ANALYSIS OF SELF SUPPORTED STEEL CHIMNEY AS PER INDIAN STANDARD

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This is to certify that the thesis entitled, "**ANALYSIS OF SELF SUPPORTED STEEL CHIMNEY AS PER INDIAN STANDARD**" submitted by **Kirtikanta Sahoo** in partial fulfillment of the requirement for the award of **Master of Technology** degree in **Civil Engineering** with specialization in **Structural Engineering** at the National Institute of Technology Rourkela is an authentic work carried out by her under our supervision and guidance. To the best of our knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: self supporting steel chimney, dynamic wind, vortex shedding, geometry limitations, resonance, stroughal critical velocity

Most of the industrial steel chimneys are tall structures with circular cross-sections. Such slender, lightly damped structures are prone to wind-exited vibration. Geometry of a self supporting steel chimney plays an important role in its structural behaviour under lateral dynamic loading. This is because geometry is primarily responsible for the stiffness parameters of the chimney. However, basic dimensions of industrial self supporting steel chimney, such as height, diameter at exit, etc., are generally derived from the associated environmental conditions. To ensure a desired failure mode design code (IS-6533: 1989 Part 2) imposes several criteria on the geometry (top-to-base diameter ratio and height-to-base diameter ratio) of steel chimneys. The objective of the present study is to justify the code criteria with regard to basic dimensions of industrial steel chimney.

A total of 66 numbers self supporting steel flared unlined chimneys with different top-to-base diameter ratio and height-to-base diameter ratio were considered for this study. The thickness of the chimney was kept constant for all the cases. Maximum bending moment and stress for all the chimneys were calculated for dynamic wind load as per the procedure given in IS 6533: 1989 (Part 2) using MathCAD software. Also the results were verified with the finite element analysis using commercial software ANSYS. Basic wind speed of 210 km/h

which corresponds to costal Orissa area is considered for these calculations. Maximum base moments and associated steel stresses were plotted as a function of top-to-base diameter ratio and height-to-base diameter ratio. The results obtained from this analysis do not agree with the code criteria.

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ABBREVIATIONS

ACI	American Concrete Institute
ASME	American Society of Mechanical Engineers
CICIND	International Committee on Industrial Chimneys
DIN	Deutsches Institut für Normung
IS	Indian Standards
GLC	Ground level concentration
MEF	Ministry of Environment and Forest

NOTATIONS

ENGLISH

A	Area of section normal to wind direction
A_h	Horizontal acceleration spectrum
A_n	Aerodynamic admittance at the structure's natural frequency
C	Maximum permissible ground level concentration of pollutant
C_d	Drag coefficient
$C_{permissible}$	Maximum permissible ground level concentration pollutants
C_t	Coefficient depending on slenderness ratio of the structure
C_T	Coefficient depending upon slenderness ratio
D	Mean diameter at the chimney
D_{fuel}	Density of the fuel
d_m	Mass of the chimney
E_s	Modulus of elasticity of material of the structural shell
F	Fundamental frequency
F_d	Drag force
$F_{dust=}$	Dimensionless coefficient rate of precipatations
f_y	Yield stress of the steel
G	Acceleration due to gravity
H	Height of the structure above the base
I	Importance factor
K_1	Probability factor (risk coefficient)

K_2	Terrain, height and structure size factor
K_3	Topography factor
M	Estimated mass rate of emission of pollutants
m_k	coefficient of pulsation of speed thrust
$Q_{sulphur}$	Total quantity of the sulphur quantity
Q_t	Quantity of the gas
R	Response reduction factor
R_e	Reyonlds number
$S_{a/g}$	Spectral acceleration coefficient
T_i	The period of i^{th} mode
$\bar{U}_t$	Mean wind speed at top of a chimney
ν	Coefficient which takes care of the space
V	Estimated volume rates of emission of total flue gases
V_b	Basic wind speed
V_B	Design base shear
V_z	Design wind speed
W_t	Total weight of the structure including weight of lining and contents above the base
W_{fuel}	Weight of the fuel
Z	Zone factor

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Chimneys or stacks are very important industrial structures for emission of poisonous gases to a higher elevation such that the gases do not contaminate surrounding atmosphere. These structures are tall, slender and generally with circular cross-sections. Different construction materials, such as concrete, steel or masonry, are used to build chimneys. Steel chimneys are ideally suited for process work where a short heat-up period and low thermal capacity are required. Also, steel chimneys are economical for height upto 45m. Fig. 1 shows a photograph of self-supporting steel chimneys located in an industrial plant.

Fig. 1: Self-supporting Steel Chimney (ref. http://www.comdynam.com/)

There are many standards available for designing self supporting industrial steel chimneys: Indian Standard IS 6533: 1989 (Part-1 and Part-2), Standards of International Committee on Industrial Chimneys CICIND 1999 (rev 1), etc.

Geometry of a self supporting steel chimney plays an important role in its structural behaviour under lateral dynamic loading. This is because geometry is primarily responsible for the stiffness parameters of the chimney. However, the basic geometrical parameters of the steel chimney (*e.g.*, overall height, diameter at exit, etc.) are associated with the corresponding environmental conditions. On top of that design code (IS-6533: 1989 Part 2) imposes several criteria on the geometry of steel chimneys to ensure a desired failure mode. Two important IS-6533: 1989 recommended geometry limitations for designing self supporting steel chimneys are as follows:

i) Minimum outside diameter of the unlined chimney at the top should be one twentieth of the height of the cylindrical portion of the chimney.

ii) Minimum outside diameter of the unlined flared chimney at the base should be 1.6 times the outside diameter of the chimney at top.

Present study attempts to justify these limitations imposed by the deign codes through finite element analyses of steel chimneys with various geometrical configurations.

1.2 LITERATURE REVIEW

A literature review is carried out on the design and analysis of steel chimney with special interest on the geometrical limitations. Although a number of literatures are available on the design and analysis of steel chimney there are only two published literature found that deals with the geometrical aspects of steel chimney. This section presents a brief report on the literatures reviewed as part of this project.

Menon and Rao (1997) reviews the international code procedures to evaluate the across wind response of RC chimneys. The disparities in the codal estimates of across wind moments as well as the load factor specifications are examined in this paper through reliability approach. This paper recommends that it is necessary to design for the across wind loading at certain conditions.

Chmielewski, *et. al*. (2005) studied about natural frequencies and natural modes of 250 m high-multi-flue industrial RC chimney with the flexibility of soil. This paper used finite element method for analysis. Also, experimental work to investigate the free vibration response is carried out by using two geophone sensors and experimental results are compared with analytical results. The results show that the soil flexibility under the foundation influences the natural modes and natural periods of the chimney by considerable margin.

Ciesielski, *et. al*. (1996) observed cross vibration on a steel chimney arising out of aerodynamic phenomenon. This paper shows that specially designed turbulizers, mechanical dampers can reduce this cross vibrations considerably.

Ciesielski, *et. al*. (1992) gives information on vortex excitation response of towers and steel chimney due to cross wind. A model is proposed to calculate maximum displacement of the chimney at top due to cross wind and the results are reported to match closely with the observed maximum top displacement.

Flaga and Lipecki (2010) analysed the lateral response of steel and concrete chimneys of circular cross-sections due to vortex excitation. A mathematical model of vortex shedding is proposed for calculating maximum displacement of the chimney at top due to vortex shedding.

Gaczek and Kawecki (1996) explained about the cross-wind response of steel chimneys with spoilers. 3-start helical strake system with strakes of pitch 5D is explained in this paper. Also, it is reported that the top displacement of a chimney depends on the parameter of excitation.

Galemann and Ruscheweyh (1992) presented the experimental work on measurements of wind induced vibrations of a steel chimney. For the along-wind vibration, the aerodynamic admission function has been developed from the vertical coherence of the wind speed as well as from the dynamic response directly. It is shown that the interaction effect between the strouhal frequency and the natural frequency of the chimney should produce a new exciting frequency which is lower than the strouhal frequency.

Hirsch and Ruscheweyh (1975) also analysed a steel chimney which is collapsed due to wind-induced vibrations. The analysis considered cross-wind oscillations of steel stacks of given structural data (such as natural frequencies and log decrements). Hydraulic automotive shock-absorber to prevent vortex-induced oscillations is also demonstrated in this paper.

Kareem and Hseih (1986) carried out the reliability analysis of concrete chimneys under wind loading. In this paper, safety criteria are taken into consideration. Excessive deflection at the top of the chimney and exceedence of the ultimate moment capacity of the chimney cross-section at any level were taken as failure criterion. Formulation for wind-induced load effects, in the both along-wind and across-wind directions, is presented according to the probabilistic structural dynamics. Covariance integration method is used to formulate a special description of fluctuating wind load effects on chimneys. Load effects and structural resistance parameters are treated as random variables. These random variables are divided into three categories such as, wind environment and meteorological data, parameters reflecting wind-structure interactions and structural properties.

Kawecki and Zuranski (2007) measured the damping properties of the steel chimney due to cross-wind vibrations and also compared different approaches to the calculation of relative amplitude of vibration at small scruton number. They also gave importance to climatic conditions during vibrations. They also presented better description of cross-wind vibrations according to the Eurocode and CICIND model code.

Ogendo, *et. al*. (1983) presented a theoretical analysis that shows that for a large class of steel chimney designs a resilient damping layer at the base can help to achieve a sufficiently high overall damping level to inhibit significant vortex-induced vibrations. Also, it is concluded from full-scale experiments that the system damping level can be increased by a factor of up to 3.

Pallares, *et. al*. (2006) discusses about the seismic behaviour of an unreinforced masonry chimney. A 3D finite element non-linear analysis is carried out incorporating cracking and crushing phenomena to obtain lateral displacements, crack pattern and failure mode. Also the maximum earthquake in terms of peak ground motion that the chimney can withstand is obtained.

