

# Optimization Design of Steam Turbine Rotors based on Thermo-Structural Coupling

Zewen Li<sup>a</sup>

School of Engineering and Technology, China University of Geosciences (Beijing), Beijing, China

<sup>a</sup>1847793996@qq.com

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## Abstract

**This study focused on the original model of a first-stage shrouded steam turbine blade and investigated its mechanical behavior under a multiphysics environment through prestressed modal analysis, transient thermo-mechanical coupling analysis, and long-term static creep analysis. The results showed that the system exhibited nodal-diameter vibration, with a first-order natural frequency of 588.88 Hz, satisfying the requirements for dynamic stability. Under steady-state conditions, the maximum equivalent stress reached 345.09 MPa and was mainly located in the shroud connection region. After service for  $6.8 \times 10^8$  s, the equivalent creep strain at the blade root accumulated to 0.19073 mm. This study identified the structural strength bottlenecks and deformation characteristics of the blade, providing a reference for the safe service of this type of turbine blade.**

## Keywords

**Steam Turbine Blade; Original Model; Prestressed Modal Analysis; Thermo-Mechanical Coupling; Static Creep; Stress Concentration; Service Safety.**

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## 1. Introduction

Against the background of the “dual carbon” goals, coal-fired power generation has been accelerating toward high-parameter operation and high-flexibility deep load regulation. First-stage steam turbine blades were exposed to extreme operating conditions, including high temperature, high pressure, and high-speed rotation, during long-term service. Under coupled multiphysics loads, these blades were highly susceptible to fatigue failure and creep rupture.<sup>[1]</sup>

Regarding the mechanical characteristics of shrouds and the life assessment of turbine blades, extensive studies had been conducted. In terms of vibration and contact mechanics, Xie Yonghui et al.<sup>[2]</sup> and Zhao Wensheng et al.<sup>[3]</sup> investigated the vibration suppression mechanism of damping shrouds and the centrifugal stiffening effect, respectively. Wang Jianming et al.<sup>[4]</sup> theoretically analyzed the local contact stress of shrouded blades. In terms of long-term service and reliability assessment, Zhang Mingwei et al.<sup>[5]</sup> simulated the high-temperature creep deformation and stress relaxation behavior of turbine blades, while Zheng Shuai et al.<sup>[6]</sup> and Sun Yujie et al.<sup>[7]</sup> proposed efficient creep-fatigue life prediction methods based on finite element nodes and digital twins, respectively.

Although existing studies had achieved significant progress in shroud-based vibration reduction and creep algorithms, systematic numerical investigations of the transient thermo-mechanical coupling characteristics of a specific first-stage shrouded blade during the full start-up process, as well as Norton-Bailey creep damage under long-term operation, still had important engineering value. Based on this, an original three-dimensional finite element model of the first-stage steam turbine blade was

established in this study. Prestressed modal analysis, transient thermo-mechanical coupling analysis, and long-term static creep analysis were then conducted sequentially, aiming to reveal the mechanical behavior of the structure under multiphysics effects and to provide theoretical support for its long-term safe service.

## 2. Theoretical Framework

To intuitively evaluate the physical influence of shroud thickness on the natural frequency of the system from a mathematical perspective, the Rayleigh quotient equation was introduced in this study:

$$\omega_i^2 = \frac{\{\phi_i\}^T [K_{total}] \{\phi_i\}}{\{\phi_i\}^T [M] \{\phi_i\}} \quad (1)$$

where  $\omega_i$  was the natural circular frequency;  $\phi_i$  was the modal shape vector;  $K_{total}$  was the total stiffness matrix, including elastic stiffness, stress-stiffening stiffness, and contact stiffness; and  $M$  was the mass matrix.

