Computer-Aided Stress Analysis and Optimization of Rolling Mill Housing

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ABSTRACT

This paper presents optimization of rolling mill housing design for rigidity to have better gage control of the material being rolled. The stress distribution of housing is analyzed using Computer-Aided Engineering (CAE) by calculating maximum static stress at critical areas. Comparing the stress distribution before and after the optimization, the stresses of housing after optimization has considerably been reduced under the given boundary conditions and is within the recommended value. To calculate the stresses in actual conditions, a prototype of optimized housing design is generated in 1:10 scale. The results of the CAE analysis are compared with the experimental results getting from the prototype of optimized design and a good correlation between the results has been observed.

Keywords: rolling mill housing, optimization, CAE analysis.
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1 INTRODUCTION

Rolling mill housing as shown in Fig. 1 encloses supports and adjusts rolls in the correct position. The rolling mill housing should be so strong that even though the roll may breaks, the housing does not deform plastically as its cost of manufacturing and time of replacement is excessively high. The forces, which act on the rolls during rolling, are completely transferred on to rolling housing through the nut of the adjusting mechanism. In addition, there exists a tendency for the roll stand to turn as a result of the torques acting on the rolls, which get transmitted to the housing in case of bearing seizures or when rolls are unable to pass the metal due to lack of sufficient power. So, the housing of rolling stand requires high rigidity, sufficient strength for taking the loads and minimum cost of production.
The objective of the work is to optimize rolling mill housing design for rigidity to have better gage control of the material being rolled. In choosing permissible stresses, the housing is the most expensive and important part of a rolling mill. The stress distribution of housing is analyzed using Computer-Aided Engineering (CAE) by calculating maximum static stress at critical areas. A prototype of optimized rolling mill housing design is generated in 1:10 scale to validate the results obtaining from CAE analysis.
In the field of structural analysis and optimization, a lot of literature is available and a number of researchers have worked upon it [2],[5],[15]. But, it is revealed that this field has not been much considered in the rolling mills. Toridis formulated a general method of static and dynamic analysis of two and three-dimensional framed structures based on finite element method [13]. Prager presented a method for the optimal design of a statically determinate or indeterminate truss [9]. Pandey developed computer simulations for rolling mills, which included optimization of roll pass sequence, calculation

of roll force, torque, temperature and detailed time studies for productivity calculations [10]. Braibant focused on the use of optimization technique in the framework of CAD. A design model was developed which could be used for structural sizing as well as for shape design [1]. Guo presented the stress analysis of rolling mill housing which was then used to calculate the life of the housing for the roll load [4]. Mahmoud recognized the structural optimization using mathematical programming technique, which can be employed efficiently only in conjunction with explicit approximate models [7]. Rong proposed a method for evolutionary structural optimization against buckling load of a structure of constant weight [11]. Salganik created a mathematical model of a rolling mill to solve various analytical problems of the system of rolls acting on strip in the rolling stands and their improvements [12]. Febres discussed a model of the behavior of metallic structures subjected to flexural effects and focused on the description of failure due to local buckling [3]. Maute presented an interactive method for the selection of design criteria and the formulation of optimization problem [6]. Malik developed a method to model both the static and dynamic characteristics of rolling mill deflection. By effectively combining numerical Finite Element Analysis (FEA) with analytical solid mechanics, the devised approach delivered a rapid, accurate, flexible, high-fidelity model useful for optimizing many important rolling parameters [8].

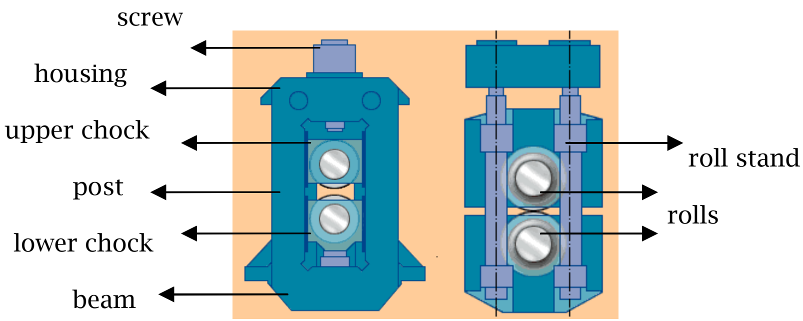

Fig. 1: Rolling mill housing.

