Design and Bolt Optimization of Steam Turbine Casing using FEM Analysis

Prathap S[1] Dr. L J Sudev[2]
[1]PG Student [2]Professor & Head
[1,2]Department of Mechanical Engineering
[1,2]VVCE, Mysuru

Abstract— Steam turbines are the device used to convert thermal energy of steam into mechanical energy to produce electrical energy. Its components are made up of alloy steels operated at high temperature and high pressures. Steam turbine casings are the massive cast structure where high temperature and high pressure steam from boiler passes through nozzles. Casing withstands steam pressure & support internal components. Material used for casing is chromium steels. Bolts and diameter of bolt holes play a vital role between casings failure of which is harmful to external environment. High pressure steam causes stresses on casing wall which is responsible for cracking & casing distortion (deformation) if it crosses yield stress. Holes & notches are the critical area for crack growth as it is highly stress concentrated area. If it is reduced the stresses can be reduced greatly and also material can be saved considerably. In the present study, design of casings is done using UG software. Linear static analysis and bolt optimization is carried out with FEM Analysis using ANSYS WORKBENCH 14.5. Linear static analysis is carried out to check the structural performance of the casing under static load condition of pressure. The bolt diameters are varied and the resulting stresses are compared for optimization. However, the results show the design is safe since stresses caused by pressure is below yield stress of 535 MPa, deformation is under limiting value of 1. Stress concentration area is reduced with the bolt optimization. Since casing with 26mm bolt diameter produces least stress it is recommended.

Key words: Casing, FEM, Bolt Pretension, Pressure, Optimization

I. INTRODUCTION

A steam turbine is a form of heat engine that derives much of its improvement in thermodynamic efficiency from the use of multiple stages in the expansion of the steam, which results in a closer approach to the ideal reversible expansion process.

A turbine casing is a massive cast structure with a large wall thickness. A casing is subjected to pressure across wall & bolts in service. Materials used for casings are usually low alloy Cr-Mo, and Cr-Mo-V cast steels, with ferrite, ferrite-bainite, or tempered martensite microstructure. Bolted joints are one of the most common elements in construction and machine design. They consist of fasteners that capture and join other parts, and are secured with the mating of screw threads. There are two main types of bolted joint designs: tension joints and shear joints.

High pressure steam causes stresses on casing wall which is responsible for cracking & casing distortion (deformation) if it crosses yield stress for chromium steel. Holes & notches are the critical area for crack growth as it is highly stress concentrated area. If it is reduced the stresses can be reduced greatly and also material can be saved considerably.

Finite Element Method (FEM) is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. It uses subdivision of a whole problem domain into simpler parts, called finite elements. The analysis is commenced with linear static analysis.Linear means straight line. $\sigma = €E$ is the equation of straight line ($y = mx+c$) passing through origin. 'E', Young's modulus is the slope of curve and is a constant. Component break into two separate pieces after crossing ultimate stress. Analyst has to conclude whether the component is safe or fail by comparing maximum stress value with the yield or ultimate stress. Optimization work is based on the comparison of stresses value obtained for different bolt diameters. The bolt diameter which produces least stresses is recommended at the end.

II. LITERATURE SURVEY

Malagowda patil et al.[1] has studied the problem of frequency of start-ups & load changes within the casing which is higher and can results in non-uniform stress-strain distribution. In this study, steady state thermal analysis was evaluated and results are compared with analytical results. Results confirm more stresses are developed in initial condition.

G Das [2] has studied the failure of a steam turbine casing due to improper welding in the casing. Various case studies like microstructure, composition, fractography, were studied to know the cause of failure. Results showed that crack originated around the weld region due to inefficient choice of electrodes, & in welding process.

Gordana M. BAKI et al. [3] has studied the results of residual life assessment of one high pressure steam turbine casing. The stress states of casing for stationary and non-stationary working regime were obtained. Residual life assessment of HP turbine casing was conducted considering the influence of thermal fatigue and creep.

Laxminarayan, K.et al. [4] has studied about Contact pressure analysis & static analysis of steam turbine which needs to be addressed for structural integrity. In this work, the contact pressure analysis of steam turbine is validated by using the comparison of hand calculation and Finite element analysis results.

A.Sudheer Reddy et al. [5] has focused mainly about the working process of a steam turbine. The thermal efficiency of a steam turbine is much higher than that of a steam engine. This paper has attempted to cover some of the issues related to Steam turbines which designer should be aware of & also the guidelines were provided.