The evolution of the temperature field in the first-stage steam turbine blade during start-up and shutdown followed the law of energy conservation. The three-dimensional transient heat conduction differential equation was used to solve the time-dependent temperature distribution  $T$  of the blade:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right) + Q \quad (2)$$

where  $\rho$  was the material density;  $c$  was the specific heat capacity;  $k_x$ ,  $k_y$  and  $k_z$  were the thermal conductivity coefficients; and  $Q$  was the internal heat source density, which was set to 0 in this study. After the transient temperature field was obtained, it was converted into equivalent loads through the thermo-mechanical equilibrium equation, and the stress and deformation histories were then solved.

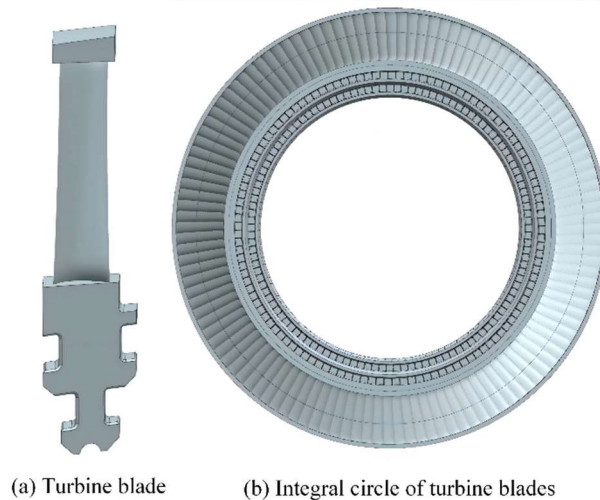
Under long-term high-temperature service conditions, the irreversible creep strain generated in the blade was converted into equivalent nodal loads, driving stress relaxation of the system. The nonlinear global static equilibrium equation incorporating the time history was expressed as follows:

$$[K(t)]\{u(t)\} = \{F_{mech}\} + \int_V [B]^T [D] \{\epsilon^{cr}(t)\} dV \quad (3)$$

where  $[K(t)]$  was the stiffness matrix varying with the contact state and temperature;  $\{u(t)\}$  was the nodal displacement vector;  $\{F_{mech}\}$  represented mechanical loads such as centrifugal force; and the integral term represented the equivalent load converted from the accumulated creep strain  $\{\epsilon^{cr}(t)\}$ .

## 3. Results and discussion

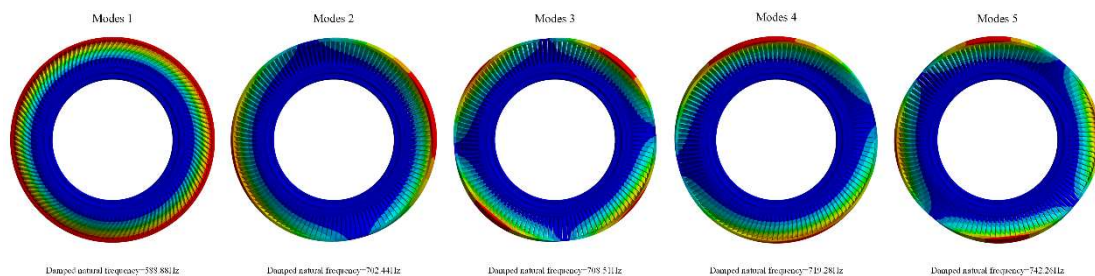
As shown in Fig. 1, a three-dimensional finite element model of the steam turbine blade was constructed in this study. Rotational speed and third-type thermal boundary conditions were applied according to conventional settings for subsequent analysis.



**Fig. 1** Original model of the steam turbine Blade

### 3.1 Modal Analysis

Under high-speed rotational operating conditions, the dynamic characteristics of steam turbine blades were jointly governed by the centrifugal stress-stiffening effect and complex boundary conditions. To accurately evaluate the dynamic response characteristics of the original model, prestressed modal analysis was performed on the full-circle shrouded blade system under a centrifugal force field corresponding to the rated rotational speed of 3000 r/min. The extracted first five natural frequencies and modal shape characteristics were as follows: the first mode exhibited a standard nodal-circle vibration; the second mode exhibited a one-nodal-diameter vibration; the third mode exhibited a two-nodal-diameter vibration; the fourth mode showed coupled nodal-circle and nodal-diameter vibration; and the fifth mode showed coupled two-nodal-diameter and nodal-circle vibration.



