

# Structural modification of a steam turbine blade

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**Abstract.** Blades are significant components of steam turbines which are failed due to stresses arising from centrifugal and bending forces. The turbine blade has a number of geometrical variables that need to be considered at the design stage. Hence, this paper investigated a three-dimensional model of steam turbine blade with different lengths and thicknesses using finite element method. A three-dimensional model of blade was developed using a computer-aided design software. All materials were assumed linear, homogenous, elastic and isotropic. A 5 N widespread force was applied to the blade. The results of this study showed that longer blades are experienced higher maximum Von Mises stress and strain than shorter ones. The blade with the length of 400 mm and thickness of 20 mm experienced the lowest maximum Von Mises stress at 51 kPa. Furthermore, blade with the length of 400 mm and 600 mm experienced the lowest and highest strain at  $3.07 \times 10^{-6}$  and  $4.3 \times 10^{-6}$  respectively. In addition, thicker blades were undergone less maximum Von Mises stress and strain than thinner ones. Understanding stress and strain pattern in turbine blades provides useful knowledge which can be useful to estimate the fatigue in turbine blades.

**Keywords:** Steam turbine blade, Stress distribution, Strain, Finite element analysis

## 1. Introduction

Steam turbines are used in various types of power generation including nuclear power generation, coal-fired power generation, gas turbine combined-cycle power generation, and other power generation systems. Together, they provide the world with more than 60% of its electric power. Along with the extended use of renewable energy, providing electric power generated by steam turbines is about to increase [1]. In the thermal power station, the steam turbine is the prime mover which generates enough torque to produce power from generator. Steam turbine obtains its power by the adiabatic expansion of steam flow through the blades. Turbine has several parts which participate in the conversion of kinetic energy to mechanical energy [2]. Steam turbine blades are the heart of turbine which experiences the most intense static and dynamic conditions throughout their life span. Therefore, analysis of blades is compulsory to avoid any failure [3].

The blade system consists the turbine stages set in a series of subsequent units including rings of wide-ranging devices and rotor blades. Blade design combines the disciplines of thermo/aerodynamics and structural mechanics. While, the first ones strive for a design with maximum efficiency, second one is a restricting factor. In an optimization process, the mechanics provide the restrictions, while

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thermal/aerodynamics defines the objective function. Designing a blade is an iterative process with multiple levels of iterations. At first level, thermodynamical boundary conditions are calculated on the basis of black box models representing pipes, stage groups, turbine sections, valves, and etc. The second iteration level remarks a stage group with its geometrical data and considers aerodynamic variables, as e.g. structure mechanical variables e.g. natural frequencies and stresses. On further levels, individual optimizations, for blade fixations, are performed. Individual consists either just mechanical or just aero-dynamical variables [4, 5].

Blades are exposed to failure due to stresses arising primarily from centrifugal loads and bending forces related to the steam mass flow [6]. Furthermore, corrosion, causing crack initiation and propagation, is an significant failure mechanism in blades. This causes blades to be replaced or repaired and even probable re-design of elements [7]. In order to design a highly efficient steam turbine, it is essential to consider many design objective functions about the fluid dynamic performance (the smooth guidance of working steam, etc.) at the same time. Moreover, the steam turbine has a number of geometrical and topological variables (blade shape, the number of blades, number of stages, etc.) that also need to be considered at the design stage simultaneously [8].

Various blades exist which can be categorized based on their usage in the three turbine modules as high-pressure (HP), intermediate-pressure (IP) and low-pressure blades (LP). The first two turbine modules, HP and IP, are characterized by high temperatures and they contain small blades that should sustain small centrifugal forces, however, large blades contains bending forces due to impulse changes and high static pressure. They are equipped with T-roots assembled in tangential grooves around the rotor. The blades are bound to each other through integral roots and shrouds that ensure high stiffness of the blade row and as well as frictional damping to the structure. For the last stage blades, centrifugal forces are so high and bending by steam forces is approximately negligible. The largest rotating blades are equipped with fir-tree roots assembled in axial grooves. These roots include three or more lug pairs transmitting the forces portion-wise into the corresponding rotor lugs [5].