Through an exhaustive literature review it is observed that the literature is rich in study of the casing with different boundary conditions. The bolts play a critical role between top & bottom casing, failure of which can cause hazardous to the external environment as well as workers. According to Laxminarayan.k [4] paper the research is concentrated on structural performance of casings & contact pressure analysis. Among several parts of steam turbine it is understood that bolts are the parts where least stresses are developed. However, the research work on optimization of bolts with static analysis of casings is rare. Thus, there is extensive scope to explore the behaviour of bolts under operating boundary conditions along with static analysis.

III. OBJECTIVES

The objectives of this present work are:

- Design of casing of steam turbine
- Linear static analysis of casing of a steam turbine using FEM approach
- Bolts design and optimization in steam turbine casing.

IV. METHODOLOGY

Casings are subjected to very high pressure & high temperature steam. High pressure steam causes stresses on casing wall which is responsible for cracking & casing distortion (deformation) if it crosses yield stress of 535 MPa specified for chromium steel. Holes & notches are the critical area for crack growth as it is highly stress concentrated area. If it is reduced the stresses can be reduced greatly and also material can be saved considerably.

Linear static analysis is performed to overcome the problem of cracking & distortions. Linear means straight line. σ = €E is the equation of straight line (y = mx+c) passing through origin. Where, 'σ ' is stress,' €' is strain'E' isYoung's modulus is the slope of curve and is a constant. Pretension load is calculated and applied according to theoretical calculations. The casing is subjected inner pressure of 5 MPa[4] which causes stresses on casing walls. Casing undergoes cracking & distortion after crossing yield stress of 535 MPa specified for chromium steel. Analyst has to conclude whether the component is safe or fail by comparing maximum stress value with the yield stress. Bolt optimization is performed for the problem of crack growth. Here, static analysis is performed for Casing of different bolt diameters by imposing inner pressure of 5 MPa. Pretension load is calculated for each Cases and applied for each cases. The stress developed for each cases is compared with yield stress of 535 MPa specified for chromium steel. The bolt diameter which produces least stresses is recommended.

Chromium steel (G17CrMo55) is used for casing and bolts material with specific mechanical properties. The geometric model is generated using CAD package. The model of 40mm is generated with the help of UG-NX software. Initially 2-D model was created & converted to 3-D. The model is then imported to the ANSYS WORKBENCH 14.5 software. The analysis begins with pre-processor. Here material properties for the casing and bolt material, meshing, boundary conditions for the specified problem, application of load/pressure, is defined. Based on the pre-processing stage the work path follows solution stage. Here the problem is evaluated according to required scenario. After the results are shown in post-processing stage, the behaviour of problem/model under various loads/boundary conditions is displayed. Post processing stage follows the conclusion part based on the results obtained.

V. THEORETICAL CALCULATIONS

Bolt preloading is the load applied for the bolts to ensure firm contact between the casings and calculated pretension load to be applied for the analysis. Bolt Preloading is the minimum load applied on the bolts such that two parting surface establish contact between themselves firmly is said to be preload. Calculated pretension value is applied for the bolts during pre-processing. Pretension load applied ensure that bolt is subjected to tension and the casing is subjected to compression.

A. Calculation of Pretension Load for Different Bolt Diameters

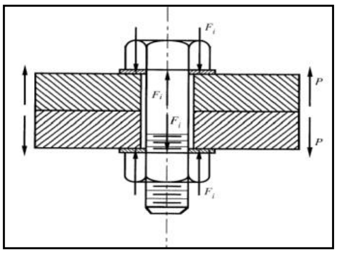

Fig. 1: Forces Acting upon a Bolted Preloaded Connection

Bolt size 40 mm [4], stress = 232Mpa, [4]

Stress = Pretension Load/Area of bolt, Area of bolt = $\pi d^2/4$

For 40mm diameter bolt A = 1256.63mm^2.

Therefore, Pretension Load for bolt diameter 40mm = stress × area=321320N.

Inner pressure applied=5MPa. [4]

Yield stress for chromium steel=535MPa. [4]

Case no.	Stress value (In MPa)	Diameter of bolt (In mm)	Area (In mm^2)	Pretension load (in Newton)
1	232	40	1256.63	321320
2	232	32	804.352	186609.664
3	232	26	706.95	164012.4

Table 1: Yield stress

VI. FEM ANALYSIS

A. Linear Static Analysis (40 Dia Bolt)

It is the simplest and most commonly used type of analysis. Linear means straight line. σ = €E is the equation of straight line (y = mx+c) passing through origin. Analyst has to conclude whether the component is safe or fail by comparing maximum stress value with the yield or ultimate stress.