**Fig. 2** Modal voutours of the steam turbine blade

### 3.2 Thermo-mechanical Coupling Analysis

Based on the thermo-mechanical coupling analysis, the original model exhibited obvious non-uniform temperature rise and thermal inertia during start-up and steady-state operation. The leading- and trailing-edge regions heated up more rapidly and eventually reached a thermal equilibrium state of 599.57 °C at 50,000 s. Under the coupled effects of multiple loads, the maximum equivalent stress of the structure reached 345.09 MPa, governed jointly by rotational centrifugal force and the extrusion effect between adjacent shrouds. This stress concentration was locked in the transition region between the blade body and the shroud, forming the core strength bottleneck affecting service reliability. In addition, the radial displacement of the blade tip, induced by the combined effects of centrifugal stretching and thermal expansion, reached 1.2322 mm under steady-state conditions. This reflected the geometric elongation characteristics of this type of blade under extreme operating conditions, providing not only an initial mechanical basis for subsequent long-term static creep analysis but also important reference data for the precise control of blade tip clearance.

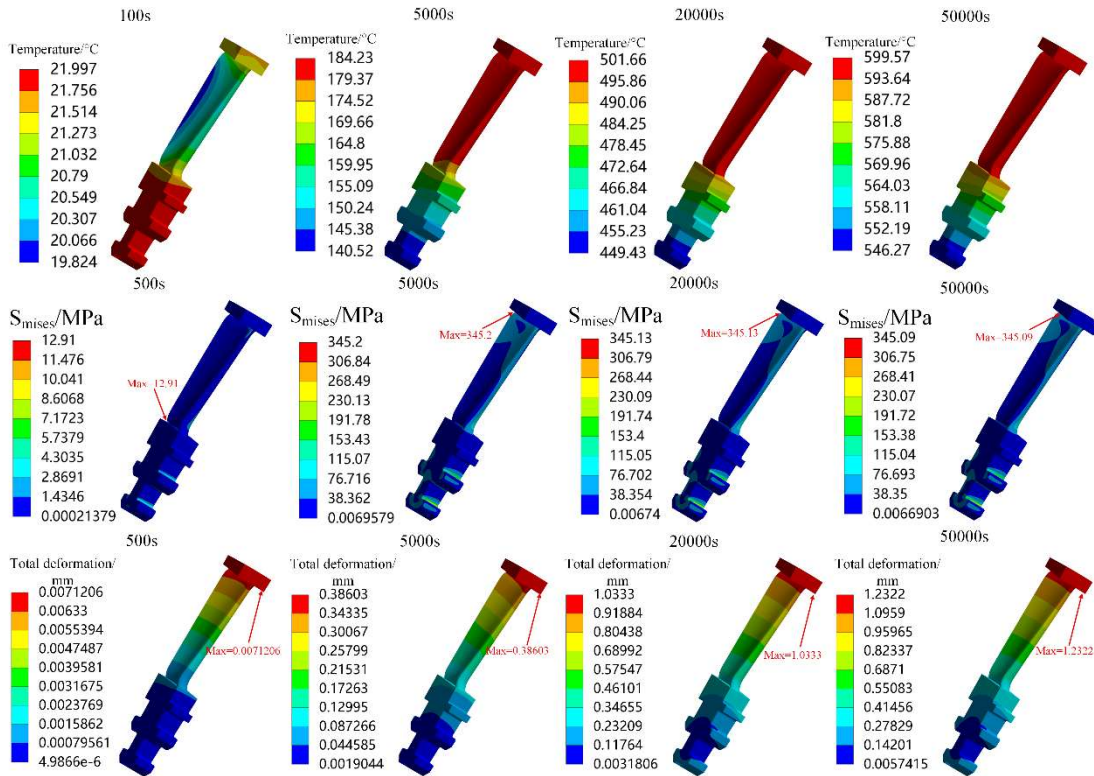


Fig. 3 Thermo-mechanical coupling contours

### 3.3 Analysis of Static Creep Mechanical Behavior and Damage Evolution

In the long-term service safety assessment of steam turbine blades, irreversible creep damage was the core failure mode determining the ultimate structural life. In this study, the Norton–Bailey time-hardening constitutive model was introduced into the static analysis module, and implicit integration was performed for the original model under constant aerodynamic and thermal loads over an extreme operating period of approximately 21.5 years, corresponding to  $6.8 \times 10^8$  s. The computational results showed that, driven by long-term heat conduction, the maximum blade temperature stably converged to 599.57°C. Dominated by centrifugal tensile force, the global maximum equivalent stress of the original model was 223.58 MPa, which served as the key mechanical basis for the subsequent evolution of creep damage. Under the long-term combined effects of high stress and high temperature, the maximum total deformation at the blade