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Optimization and Analysis of Steel Stacks for Weight Reduction.

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Abstract: *In today's highly competent world, it has become very important to design an efficient and cost effective system. Proper analytical and optimum design concepts are needed to design such systems. Steel stacks play an important role in this era of industrialization. Stacks are vertical tall slender structures which discharge chemical waste gases from industries to the atmosphere. The main aim of this paper is to minimize total weight and thus, cost of the steel chimney. Our attempt is to generate data and optimize the various design parameters of steel stack. Weight reduction of steel stack will occur by reducing values of the design variables but to an extent such that the steel stack continues to stand and it does not fail in stress analysis. Wind force calculations, stress calculations and deflection calculations have been done in excel sheet referring to IS 875 and IS 6533. Further optimization of these design parameters have been done referring to BS code guidelines. This excel sheet program will also save an individual's time for manual calculations. Analysis of steel stack has been done using ANSYS WORKBENCH. Optimization techniques play a big role in structural design. The purpose is to find an economic path so that a designer or a decision maker can derive maximum benefit from the available resources.*

Keywords: *Steel Stack, IS: Indian standards, BS: British Standards, UBC: Uniform Building Code, Static wind force, Static wind moment, Stress Analysis, Deformation Analysis*

I. Introduction

A stack or a chimney is a vertical tall structure through which smoke and combustion gases pass out of a building. Stacks are used to emit the exhaust gases higher up in the atmosphere so that diffusion of gases may take place. Stacks may be constructed of steel or R.C.C. Steel stacks are mainly used in the sugar factories, food processing industries, thermal plants etc[1]. Steel stacks are suited for process work where a short heat-up period and low thermal capacity are required. Also, steel chimneys are economical for height up to 45 to 50 m. [2]. Steel chimneys experience various loads in vertical and lateral directions. Steel stack often experiences wind loads, earthquake loads, and temperature loads apart from self-weight. Tall and slender steel stacks are susceptible to wind action. Hence, wind loading is an important design criteria[3].

Fig.1 Industrial Steel Stacks

In this work, analysis of steel stack is performed by analytical and simulation for wind loads. The weight of the stack depends on the design variables. These design variables are stack diameters (d), shell thickness (t), and height (h). Wind forces, wind moments, stresses (bending, direct & total) and deflections are calculated using the input values. The value of allowable stress depends on the type of material used. The calculated total stress should be smaller than the allowable stress for steel stack. Similarly, the observed deflections should albe less than the calculated deflections for the stack to stand. In order to optimize the input variables certain iterations have been performed in the excel sheet program considering the stress and deflection checks.

II. Problem Formulation And Objectives

Optimization and analysis of steel stack for weight reduction using BS Code guidelines.

i. Finding and finalizing the design parameters of steel stack to be varied.
ii. Optimizing the design variables of the existing steel stack on excel sheet.
iii. Creating a standardized excel sheet program to reduce human efforts and errors.
iv. Simulation and analysis of steel stack using Ansys Workbench.

III. Terminology

1. Wind loads

The wind force acting on steel stack depends upon its location and height. Wind pressure varies with height. Hence, the stack has to be divided into a number of sections to calculate wind force correctly. The wind pressure acting over each section is assumed to be uniform and the resultant is assumed to be acting at mid-height of that portion. These wind forces result in bending moment in steel stack[4].

2. Design Wind Pressure

The design wind pressure at any height above ground level can be calculated by using the following relationship between wind pressure, P_z (N/m²), and the design wind velocity, V_z (m/s):-

$$P_z = 0.6V_z^2$$

The coefficient 0.6 in the above equation depends upon a number of factors and primarily on the atmospheric pressure and air temperature. The design wind velocity at any height of steel stack is obtained from the basic wind speed (V_b). Basic wind speed depends on the following factors: (1) risk level, (2) terrain roughness, (3) Size and height of structure and (4) local topography. It can be mathematically expressed as:-

$$V_z = V_b \times k_1 \times k_2 \times k_3$$

Where

V_b= basic wind speed

K_1 = probability factor (risk coefficient)

K_2 = multiplying factor by which the basic wind speed is multiplied to obtain the wind speed at different heights in each terrain category.

K_3 = the topography factor.