2 ROLLING LOAD CALCULATION

The rolling load is taken by the roll neck bearings which are supported in the chocks; the lower chock rests on a spherical liner, which in turn is supported by the beam of the housing (Fig. 1). The upper chock has spherical seating on the screw. The rolling load is transferred through upper and lower chock to the housing. The rolling load for an industrial rolling mill with chromium steel rolls is calculated by Tselikov theory [14]. The rolling mill consist of roll neck bearings (number '23056') with diameter (d), outer diameter (D), width (B) and dynamic capacity (C) of values 280 mm, 420 mm, 106 mm and 1520 KN respectively. The load on the roll neck bearing and in the housing is considered as identical. Depending upon the material of the roll (chromium steel), rolling load (P) is calculated as 769.1 KN to 922.92 KN using the following equation.

$$P = (1.0\text{-}1.2)d^2, \text{ where P is in 'KN'} \qquad (1)$$

In order to achieve a minimum service life of about 30,000 hrs at 30 rpm, the rolling load is also calculated from its dynamic capacity and service life. The ratio of bearing capacity to rolling load (C/P) is derived as 3.25 from the life calculation chart [14] and accordingly rolling load is calculated as 465 KN for a bearing. Since each roll neck has two bearings, total load on two bearings is 930 KN. For the desired roll material and service life, 900 KN of rolling load is considered as design load for the rolling mill housing design.

3 ANALYSIS

The rolling load imparts tensile stress to the posts (vertical pillars), compressive stress to the screw and bending stress to the beams of housing. Due to bending in the beams, the posts will tend to bend inwards. This bending of the posts will induce compressive and tensile stresses at its outer and inner respectively. If the posts are slender and the beams are heavy, bending of the beams will be small with considerable bending of the posts. On the other hand, if the posts are heavy and the beams are light, then the beams will bend considerably with little bending of the posts. This phenomenon is known as hour-glassing effect. ANSYS finite element solver is used for the analysis of the housing and following steps are carried out:

- Modeling: A 3-D CAD model of the rolling mill housing is generated as shown in Fig. 2.
- Defining Element Type: A 20-nodded brick element is considered for the analysis.
- Defining Material Properties: Mild Steel is considered as a material for rolling mill housing and its properties are taken as per Tab. 1.
- Discretization: The CAD solid model is discretized into small elements depending upon the accuracy of results. Finer the mesh, more accurate will be the results.
- Applying Boundary Conditions: The base of the housing is fixed (Fig. 3). The design rolling load of +900 KN is applied on the cross section where the top chock rests and -900 KN on seat where the lower chock rests.
- Solution Solving: Simultaneous equations generated with the finite element method are solved by the analysis solver. The results are the nodal values giving the primary solution and derived values forming the element solution.
- Post-Processing: Post processing reviews the results of CAD model of the housing (Fig. 4).