shroud accumulated to 0.1908 mm. The high-risk region of equivalent creep strain remained concentrated in the blade-root tenon transition region, which sustained extremely high centrifugal tensile loads. The maximum equivalent creep strain reached 0.19073 mm, quantitatively revealing the evolution from elastic strain to plastic strain during long-term service and providing critical data support for durability life prediction and reliability assessment of this type of blade.

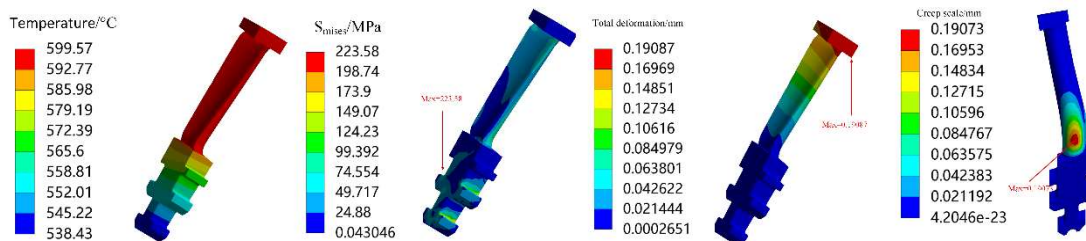


Fig. 4 Static and creep contours

## 4. Conclusion

This study focused on a first-stage shrouded steam turbine blade and conducted finite element analyses involving prestressed modal analysis, transient thermo-mechanical coupling analysis, and long-term static creep analysis. The mechanical response and damage evolution of the blade under coupled multiphysics effects were investigated. The results showed that the mechanical interlocking effect of the full-circle shroud enhanced the circumferential stiffness of the system, causing the structure to exhibit nodal-circle vibration. The first-order natural frequency was 588.88 Hz, which ensured the dynamic stability of the blade. Under thermo-mechanical coupling, the blade experienced a non-uniform temperature rise and eventually reached thermal equilibrium at 599.57 °C. Owing to the combined effects of high-speed centrifugal force and contact extrusion between adjacent shrouds, the maximum equivalent stress reached 345.09 MPa and was mainly concentrated at the connection between the shroud and the blade body. Meanwhile, the structure produced a radial tensile displacement of 1.2322 mm. In addition, during the long-term operating period of  $6.8 \times 10^8$  s, the blade-root tenon transition region became the main creep-damage area because it sustained the global tensile load, and the maximum equivalent creep strain accumulated to 0.19073 mm. In summary, this type of blade possessed a certain vibration-resistance safety margin. However, the local stress concentration at the shroud connection and the long-term irreversible creep flow at the blade root constituted the strength bottlenecks limiting its service life. The findings of this study provided a useful reference for the safe operation and reliability assessment of the unit.

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