Verboom and Koten (2010) shows that the design rules for cross-wind vibrations for steel chimney given by DIN 4133 and CICIND model code can differ by a factor 6 or more in terms of stress. Chimneys are modelled according to the Vickery-Basu model. This paper formulates a design rule that computes more accurately the stresses in industrial chimneys due to vortex excitation. It is shown that the results obtained from this formulation gives superior results compared to the DIN 4133 or CICIND model code.

Wilson (2003) conducted experimental program to show the earthquake response of tall reinforced concrete chimney. A non-linear dynamic analysis procedure is developed to evaluate the inelastic response of tall concrete chimney subjected to earthquake excitation. Based on experiments, the results encourage reliance on the development of ductility in reinforced concrete chimneys to prevent the formation of brittle failure modes.

Kiran (2001) presented design and analysis of concrete chimney in conformity with various code such as IS 4998, ACI 307, CICIND, etc.

The literature review presented above shows that there are a number of published work on steel and concrete chimneys. Experimental and theoretical studies are presented on the behaviour of tall chimneys subjected to wind and seismic force. It is found that majority of the research papers on chimney are concentrated on its response to vortex shedding. However, a very less research effort is found on the geometric limitations of the design code with regard to steel chimneys.

1.3 OBJECTIVES

Based on the literature review presented in the previous section the objective of the present study is defined as follows:

- Assess the geometry limitations imposed by IS 6533:1989 for designing self supporting steel chimney.

1.4 SCOPE

i) Self-supporting flared steel chimney is considered for the present study

ii) Chimneys are considered to be fixed at their support. Soil flexibility is not considered in the present study

iii) All chimneys considered here are of single-flue type

iv) Uniform thickness is considered over the full height of the chimney.

v) Only wind load and seismic load are taken into consideration for design of the chimney.

1.5 METHODOLOGY

To achieve the above objective following step-by-step procedures are followed:

- Carry out literature study to find out the objectives of the project work.
- Understand the design procedure of a self-supporting steel chimney as per Indian Standard IS 6533:1989.
- Select various chimney geometry considering and ignoring code (IS 6533:1989) limitations.
- Analyse all the selected chimney models using manual calculations (MathCAD) and finite element analysis (ANSYS).
- Evaluate the analysis results and verify the requirement of the geometrical limitations.

1.6 ORGANISATION OF THE THESIS

This introductory chapter (Chapter 1) presents the background and motivation behind this study followed by a brief report on the literature survey. The objective, scope and methodology of the proposed research work are also presented in this chapter.

Chapter 2 reviews load effects on the steel chimney as per Indian Standard. It also describe about the nature and effects of each type of load including the calculation of the loads.

Chapter 3 explains the design and analysis of steel chimney as per IS 6533: 1989 (Part 1 & 2). The design procedure is demonstrated through sample calculations.

Chapter 4 presents the effect of geometry on the design of self supporting steel chimney and critically evaluate the geometric limitations imposed by IS 6533:1989.

Chapter 5 presents the summery and conclusion obtained from the present study.

CHAPTER 2

LOAD EFFECTS ON STEEL CHIMNEY

2.1 OVERVIEW

Self supporting steel chimneys experience various loads in vertical and lateral directions. Important loads that a steel chimney often experiences are wind loads, earthquake loads, and temperature loads apart from self weight, loads from the attachments, imposed loads on the service platforms. Wind effects on chimney plays an important role on its safety as steel chimneys are generally very tall structures. The circular cross section of the chimney subjects to aerodynamic lift under wind load.

Again seismic load is a major consideration for chimney as it is considered as natural load. This load is normally dynamic in nature. According to code provision quasi-static methods are used for evaluation of this load and recommend amplification of the normalized response of the chimney with a factor that depending on the soil and intensity of earthquake.

In majority of the cases flue gases with very high temperature released inside a chimney. Due to this a temperature gradient with respect to ambient temperature outside is developed and hence caused for stresses in the cell. Therefore, temperature effects are also important factor to be considered in the steel design of chimney.

This chapter describes the wind load and seismic load effects on self-supporting steel chimney.

2.2 WIND ENGINEERING

For self-supporting steel chimney, wind is considered as major source of loads. This load can be divided into two components respectively such as,

i) Along-wind effect

ii) Across -wind effect

The wind load exerted at any point on a chimney can be considered as the sum of quasi-static and a dynamic-load component. The static-load component is that force which wind will exert if it blows at a mean (time-average) steady speed and which will tend to produce a steady displacement in a structure. The dynamic component, which can cause oscillations of a structure, is generated due to the following reasons:

i) Gusts

ii) Vortex shedding

iii) Buffeting

2.2.1. Along Wind Effects

Along wind effects are happened by the drag component of the wind force on the chimney. When wind flows on the face of the structure, a direct buffeting action is produced. To estimate such type of loads it is required to model the chimney as a cantilever, fixed to the ground. In this model the wind load is acting on the exposed face of the chimney to create predominant moments. But there is a problem that wind does not blow at a fixed rate always. So the corresponding loads should be dynamic in nature. For evaluation of along wind loads the chimney is modelled as bluff body with turbulent wind flow. In many codes including IS: 6533: 1989, equivalent static method is used for estimating these loads. In this procedure the wind pressure is determined which acts on the face of the chimney as a static wind load. Then it is amplified using gust factor to calculate the dynamic effects.

2.2.2. Across wind effects

Across wind effect is not fully solved and it is required a considerable research work on it. For design of self supporting steel chimney, Indian standard remain silent about it. But it is mentioned in IS 4998 (part 1): 1992 and ACI 307-95 which is applicable for concrete chimney only. Also CICIND code does not mention this effects and depends on IS 4998 (part 1): 1992 and ACI 307-95.

Generally chimney-like tall structures are considered as bluff body and oppose to a streamlines one. When the streamlined body causes the oncoming wind flow, the bluff body causes the wind to separate from the body. Due to this a negative regions are formed in the wake region behind the chimney. This wake region produces highly turbulent region and forms high speed eddies called vortices. These vortices alternatively forms lift forces and it acts in a direction perpendicular to the incident wind direction. Chimney oscillates in a direct ion perpendicular to the wind flow due to this lift forces.

2.3 WIND LOAD CALCULATION

According to IS 875 (part 3):1987 basic wind speed can be calculated,

$$V_z = V_b K_1 K_2 K_3 \tag{2.1}$$

Where

V_z= design wind speed at any height z m/s

K_1= probability factor (risk coefficient)

K_2= terrain, height and structure size factor

K_3= topography factor

2.4 STATIC WIND EFFECTS

A static force called as drag force, obstructs an air stream on a bluff body like chimney. The distribution of wind pressure depends upon the shape and direction of wind incidence. Due to this a circumferential bending occurs and it is more significant for larger diameter chimney. Also drag force creates along-wind shear forces and bending moments.

(a) Drag

The drag force on a single stationary bluff body is,

$$F_d = \tfrac{1}{2} C_d . A . \rho_a . \overline{U}^2 \tag{2.2}$$

Where F_d = drag force, N

C_d = Drag coefficient

A = area of section normal to wind direction, sq. m

The value of drag coefficient depends on Reyonlds number, shape and aspect ratio of a structure.

(b) Circumferential bending

The radial distribution of wind pressure on horizontal section depends on R_e. normally the resultant force of along wind is counteracted by shear force s which is induced in the structure. These shear forces are assumed to vary sinusoidally along the circumference of the chimney cell.

(c) Wind load on liners

In both single-flue and multi-flue chimneys metal liners are being used but these are not directly contact or exposed to wind. But they are designed for wind loads which are transmitted through the chimney cell. The magnitude of the force can be estimated by considering the liner as a beam of varying moment of inertia, acted upon by a transverse load at the top and deflection is calculated at the top of the cell.

2.5 DYNAMIC-WIND EFFECTS

Wind load is a combination of steady and a fluctuating component. Due to turbulence effect the wind load varies in its magnitude.

(a) Gust loading

Due to fluctuations wind load is random in nature. This load can be expressed as

$$F(t) = K\left(\overline{U} + \rho_u\right)^2 \tag{2.3}$$

$$= K\left(\overline{U}^2 + 2\overline{U}\rho_u\right)$$, for small values of ρ_u

Where $K = \frac{1}{2} C_d . A . \rho_a$

In the above expression ($K\,\bar{U}^2$) is quassi-static and $\bar{U}$ is the mean velocity.

(b) Aerodynamic Effects

In wind engineering there is a term called "aerodynamic admittance coefficient" which depends on spatial characteristics of wind turbulence. Spatial characteristics relates to structure's response to wind load, at any frequency. This coefficient is expressed as;

$$A_n = \frac{1}{\left(1+\frac{8Hn}{3\bar{U}_t}\right)\left(1+\frac{10nD_{co}}{\bar{U}_t}\right)} \tag{2.4}$$

Where A_n = aerodynamic admittance at the structure's natural frequency n, Hz

$\bar{U}_t$ = mean wind speed at top of a chimney, m/s

Always this coefficient has to be multiplied with response of a structure due to wind loads because it allows response modification due to spatial wind-turbulence characteristics.

(c) Vortex formation

When wind flows through a circular cross section like chimney vortices are formed. These vortices cause a pressure drop across the chimney at regular pressure intervals. Due to this change in pressure, a lateral force perpendicular to wind direction is created. It depends on Reyonld's number which has a range such as sub-critical (R_e<3× 10^5), ultra-critical (R_e >3× 10^5) and super-critical (3×10^5 to 3× 10^6).