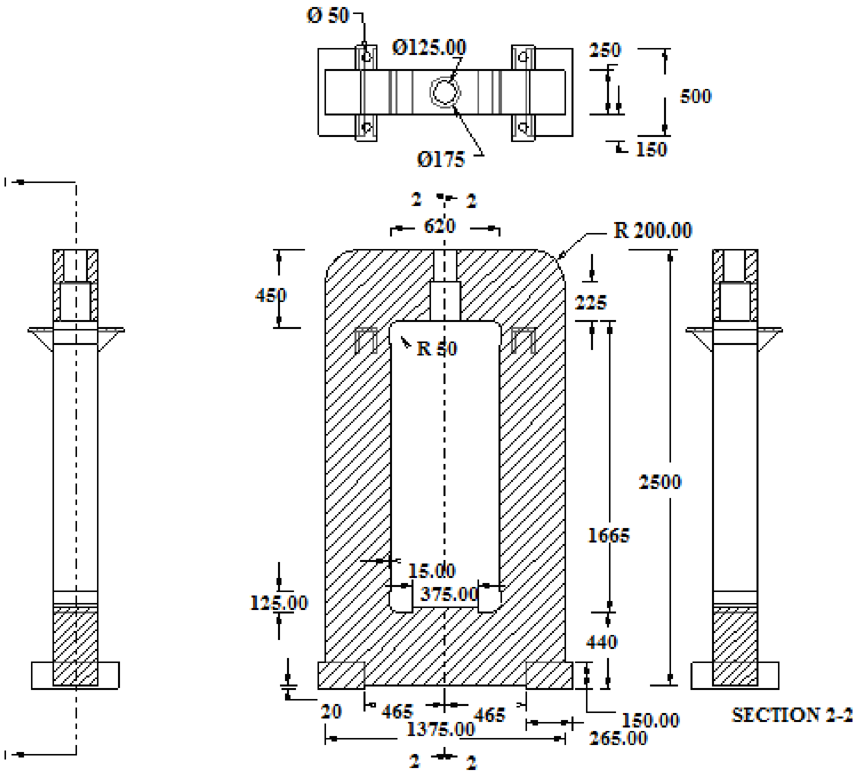

Fig. 2: Drawing of rolling mill housing before optimization.

Young’s Modulus	2e+11 N/m^2
Poisson Ratio	0.266
Density	7860 kg/m^3
Yield Strength	2.5e+008 N/m^2

Tab. 1: The structural properties of the mild steel material.

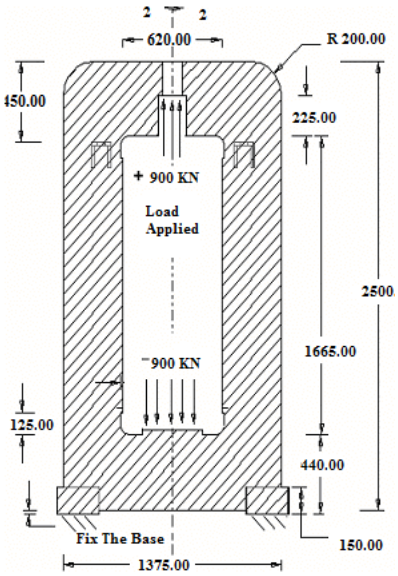

Fig. 3: Boundary conditions on rolling mill housing.

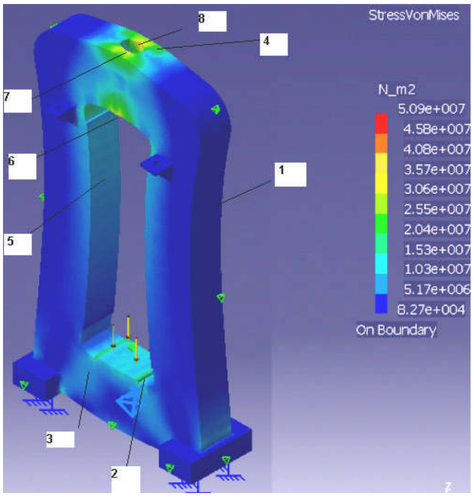

Fig. 4: Von-Mises stress analysis of rolling mill housing before optimization.