B. Modelling

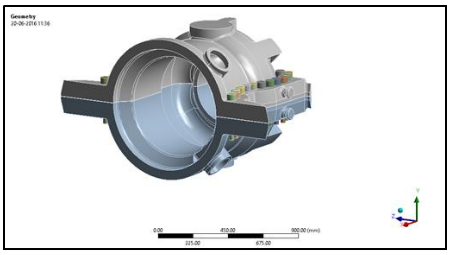

Fig. 2: Isometric View of Steam Turbine Casing

The model of 40mm is generated with the help of UG-NX software. Initially 2-D model was created & converted to 3-D.

The element type used is 8 node 184, Tetra dominant method is used for meshing and size of each bolt is 40mm. The analysis has 3 basic steps: pre-processing stage, solution stage, post-processing stage.

1) Pre Processing Stage

Pre-processing stage is the fundamental stage of any engineering analysis. The material property, different boundary conditions, meshing, operating parameters, application of loads, etc. Need to be specified before entering into the solution stage.

a) Material Property

Material property has to be defined for any engineering analysis to view the performance of the model/object under various boundary conditions. Materials used for casings are usually low alloy Cr-Mo, and Cr-Mo-v cast steels, ferrite-bainite, or tempered martensite microstructure. The strength of these steels at elevated temperature is obtained by solid solution strengthening and precipitation hardening.

Description	Casing & bolt
Name	Chromium steel
Density (tonnes/mm3)	7.8E-9
Young's modulus	2.1E-5
Poisson's ratio	0.3

Table 1: Material property

Table 1 describes the material property of both casing and bolt material. The material properties like density, young's modulus, and Poisson's ratio are specified in pre-processor of software for the more approximate analysis of practical problem.

b) Meshing

For the sake of analysis the given model is divided into finite number of elements. The elements are so connected for the smooth analysis of problem. The connection of elements is called 'MESHING'.

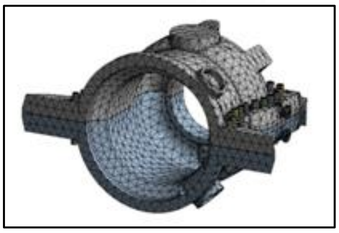

Fig. 3: Meshing/Discretesiation of Steam Turbine Casing

Statistics	
Nodes	81122
Elements	34045
Mesh Metric	None

Table 2: Statistics for Meshing

Table 2 represents the statistics for meshing. The number of nodes generated is 81122 and number of elements generated is 34045.

c) Boundary Condition and loads

The boundary condition need to be specified before solving any engineering problem. It specifies the specific boundary within which problem need to be solved. The minimum load applied on the bolts such that two parting surface establish contact between them firmly is said to be preload. Pretension load applied ensures that bolt is subjected to tension and the casing is subjected to compression.

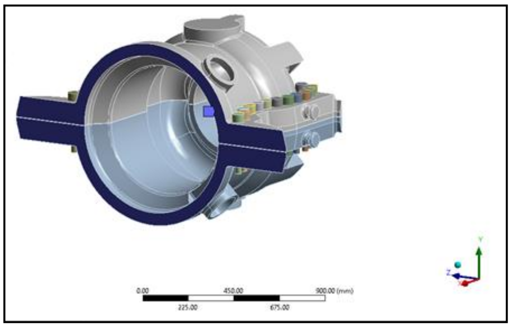

Fig. 4: Boundary Condition for casing

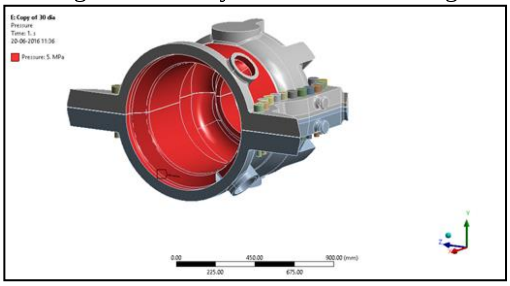

Fig. 5: Application of 5 MPa Pressure

Figure 4 represents the bounary conditions applied for the static model. The top and bottom casings are fixed to analyze the model. Figure 5 represents the casing subjected to inner pressure of 5 MPa as per the calculations. The inner pressure of 5MPa is developed due to the insertion of steam and combinational pressure developed due to the combined effect of blades, bolts, inner components which is the reason for the stresses developed on the casing wall.

2) Solution Stage

After the model is built in the pre-processing phase, the solution of the analysis need to be obtained for the complete analysis of problem under different boundary conditions. Processing requires no user interaction.

The solution stage is completed for the given model under the pre-processing stage successfully. The solution is available and represented in the post-processing stage for the further analysis.

