Strength analysis on load rejection working condition of steam turbine

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Abstract: The load rejection is regarded as a vital process for a steam turbine performing commission operation or encountering some emergent accidents. Under the combination of the boiler and the turbine control valve, the steam temperature could be rapidly reduced and the turbine load could be cut back. In order to analyze the stress of the steam turbine during load rejection, the first stage rotating blades and grooves are taken as research subjects and the commercial software "Abaqus" is employed to perform the FEA process. The stress, which is strongly impacted by rapid cooling process in four periods, is calculated in this paper. The result indicates that the stress of rotating blade and rotor groove is sensitive to temperature change in short time. The stress increases quickly when the steam temperature drops rapidly. When the steam temperature drops to a certain level, the internal stress of the model is redistributed, and it always takes a rather long time for the stress to restore a uniform profile where the local peak stress occurs. In gradual cooling, the stress gets accumulated and tends to become higher. Although the redistribution of the stress takes a very long time, it is recommended to let the temperature drop to a low level before the next cooling process. During all four cooling steps, the stress of the components is well controlled within the elastic range of the material noted in this paper.

Key word: Steam turbine; Load rejection; Heat impaction; Strength analysis; Low cycle fatigue

1. Introduction

In the modern design process for steam turbines, the finite element method has been widely used. The engineers in Shanghai Turbine Works Company have introduced Abaqus software for solving lots of engineering problems of turbines for many years, such as strength problems for steady or unsteady conditions; the natural frequencies calculation of the interlocked whole-cycle blades; heat transfer (steady/unsteady) in the flow passage; and high temperature creep problems on blades, control valves, and rotors. The paper presents the stress conditions when the high temperature components are cooled in a short time. The model is from a 300MW steam turbine, selecting the rotating blades and rotor grooves in the first stage of the HP (high pressure) cylinder.

2. Finite element calculation and methods

2.1 Modeling

HP (high pressure cylinder) rotating blades of the first stage in a steam turbine are assembled, shown in Figure 1. The whole-cycle-blades are circular symmetrical, so in order to simplify the model, a blade is selected for analysis modeling using the cyclic symmetric method, which is shown in Figure 2. Here the rotor is hollowed out to reduce the complexity of modeling [2-3].

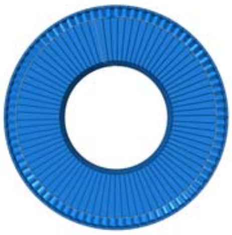

Figure 1. Blades assembly

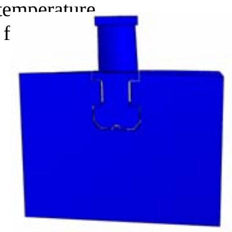

Figure 2. Analysis modeling

2.2 Meshing and elements selecting

The element C3D8RT (3-dimensional linear 8-nodes reduced thermal analysis element) is adopted for the rotor's elements type, and the total number of elements is 6040, shown in Figure 3.1 and Figure 3.2. The FEA elements of blade are divided into two parts, one part for platform and root, using C3D10MT element (3-dimensional 10-nodes modified thermal analysis element), and the other for blade foil and shroud, using C3D8RT unit (3-dimensional linear 8-node reduced thermal analysis element). The total number of elements is 17892, shown in Figure 3.3. Grids in groove fillet and blade root fillet where the stresses are concentrated, will be meshed more densely.

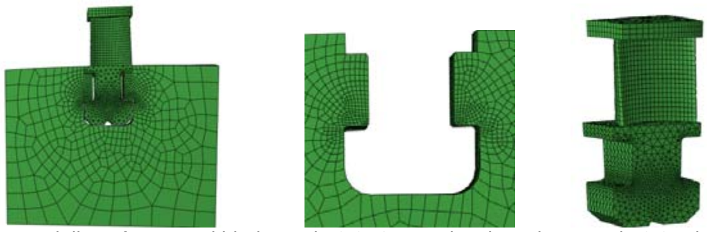

Fig 3.1. Modeling of rotor and blade Fig 3.2. Groove local mesh Fig 3.3. Blade mesh

Figure 3. Mesh modeling

2.3 Calculation Method

2.3.1 Material properties

Material properties are defined, including elastic modulus in the temperature range of 20-600 degrees Celsius, Poisson's ratio, density, thermal conductivity, specific heat capacity, and expansion coefficient.