(d) Vortex excitation

The alternate shedding of vertices creates a transverse forces called as lift. According to practical design purpose it is divided into two forms, such as

(i) In sub-critical and ultra-critical Re range

The frequency of lift force is regular, but magnitude is random. When frequency of vortex shedding is close to natural frequency of a chimney (when its motion is near sinusoidal), maximum response is obtained. The exciting force should be taken as,

$$F_L = \frac{1}{2}\rho_a A\overline{U}^2 \sin \omega_t \bar{c}_L \tag{2.5}$$

The response of the structure depends on the time-average energy input from the vortex shedding forces. In the expression C_l has the time-average value rms value of the lifting force coefficient with a range of frequencies close to the natural frequency ω_o of the structure.

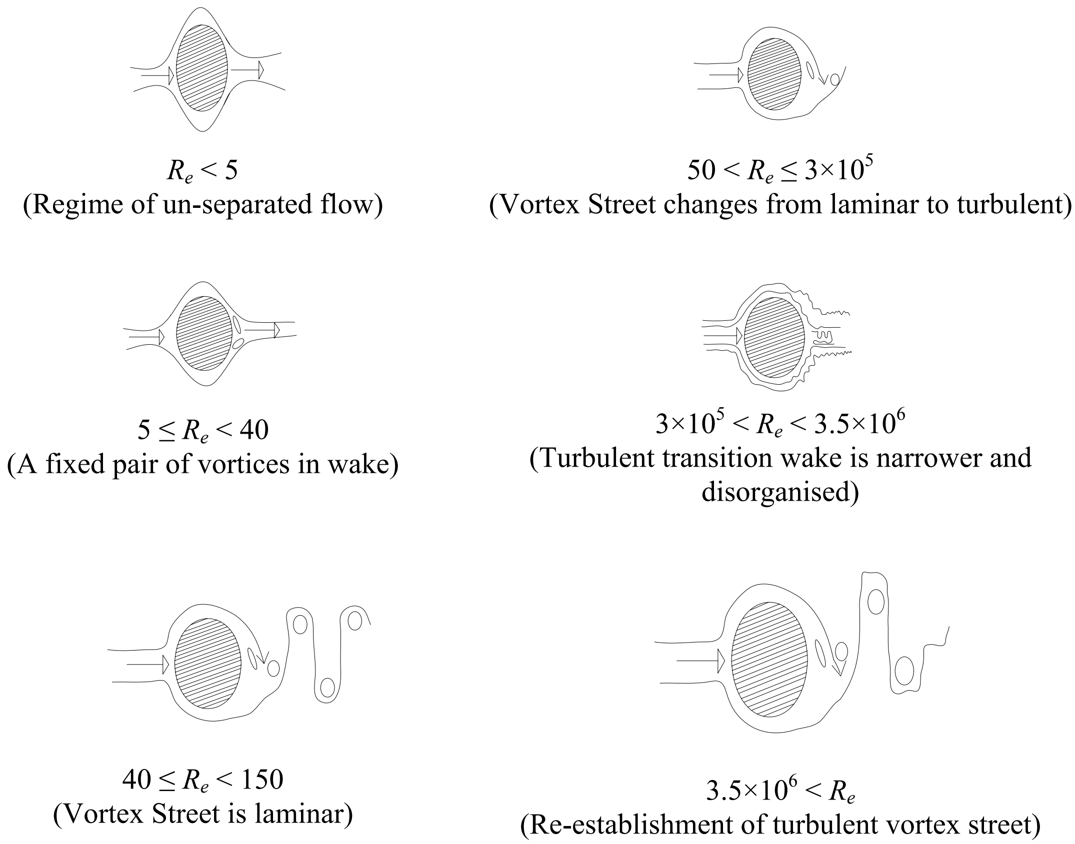

Fig. 2.1: Regimes of fluid flow across circular cylinders

(ii) In super-critical R_e range

In this range both frequency and magnitude are random in nature. Here structure's response depends on the power input. If we plot power –input density function S'_l (St) against non-dimensional frequency St, then the power spectrum of the lift-force should be expressed as,

$$S_l = \left[\tfrac{1}{2}.\rho_a.A.\overline{U}^2.\sqrt{\overline{C_L^{\,2}}}\right].S_l^{'}\left(S_t\right) \tag{2.6}$$

According to the (IS-6533 part-2:1989), if period of natural oscillation for the self-supported chimney exceeds 0.25 seconds, the design wind load should take into consideration the dynamic effect due to pulsation of thrust caused by the wind velocity in addition to the static wind load. It depends on the fundamental period of vibration of the chimney.

2.6 SEISMIC EFFECTS

Due to seismic action, an additional load is acted on the chimney. It is considered as vulnerable because chimney is tall and slender structure. Seismic force is estimated as cyclic in nature for a short period of time. When chimney subjected to cyclic loading, the friction with air, friction between the particles which construct the structure, friction at the junctions of structural elements, yielding of the structural elements decrease the amplitude of motion of a vibrating structure and reduce to normal with corresponding to time. When this friction fully dissipates the structural energy during its motion, the structure is called critically damped.

For designing earthquake resistant structures, it is necessary to evaluate the structural response to ground motion and calculate respective shear force, bending moments. Hence ground motion is the important factor for seismic evaluation. To estimate exact future ground motion and its corresponding response of the structure, it depends on soil-structure interaction, structural stiffness, damping etc.

For analysis purpose, chimney is behaved like a cantilever beam with flexural deformations. Analysis is carried out by following one of the methods according to the IS codal provision,

1. Response-spectrum method (first mode)
2. Modal-analysis technique (using response spectrum)
3. Time-history response analysis.

For chimneys which are less than 90m high called as short chimney, response spectrum method is used.

2.6.1. Response-spectrum method

This method consists of three steps such as,

I. Fundamental period

II. Horizontal seismic force

III. Determine design shears and moments

The fundamental period of the free vibration is calculated as,

$$T = C_T \sqrt{\frac{W_t.h}{E_s.A.g}} \tag{2.7}$$

Where C_t = coefficient depending on slenderness ratio of the structure

W_t= total weight of the structure including weight of lining and contents above the base,

A = area of cross-section at the base of the structural shell

h = height of the structure above the base

E_s= modulus of elasticity of material of the structural shell

g= acceleration due to gravity

Stiffness of the flared chimney is approximately two times the prismatic chimney. Therefore the the a conservative estimate of natural time period for this self supported steel chimney will be:

$$T_{emprical} = \frac{T}{2}$$

2.6.2. Horizontal seismic force

The horizontal seismic force (A_h) is to be calculated according to IS 1893 (Part 1): 2002 as follows:

$$A_h = \frac{\left[\frac{Z}{2}\right]\left[\frac{S_a}{g}\right]}{\left(R/I\right)} \tag{2.8}$$

Where Z= zone factor

I= importance factor

R= response reduction factor. The ratio shall not be less than 1.0

$S_{a/g}$= spectral acceleration coefficient for rock and soil sites

2.7 SHEAR AND MOMENT

Base moment and base shear can be calculated as follows

$$p_{dyn} = \int_0^h dp_{dyn}$$

$$M_{dyn} = \int_0^h x \times dp_{dyn}$$

As per IS 6533 (Part-2): 1989 Inertia force, dP_{dyn}, for i^{th} mode for an infinitesimal height dx at a height x from the base of the chimney is as follows:

$$dP_{dyn} = dm \times \xi_i \times \eta_i \times \nu$$

Where,

dm = mass of the chimney for an infinitesimal height dx at height x from the base of the chimney,

$\xi_i = \left(T_i V_b\right)/1200$ is the dynamic coefficient for the i^{th} mode of vibration,

T_i = the period of i^{th} mode

V_b = basic wind speed in m/s,

ν = coefficient which takes care of the space

2.8 TEMPERATURE EFFECTS

The shell of the chimney should withstand the effects of thermal gradient. Due to thermal gradient vertical and circumferential stress are developed and this values estimated by the magnitude of the thermal gradient under steady state condition.

2.9 SUMMERY

This Chapter presents the effects of wind and seismic load on self-supporting steel chimneys. It also describes briefly the procedures to calculate static wind, dynamic wind and seismic force as per Indian Standard IS 6533 (Part-2):1989.

CHAPTER 3

DESIGN OF STEEL CHIMNEY

3.1 OVERVIEW

This chapter presents procedures to design self-supported steel chimney as per Indian Standard IS 6533 (Part 1 & 2):1989 through an example calculation. A typical chimney to be located at coastal Odisha for an exit flue discharge of 100000 m^3/s is taken for the example. The chimney is first designed for static wind load and then the design is checked against dynamic wind load, possible resonance and seismic load.

3.2 DESIGN ASPECTS OF STEEL CHIMNEY

3.2.1 Mechanical aspects

This part covers design, construction maintenance and inspection of steel stacks. This also includes lining materials, draft calculations, consideration for dispersion of pollutants into atmosphere and ash disposal.

The sizing of stack depends upon many factors, broadly it can be said that a stack is sized such that it can be exhaust a given quantity of flue gases at a suitable elevation and with such a velocity that the ground level concentration (GLC) of pollutants, after atmospheric dispersion, is within the limits prescribed in pollution regulatory standards, while the stack retains structural integrity. Thus, while handling a given quantity of flue gases, the major factors which influence a stack dimensions are:

i. Draft requirements

ii. Environmental regulations

iii. Structural considerations

iv. Compositions of flue gas are specific weight, quantity of dust data above the aggressiveness of gases.

In order to minimize loss of heat from a stack and to maintain the temperature of the steel shell above the acid due point level external insulations may be fitted. The amount of insulation required to maintain the temperature of flue gases above he acid dew point depends upon

I. Effective of insulation

II. Te velocity of the gases

III. The inlet temperature of the flue gases

According to Indian standard code IS: 14164-2008, industrial application and finishings of thermal insulation materials at temperatures above -80^0 C and up to 750^0 C, code of practice deals with the material selection for selection for insulation and method of application.