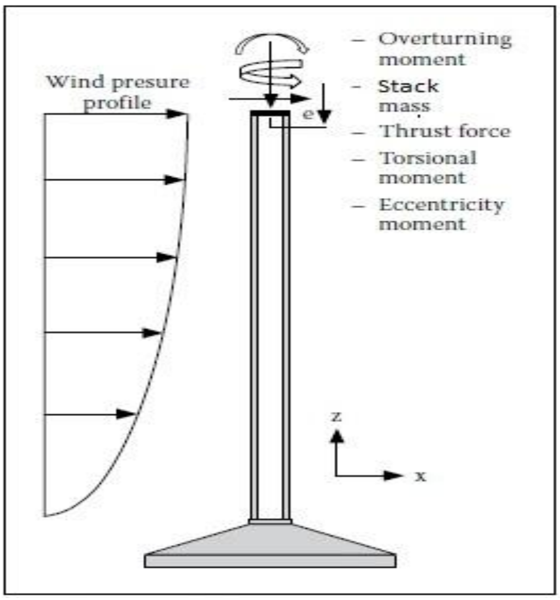

Fig 2. Wind load Profile on steel stacks

Note:- k_1 and k_3 are fixed depending upon zone, life of structure, terrain category and class of structure.
k_2 varies with height of element.
Terrain category:
It is classified according to the characteristics of ground surface irregularities. They are numbered in increasing order of roughness[5].

3. Wind Force
Wind force is the product of wind pressure acting on each segment and surface area at each segment.

4. Wind shear
Wind shear is calculated by cumulative addition of wind forces acting on each segment of stack. Wind velocity varies along a direction at right angles to the wind's direction which exerts turning force.

5. Wind Moment
Wind moment for each segment is the cumulative sum of product of wind force and vertical distance of each segment.

IV. Analytical Method
In this work, the input design variables considered are height, diameter and thickness for weight reduction. The steel stack of 35m height and 2.4m diameter of weight 28754 kg is considered. Wind velocity considered is 45 m/s. The temperature of stack is 250°C. The excel sheet calculations for stresses and deformation have been performed as given below:

Table 1: Input for stack problem

Outer diameter	Inner diameter	Total height
2.4	2	35

The wind pressure calculations has been done as per UBC 1997 (DIV III)[7]. In our example we have considered the basic wind speed as 45 m/s.
The design wind pressure has been calculated by the following formula :-

$$\mathbf{P_z = C_e \times C_q \times q_s \times l_w}$$

Where,
Pz = design wind pressure
Ce = Combined height, exposure and gust factor coefficient (Refer Table 1)

Table 2: Values of Ce

UBC 97	
Mtr	Ce
0.0000	1.0600
4.5720	1.0600
6.0960	1.1300
7.6200	1.1900
9.1440	1.2300
12.1920	1.3100
18.2880	1.4300
24.3840	1.5300
30.4800	1.6100
36.5760	1.6700
48.7680	1.7900
60.9600	1.8700
91.4400	2.0500

Cq = Pressure coefficient of structure
= 0.8
lw = Importance factor=1
qs = Wind stagnation pressure (Corresponding to design wind speed)
= 125 kg/sqm
Static Wind force on the shell is calculated as
F = (Do x Pz x Cf x 1) Kg

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Where
Do = Outside diameter of stack
Cf = Shape factor

Static wind shear at a section is the sum of wind forces acting at sections above it and also includes the wind force at that section.

Direct stress is calculated by

$$\text{Direct Stress} = \frac{\text{Shell weight}}{\text{Corroded shell area}} \quad \text{(kg/sq.cm)}$$

Bending stress is calculated by

$$\text{Bending stres} = \frac{\text{Moment at the Base}}{(I / r)} \quad \text{(kg/sq.cm)}$$

r = Radius of the shell, in meter
I = corroded moment of inertia (m^4)

Total Stress is calculated by

Total Stress = Direct stress + Bending stress (kg/sq.cm)

Allowable stress is calculated by taking into account the most adverse temperature to which stack may be expected to exposed[6].

Table3: Temperature coefficient K_t

Temp in C	200	250	300	350	400
K_t	1.0	0.75	0.67	0.6	0.5

Since the temperature of stack is 250^0C , the value of temperature coefficient is 0.75.

Stack Deflection is calculated by

$$\text{Deflection} = \frac{FL^3}{3EI}$$

Where
F = Wind Force
L = Length of each segment
E = Young's Modulus
I = Moment of Inertia

V. Numerical Method

The 3D modelling and analysis of steel stack is done using Ansys Workbench.