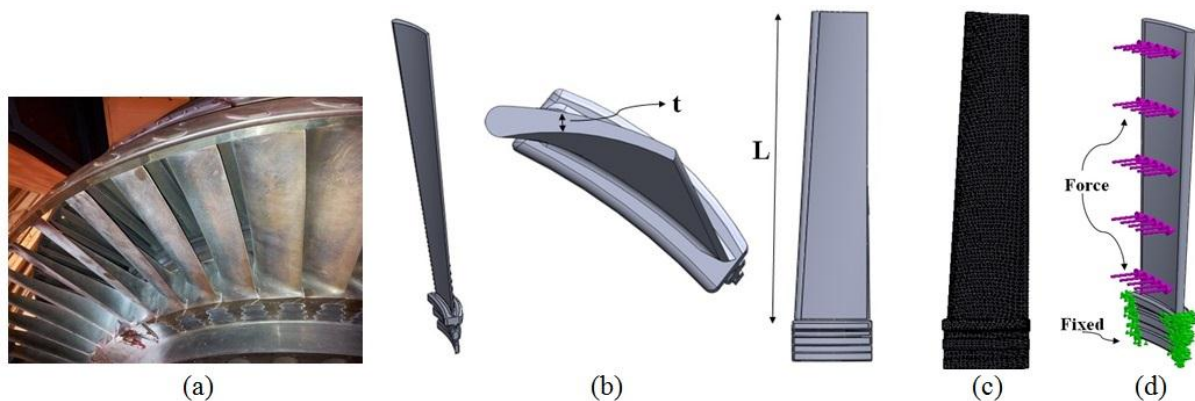
Richter et al. provided an overview of the structural design of modern steam turbine blades at Siemens power generation using the finite element code ADINAe [1]. The different types of blades including types of root shapes, root plus rotor steeple, different types of shrouds, and different types of snubbers were described in detail about their geometry and loading. For various analyses, a fatigue post-processor were implemented. Gajbhiye et al. performed vibration analysis using finite element analysis (FEA) technique on turbine blade and maximum allowable frequency was calculated. They showed that if the value of blade frequency rises beyond the natural frequency of blade the permanent damage accuses on blade [9]. Saxena et al. investigated failure in a more than 30 years old LMW design thermal power plant using FEA. The presented turbine blade failure was of LP turbine which has 8 stages. The results of each investigation were interpreted that leads finding the location of primary failure of the turbine blade, sequence and the root cause of its failure [10]. Segawa et al. developed a new rotor blade for steam turbine plants [11]. The new blade design optimized blade aerodynamics near the root section of the blade, hence reducing both profile and end wall losses. The new rotor blade was found to increase stage efficiency by about 0.3%.

This paper investigates a three-dimensional (3D) model of steam turbine blade with different lengths and thicknesses. A 3D model of steam turbine blade was developed using computer-aided design (CAD) software. Material properties and boundary conditions were applied. The models were analysed using finite element method (FEM) in order to obtain the Von Mises stress and strain in blades.

## 2. Materials and methods

A steam turbine blade was modelled using SolidWorks (Dassault Systemes SolidWorks Corp, USA) software. SolidWorks is a solid modelling CAD and computer-aided engineering (CAE) computer program. CAD model was prepared by taking dimensions of steam turbine blade from previous studies (Figure 1b). In order to model, the first stage steam turbine blade was chosen. The modelling of blade profile is an important task due to its direct effect on the simulation results. Cosmosworks (Dassault

Systems SolidWorks Corp, USA) was used for FEA using triangular mesh with the size of 2 mm. All materials were assumed linear, homogenous, elastic and isotropic. Elastic modulus and yield stress for turbine blade (chrome steel) were considered  $E=210$  GPa and 585 Mpa respectively. Poisson's ratio ( $\nu$ ) and density were also set 0.3 and 7900 kg/m<sup>3</sup> respectively [12]. Wide range amount of axial forces has been used for analysis of turbine blade, therefore in the present study a 5 N widespread axial force was applied to the blade which is relatively close to amount of previous studies [13]. The root of blade (base) was fixed in three directions (X,Y, Z) (Figure 2d). After applying material properties and meshing, next step was the solution using FEA. We selected the length (L) and thickness (t) of the blade as variable parameters for analysis. Therefore, 9 different cases was made as shown in table 1. The described models were used to obtain the Von Mises stress and strain in blades.