3.2.2 Structural aspects

It covers loadings, load combinations, materials of construction, inspection, maintenance and painting of both self supporting and guyed steel stacks (with or without lining) and there supporting structures.

3.3 APPLICABLE CODES FOR DESIGN

3.3.1 IS 875 (Part-3):1987

Code of practice for design loads other than earthquake for buildings and structures (wind loads). This Indian standard IS: 875 (Part-3) was adopted by bureau of Indian Standards after the draft finalized by the structural safety sectional committee had been approved by the civil engineering division council. This part covers

a. Wind loads to be considered when designing buildings, structures and components.
b. It gives the basic wind speeds for various locations in India.
c. Factors to be considered while estimating the design wind speed/pressure.

3.3.2 IS 6533 (Part-1): 1989

Indian standard design and construction of steel stacks-code of practice (Mechanical aspects). This includes

a. Determination of inside diameter.
b. Determination of stack height based on pollution norms and dispersion of gases into the atmosphere.
c. Estimation of draft losses.
d. General requirements for materials of construction, insulation, lining and cladding.

3.3.3 IS 6533 (Part-2): 1989

This is Indian Standard Code of practice for design and construction of steel chimneys (structural aspect). This includes

a. Material of construction for bolts, plates, rivets and welding
b. Loadings and load combinations
c. General design aspects covering minimum thickness of shell. Allowable stresses, allowable deflection, determination of dynamic force and checking for resonance.

d. Typical ladder details, painters trolley, location of warning lamps and the flue opening details, inspection, maintenance and protective coatings.

3.3.4 ASME-STS-1_2000

This standards covers many faces of the steel stack, it outlines the considerations which must be made for the mechanical and structural design. This includes

a. Mechanical design- Size selection (Height, diameter, size), available draft, heat losses, materials, linings and coatings.
b. Structural design- scope, types of construction, materials, allowable stresses, applied loadings, foundation, vibration, dynamic responses, wind responses, earthquake responses, prevention of excessive vibrations
c. Access and safety- ladders, platforms.
d. Fabrication and erection- codes and standards, welding, tolerances, grouting.
e. Inspection and maintenance- inspection procedure and maintenance.
f. Stack test requirements, mathematical expressions.

3.5 DESIGN METHODOLOGY

IS:6533 (Part-1 & 2): 1989, IS 875 (Part-3 & 4): 1987, and IS 1893 (Part-4):2005 will be used as the basis for design, which gives detailed procedure to determine static, dynamic and seismic loads coming on the structure.

3.5.1 Assumptions

1. The wind pressure varies with the height. It is zero at the ground and increase as the

height increases. For the purpose of design it is assumed the wind pressure is uniform throughout the height of the structure.

2. For the purpose of calculations, it is assumed that the static wind load (projected area multiplied by the wind pressure) is acting at the centre of pressure.
3. In calculating the allowable stresses both tensile and bending, the joint efficiency for butt welds is assumed to be 0.85.
4. The base of the stack is perfectly rigid and the effect of the gussets and stool plate on the deflection and the stresses in the stack is not considered. This is applicable only for manual calculations.
5. There are no additional lateral movements from the duct transferred to the stack; suitable arrangement has to be provided to absorb this movement from the duct.
6. Earthquake causes impulsive ground motions, which are complex and irregular in character, changing in period and amplitude each lasting for a small duration. Therefore resonance of the type as visualized under steady-state sinusoidal excitations will not occur, as it would need time to build up such amplitudes.
7. Earthquake is not likely to occur simultaneously with maximum wind or maximum flood or maximum sea waves.

3.5.2 Loadings and Load Combinations

The followings loads are to be estimated while designing the steel chimney

a. Wind load
b. Earthquake load
c. Imposed load

3.5.2.1 Load combinations

As per IS: 6533 (Part 2), the following load causes are to be considered while designing the stack

a. Load case 1 = Dead load + wind load (along X direction) + Imposed load

b. Load case 2 = Dead load + wind load (along Y direction) + Imposed load

c. Load case 3 = Dead load + Imposed load + earthquake load

3.6 SAMPLE DESIGN CALCULATIONS

3.6.1. Design Inputs

Burner capacity of the each dryer: $Q_{capa} := 600 \frac{1}{hr} = 1.667 \times 10^{-4} \frac{m^3}{s}$

Total no of dryer: $n := 2$

Density of the fuel: $d_{fuel} := 0.9 \frac{kg}{l}$

Sulphur content in fuel is 4% of the total fuel weight.

Estimated volume rates of emission of total flue gases: $V_{emission} := 100000 \frac{m^3}{hr} = 27.778 \frac{m^3}{s}$

Basic wind speed in the site is: $v_b := 210 \frac{km}{hr} = 58.333 \frac{m}{s}$

Chimney is to be located on a level ground

The material of construction of chimney should conform to IS 2062:2006

The temperature to which the chimney shell is expected to be exposed is limited to $0 - 200^0 c$

The chimney site is located on Terrain Category 1 and Seismic Zone III.

The supporting soil condition is Medium (Type-II)

3.6.1. Determination of the Height of the Chimney

(a) Height as per Environment (protection) third amendment rules, 2002

Considering one dryer will function at a time and the burner will run on its capacity, weight of the fuel burned: $W_{fuel} := Q_{capa} . d_{fuel} = 540 \frac{kg}{hr}$

Amount of sulphur content in fuel is 4% of the total fuel weight. Therefore total sulphur quantity burned: $Q_{sulphur} := 4\%W_{fuel} = 21.6\frac{kg}{hr}$

1 mole of sulphur will react with 1 mole of O_2 to form 1 mole of

SO_2: $S + O_2 = SO_2$

Relative atomic weight of sulphur is 32g and that for oxygen is 16g. Atomic weight of SO_2 produced from 32g of sulphur is 64g. Therefore the weight of SO_2 produced is double the atomic weight of sulphur burned.

Quantity of sulphur dioxide is then equals to total sulphur burned: $Q_{SO_2} := 2.Q_{sulhur} = 43.2\frac{kg}{hr}$

Height of stack as per environment (protection) Third Amendment Rules, 2002; ministry of Environment and Forests:

$$H_{stack1} := 14.\left(\frac{Q_{SO_2}}{1\frac{kg}{hr}}\right)^{0.3}.1m = 43.328m$$

<u>(b) Height as per IS 6533(Part-1):1989</u>

Coefficient of temperature gradient of atmosphere for horizontal and vertical mixing of plume:

$A_{tropical} := 280$

Estimated mass rate of emission of pollutants: $Q_{SO_2} = 12\frac{gm}{s}$

Dimensionless coefficient of rate of precipitation: $F_{dust} := 2$

Maximum permissible ground level concentration pollutant: $C_{permissible} := 0.5\frac{mg}{m^3}$

Estimated volume rates of emission of total flue gases: $V_{emission} := 100000\,\frac{m^3}{hr} = 27.778\,\frac{m^3}{s}$

Assumed diameter of the chimney at exit: $d_{assumed} := 2m$

Height of stack as per Clause B-1.1; IS-6533 Part-1:1989:

$$H_{stack2} := \left[\frac{A_{tropical}\left(\frac{Q_{SO_2}}{1\frac{gm}{s}}\right).F_{dust}.\left(\frac{d_{assumed}}{1m}\right)^{\frac{3}{4}}}{8.\left(\frac{C_{permissible}}{1\frac{mg}{m^3}}\right).\left(\frac{V_{emission}}{1\frac{m^3}{s}}\right)}\right]^{\frac{3}{4}}.1m == 36.474m$$

Minimum stack height: $H_{stack\_\min} := 30m$

Height of chimney should be maximum of all the above calculated heights:

$Ht_{stack} := \max\left(H_{stack1}, H_{stack2,} H_{stack\_\min}\right) = 43.328m$

Height of the chimney considered: $Ht := 45m$

3.6.3 Other Dimensions

Height of the chimney $Ht := 45m$

Minimum height of the flare: $h_{flare.\min} := \frac{Ht}{3} = 15m$ (ref. clause 7.2.4; IS-6533 Part-2: 1989)

Consider the height of the flare: $h_{flare} := 15m$

Height of the cylindrical portion of the chimney: $h_{cy1} := Ht - h_{flare} = 30m$

Minimum outside diameter of unlined chimney at the top: $d_{top.\min} := \frac{h_{cy1}}{20} = 1.5m$ (ref. Clause 7.24;

I S-6533 Part-2:1989)

Capacity of each exhaust fan: $capa := 100000 \frac{m^3}{hr}$ (ref. input data)

Total no of dryer : $n := 2$ (ref. input data)

Quantity of the gas $Q := n.capa = 55.556 \frac{m^3}{s}$

Velocity of the flue gas at exit point of chimney: $V_{O2} := 20 \frac{m}{s}$

Inside diameter of the chimney: $D := \sqrt{\frac{4Q}{\pi.V_{O2}}} = 1.881m$ (ref. clause 6.2; IS-6533 Part-1:1989)

Consider outside diameter of the chimney at top: $d_{top} := 2m$

Minimum outside diameter of flared chimney at base: $d_{base.\min} := 1.6d_{top} = 3.2m$

Consider outside diameter of the chimney at base: $d_{base} := 3.2m$

Minimum thickness of the shell: $T_{\min} := \frac{d_{top}}{500} = 4mm$

Consider a shell thickness: $T_{topA} := 6mm$ (>5mm, therefore, compliant)

External corrosion allowance $T_{ce} := 3mm$ (ref.Table-1; IS-6533 part-2:1989 for non-copper bearing steel and design life 20 years)

