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Analysis of the sealing performance and creep behavior of the inner casing of a 1000 MW supercritical steam turbine under bolt relaxation

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ABSTRACT

The creep behavior and sealing performance of the inner casing of a 1000 MW supercritical steam turbine were investigated during 200,000 h of steady operation at high temperatures. The influence of the stress relaxation of bolts on creep behavior and sealing performance was specifically demonstrated. A constitutive creep model based on continuum damage mechanics and a multiaxial creep strain formula was used to describe the stress–strain behavior and calculate the multiaxial strain. Due to significant bolt relaxation in the high-temperature region, stress in the steam inlet region decreased dramatically; likewise, multiaxial creep strain decreased markedly in this region. Contact pressure significantly decreased during the first 10,000 h, especially in the regions between bolts 1 and 9, and the largest decrease in contact pressure exceeded 340 MPa. This reduced sealing performance at high temperatures. Further comparison of the contact pressure and the opening displacement at the contact surface was carried out with and without bolt relaxation. The massive difference of 153 MPa between these two cases in the primary creep phase demonstrated that bolt relaxation significantly influences sealing performance.

1. Introduction

As demand for thermal power has increased over the past decade, large-capacity steam turbines, e.g. supercritical and ultra-supercritical power units, have become common in coal-fired power plants, particularly in Asian countries. To conserve primary energy resources, steam parameters must be maximized to an economically reasonable extent. However, the structural strength of complex thick-walled components, such as steam turbine casings, may be affected when subjected to both creep and the stress relaxation of bolts at high temperatures, potentially affecting steam turbine design. Thus, understanding of the creep behavior of the steam turbine casing under the bolt stress relaxation at high temperatures will have a significant practical effect on the design and operation of large-capacity steam turbines.

Numerous studies have been carried out to investigate the structural strength of turbine casings. Considerable efforts [1–5] have been made to improve the creep rupture strengths of 9–12%Cr martensitic stainless steel at high temperatures by, for example, adding elements to the materials or applying special heat treatments. Steam turbine casings manufactured using these improved 9–12%Cr martensitic stainless steels have mechanical properties that are actually much more complex than those of the material itself because these structures sustain multiaxial creep strain during long-term operation at high temperatures. Moreover, laboratory experiments on the predicted life of steam turbine casings and the effects of multiaxial creep are, in most cases, impossible. Constitutive models have thus been developed to simulate the creep behavior of the structures and materials. During the first half of the 20th century,

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classical plastic theory was used in such constitutive models. However, a time-dependent multiaxial creep design method based on classic plastic theory is limited in its practical application due as it is derived from the criteria of yielding failure. Subsequently, design criteria for multiaxial creep that used models based on cavity growth mechanisms and continuum damage mechanics (CDM) were established to study the effect of multiaxial creep stresses [6,7]. A CDM-based constitutive model was successfully used to simulate the creep and fatigue behavior of rotors [8–10]. In the present study, a CDM-based constitutive model for creep is used to simulate the creep behavior of a steam turbine casing.

To study the structural mechanical behavior of turbine casings, in 1985 Spencer [11] evaluated the residual life of a 20 MW turbine casing by using the R6 method to perform a sensitivity analysis of the effect of varying the input data on the acceptability of a crack. Rao et al. [12] showed that estimation of the transient thermal stress is an important consideration for start-up optimization in steam turbines. Choi and Hyun [13] calculated the fatigue damage of steam turbine inner casings by applying the inelastic analysis method. Another study [14] defined a thermal stress concentration factor for the inner surface of casings to account for variations in geometry, using a 3-D finite element analysis. These studies mainly focused on fatigue and creep behavior of turbine casings. In the present study, an integral inner casing is assembled from two half inner casings connected with bolts. Bolt stress relaxation at high temperatures is likely to affect the sealing performance of the turbine casing.

Considerable efforts have been made to study the sealing performance and creep behavior of bolt-flange structures in numerous applications, and a survey of the literature in this area has been published [15]. This survey revealed that the problems of leakage and creep failure of the bolt–flange–seal couplings at high temperatures and pressures have not been fully solved. A steam turbine casing is a thick-walled component that experiences complex creep behavior during long-term steady operation in a high-temperature environment. Stress relaxation of bolts at high temperatures significantly decreases contact pressure at the contact surface. It is thus important to understand the creep behavior of steam turbine casings under the influence of bolt stress relaxation.

This paper numerically investigates the creep behavior of a 1000 MW supercritical steam turbine inner casing during 200,000 h of operation in a high-temperature environment. A numerical model for the inner casing is established using a finite element method. Heat transfer coefficients are calculated for the inside and outside surfaces of the inner casing. A CDM-based constitutive model for creep is used to describe the stress–strain behavior and a multiaxial toughness factor is modeled to describe the multiaxial stress state. Creep behavior is explained in terms of strain, stress and the multiaxial toughness factor. The variation in the contact pressure at the contact surface is extracted to describe the influence of bolt stress relaxation on sealing performance. In addition, a comparison of the results with and without bolt stress relaxation is made.

2. Mathematical model

2.1. Heat transfer model

In this study, heat transfer between the inner casing and steam is calculated using the heat transfer coefficient and the steam temperature. Fig. 1(a) shows the geometry of the inner casing, comprising the steam inlet and steam outlet, the inner and outer smooth surfaces, the geometry of the seal at the tip clearance of the movable blade, the vane blade groove and the cooling holes. The heat transfer coefficient must be determined for each geometry.

The heat transfer coefficients at the steam inlet and steam outlet are defined as:

$$h = 0.023\left(\frac{\lambda_s}{D_e}\right)\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}; \quad \mathrm{Re} = \frac{uD_e}{\nu}; \quad D_e = \frac{4A_f}{P_w}, \tag{1}$$

where h is the heat transfer coefficient, λ_s is the thermal conductivity coefficient, D_e is the hydraulic diameter, u is the flow velocity, v is the kinematic viscosity of the flow and Pr is the Prandtl number.

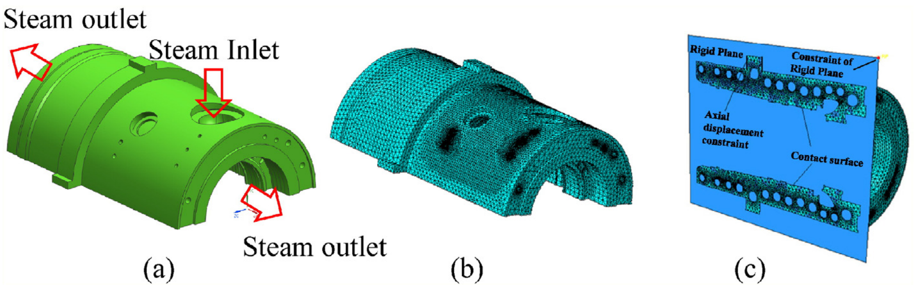

Fig. 1. (a) Structure, (b) mesh and (c) constraints of the casing.