4 OPTIMIZATION

There are many famous CAE tools such as Pro-Mechanica, HyperSizer, ANSYS, MSC Nastran and NEi Nastran available in the market that can perform analysis and design optimization. All of these Finite Element Analysis (FEA) solvers can perform sizing, shape and topology optimizations. The optimization of rolling mill housing is performed with ANSYS which is an integrated analysis and design optimization software which characterizing a design process with design, state and objective variables. Several optimization methods are available with the software, but “Sub problem Approximation” method is used in the work defining design variables as independent variables and state variables as dependent variables. The optimization method minimizes the objective variable. The

dependent variables are replaced with approximations by means of least squares fitting. The method randomly generates value of design variables between the specified upper and lower limits and performs desired number of specified loops with random design variable values at each loop. Specified upper and lower limits are served as “constraints” on the design variables. At all iterations, minimization is performed on the approximated function until convergence is achieved.
It can be seen from the Fig. 4 that the stresses in the posts are within control limits (30-40 MN/m^2), so no change in its design is recommended. The beam of the housing experiences higher stresses at the place where nut of the housing screw is nested in the beam which may result into failure at that place. Therefore, design of the beam has to be optimized and the following steps are performed for optimization.

- Specify Design Variables: Diameter D_1 of uniform circular cross section added around the nut and diameter D_2 of hole where nut rests are chosen as design variables for optimization of the rolling mill housing (Fig. 5). Upper and lower limits are specified to serve as “constraints” on the design variables. These limits define the range of variation for the design variables. The ranges of D_1 and D_2 are 350-480 mm and 175-240 mm respectively.
- Specify State Variables: Total recommended stresses in the housing (30 $N/mm^2 < \sigma < 42$ N/mm^2) and total deflection of the rolling mill system (x<0.01 mm) are taken as state variables. Stress distribution in the housing should be uniform over the cross section to make it balanced design. For thin rolled products, the total deflection of the rolling mill system should be such that the stock material would be able to remain with-in the close tolerances.
- Define Objective Variable: The weight of the housing is considered as objective variable which is function of design variables and needs to be minimized. The weight of the mild steel housing is taken equal to (7.85 e-3) V, where V is the volume of housing.

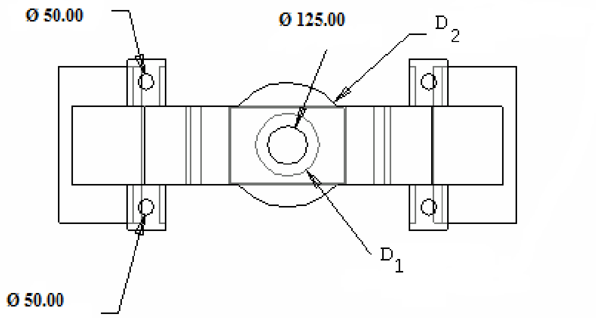

Fig. 5: Design variables for optimization of rolling mill housing.

After optimization, the values of design and state variables to obtain the objective function are retrieved as D_1 = 400 mm, D_2 = 200 mm, σ = 32.2 N/mm^2 and x = 0.905 e -5 mm. Comparing the results of analysis in Fig. 4 and Fig. 6, the stress distribution in the beam of housing is found to be more uniform after optimization. Stress values at critical areas (Tab.2) have considerably been reduced under the given conditions. The results are also plotted in Fig. 7 to have a better view of the distribution. Although the weight of the housing increases by about 70 kg (3.5%), but decrease in the stresses will ensure that no plastic deformation takes place even if the rolling load increases by 36%. Since the values of optimization variables are within the control limits, therefore design of the housing is optimized.

5 PROTOTYPE GENERATION

To calculate the stresses in actual conditions, a prototype for optimized housing is generated in 1:10 scale. Universal Testing Machine is used to apply the load on the prototype (Fig. 8). The strain gauges are calibrated and cemented at critical points (Fig. 9) to calculate the strain under varying load of 1-10 KN. The specifications of the strain gauges used in the experimental setup are shown in Tab. 3. Strain indicator circuit (Fig 10) having resistances R_1, R_2, R_3 and R_4 is used for calibrating the strain gauges. Under no load condition, the bridge is in balanced position. For input voltage (V_i) of 5 volt, the output voltage (V_o) and strain (e) are derived as:

$$V_o = (V_i/4)\ (\Delta R_1/R_1) \tag{2}$$

$$= (V_i/4)\ G_f\ (\Delta L/L) = (V_i/4)\ G_f\ e \tag{3}$$

$$e = (4V_o)/(V_i\, G_f) = 0.4V_o \tag{4}$$

The experimental values of strains under different loading conditions are found to further calculate value of stresses at critical points as represented in Tab. 4.