C. Bolt Optimization

The diameter of each bolts are varied such as 40, 32, 26 by trial and error method. The geometric model of steam turbine casing is generated with the help of UG software for each diameters. initially 2-D model was created & converted to 3-D. The element type used is 8 node 184, Tetra dominant method is used for meshing. Material properties are defined in pre processing stage. Boundary canditions are applied. A pretension loads of 321320N is applied for 40mm dia., 186609.664N is applied for 32mm dia., and 164012.4N is applied for 26mm dia as per the calculations and inner pressure of 5MPa is applied for each cases to know its effect on design in each cases. All the 3 cases are solved in solution stage and results are analysed in post-processing stage.

VII. RESULTS AND DISCUSSIONS

Post processing stage is the final stage of ANSYS analysis. The post processing of data includes presentation of result such component/assembly deformed shapes, strains and stress distribution etc. The major job of post-processor is to present results in an easy way with pictorial representation.

The results are analyzed to get conclusion of the present work.

A. Linear Static Analysis (40mm Dia)

After this the design os casing with bolt diameter of 40mm it is allowed to solve in solution stage with the pre-processing work. the post-processing works are discussed with the help of results as below.

1) Von-Mises Stress& Maximum Principal Stress

Von Mises stress is the average stress developed for the casing under static load condition. Maximum principal stress is the maximum stress developed for the casing under static load condition.The stresses developed are displayed in various colour bands from red band to blue band. The red band shows the maximum stress and blue band shows the minimum stress. Remaining colour band shows intermediate stress zones.

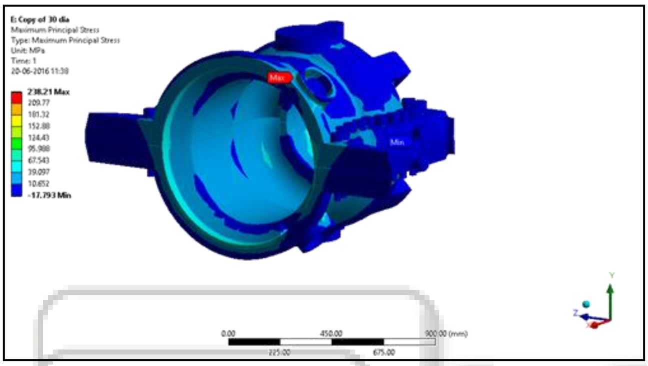

Fig. 7: Von Mises Stress is 238.21 MPa

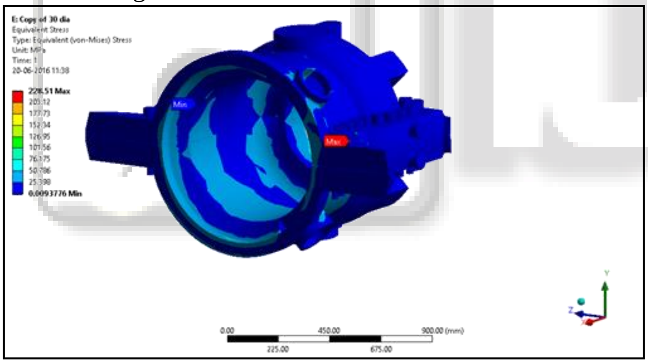

Fig. 8: Maximum Principal Stresses is 228.51Mpa

The results in fig7 & 8 describe about von mises stress and maximum principal stress developed in casing upon analysis. Since both the stresses are below the yield stress of chromium steel i.e. 535 MPa the design is safe under statical load conditions of 5MPa.

2) Minimum principal stress and deformation

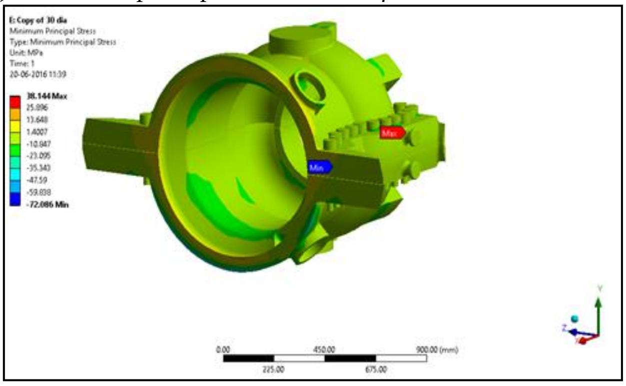

Fig. 9: Minimum Principal Stresses Is 38.144MPa

Minimum Principal Stress is the Minimum Stress developed for the casing under static load condition. Deformation is the change in geometry of component due to the effect of stresses.The stresses developed are displayed in various colour bands from red band to blue band. The red band shows the maximum stress and blue band shows the minimum stress. Remaining colour band shows intermediate stress zones.