**Figure 1.** Steam turbine blade (a) Real steam turbine blade (b) modelled blade (c) Meshed blade (d) Applied force and boundary conditions

**Table 1.** Variable parameters for turbine blade analysis

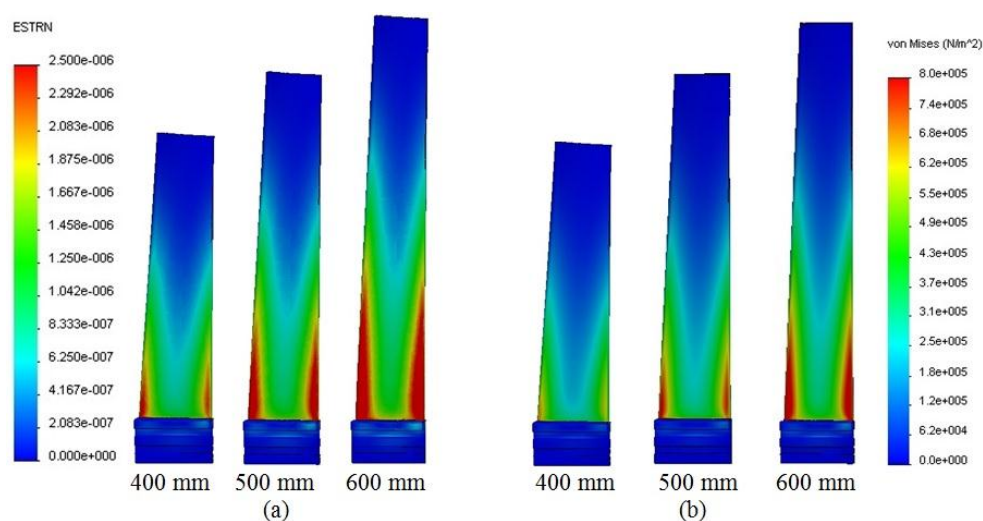
Case	Length (L)	Thickness (t)
1	400	10
2	400	15
3	400	20
4	500	10
5	500	15
6	500	20
7	600	10
8	600	15
9	600	20

### 3. Results

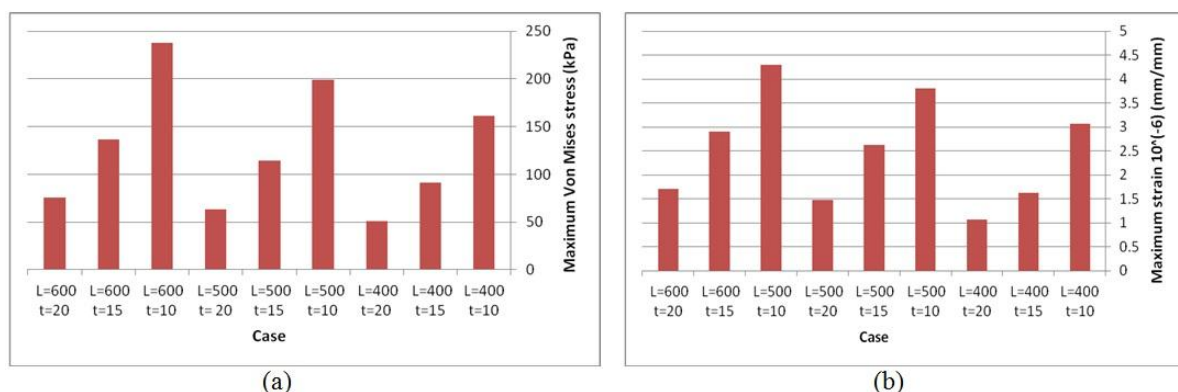
Results were obtained for nine various turbine blades. The different geometries affected the Von Mises stress and strain of blade (Figure 2). The highest stress was observed at the base of all blades with thickness of 10 mm. However, the lowest stress was seen in the tip of blades. Similarly, the most strain was seen in the base of blades, however, the tip of blades did not undergo any strain. Less stress was seen in the base of the blade with the length of 400 mm compared to blades with the length of 500 mm and 600 mm. As can be seen in Figure 3, blade with the length of 400 mm and thickness of 20 mm experienced the lowest maximum Von Mises stress at 51 kPa in comparison with all other models. However, blade with the length of 600 mm and thickness of 10 mm showed the highest maximum Von Mises stress at 237.73 kPa. For blade with the length of 400 mm, it was seen less maximum Von Mises stress in the