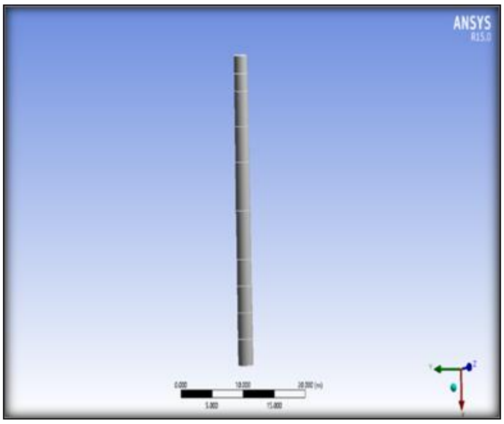

Fig.3a) 3D model of steel stack

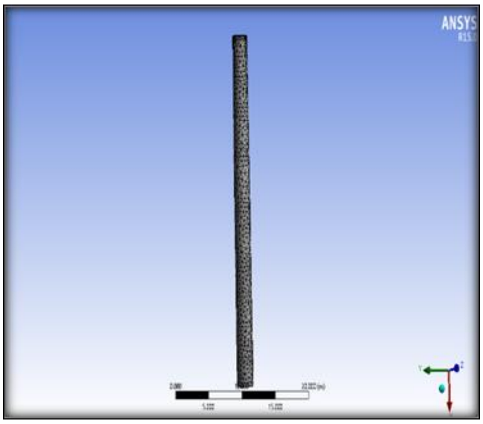

Fig.3b) Meshing Model of steel stack

Fig.3a). shows 3D model of steel stack and Fig.3b) shows the meshing model of steel stack. Since, the analysis is being done on steel stack, the material selected is structural steel. The 35m steel stack has been divided into 5 sections of varying thickness. Wind forces and wind moments for each section is applied at the centroid of each section of steel stack. Total deformation and stress analysis has been done on steel stack.

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VI. Results And Discussions

In this paper we have performed the above mentioned wind force, wind moment calculations in the excel sheet.

1) Summary Calculation

Summary of the excel sheet calculation is as follows:

Table 4-Existing Steel Stack

Elevation from base H (m)	Outside Dia Do (mm)	Shell thickness t (mm)	Static Wind Force (N)	Static Wind Moment (N/m)	Total Stress (N/mm^2)	Allow-able stress (N/mm^2)	Total deflection (mm)	Allow-able deflection (mm)	U.C Ratio
0-6	2400	20	1767.21	1920799.37	23.3	70.31	0.0043	15	0.33
6-12	2400	16	2040.32	1319817.78	20.13	70.31	0.14	47.5	0.29
12-23	2400	12	2340.725	674581.079	13.97	70.31	1.28	90	0.20
23-31	2400	10	4437.102	158686.56	4.33	70.31	8.16	137.5	0.06
31-35	2400	8	4632.75	11646.92	0.6	70.31	15.98	167.5	0.0085

Output : Total weight of stack = 28754 kg

Table 5-Optimization of steel stack for change in diameter

Elevation from base H (m)	Outside Dia Do (mm)	Shell thickness t (mm)	Static Wind Force (N)	Static Wind Moment (N/m)	Total Stress (N/mm^2)	Allow-able stress (N/mm^2)	Total deflection (mm)	Allow-able deflection (mm)	U.C Ratio
0-6	2200	20	1619.94	1760733.84	25.23	70.313	0.007	15	0.36
6-12	2200	16	1870.03	1209832.965	21.79	70.313	0.165	47.5	0.31
12-23	2200	12	1960.8	539138.87	15.14	70.313	1.52	90	0.21
23-31	2200	10	3565.24	145462.68	4.65	70.313	9.69	137.5	0.066
31-35	2200	8	4314.67	10680.64	0.625	70.313	18.99	167.5	0.008

From Table 6**,**

Output : Total weight of stack = 26387

Weight reduction : 8.23%

Output : Total weight of stack = 22827 kg

Weight reduction : 20.61%

In this work, U.C ratio or stress check has been calculated. U.C Ratio is calculated as ratio of total stress to allowable stress. U.C Ratio is less than 0.8 for the considered stack, hence, it is completely safe.In this work deflection check has also been performed. Since deflection is less than allowable deflection of 175 mm (height/200) hence stack is safe in deflection

.

2) Software Analysis

Total deformation and stress analysis has been done on steel stack.