Internal corrosion allowance $T_{ci} := 5mm$

(Ref. Table-1; IS-6533 part-2:1989 for non-copper bearing steel and design life 20 years)

$T_{top} := T_{topA} + T_{ce} + T_{ci} = 14mm$

3.6.4. Load Combinations

Reference: clauses 6.5, IS 6533(Part-2):1989

(a) Dead load+ Wind load

(b) Dead load + Earthquake load

(c) Dead load+ Load due to lining+ Imposed load on service platforms + Wind load

(d) Dead load++ Load due to lining+ Imposed load on service platforms+ Earthquake load

3.6.5. Permissible Stress

The material of construction of chimney should conform to IS 2062:2006

Yield stress of the steel: $f_y := 250Mpa$

The minimum permissible stress in compression due to above load combinations for circular chimney with construction material mentioned above is given in table-3, IS 6553(part2): 1989 as a function of:

h_{level} =effective height for consideration of buckling

D= mean diameter of the chimney at the level considered

T=thickness at the level considered

Maximum permissible stress in tension:

Permissible stress in tension: $f_{allowtension} := 0.6 f_y = 150Mpa$ (Ref: IS-800: 1984; Clause: 4.11)

Efficiency of the butt weld: efficiency: = 0.85

Allowable tensile stress: $f_{allowT} := efficiency.f_{allowTension} = 127.5Mpa$

Maximum permissible stress in shear: $f_{allowSh} := 0.4.f_y = 100Mpa$

(For un-stiffen web as per Ref:-IS-800:1984; Clause: 6.4.2)

3.6.6. Chimney Weight

Let h_{level} be the distance from the top of chimney to the level considered

G_i =weight of the part of the chimney above the level considered

A_i = area of the steel section at the level considered

Mass density of the construction material used for chimney

$$den := 78.5 \frac{kN}{m^3}$$

Weight of the (platform+ access ladder+ helical strake+ rain cap + etc) is assumed to be 20% of the self weight of chimney shell.

3.6.7. Wind Load Calculation

Considering general structure with mean probable design life of 50 years

k1:=1.0 (ref. clause 5.3.1; IS-875 Part-3:1987)

As the chimney is to be located on a level ground

k3:=1.0(ref. clause 5.3.1; IS-875 Part-3:1987)

As the chimney site is located on Terrain category 1 is considered for the wind load calculation as per clauses 5.3.2.1, IS-875 (Part-3):1987

As the chimney is 45m tall, the size class of the structure is considered as Class-B as per clause 5.3.2.2, IS-873(part-3):1987

As per the input provided, the basic wind speed in the site is: $v_b := 210 \frac{km}{hr} = 58.333 \frac{m}{s}$

Wind load on the chimney will be increased due to the presence of platform, ladder, and other fittings.5% of the wind force on the chimney shell is considered in excess to account this.

3.6.8. Design for Static Wind

For computing wind loads and design of chimney the total height of the is divided into 4 parts:35m to 45m,25m to 35m,15m to 25m, and 0 to 15m.

Part-1

Part-1 is located at a height 35m to 45m from ground. Considering K_2 factor in this height range as per table 2, IS-875 (Part-3):1987, lateral wind force

$$P_1 := \int_{35m}^{Ht} o.6\left[k1\left[1.13+\frac{(h-30m)(1.18-1.13)}{50m-30m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}.d_{top}dh = 54.475kN$$

Moment due to the wind force at base of Part-1(i.e. at 35m height)

$$M_1 := \int_{35m}^{Ht} o.6\left[k1\left[1.13+\frac{(h-30m).(1.18-1.13)}{50m-30m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}.d_{top}(h-5m)dh = 546.713kN$$

Section modulus (Z) of the tubular chimney section at 35m level

$$Z_1 := \frac{\pi.d_{top}{}^2T_{topA}}{4} = 0.019m^3$$

Bending stress at the extreme fibre of the chimney shell at 35m level:

$$f_{mol} = \frac{1.05M_1}{Z_1} = 30.454MPa$$

Axial compression stress due to self weight of the chimney shell

$$f_{st1} := \frac{\int_{35m}^{Ht}\left(\pi d_{top}.T_{top}\right).den.dh}{\left(\pi d_{top}.T_{topA}\right)} = 1.832MPa$$

Axial compression stress due to platform etc: $f_{pl1} := 0.2.f_{st1} = 0.366MPa$

Maximum tensile stress: $f_{t1} := f_{mo1} + f_{st1} + f_{pl1} = 32.652MPa$

Maximum permissible stress at 35m level:

$h_{level1} := Ht - 35m = 10m$ $\quad \frac{h_{level1}}{d_{top}} = 3\,(i.e., <20)$ $\quad \frac{d_{top}}{T_{topA}} = 333.333$

Maximum permissible compressive stress at 35m level as per clause 7.7 of IS 6533(Part-2): 1989 (as per the input the temperature to which the chimney shell is expected to be exposed is limited to $0 - 200^0 c$)

$$f_{allowC1} := 78MPa + \frac{(87-78)MPa.\left(350 - \frac{d_{top}}{T_{topA}}\right)}{(350-300)} = 81MPa$$ therefore, $f_{c1} < f_{allowC1}$

Maximum shear stress: $f_{sh1} := \frac{1.05P_1}{\pi d_{top}.T_{topA}} = 1.517MPa$ therefore, $f_{sh1} < f_{allowSh}$

Part-2

Part-2 is located at a height 25m to 35m from ground. Considering K_2 factor in this height range as per table 2, IS-875(Part-3):1987, lateral wind force

$$P_{2a} := \int_{30m}^{35m} o.6\left[k1\left[1.13 + \frac{(h-30m)(1.18-1.13)}{50m-30m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}.d_{top}dh = 26.359kN$$

$$P_{2b} := \int_{25m}^{30m} o.6\left[k1\left[1.10 + \frac{(h-20m)(1.13-1.10)}{30m-20m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}.d_{top}dh = 25.726kN$$

Shear force due to wind force at the base of Part-2 (*i.e.*, at 25m level):

$P_2 := P_1 + P_{2a} + P_{2b} = 106.56kN$

Moment due to the wind force at base of Part-2 (*i.e.*, at 25m height):

$$M_{2a} := \int_{25m}^{30m} o.6\left[k1\left[1.10 + \frac{(h-20m).(1.13-1.10)}{30m-20m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}.d_{top}(h-25m)dh$$

$$M_{2b} := \int_{30m}^{Ht} o.6\left[k1\left[1.13 + \frac{(h-30m).(1.18-1.13)}{50m-30m}\right]k3.\left(v_b \cdot \frac{s}{m}\right)\right]^2 \cdot \frac{N}{m^2}.d_{top}(h-25m)dh$$

$$M_2 := (M_{2a} + M_{2b}) = 1081.6kN.m$$

Considering an improved wall thickness for this part: $T_{2A} := T_{topA} + 2mm = 8mm$

Therefore overall wall thickness of the shell including the corrosion resistance:

$$T_2 := T_{2A} + T_{ce} + T_{ci} = 0.016m$$

Section modulus (Z) of the tubular chimney section at 25m level: $Z_2 := \frac{\pi.d_{top}{}^2.T_{2A}}{4} = 0.025m^3$

Bending stress at the extreme fibre of the chimney shell at 25m level:

$$f_{mo2} := \frac{1.05M_2}{Z_2} = 45.188MPa$$

Axial compression stress due to platform etc: $f_{pl2} := 0.2.f_{st2} = 0.589MPa$

Maximum tensile stress: $f_{t2} := f_{mo2} = 45.188MPa$ therefore, $f_{t2} < f_{allowT} = 127.5MPa$

Maximum compressive stress: $f_{c2} := f_{mo2} + f_{st2} + f_{pl2} = 48.721MPa$

Maximum permissible stress at 25m level:

$h_{level2} := Ht - 25m = 20m$ $\quad \frac{h_{level2}}{d_{top}} = 10$ (*i.e.*, <20) $\quad \frac{d_{top}}{T_{2A}} = 250$

Maximum permissible compressive stress at 25m level as per clause 7.7 of IS 6533(Part-2)1989:

(The temperature to which the chimney shell is expected to exposed is limited to $0 - 200^0C$)

Corresponding allowable compressive stress: $f_{allowC2} := 99MPa$

(ref. Table-3, IS 6533 Part-2:1989) therefore, $f_{c2} < f_{allowC2}$

Maximum shear stress: $f_{sh2} := \frac{1.05.P_2}{\pi d_{top}.T_{2A}} = 2.226MPa$ therefore, $f_{sh2} < f_{allowSh}$

Part-3

Part-3 is located at a height 15m to25m from ground. Considering k_2 factor in this height range as per table 2, IS-875(Part-3):1987, lateral wind force

$$P_{3a} := \int_{20m}^{25m} o.6\left[k1\left[1.10 + \frac{(h-20m)(1.13-1.10)}{30m-20m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2 .\frac{N}{m^2}.d_{top}dh = 25.043kN$$

$$P_{3b} := \int_{15m}^{20m} o.6\left[k1\left[1.07 + \frac{(h-15m)(1.10-1.07)}{20m-15m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2 .\frac{N}{m^2}.d_{top}dh = 24.037kN$$