blade with the thickness of 20 mm compared to the blade with the thickness of 15 mm (91.66 kPa) and 10 mm (161.34 kPa). Similarly, for the length of 500 mm, blade with the thickness of 10 mm experienced higher maximum Von Mises stress at 199.36 kPa than the blade with the thickness of 15 mm and 20 mm at 114.17 kPa and 63.43 kPa respectively. This trend was also observed for the blade with the length of 600 mm. Thicker blade (20 mm) showed less maximum Von Mises stress at 75.77 kPa than the blade with the thickness of 15 mm and 10 mm.

Blade with the length of 400 mm experienced the lowest strain at  $3.07 \times 10^{-6}$  while, the blade with the length of 600 mm showed the highest strain at  $4.3 \times 10^{-6}$ . For the blade with the length of 500 mm, strain decreased significantly from  $3.8 \times 10^{-6}$  for the thickness of 10 mm to  $1.48 \times 10^{-6}$  for the thickness of 20 mm. This trend was seen in a similar way for the blades with the length of 400 mm and 600 mm.



**Figure 2.** Various blades with thickness of 10 mm (a) Strain (b) Von Mises stress distribution



**Figure 3.** (a) Maximum Von Mises stress (b) Maximum strain for blade with different lengths (L) and thicknesses (t)

#### 4. Discussion

In the present study, a steam turbine blade with various lengths and thicknesses were analyzed using FEM to obtain strain and Von Mises stress. Proper blade design with conservative stress and strain level is important for blade design. The major cause of malfunction in steam turbines is the failure of the blade. The failure of the blade may result catastrophic consequences both economically and physically. Therefore, the sufficient design of the turbine blade plays a significant role in the suitable functioning of

the turbine [13]. A good design of the turbine blade consists the determination of steady loads acting on the blade and stressing due to them, determination of unsteady forces due to stage flow interaction, determination of geometric characteristics from gas dynamic analysis, determination of natural frequencies and mode shapes, and determination of dynamic forces and life estimation based on the cumulative damage fatigue theories [14]. However, in this study, we only concentrated on the effect of changing the geometry of blade on stress and strain.

Based on results, stress and strain were higher in base of blades than tip. The blade with the length of 400 mm and thickness of 20 mm experienced the lowest maximum Von Mises stress at 51 kPa in comparison with all other models. However, blade with the length of 600 mm and thickness of 10 mm showed the highest maximum Von Mises stress at 237.73 kPa. It presents preference of shorter and thicker blades to reduce Von Mises stress and strain compared with longer and thinner ones. Shorter blades have less surface and therefore, they are exposed to less force and deformation in comparison with longer ones. Moreover, higher thickness causes blades to bend or deform less than thinner ones. In addition to this, blades with the length of 400 mm and 600 mm experienced the lowest and highest strain at  $3.07 \times 10^{-6}$  and  $4.3 \times 10^{-6}$  respectively. This is due to the fact that possibility of elongation in short blade are less than longer one. Understanding the stress and strain pattern in turbine blades provides useful knowledge which can be useful to estimate fatigue in turbine blades.