Fig. 4 shows deformation analysis for existing stack

Table 6-Optimization of steel stack for change in thickness

Elevation from base H (m)	Outside Dia Do (mm)	Shell thickness t (mm)	Static Wind Force (N)	Static Wind Moment (N/m)	Total Stress (N/mm^2)	Allowable stress (N/mm^2)	Total deflection (mm)	Allowable deflection (mm)	U.C Ratio
0-6	2400	16	1767.21	1920799.373	28.7	70.313	0.0043	15	0.41
6-12	2400	12	2040.32	1319817.78	26.45	70.313	0.14	47.5	0.38
12-23	2400	10	2340.725	674581.0792	16.53	70.313	1.28	90	0.24
23-31	2400	8	4437.102	158686.56	5.25	70.313	8.2	137.5	0.075
31-35	2400	6	4632.75	11646.923	0.73	70.313	16.06	167.5	0.01

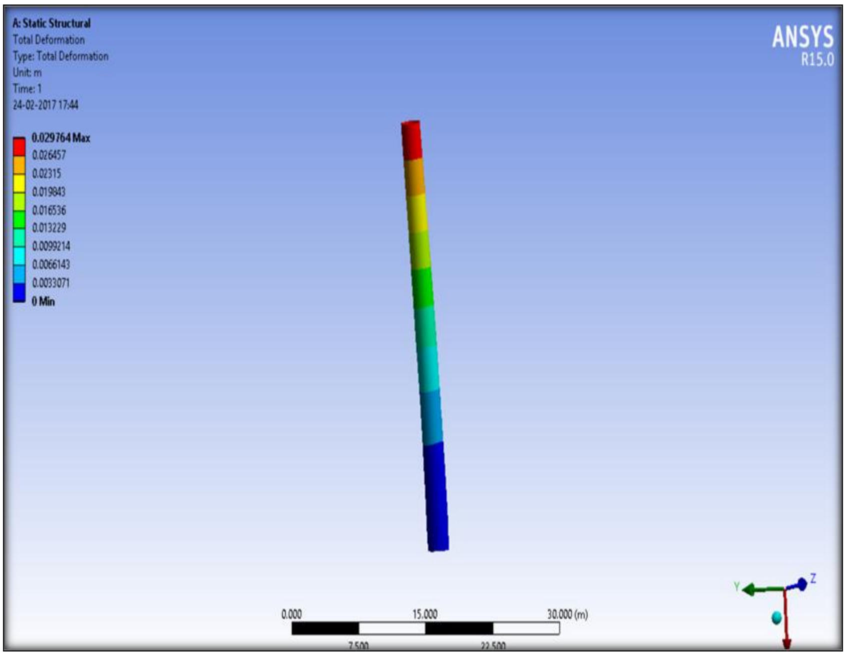

Fig.4. Deformation Analysis on Existing Stack

Fig. 5 shows stress analysis for existing stack and Fig. 6 shows deformation analysis for optimized stack . Fig. 7 shows stress analysis for optimized stack. In the second iteration,diameter is unvaried, hence, the forces and moments acting on stack is same as original.Maximum stress values and deformation values for the existing stack obtained from table 4 is almost similar to the corresponding values obtained from figure 4 and figure 5.Similarly, maximum stress and deformation values for the optimized stack obtained from Table 5 is almost similar to the corresponding values obtained from Figs. 6 and 7.