Shear force due to wind force at the base of Part-3(*i.e.*, at 15m level):

$$P_3 := P_2 + P_{3a} + P_{3b} = 155.639kN$$

Moment due to the wind force at base of Part-3 (*i.e.*, at 15m height):

$$M_{3a} := \int_{15m}^{20m} o.6\left[k1\left[1.07 + \frac{(h-15m).(1.10-1.07)}{20m-15m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2 .\frac{N}{m^2}.d_{top}(h-15m)dh$$

$$M_{3b} := \int_{20m}^{30m} o.6\left[k1\left[1.10 + \frac{(h-20m).(1.13-1.10)}{30m-20m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2 .\frac{N}{m^2}.d_{top}(h-15m)dh$$

$$M_{3c} := \int_{30m}^{Ht} o.6\left[k1\left[1.13 + \frac{(h-30m).(1.18-1.13)}{50m-30m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2 .\frac{N}{m^2}.d_{top}(h-15m)dh$$

$$M_3 := (M_{3a} + M_{3b} + M_{3c}) = 2396kN.m$$

Considering an improved wall thickness for this part: $T_{3A} := T_{2A} + 2mm = 10mm$

Therefore overall wall thickness of the shell including the corrosion resistance:

$$T_3 := T_{3A} + T_{ce} + T_{ci} = 18mm$$

Therefore, Section modulus (Z) of the tubular chimney section at 15m level:

$$Z_2 := \frac{\pi.d_{top}{}^2.T_{3A}}{4} = 0.031m^3$$

Bending stress at the extreme fibre of the chimney shell at 15m level:

$$f_{mo3} := \frac{1.05M_3}{Z_3} = 80.079MPa$$

$$f_{st3} := \frac{\int_{35m}^{Ht} (\pi d_{top}.T_{top}).den.dh + \int_{25m}^{35m} (\pi d_{top}.T_{top}).den.dh + \int_{15m}^{25m} (\pi d_{top}.T_{top}).den.dh}{(\pi.d_{top}.T_{3A})} = 3.768MPa$$

Axial compression stress due to platform etc: $f_{pl3} := 0.2.f_{st3} = 0.754MPa$

Maximum tensile stress: $f_{t3} := f_{mo3} = 80.079MPa$ therefore, $f_{t3} < f_{allowT} = 127.5MPa$

Maximum compressive stress: $f_{c3} := f_{mo3} + f_{st3} + f_{pl3} = 84.601MPa$

Maximum permissible stress at 15m level:

$h_{level3} := Ht - 15m = 30m$ $\quad \frac{h_{level3}}{d_{top}} = 15\,(i.e., <20)$ $\quad \frac{d_{top}}{T_{3A}} = 200$

Corresponding allowable compressive stress: $f_{allowC3} := 112MPa$

(ref. Table-3, IS 6533 Part-2:1989) therefore, $f_{c3} < f_{allowC3}$

Maximum shear stress: $f_{sh3} := \frac{1.05.P_3}{\pi d_{top}.T_{3A}} = 2.601MPa$ therefore, $f_{sh3} < f_{allowSh}$

Part-4

Part-4 is located at a height 0 to 15m from ground. Considering K_2 factor in this height range as per table 2, IS-875 (Part-3):1987, lateral wind force

$$P_{4a} := \left[\int_{0m}^{10m} o.6\left[k1.(1.03)k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}.\left[d_{base} - \left[h.\frac{(d_{base} - d_{top})}{h_{flare}}\right]\right]dh\right]$$

$$P_{4b} := \left[\int_{10m}^{15m} o.6\left[k1\left[1.03 + \frac{(h-10m)(1.07-1.03)}{15m-10m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}\left[d_{base} - \left[h.\frac{(d_{base}-d_{top})}{h_{flare}}\right]\right].dh\right]$$

Shear force due to wind force at the base of Part-4(*i.e.*, at the base of the chimney):

$$P_4 := P_3 + P_{4a} + P_{4b} = 241.022kN$$

Moment due to the wind force at base of Part-4(*i.e.*, at the base of the chimney):

$$M_{4a} := \int_{0m}^{10m} o.6\left[k1.(1.03)k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}.\left[d_{base} - \left[h.\frac{(d_{base}-d_{top})}{h_{flare}}\right]\right].hdh$$

$$M_{4b} := \int_{10m}^{15m} o.6\left[k1\left[1.03 + \frac{(h-10m).(1.07-1.03)}{15m-10m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}.\left[d_{base} - \left[h.\frac{(d_{base}-d_{top})}{h_{flare}}\right]\right].hdh$$

$$M_{4c} := \int_{15m}^{20m} o.6\left[k1\left[1.07 + \frac{(h-15m).(1.10-1.07)}{20m-15m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}.d_{top}.hdh$$

$$M_{4d} := \int_{20m}^{30m} o.6\left[k1\left[1.10 + \frac{(h-20m).(1.13-1.10)}{30m-20m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}.d_{top}.hdh$$

$$M_{4e} := \int_{30m}^{Ht} o.6\left[k1\left[1.13 + \frac{(h-30m).(1.18-1.13)}{50m-30m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}.d_{top}.hdh$$

$$M_4 := (M_{4a} + M_{4b} + M_{4c} + M_{4d} + M_{4e}) = 5327.4kN.m$$

Considering an improved wall thickness for this part: $T_{4A} := T_{3A} + 2mm = 12mm$

Therefore overall wall thickness of the shell including the corrosion resistance:

$$T_4 := T_{4A} + T_{ce} + T_{ci} = 20mm$$

Therefore, Section modulus (Z) of the tubular chimney section at base (0m level):

$$Z_4 := \frac{\pi.d_{top}{}^2.T_{4A}}{4} = 0.097m^3$$

Bending stress at the extreme fibre of the chimney shell at base (0m level):

$$f_{mo4} := \frac{1.05M_4}{Z_4} = 57.961MPa$$

Axial compression stress due to self-weight of chimney at base (0m level): renaming $T_t := T_{top} = 14mm$

$$f_{st4} := \frac{\int_{35m}^{Ht}\left(\pi d_{top}.T_{top}\right).den.dh + \int_{25m}^{35m}\left(\pi d_{top}.T_{top}\right).den.dh + \int_{15m}^{25m}\left(\pi d_{top}.T_{top}\right).den.dh + \int_{0m}^{15m}\left(\pi d_{top}.T_{top}\right).den.dh}{\left(\pi.d_{top}.T_{3A}\right)}$$

f_{st4} =3.925MPa

Axial compression stress due to platform etc.: $f_{pl4} := 0.2.f_{st4} = 0.785MPa$

Maximum tensile stress: $f_{t4} := f_{mo4} = MPa57.961$ therefore, $f_{t4} < f_{allowT} = 127.5MPa$

Maximum compressive stress: $f_{c4} := f_{mo4} + f_{st4} + f_{pl4} = 62.671MPa$

Maximum permissible stress at base (at 0m Level):

$$h_{level4} := Ht - 0m = 45m$$

Mean diameter for this part: $d_{level4} := \frac{d_{top} + d_{base}}{2} = 2.6m$

$\frac{h_{level4}}{d_{level4}} = 17.308\,(i.e., <20)$ $\frac{d_{base}}{T_{4A}} = 266.667$

Corresponding allowable compressive stress:

$$f_{allowC4} := 99MPa + \frac{(99-87)MPa.\left(300 - \frac{d_{base}}{T_{4A}}\right)}{(300-250)} = 107MPa$$

(Ref.Table-3, IS 6533 Part-2:1989) therefore, $f_{c4} < f_{allowC4}$

Maximum shear stress: $f_{sh4} := \frac{1.05.P_4}{\pi d_{top}.T_{4A}} = 2.098MPa$ therefore, $f_{sh4} < f_{allowSh}$

3.6.9. Check for Seismic Force

Area of cross section at base of chimney shell: $A_{base} := \pi.d_{base}.T_3 = 0.181m^2$

Radius of gyration of the structural shell at the base section: $r_e := \frac{1}{\sqrt{2}}\left(\frac{d_{base}}{2}\right) = 1.131m$

Slenderness ratio: $k := \frac{Ht}{r_e} = 39.775$

Coefficient depending upon slenderness ratio: $C_T := 65.0 + \frac{(73.8 - 65.0).(k - 35)}{(40 - 35)} = 73.40$

(ref. clause 14.1 and Table-6; IS-1893 Part-4:2005)

Weight of the chimney shell: renaming $d_b := d_{base}$ and $d_t := d_{top}$

$$W_s := \int_{35m}^{Ht} (\pi d_{top}.T_t).den.dh + \int_{25m}^{35m} (\pi d_{top}.T_t).den.dh + \int_{15m}^{25mt} (\pi d_{top}.T_t).den.dh + \int_{0m}^{15m} \left(\pi.\frac{d_b + d_t}{2}.T_4\right).den.dh$$

Weight of the platform, ladder, etc.: $W_p := 2.W_s = 85.822.kN$

Total weight of the chimney: $W_T := W_s + W_p = 515.932.kN$

Modulus of elasticity of the material of structural shell: $E_s := 200000MPa$

The fundamental period of vibration (ref. clause 14.1; IS-1893 Part-4:2005):

$$T_n := C_T.\sqrt{\frac{W_T.Ht}{E_s.A_{base}.g}} = 0.593s$$

Stiffness of the flared chimney is approximately two times the prismatic chimney. Therefore the conservative estimate of natural time period for this chimney will be: $T_{n\_empirical} := \frac{T_n}{2} = 0.297s$

Modal analysis result (STADD-pro): $T_{modal} := 0.381s$

Maximum spectral acceleration value corresponding to the above period (ref. Clause 6.4.5; IS 1893 Part-1:2002):

$S_a := 1.4.(2.5.g) = 3.5.g$ (for all soil types consideration 2% damping)

Importance factor for steel stack: $I := 1.5$ (ref. table-8, IS 1893 Part-4:2005)

Response reduction factor: $R_f := 2$ (ref. table-9, IS 1893 Part-4:2005)

Zone factor: $Z := 0.10$ (ref. table-2, IS 1893 Part-1:2002 for zone ii)

