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The effect of in-service steam temperature transients on the damage behavior of a steam turbine rotor

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ABSTRACT

This study was aimed at identifying the influence of the temperature transient on the creep–fatigue behavior of a steam turbine rotor. Especially, the steam temperature fluctuations during the steady state operation phase could lead the stress to the oscillation, which also contributes to the fatigue damage. Toward this end, in-service operating data during startup, shutdown and steady state operation phases was chosen to investigate the creep–fatigue damage of a 1000 MW steam turbine rotor. A viscoplastic constitutive model with damage was presented to describe creep–fatigue deformation behavior. A significant growth in creep damage was found under the influence of the temperature fluctuation compared to the creep damage under the stable temperature condition. In addition, steam temperature fluctuation induced the larger thermal gradient and temperature difference at the location where is closer to the rotor surface. The correlation of the stress range due to these temperature fluctuations has been established by carrying out the transient thermo-mechanical FE analysis. Frequent thermal fluctuations during the steady state operation phase were identified as one of the most influential factors for the creep–fatigue damage of the steam turbine rotor.

1. Introduction

Steam turbine rotor is one of the most critical components in the power units, and the structural strength of the rotor is usually influenced by variable loading conditions. Temperature transients during the startup and shutdown phases, and constant speed of turbine rotors during the steady state operation, etc., produce a large variety of combined static and variable loading conditions. As a consequence, creep–fatigue interaction is considered to be the critical loading conditions for the investigations of the high-temperature rotor behavior. In the design procedure, most of the rotors were designed in the steady state operation to be continuously operated without considering cyclic effects due to the temperature fluctuation. However, power plants have been forced to operate their units in a more cyclic manner than originally intended. Furthermore, it is also difficult to operate the plants as the absolute steady state of the steam temperature. Cyclic stress and strain due to the temperature fluctuation in the steady state operation cause the additional fatigue damage. Thus, the temperature transient induced creep–fatigue damage during the startup, the steady state operation and shutdown phases can significantly lead to premature failure in terms of operating hours.

Thermo-mechanical fatigue (TMF) behavior caused by transient temperature during the startup and shutdown phases of a rotor has increasingly become an area of great interest, and numerous experimental and numerical studies on the TMF behavior have been carried out. Reigl and Dave [1] assessed the an-isothermal creep–fatigue of steam turbine rotor steels. Holdsworth et al. [2] performed detailed service-cycle TMF tests to characterize the associated thermal fatigue damage mechanisms and further developed the thermal fatigue damage model in 1CrMoV rotor steel. Fournier et al. [3] applied the previous physically based model [4] to three other 9–12%Cr martensitic steels for the lifetime prediction of steels subjected to creep–fatigue at high temperatures. Recently, Cui et al. [5] carried out TMF experiments based on the analysis of load conditions at a turbine rotor and found a significant lifetime reduction compared to isothermal conditions. In addition, a phenomenological and constitutive crack initiation lifetime estimation model for steam turbine components under TMF loading was introduced [6–8]. Recently, Wang et al. [9]

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numerically studied the creep–fatigue behavior in steam turbine rotors using an elasto–viscoplastic constitutive model with damage. Although the structural analysis of steam turbine rotors have been carried out and the loading conditions due to the temperature transient under startup and shutdown phases were fully considered in the analysis, few consideration of the temperature fluctuation during the steady state operation has been taken into the study of the creep–fatigue behavior in steam turbine rotors. Actually, Kennedy [10] mentioned that fluctuating temperature and stress during thermal cyclic produced primary creep contributions prior to the onset of secondary creep. Creep deformation is accompanied by elastic and rate-independent plastic strain as temperature fluctuates during a thermal cycle. Thus, numerous investigations of the temperature transient on the creep–fatigue of the high-temperature components were performed.

Lejeail and Kasahara [11] experimentally validated CEA (Atomic Energy Commission) and JNC (Japan Nuclear Cycle Development Institute) organizations proposed evaluation procedures for thermal fatigue of cylinders and plates of a nuclear reactor due to fluid temperature fluctuations. Kwon et al. [12] carried out the analysis on the superheater header and found that stress changes due to the steam temperature fluctuations during the steady state operation significantly contributed to crack growth. Numerical study on the lifetime due to the temperature fluctuations at steady state operation also revealed that frequent thermal fluctuations was the most influential factor for the remnant life of the header. Subsequently, on-line life assessment of critical plant components was developed by Samal et al. [13], and this system processed plant transients in real time to evaluate the stress, temperature and damage distribution in the components. Recently, Farragher et al. [14] presented a finite element methodology for TMF analysis of a header under realistic loading conditions. The influence of temperature fluctuations on stress–strain response was taken into consideration; however, the damage contributions from small cycles associated with temperature fluctuations were neglected in TMF fatigue life prediction. In addition, Kamaya [15,16] numerically studied the fluctuating thermal stress of the elbow pipe under local fluid temperature fluctuation, and assessed the crack growth due to thermal fatigue caused by the local temperature fluctuation. As stated, the main concern of previous study was the influence of temperature fluctuation on the thick-wall component, e.g., pipes, header and superheater header, and thermal stress due to the thermal gradient is one of the root causes of the damage in the wall thickness. Few studies on the influence of temperature transient on the steam turbine rotor, especially at the steady state operation, were carried out. Accordingly, numerical investigations of the influence of the temperature transient on the creep–fatigue damage of the steam turbine rotor would be of great value for the design and operation of the rotors.