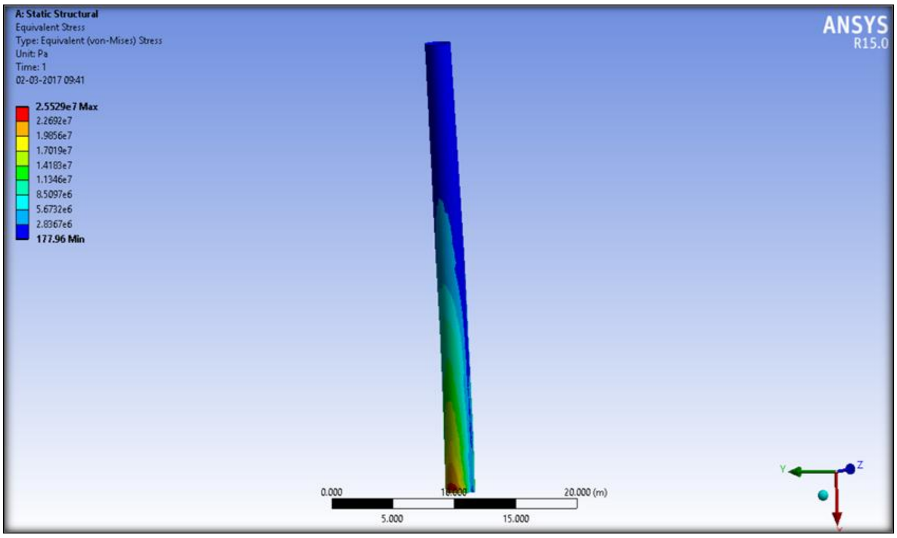

Fig.5.Stress Analysis on Existing Stack

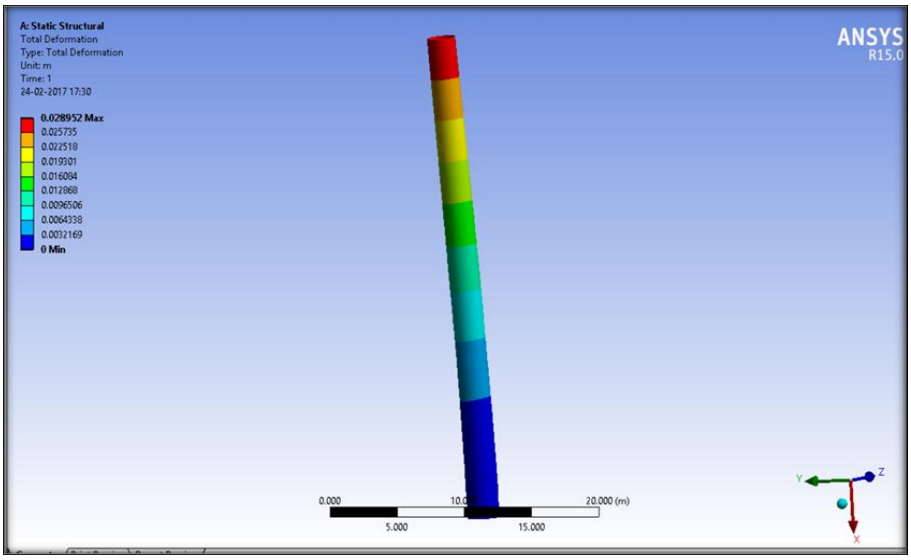

Fig 6 Deformation Analysis on optimized stack

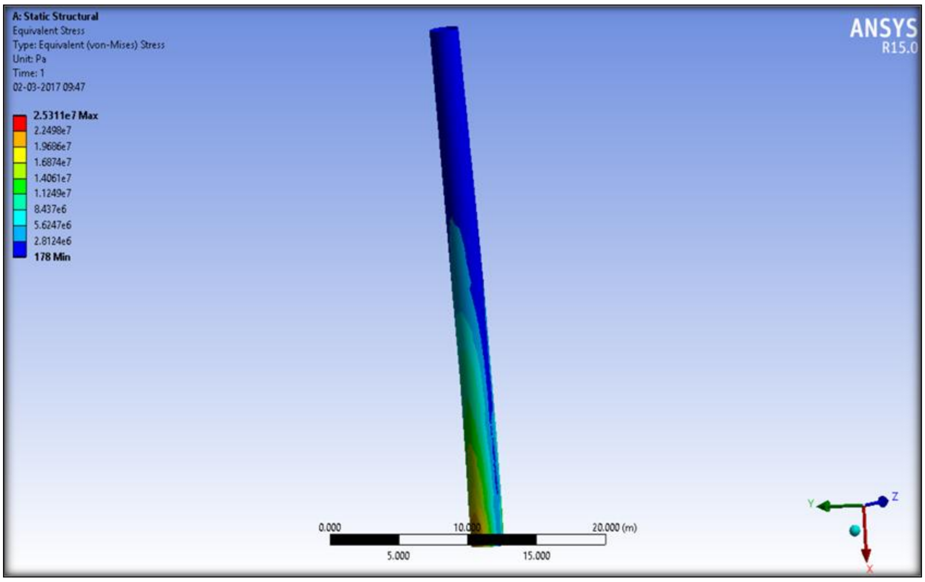

Fig 7 Stress Analysis on optimized stack

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VII. Conclusion

Two iterations for optimization have been performed on the already existing stack.

- In the first optimization, the outer diameter was reduced from 2.4 m to 2.2 which resulted in 8.23 % weight reduction.
- In the second optimization, the thickness of varying sections were reduced which resulted in 20.91% weight reduction
- The design is safe as the ratio of total stress to allowable stress is below the limit(< 0.8).

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