Studies on the state of stress and strain due to changing blade geometry are limited. Therefore, there is a call for further studies and investigations. Therefore, the present study introduced the modification of a steam turbine blade to decrease the factors that cause failure in blade including stress and strain using FEA. Length and thickness of turbine blade are design parameters which affect the longevity of the implant. The steam turbine blade is designed to work on high stresses so that it can withstand to high pressure and temperature. As it rotates at very high speed (approximate 25000 rpm) there are several chances of failure even though its advanced material composition and design [9]. As well as, the major cause of fatigue can be considered high stress and strain. Hence, designers need to observe significant consideration in order to reduce stress and strain in blades. Various limitations were witnessed in the present study. Material properties were assumed linear, however, considering nonlinear materials may be accommodated more reliable results. Centrifugal force and steam pressure are major forces which act on the blade. However, in this study steam pressure did not apply for analysis, which may or may not play a significant role in obtaining stress and strain changes in various blades.

## 5. Conclusion

The objective of this study was to modify a steam turbine blade using FEM. It was found that changing the geometry of turbine blade including length and thickness can be useful in decreasing Von Mises stress and strain. Results showed higher stress and strain at the base of blades rather than tips. It can be concluded that using shorter and thicker blades are better to reduce stress and strain, which may provide more durability.

## References

- [1] Senoo S, Asai K, Kurosawa A and Lee G 2013 Titanium 50-inch and 60-inch Last-stage Blades for Steam Turbines *Hitachi Review* **62**(1) 23-30
- [2] Nurbanasari M A, Crack of a first stage blade in a steam turbine 2014 *Case Stud Eng Fail* **2** 54-60
- [3] Shukla A and Harsha S P 2015 An experimental and FEM modal analysis of cracked and normal Steam Turbine Blade *Materials Today: Proceedings* **2** 2056-2063
- [4] Jolanta B 2016 Redesign of steam turbine rotor blades and rotor packages- Environmental analysis within systematic eco-design approach *Energy Conversion and Management* **116** 18-31
- [5] Christoph H R 2003 Structural design of modern steam turbine blades using ADINA *Computers and Structures* **81** 919-927



- [6] Singh M P and Lucas G M 2011 Blade design and analysis for steam turbines The McGraw-Hill Companies Inc, New York united states of america.
- [7] Arteaga C C, Rodríguez J A, Clemente C M, Segura J A and Urquiza G 2013 Estimation of useful life turbines blades with cracks in corrosive environment *Eng Fail Anal* **35** 576-589
- [8] Shimoyama K, Yoshimzu S, Jeong S, Obayashi S and Yokono Y 2011 Multi-objective design optimization for a steam turbine stator blade using LES and GA. *J Comput Sci Technol* **5** 134-147.
- [9] Bhupendra E G, Sachin V B and Kapil B S 2014 Vibration analysis of gas turbine blade profile blade using FEM technique and tool *I J Research in Advent Technology* **2(1)** 182-189
- [10] Saxena S, Pandey J P, Solanki R S, Gaurav K G and Modi O P 2015 Coupled mechanical, metallurgical and FEM based failure investigation of steam turbine blade *Engineering Failure Analysis* **52** 35-44
- [11] Segawa K, Shikano Y, Tsubouchi K and Shibashita N 2002 Development of a Highly Loaded Rotor Blade for Steam Turbines *JSME International Journal Series B* **45(4)** 881-890
- [12] Tulsidas D, Shantharaja M and Bharath V G 2014 Life Estimation of a Steam Turbine Blade Using Low Cycle Fatigue Analysis *Procedia Materials Science* **5** 2392-2401
- [13] Jabbari A A, Rai A K, Reedy P R and Dakhil M H 2014 Design and analysis of gas turbine rotor blade using finite element method, *International J Mechanical and Production Engineering Research and Development* **4** 73-94
- [14] Soares C 2008 Gas turbine a hand book of air ,land and sea applications **2** Elsevier Inc, united states of america.