2.3.2 Analysis step

1) Steady stress analysis.
The speed of the rotor is accelerated from 0 to 3000 rpm. A steady stress analysis is processed at 3000 rpm speed.
2) Steady thermal stress analysis.
The blades and rotor are heated from room temperature to 532 degrees Celsius.
3) Transient thermal stress analysis.
When the load is being rejected, the high temperature steam will rapidly cool, and the rotor and blades will quickly contract. As the parts contract, the local stress will be increased. Furthermore, as the difference of the heat transfer properties between blades and rotor increases, it will lead to generating additional stress on the contact surface.

2.3.3 Loading

1) Preliminary centrifugal force loading.
Generally, a small centrifugal force is applied as a tentative initial loading. The purpose is two-fold; first, if the preliminary loading is too strong, the contact pairs will be deformed too easily, resulting in some local deformity of the stiffness matrix, and then the equation will not easily be converged; second, due to the boundary constraint on the blade established by the contact friction of blade root and rotor groove, it is a requirement that the friction condition should build up in the initial calculation. So if the preliminary loading is too small, some uncertain results would appear due to lack of boundary conditions. It also will make the equation difficult to converge or cause some errors.
2) Design condition centrifugal force loading.
After the contact pairs are contacting each other completely and forming the friction restriction, the design condition centrifugal force is loaded (the speed is 3000 rpm) until the end of the calculation.
3) Heat loading
First, a steady heat load is applied. Generally, the dimensions of the components in the design drawings are for room temperature, so the CAD production modeling input to Abaqus still maintains the room temperature size. In order to analyze the load rejection case, an initial steady heat analysis is needed. The components are heated from room temperature to the steady operating temperature, thereby obtaining the size after expansion.
Second, a transient heat load is applied. Steam temperature is reduced step by step, until it is cooled to a certain level, and by maintaining some minutes at a constant level, the steam is again cooled continually step by step until it is reduced to the design temperature.

2.3.4 Boundary conditions and initial conditions

Correct and reasonable boundary conditions can make the finite element equations simulate the real situation very well. But considering the computer hardware's ability, it is vitally important to simplify the model reasonably. Similarly, according to the analysis requirements, some complex boundary conditions would cause trouble for solving the finite element equations, so it is necessary to reasonably simplify some complex boundary conditions.

1) Rotor boundary condition

The rotor's bottom displacement in the three XYZ coordinate directions is restricted [4], as well as one side of the rotor axial displacement. After the completion of the first load step (preliminary centrifugal force loading), the constraints of axial displacement in the rotor's side can be removed.

2) Blade boundary conditions.

Displacement constraints of blades are established through the frictional contact of blades roots in the rotor grooves. Here the contact properties have been given, setting the tangential contact friction coefficient value at 0.2 and the contact property for "hard contact". Thus the displacement of blade roots in tangential and radial directions has been restricted by the friction.

The initial temperature is set to 20 degrees Celsius.

2.3.5 Heat transfer coefficient

Blades and rotor are impacted strongly by high temperature and high pressure steam. They exchange the thermal energy through the flow boundary layer. The efficiency of heat transfer in the flow field is determined by convective heat transfer coefficients which vary with steam properties (temperature, pressure, viscosity, etc.) as well as the flow conditions at different times or in different locations. In a steady flow, the time factor can be ignored, but it is a bit tricky to specify the coefficients in some different locations. The values of the heat transfer coefficients directly affect the calculation accuracy of the component's temperature field and thermal stress field and life. A strict solution method should make use of the CFD analysis tools, obtaining the coefficient value at each element node. While this method is pretty good, the process is more cumbersome. In engineering, empirical formulas are often used to solve the problem well if the flow passage is not very complicated.

Referring to the handbook of Shanghai Turbine Works Co., Ltd., the convective heat transfer coefficient of the high pressure inlet domain is

$$\alpha = 0.023\left(\frac{\lambda}{D_e}\right)_f Re_{\mathrm{f}}^{0.8} Pr_f^{0.4}$$

Where:

α is the Convective heat transfer coefficient（$W/m^2\,{}^{o}C$）;

λ is the Fluid heat conductivity coefficient（$W/m\ {}^{o}C$）;

D_e is the Hydraulic diameter（m）;

Re_{f} is Reynolds number;

Pr_f is Fluid Prandtl number.

By using the formula, the solution region could be equivalent to a circular fluid domain, and the result of the convective heat transfer coefficient on the wall is 10,918 $W/m^2{}^oC$, which would be an approximation value in the flow passage of the HP first stage.