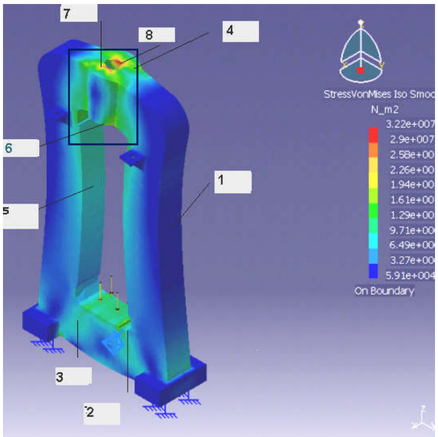

Fig. 6: Von Mises stress analysis after optimization.

Different locations of the housing	Stresses before optimization from Fig. 4 (N/mm²)	Stresses after optimization from Fig. 6 (N/mm²)
1	0.0827	0.0591
2	5.17	6.49
3	20.4	9.71
4	25.5	12.9
5	30.6	16.1
6	35.7	25.8
7	45.8	29
8	50.9	32.2

Tab. 2: Stresses before and after optimization.

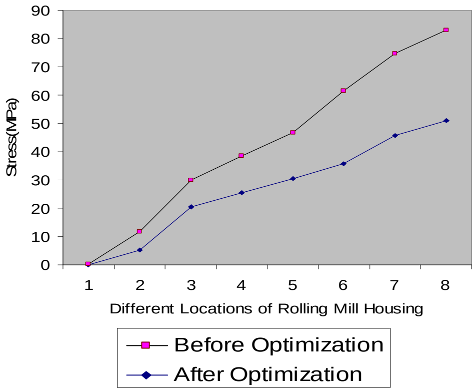

Fig. 7: The Comparison of stresses before and after optimization.

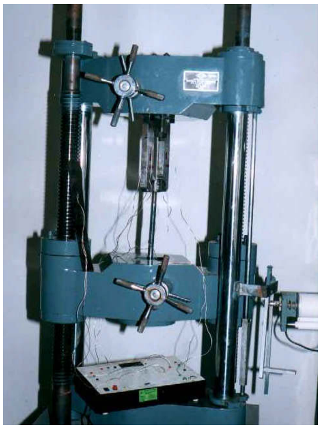

Fig. 8: Experimental setup.

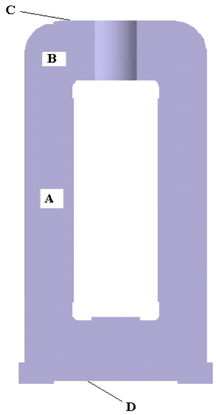

Fig. 9: Critical points on the housing.

Type	BKCT-10
Resistance in Ohms	120.2 ± 0.2
Gauge Factor (G_f)	2.0 ± 2%
Gauge Length (mm)	10

Tab. 3: Specifications of strain gauges.

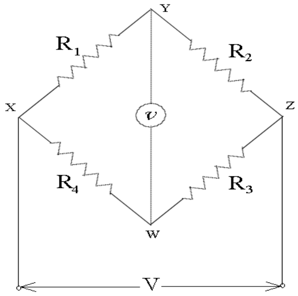

Fig. 10: Circuit used in strain indicator.

Load(KN)	Experimental Stress (MPa)			
	A	B	C	D
1	0.615	1.23	1.27	0.534
2	1.23	1.62	2.53	0.572
3	1.85	2.42	3.8	2.09
4	2.46	3.23	5.06	2.14
5	3.08	6.17	6.33	2.67
6	4.02	7.4	7.6	3.2
7	4.31	8.64	8.86	3.74
8	4.92	9.2	10.1	4.64
9	5.47	10.4	11.8	5.19
10	7.6	12.78	14.0	7.3

Tab. 4: Experimental stresses at critical points.