Design horizontal acceleration spectrum value: $A_h := \frac{\left(\frac{Z}{2}\right).\left(\frac{S_a}{g}\right)}{\left(\frac{R_f}{I}\right)} = 0.131$ (ref. clause 8.3.2, IS 1893 Part-4: 2005 for design basis earthquake)

Design base shear: $V_B := A_h.W_T = 67.585kN$ (this value is less than the base shear obtained from the wind load)

Calculation of design moment:

$$Denominator_1 := \int_{35m}^{Ht} \pi.d_{top}.T_{top}.den.h^2 dh$$

$$Denominator_2 := \int_{25m}^{35m} \pi.d_{top}.T_2.den.h^2 dh$$

$$Denominator_3 := \int_{15m}^{25m} \pi d_{top}.T_3.den.h^2 dh$$

$$Denominator_4 := \int_{0}^{15m} \pi.\left[d_{base} - \frac{(d_{base} - d_{top}).h}{(15m - 0m)}\right].T_4.den.h^2 dh$$

$$Denominator := Denominator_1 + Denominator_2 + Denominator_3 + Denominator_4$$

Moment due to seismic force at the 35m level

$$M_{s1} := \frac{\int_{35m}^{Ht} \pi.d_{top}.T_{top}.den.h^2.V_B.\left(h-35m\right)dh}{Deno\min ator} = 175.36.kN.m$$

$$f_{smo1} := \frac{1.05 M_{s1}}{Z_1} = 9.768.MPa$$

$f_{sc1} := f_{smo1} + f_{st1} + f_{pl1} = 11.966MPa$ $\quad$ $f_{alloeC1} = 81.MPa$ $\quad$ Therefore safe

Moment due to seismic force at the 25m level

$$Numerator_{2a} := \int_{35m}^{Ht} \pi.d_{top}.T_{top}.den.h^2.V_B.(h-25m)dh$$

$$Numerator_{2b} := \int_{25m}^{35m} \pi.d_{top}.T_2.den.h^2.V_B.(h-25m)dh$$

$$M_{s2} := \frac{Numerator_{2a} + Numerator_{2b}}{Deno\min ator} = 615.258.kN.m$$

$$f_{smo2} := \frac{1.05 M_{s2}}{Z_2} = 25.704.MPa$$

$f_{sc2} := f_{smo2} + f_{st2} + f_{pl2} = 29.237MPa$ $\quad$ $f_{allowC2} := 99.MPa$ $\quad$ Therefore safe

Moment due to seismic force at the 15m level

$$Numerator_{3a} := \int_{35m}^{Ht} \pi.d_{top}.T_{top}.den.h^2.V_B.(h-15m)dh$$

$$Numerator_{3b} := \int_{25m}^{35m} \pi.d_{top}.T_2.den.h^2.V_B.(h-15m)dh$$

$$Numerator_{3c} := \int_{15m}^{25m} \pi.d_{top}.T_3.den.h^2.V_B.(h-15m)dh$$

$$M_{s3} := \frac{Numerator_{3a} + Numerator_{3b} + Numerator_{3c}}{Denominator} = 1209.659 . kN.m$$

$$f_{smo3} := \frac{1.05 M_{s3}}{Z_3} = 40.43 MPa$$

$$f_{sc3} := f_{smo3} + f_{st3} + f_{pl3} = 44.951 MPa \qquad f_{allowC3} := 112 MPa$$ Therefore safe

Moment due to seismic force at the base (0m level)

$$Numerator_{4a} := \int_{35m}^{Ht} \pi . d_{top} . T_{top} . den . h^2 . V_B . h . dh$$

$$Numerator_{4b} := \int_{25m}^{35m} \pi . d_{top} . T_2 . den . h^2 . V_B . h . dh$$

$$Numerator_{4c} := \int_{15m}^{25m} \pi . d_{top} . T_3 . den . h^2 . V_B . h . dh$$

$$Numerator_{4d} := \int_{0m}^{15m} \pi . \left[d_{base} - \frac{\left(d_{base} - d_{top}\right) . h}{\left(15m - 0m\right)} \right] . T_4 . den . h^2 . V_B . h . dh$$

$$M_{s4} := \frac{Numerator_{4a} + Numerator_{4b} + Numerator_{4c} + Numerator_{4d}}{Denominator} = 2208.383 kN.m$$

$$f_{smo4} := \frac{1.05 M_{s4}}{Z_4} = 24.027 MPa$$

$$f_{sc4} := f_{smo4} + f_{st4} + f_{pl4} = 28.737 MPa \qquad f_{allowC4} := 107 . MPa$$ Therefore safe

3.6.10. Calculation of Dynamic Wind Load

Fundamental period of vibration or the chimney: $T_{n\_empirical} = 0.297 s$

As the period of natural oscillation for the self-supported chimney exceeds 0.25 seconds, the design wind load should take into consideration the dynamic effect due to pulsation of thrust caused by the wind velocity in addition to the static wind load.(ref. clause 8.3.1, IS-6533 Part-2:1989)

Dynamic coefficient for the 1st mode: $dc_1 := \frac{T_{n\_empirical} . v_b}{1200m} = 0.014$ (ref. clause 8.3.1, IS-6533 Part-2:1989)

Coefficient of dynamic influence corresponding to the above value of dynamic coefficient:

$$E_1 := 1.3 + \frac{(2.5 - 1.3).(dc_1 - 0)}{(0.025 - 0.0)} = 1.992$$

(ref. table-5,IS-6533 Part-2:1989)

Coefficient which takes care of the space correlation of wind pulsation speed according to height and vicinity of building structures: $v_1 = 0.7$

(ref. table-7,IS-6533 Part-2:1989 for 45m height and dc_1 =0.029)

Assuming the fundamental mode shape of the chimney is represented by second degree parabola whose ordinate at the top of the chimney is unity. So, the ordinate, y (in m) of the mode shape at a height ‘x (in m)’ from the ground is as follows (where Ht =total height of the chimney in m):

$$y = \left(\frac{x}{Ht}\right)^2$$

Coefficient of pulsation of speed thrust, as per table-6, IS-6533 Part-2:1989 for type A location (sea coast):

Calculation of deduced acceleration:

$$N_a := \int_{0m}^{10m} \left(\frac{h}{Ht}\right)^2 0.6.\left[k1.(1.03)k3.\left(v_b.\frac{s}{m}\right)\right]^2 .\frac{N}{m^2}.\left[d_{base} - \left[h.\frac{d_{base} - d_{top}}{h_{flare}}\right]\right].(0.6)dh$$

$$N_b := \int_{10m}^{15m} \left(\frac{h}{Ht}\right)^2 0.6.\left[k1.\left[1.03 + \frac{(h-10m).0.04}{15m-10m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}.\left[d_b - \left[h.\frac{d_b - d_t}{h_{flare}}\right]\right].\left[0.6 - \frac{0.05.(h-10m)}{10m}\right]dh$$

$$N_c := \int_{15m}^{20m} \left(\frac{h}{Ht}\right)^2 0.6.\left[k1.\left[1.07 + \frac{(h-15m).(1.10-1.07)}{20m-15m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}.d_{top}.\left[0.6 - \frac{0.05.(h-10m)}{10m}\right]dh$$

$$N_d := \int_{20m}^{15m} \left(\frac{h}{Ht}\right)^2 0.6.\left[k1.\left[1.10 + \frac{(h-20m).(1.13-1.10)}{30m-20m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}.d_{top}.\left[0.55 - \frac{0.07.(h-20m)}{20m}\right]dh$$

$$N_e := \int_{30m}^{40m} \left(\frac{h}{Ht}\right)^2 0.6.\left[k1.\left[1.13 + \frac{(h-30m).(1.18-1.13)}{50m-30m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}.d_{top}.\left[0.55 - \frac{0.07.(h-20m)}{20m}\right]dh$$

$$N_f := \int_{40m}^{Ht} \left(\frac{h}{Ht}\right)^2 0.6.\left[k1.\left[1.13 + \frac{(h-30m).(1.18-1.13)}{50m-30m}\right]k3.\left(v_b.\frac{s}{m}\right)\right]^2.\frac{N}{m^2}.d_{top}.\left[0.48 - \frac{0.02.(h-40m)}{20m}\right]dh$$

$$Numerator_{da} := N_a + N_b + N_c + N_d + N_e + N_f = 40.056KN$$

$$D_a := \int_{35m}^{Ht} \left(\frac{h}{Ht}\right)^4 .\pi.d_{top}.T_{top}.\frac{den}{g}.dh$$

$$D_b := \int_{25m}^{35m} \left(\frac{h}{Ht}\right)^4 .\pi.d_{top}.T_2.\frac{den}{g}.dh$$

$$D_c := \int_{15m}^{25m} \left(\frac{h}{Ht}\right)^4 .\pi.d_{top}.T_3.\frac{den}{g}.dh$$

$$D_d := \int_{0m}^{15m} \left(\frac{h}{Ht}\right)^4 .\pi.\left[d_{base} - \frac{(d_{base} - d_{top}).h}{(15m-0m)}\right].T_4.\frac{den}{g}.dh$$

$$Deno\min ator_{da} := 1.05(D_a + D_b + D_c + D_d) = 6.983\frac{s^2}{m}.kN$$

$$factor_{da} := \frac{Numerator_{da}}{Deno\min ator_{da}} := 5.736\frac{m}{s^2}$$

Inertia force at 35m level

$$P_{dyn1} := \int_{35m}^{Ht} \left(\pi.d_{top}.T_{top}.\frac{den}{g} \right).E_1.\left[\left(\frac{h}{Ht} \right)^2 .factor_{da} \right].v_1.dh = 44.732.kN$$

$$M_{dyn1} := \int_{35m}^{Ht} \left(\pi.d_{top}.T_{top}.\frac{den}{g} \right).E_1.\left[\left(\frac{h}{Ht} \right)^2 .factor_{da} \right].v_1.(h - 35m).dh = 242.204.kN$$