In the present study, the main objective is to numerically investigate the influence of temperature transient on a steam turbine rotor under an in-service loading condition. The rotor of a 1000-MW supercritical steam turbine was selected for study. In-service loading condition from the power plant DCS (Distributed Control System) system database was adopted, shown in Fig. 1. The elasto–viscoplastic material model of the Chaboche–Nouailhas–Ohno–Wang (CNOW model) [17] was implemented in ABAQUS software using a subroutine to describe the time-independent plastic deformation and the time-dependent viscous material behavior. The model was specifically validated by authors [9] through experimental measurements of creep, cyclic hysteresis loop, cyclic softening stress, multiaxial stresses, and damage. In the present paper, the effect of temperature transient on the creep–fatigue behavior was numerically investigated in terms of temperature fluctuation, stress fluctuation, accumulated plastic strain evolution, and creep–fatigue damage evolution.

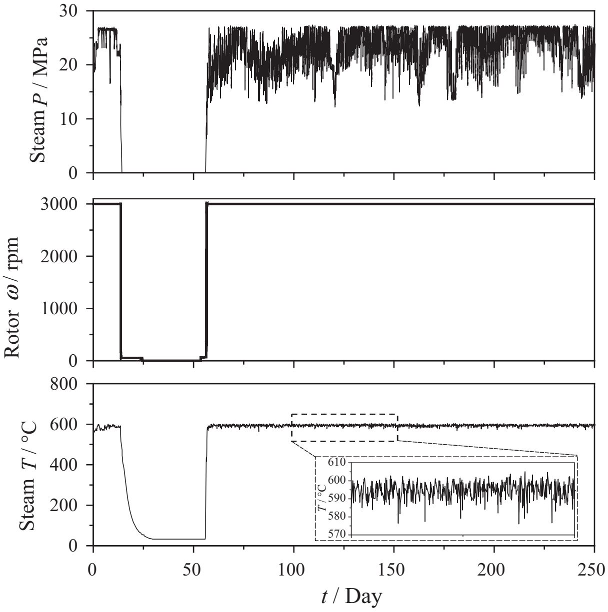

Fig. 1. In-service operating data: steam pressure, rotating speed, and steam temperature.

2. Mathematical model

2.1. Constitutive law

The total strain rate includes three parts: elastic $\dot{\bar{\bar{\varepsilon}}}_{el}$, inelastic $\dot{\bar{\bar{\varepsilon}}}_{in}$, and thermal expansion $\dot{\bar{\bar{\varepsilon}}}_{th}$, and is given as

$$\dot{\bar{\bar{\varepsilon}}} = \dot{\bar{\bar{\varepsilon}}}_{el} + \dot{\bar{\bar{\varepsilon}}}_{in} + \dot{\bar{\bar{\varepsilon}}}_{th}. \tag{1}$$

For the expansion part, the thermal strain is defined as

$$\bar{\bar{\varepsilon}}_{th} = \alpha_T \cdot (T - T_{ref})\bar{\bar{1}}, \tag{2}$$

where α_T is the heat transfer coefficient, T is the temperature, and T_{ref} is the reference temperature. For the elastic part, the stress tensor is related to the elastic strain and the expression is given as

$$\bar{\bar{\sigma}} = (1 - D) \cdot \bar{\bar{\bar{\bar{C}}}}_{el} : \bar{\bar{\varepsilon}}_{el} = (1 - D) \cdot \bar{\bar{\bar{\bar{C}}}}_{el} : \left(\bar{\bar{\varepsilon}} - \bar{\bar{\varepsilon}}_{th} - \bar{\bar{\varepsilon}}_{in}\right), \tag{3}$$

where $\bar{\bar{\bar{\bar{C}}}}_{el}$ is the tensor of elastic modulus and D is a damage variable. Damage is only considered when a material or a structure generates inelastic deformation. For the inelastic part, a viscoplastic equation with back stress is used and listed below

$$\dot{\bar{\bar{\varepsilon}}}_{in} = \frac{3}{2} \cdot \dot{p} \cdot \frac{\bar{\bar{\sigma}}' - \bar{\bar{X}}'}{J_2\left(\bar{\bar{\sigma}} - \bar{\bar{X}}\right)}, \tag{4}$$

where $\bar{\bar{\sigma}}'$ is the deviator of the stress tensor $\bar{\bar{\sigma}}$ and $\bar{\bar{X}}'$ is the deviator of the back stress tensor $\bar{\bar{X}}$. $J_2\left(\bar{\bar{\sigma}} - \bar{\bar{X}}\right)$, $\bar{\bar{\sigma}}'$, and $\bar{\bar{X}}'$ can be calculated by Eqs. (5) and (6),

$$J_2\left(\bar{\bar{\sigma}} - \bar{\bar{X}}\right) = \sqrt{\frac{3}{2}\left(\bar{\bar{\sigma}}' - \bar{\bar{X}}'\right) : \left(\bar{\bar{\sigma}}' - \bar{\bar{X}}'\right)}, \tag{5}$$

$$\bar{\bar{\sigma}}' = \bar{\bar{\sigma}} - \sigma_{hyd} \cdot \bar{\bar{1}}, \quad \bar{\bar{X}}' = \bar{\bar{X}} - X_{hyd} \cdot \bar{\bar{1}}. \tag{6}$$

In Eq. (4), $\dot{p}$ is the accumulated viscoplastic strain rate and defined as follows

$$\dot{p} = \sqrt{\frac{2}{3}\dot{\bar{\bar{\varepsilon}}}_{in} : \dot{\bar{\bar{\varepsilon}}}_{in}} = \left\langle \frac{J_2\left(\bar{\bar{\sigma}} - \bar{\bar{X}}\right) - k - R}{K \cdot (1 - D)} \right\rangle^n, \tag{7}$$