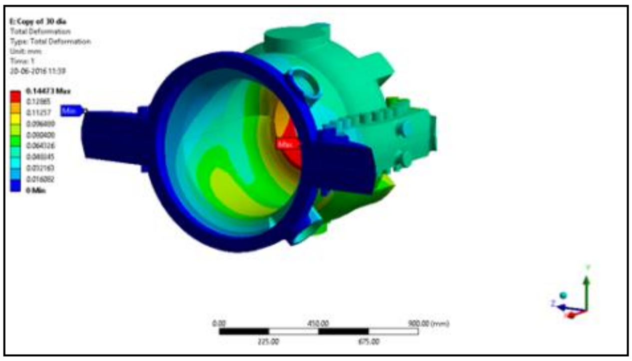

Fig. 10: Deformation in Casing is 0.1427

The results in fig 9 & 10 describes about minimum principal stress developed in casing upon analysis. Since stresses are below the yield stress of chromium steel i.e. 535 MPa the design is safe for statical load conditions of 5MPa. Since deformation (0.1427) developed is within 1 the design is safe for deformation effects.

B. Bolt Optimization

The diameter of each bolts are varied such as 40, 32, 26 by trial and error method. The inner pressure of 5MPa is applied for each cases. The solution is completed successfully for each cases. The post-processing results for each cases are tabulated as in below table.

Sl No.	Bolt size In (mm)	Von-Mises stress In (MPa)	Maximum Principal stress In (MPa)	Minimum Principal stress In (MPa)
1	40	228.51	238.21	38.144
2	32	204.15	178.66	28.326
3	26	126.88	139.64	19.526

Table 3: Bolt Diameters comparison and resuled stresses

Table 3 represents the comparison and resuled stresses It consists of 3 cases of bolt diameter chosen by trial and error method. The size of bolt size is 40, 32, and 26 respectively. The size of the bolt needs to be selected in decreasing order. The choice of bolt size is restricted to 26mm. If size of the bolt reduced further, the strength of the bolt is reduced, and also stresses developed upon application of temperature crosses yield limit based on the analysis done. The material fails after the yield limit and need to be avoided. The stresses developed for each cases are tabulated as above. It can be seen that the stresses are decreased as the size of the bolt are reduced. As the bolt size is reduced the area of the bolt hole is also reduced. This leads to the reduction of stress intensity area corresponding to the hole. All the cases have the stresses which is less than the yield stress of 535 MPa. Hence the basic criteria for designing are fulfilled. As compared from the above 3 cases, case 3 bolt size witnesses least stresses in all form of stresses and it is well within the yield stress. Since the stresses developed is within the yield stress and also because of the least stress case 3 is preferred over other cases.

VIII. CONCLUSIONS

The objectives of this present work are to study the Linear static analysis, Bolts optimization of casing of a steam turbine. In this work, the 2-D model of was generated with the help of drawing provided by the maxwatt company. The 2-D modelling was generated with the help of UG software. The same model is converted into 3-D model with the same software. The work is then imported to the ANSYS WORKBENCH 14.5 for the analysis process. Casings are subjected to very high pressure & high temperature steam. High pressure steam causes stresses on casing wall which is responsible for cracking & casing distortion (deformation) if it crosses yield stress. Model is imported & analysis commenced with linear static analysis for the casing with 40mm diameter bolts. Here, the pre-processing stage is carried out to give various inputs like mechanical properties, boundary conditions; pretension load (from theoretical calculations) is applied to check the static performance of casing under specified pressure of 5MPa. Solution stage is completed successfully for the given data. Results are discussed using von-mises stress, maximum principal stress, and minimum principal stress & deformation effects. Holes & notches are the critical area for crack growth as it is highly stress concentrated area. If it is reduced the stresses can be reduced greatly and also material can be saved considerably. The same procedure is repeated for the casing with 32mm and 26 mm bolts as done for 40mm diameter bolts. The static performance of casing is again solved for different bolt diameters and results are discussed for the optimization work.

From the study several conclusions can be drawn.

1) The linear static analysis showed that the design is safe for static pressure of 5MPa from the evidence of von-mises stress, principal stresses, deformation developed since it is well within the yield stress (535 MPa) specified for chromium steel and also deformation is under limiting value of 1.
2) The Static Analysis for different bolt dia i.e 40, 32, 26 of casing is performed and all the results were compared. The result proved that the casing with 26mm diameter has least stresses and it is recommended. Stress intensity area is reduced considerably.

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