}$. Details on the

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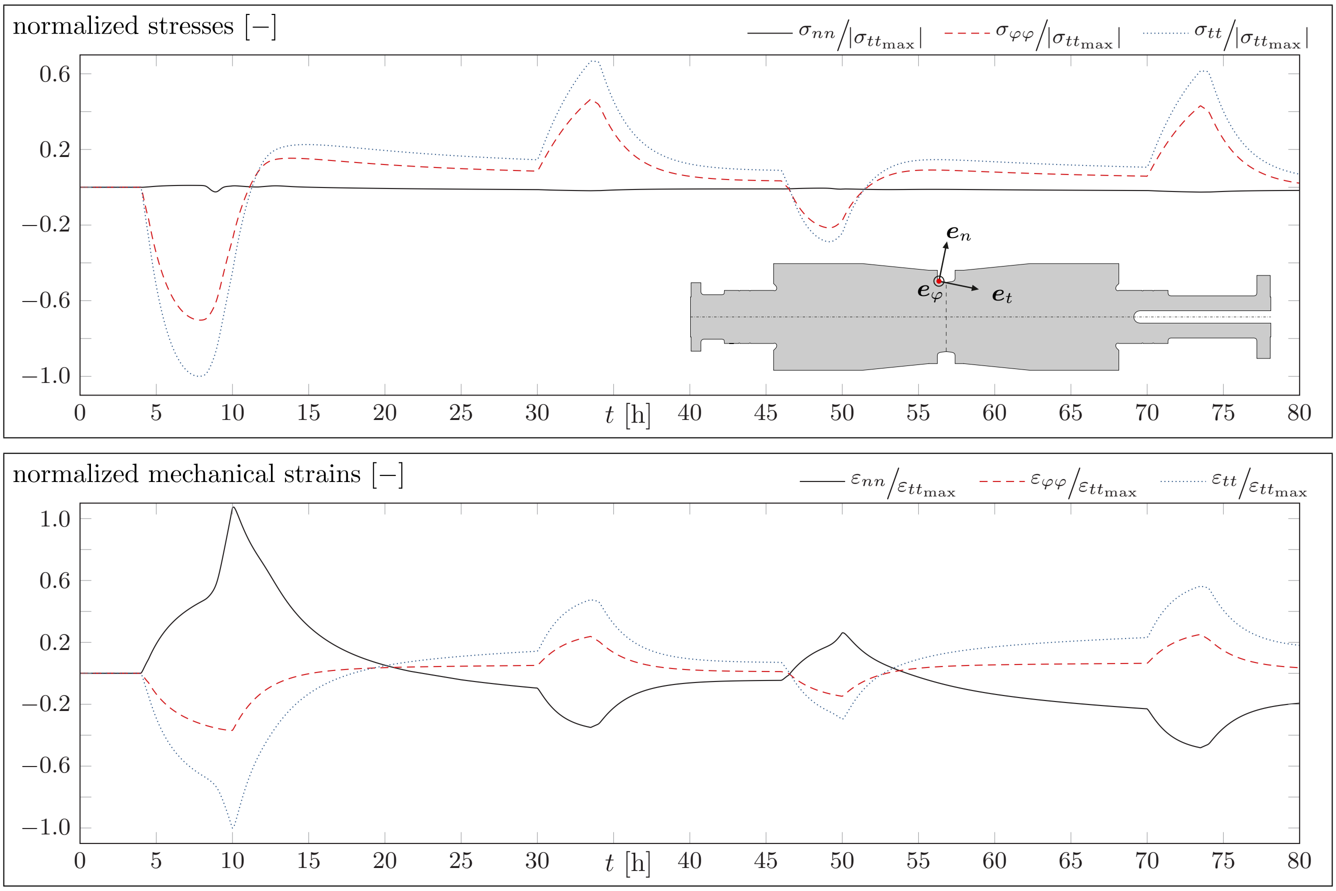

Fig. 1: Normalized stresses and strains at the notch of the rotor over time (2 cycles: cold start and warm start).

calibration of the model and the implementation into the finite element method based on the backward EULER method can be found in [4, 5].

2 Thermo-Mechanical Analysis of a Steam Turbine Rotor

In order to demonstrate the applicability of the model, we conduct a thermo-mechanical analysis of a steam turbine rotor. Note that the complex geometry as well as realistic boundary conditions are taken into account. Within the first part of the analysis, the instationary temperature field in the rotor is computed by solving the heat transfer problem. Here, typical steam temperatures in power plants and corresponding heat transfer coefficients are used as input. The resulting temperature field provides the input for the subsequent structural analysis with the mixture model. To simulate various start-up and shutdown procedures, time-dependent rotational frequencies and steam pressures are included in the numerical model.

Figure 1 depicts normalized stresses and strains over time with respect to a point at the notch root of the rotor, as indicated in the sketch in the figure. Two cycles, i.e. a cold and a hot start, are examined, while each cycle comprises a start-up, a holding stage, and a shutdown. The highest stresses and strains occur during the heating-up in the cold start ($t \approx 10\,\mathrm{h}$). Furthermore, a continuous decrease in stress, i.e. relaxation, as well as increasing strains (creep) can be observed during the holding stages ($t \approx 15 \ldots 30\,\mathrm{h}$, for example). These exemplary results represent the foundations for a subsequent damage analysis and improved prediction of the lifetime of power plant components. Note that more details on the numerical model, the analysis steps as well as further results can be found in [6].

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