3. Results and analysis

3.1 Centrifugal force load

The centrifugal tension force is a very important force in rotating machinery. When the rotor is running at 3000 rpm, blades are connected by the roots and grooves. The stress concentration areas caused by centrifugal force mainly appear in the contact pairs surfaces and the places near the rounded corners, as shown in Figures 4.1 to 4.3.

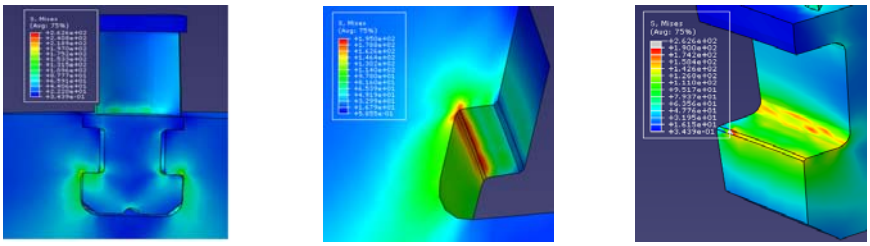

Fig. 4.1. Stress distr. of assembly   Fig. 4.2. Local stress distr. of groove   Fig. 4.3. Local stress distr. of root

Figure 4. Centrifugal stresses distributions

Figure 4.2 shows that the stress in the groove fillet is relatively concentrated, and the value is about 195Mpa which is considerably lower than the yield strength (765Mpa) of the rotor material at room temperature. As seen from Figure 4.3, the stress in the blade rounded corner is also relatively concentrated, and the value is about 190Mpa, which is also considerably lower than the yield strength (600Mpa) of the blade material at room temperature. It is safe and reliable that both stresses are in the range of the material elastic strength. As seen from Figure 4, it can be determined that the rounded corner areas of the root and groove are the areas with the most concentrated stresses, indicating where a detailed analysis should be performed, as described below.

3.2 Steady heat stress analysis

When components are heated from 20 degrees to 532 degrees steadily, the sizes of the parts are expanded in three directions. A typical element integral node in the rounded corner areas of the root and groove is taken respectively as the analysis object which is shown as the red color in Figure 5 and Figure 6. The stress at Point_A dropped from 182.5MPa to 169.8MPa after expansion; the stress at Point_B dropped from 175.2MPa to 163.0MPa after expansion. The analysis results show that the internal stress will be redistributed more uniformly after heat expansion.

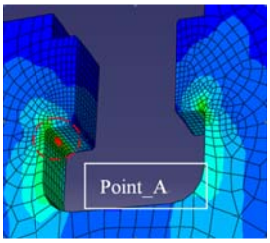

Figure 5. Typical element and node in the fillet of groove

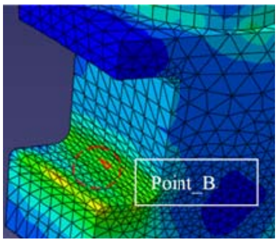

Figure 6. Typical element and node in the fillet of root

3.3 Transient heat stress analysis

Due to the requirement of operation or commission, the steam turbine unit sometimes needs to run in a load rejection condition. A sudden drop in steam temperature would greatly impact the stresses in the flow passage components. Point_A in Figure 5 and Point_B in Figure 6 are still used as the research objects for analyzing the situation of the stresses.

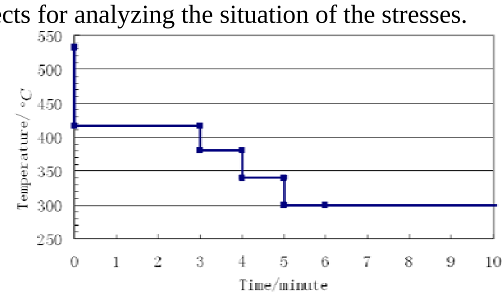

Figure 7. Variation of temperature oin load rejection condition

Figure 7 is a temperature-time graph of load rejection operating conditions. As seen from the figure, the steam temperature is quickly dropped from 532 degrees to 416 degrees, then held constant for 3 minutes, and then quickly dropped to 380 degrees for 1 minute, then quickly dropped to 340 degrees for 1 minute, and then quickly dropped to 300 degrees, last keeping 300 degrees for more than 5 minutes.