6 VALIDATION

For validation, the stress values on the optimized design of 1:10 scale after CAE analysis are derived (Tab. 5) and compared with the experimental stresses obtained from the prototype (Tab. 4). It is clear that analysis results are in good correlation with the experimental results as shown in Fig. 11.

Load(KN)	Stress on Optimized Design of 1:10 scale (MPa)			
	A	B	C	D
1	0.78	1.30	1.43	0.742
2	1.30	1.64	2.25	0.93
3	1.93	2.64	3.64	1.96
4	2.54	3.18	5.46	2.34
5	3.18	6.62	6.14	2.82
6	4.1	7.16	8.20	3.14
7	4.42	8.44	8.44	3.42
8	5.00	9.48	10.6	4.84
9	5.56	10.64	12.08	5.286
10	7.8	13.0	14.3	7.42

Tab. 5: Stress on optimized design of 1:10 scale after CAE analysis.

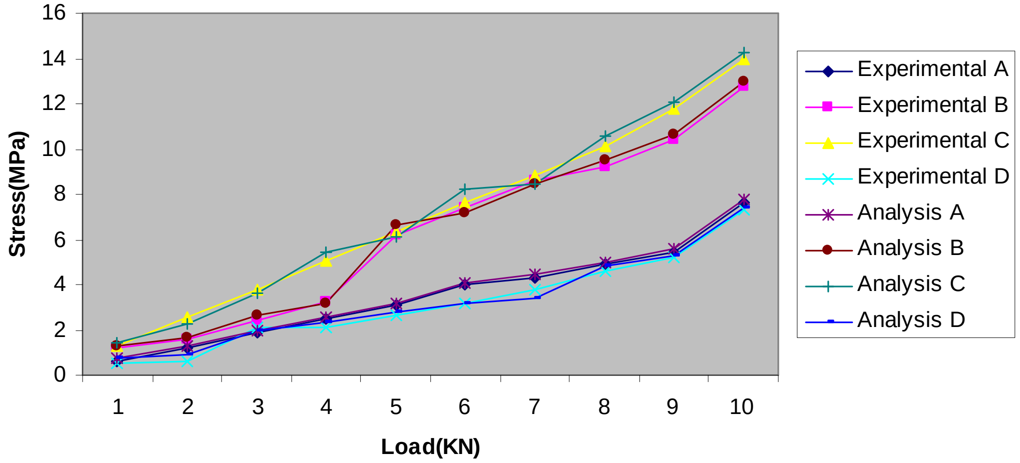

Fig. 11: Comparison between experimental and analysis results.

7 CONCLUDING REMARKS

The fatigue failure of the rolling mill housing has been found to be a very common problem in industries. This problem is very difficult to solve analytically due to complicated structural behavior of the rolling mill housing under a given loading and boundary conditions. Therefore, this failure problem has been efficiently solved using CAE with an integrated analysis and design optimization software ANSYS.

Stress analysis concludes that stresses in the housing posts are within the control limits. Higher stresses are induced at the place where nut of the housing screw is nested in the beam of housing which may result into failure at that place. The beam of housing has been optimized to drop the induced stress within the control limits which may otherwise fail the housing and involve high cost of manufacturing and time of replacement. Stresses at critical areas of the beam of housing have considerably been reduced under the given conditions after optimization and are within the

recommended values. Although the objective function (weight of the housing) increases by about 3.5% after optimization, but the decrease in the stresses would ensure that no plastic deformation takes place even if the rolling load increases by 36%.
For validation, a prototype in 1:10 scale with modified dimensions has been created. Comparing the stress values after optimization with the experimental values obtained from the prototype, it is revealed that a good correlation between the results has been observed.

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