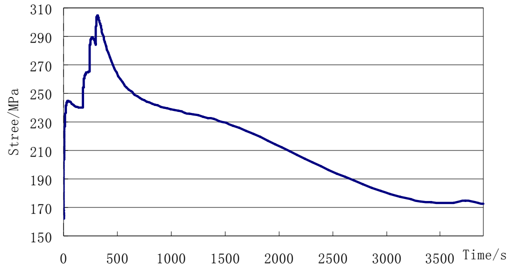

Figure 8. Transient heat stresses at groove point_A

As seen from Figure 8, in the operation of the temperature curve of the load rejection, the stress at groove Point A rises from the initial value 163.0MPa in a wavy fashion to the maximum value 304.6MPa in 317 seconds. After reaching the stress peak, the stress at Point_A declines rapidly down to 172.5Mpa after 60 minutes.

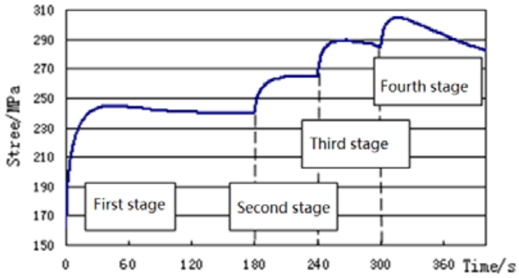

Figure 9. Partial figure of transient heat stresses at groove Point_A

As mentioned above, four stages of cooling time via stress change are shown in Figure 9. The figure shows that the stress is very sensitive to temperature changes and it can quickly react in a short time. In the first stage, the stress is raised to 244.9MPa by 43.2 seconds and then dropped to 240.2MPa by 180 seconds. By comparison, with stress increasing, a longer time is needed for stress redistribution and the gradual decrease to a certain value. Similarly, after 1minute, the stress in the second stage is increased to 265.5MPa and maintained at that value for 1minute. In the third stage, the stress is increased to 289MPa in 37 seconds, and then decreased to 284.3MPa. In the fourth stage, the stress is increased to the highest point at 304MPa in 17 seconds, and then decreased gradually.

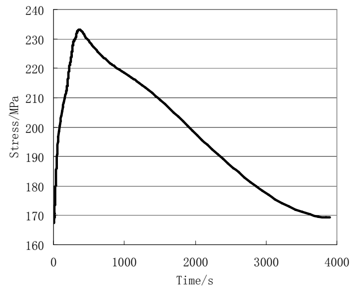

Figure 10. Transient heat stresses in root Point_B

Similarly, as shown in Figure 10, the Point_B stress is increased to the highest point 233.1MPa by 364 seconds after stresses accumulate in the front 3 stages. The time it takes the stress in the root Point_B to reach the highest point is about 47 seconds later than the blade's highest stress point. It can be indicated that the rotor material is more sensitive than the blade material to temperature.

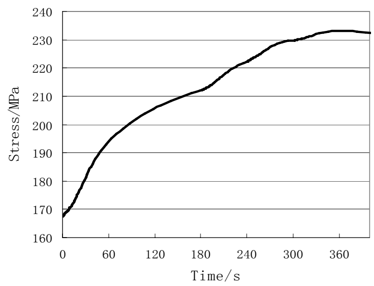

Figure 11. Partial figure of Transient thermal stress in root Point_B

Figure 11 shows that the Point_B stress is increased all the time in the four stages, which is not similar to the Point _A stress that decreases during some periods. This indicates that the time of the load rejection stage is too short for the reaction of the blade material stress, and it also shows that the stress of the blade material is not sensitive to temperature variation.

In the transient heat analysis step, it can be indicated that the highest points of the thermal stress of the blades and rotor are less than the stress yield point of the materials, so the design of the HP first stage blades and rotor are relatively conservative.

4. Conclusions

1). The blade stress is sensitive to the transient temperature gradient, and the rotor stress is relatively not sensitive to temperature change. They are all increased to a higher stress value in a short time.

2). If the temperature is constant, the stresses in the elements tend to be averaged, but it requires a very long time.

3). If the steam temperature is dropped suddenly, the components will be in contraction, and the tensile stresses in components such as blades and rotor grooves would be increased obviously in a short time.

4). Gradually cooling will result in the accumulation of stress, leading to the stress increasing more and more. Although the redistribution of the stress takes a very long time, it is recommended to let the temperature drop to a low level before the next cooling process so that the stresses can be effectively controlled in the stages of the load rejection condition.

5). The peak stresses in the four stages are all in the elastic ranges of the materials. Considering the repeated start-up and shut-down of the turbine unit and operation under the load rejection conditions, it is important and necessary to introduce an assessment criterion for judging the components' health and safety, such as the low cycle fatigue method or fracture mechanics theory.

5. Acknowledgments

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6. References

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