Check for stress at 35m level due to dynamic wind force:

$f_{dyn\_c1} := f_{c1} + \frac{M_{dyn1}}{Z_1} = 45.502.MPa$ $\quad f_{dyn\_allowC1} := 1.33.f_{allowC1} = 107.73MPa$ Therefore, safe

Inertia force at 25m level

$$P_{dyn2a} := \int_{25m}^{35m} \left(\pi.d_{top}.T_2.\frac{den}{g} \right).E_1.\left[\left(\frac{h}{Ht} \right)^2 .factor_{da} \right].v_1.dh = 28.872.kN$$

Shear force at the 25m level due to inertia: $P_{dyn2} := P_{dyn1} + P_{dyn2a}$ =73.605 kN

$$M_{dyn2a} := \int_{25m}^{35m} \left(\pi.d_{top}.T_2.\frac{den}{g} \right).E_1.\left[\left(\frac{h}{Ht} \right)^2 .factor_{da} \right].v_1.(h - 25m).dh$$

$$M_{dyn2b} := \int_{35m}^{Ht} \left(\pi.d_{top}.T_{top}.\frac{den}{g} \right).E_1.\left[\left(\frac{h}{Ht} \right)^2 .factor_{da} \right].v_1.(h - 25m).dh$$

Total moment at 25m level due to inertia: $M_{dyn2} := M_{dyn2a} + M_{dyn2b} = 849.783.kN.m$

Check for stress at 15m level due to dynamic wind force:

$f_{dyn\_c2} := f_{c2} + \frac{M_{dyn2}}{Z_2} = 82.533MPa$ $\quad f_{dyn\_allowC2} := 1.33.f_{allowC2} = 131.67MPa$ Therefore, safe

Inertia force at 15m level

$$P_{dyn3a} := \int_{15m}^{25m} \left(\pi . d_{top} . T_3 . \frac{den}{g} \right) . E_1 . \left[\left(\frac{h}{Ht} \right)^2 . factor_{da} \right] . v_1 . dh = 14.602.kN$$

Shear force at the 15m level due to inertia: $P_{dyn3} := P_{dyn2} + P_{dyn3a}$ =88.207 kN

$$M_{dyn3a} := \int_{15m}^{25m} \left(\pi . d_{top} . T_3 . \frac{den}{g} \right) . E_1 . \left[\left(\frac{h}{Ht} \right)^2 . factor_{da} \right] . v_1 . (h - 15m) . dh$$

$$M_{dyn3b} := \int_{25m}^{35m} \left(\pi . d_{top} . T_2 . \frac{den}{g} \right) . E_1 . \left[\left(\frac{h}{Ht} \right)^2 . factor_{da} \right] . v_1 . (h - 15m) . dh$$

$$M_{dyn3c} := \int_{35m}^{Ht} \left(\pi . d_{top} . T_{top} . \frac{den}{g} \right) . E_1 . \left[\left(\frac{h}{Ht} \right)^2 . factor_{da} \right] . v_1 . (h - 15m) . dh$$

Total moment at 15m level due to inertia: $M_{dyn3} := M_{dyn3a} + M_{dyn3b} + M_{dyn3c} = 1670.76.kN.m$

Check for stress at 15m level due to dynamic wind force:

$f_{dyn\_c3} := f_{c3} + \frac{M_{dyn3}}{Z_3} = 137.783 MPa$ $f_{dyn\_allowC3} := 1.33. f_{allowC3} = 148.96 MPa$ Therefore, safe

Inertia force at base (0m level)

$$P_{dyn4a} := \int_{0m}^{15m} \left(\pi . \left[d_{base} - \frac{(d_{base} - d_{top}).h}{(15m - 0m)} \right] . T_4 . \frac{den}{g} \right) . E_1 . \left[\left(\frac{h}{Ht} \right)^2 . factor_{da} \right] . v_1 . dh = 5.14.kN$$

Shear force at the base (0m level) due to inertia: $P_{dyn4} := P_{dyn3} + P_{dyn4a}$ =93.347KN

$$M_{dyn4a} := \int_{0m}^{15m} \left(\pi . \left[d_{base} - \frac{(d_{base} - d_{top}).h}{(15m - 0m)} \right] . T_4 . \frac{den}{g} \right) . E_1 . \left[\left(\frac{h}{Ht} \right)^2 . factor_{da} \right] . v_1 . h . dh = 56.321 m.kN$$

$$M_{dyn4b} := \int_{15m}^{25m} \left(\pi . d_{top} . T_3 . \frac{den}{g} \right) . E_1 . \left[\left(\frac{h}{Ht} \right)^2 . factor_{da} \right] . v_1 . h . dh$$

$$M_{dyn4c} := \int_{25m}^{35m} \left(\pi . d_{top} . T_2 . \frac{den}{g} \right) . E_1 . \left[\left(\frac{h}{Ht} \right)^2 . factor_{da} \right] . v_1 . h . dh$$

$$M_{dyn4d} := \int_{35m}^{Ht} \left(\pi.d_{top}.T_{top}.\frac{den}{g} \right).E_1.\left[\left(\frac{h}{Ht} \right)^2 .factor_{da} \right].v_1.h.dh$$

Total moment at 15m level due to inertia:

$$M_{dyn4} := M_{dyn4a} + M_{dyn4b} + M_{dyn4c} + M_{dyn4d} = 3050.18..kN.m$$

Check for stress at the base (0m level) due to dynamic wind force:

$f_{dyn\_c4} := f_{c4} + \frac{M_{dyn4}}{Z_4} = 94.276MPa$ $\quad f_{dyn\_allowC4} := 1.33.f_{allowC4} = 142.31MPa$ Therefore, safe

3.6.11. Check for Resonance

Fundamental period of vibration for this chimney: $T_{modal} = 0.381s \quad T_{n\_empirical} = 0.297s$

Fundamental frequency of the vibration: $f := \frac{1}{T_{modal}} = 2.625\frac{1}{s}$

Stroughal critical velocity: $v_{cr} := 5.d_{top}.f = 26.274\frac{m}{s}$ (ref. clause A-3, IS-6533 Part-2:1989)

Basic wind velocity: $v_b = 58.333\frac{m}{s}$

Design wind velocity: $v_d := k1.k3.(1.12).v_b = 65.333\frac{m}{s}$ (considering k2=1.12)

Velocity (stroughal critical velocity) range for resonance: $v_{resonance\_UL} := 0.8.v_d = 52.267\frac{m}{s}$

$v_{resonance\_LL} := 0.33.v_d = 21.56\frac{m}{s}$

As the stroughal critical velocity lies within the ranges of resonance limits the chimney should be checked for the resonance:

Logarithmic decrement of dampening effect for unlined steel chimney: $del := 0.05$

(ref. clause A-5, IS-6533 Part-2:1989)

Speed thrust corresponding to critical velocity: $q_{cr} := \frac{v_{cr}{}^{2}.Pa}{16.\frac{m^{2}}{s^{2}}} = 43.056Pa$

(ref. clause A-5, IS-6533 Part-2:1989)

Shape factor of the chimney: $(C_{shape} := 0.7)$ (ref. clause A-5, IS-6533 Part-2:1989)

Static wind load corresponding to the critical pressure: $(q_{cr\_stat} := C_{shape}.q_{cr} = 30.139\,pa)$ (ref. clause A-5, IS-6533 Part-2:1989)

Check at 15m level:

Static transverse force: $F_{st.15m} := (Ht - 15m).d_{top}.q_{cr\_stat} = 1.808kN$

Static transverse moment: $M_{st.15m} := 0.5.(Ht - 15m)^{2}.d_{top}.q_{cr\_stat} = 27.125.kN.m$

Transverse force at resonance: $F_{res.15m} := \left(\frac{\pi}{del}\right).F_{st.15m} = 1704.kN.m$

Moment at resonance: $M_{res.15m} := \left(\frac{\pi}{del}\right).M_{st.15m} = 1671.kN.m$

Dynamic transverse moment: $M_{dyn.15m} := M_{dyn3} = 1671.kN.m$

Design moment due to resonance: $M_{15m} := \sqrt{M_{res.15m}{}^{2} + (M_{st.15m} + M_{dyn.15m})^{2}} = 2406.kN.m$

Check for stress at 15m level due to resonance: $f_{15m} := f_{st3} + f_{pl3} + \left(\frac{M_{15m}}{Z_{3}}\right) = 81.089.MPa$

$f_{allowC3} = 112.MPa$ Therefore, safe

Check at base (i.e. at 0m level)

Static transverse force: $F_{st.0m} := \left[\left(Ht - h_{flare}\right).d_{top} + \frac{h_{flare}.\left(d_{base} + d_{top}\right)}{2}\right].q_{cr\_stat} = 2.984kN$

Static transverse moment:

$$M_{st.0m} := \left(Ht - 15m\right).\frac{(Ht + 15m)}{2}.d_{top}.q_{cr\_stat} + \int_{0m}^{15m}\left[d_{base} - \frac{\left(d_{base} - d_{top}\right).h}{2}\right].q_{cr\_stat}.h.dh = 62.388.kN.m$$

Transverse force at resonance: $F_{res.0m} := \left(\frac{\pi}{del}\right).F_{st.0m} = 187.475.kN.m$

Moment at resonance: $M_{res.0m} := \left(\frac{\pi}{del}\right).M_{st.0m} = 3920.kN.m$

Dynamic transverse force: $F_{dyn.0m} := P_{dyn4} = 93.347.kN.m$

Dynamic transverse moment: $M_{dyn.0m} := M_{dyn4} = 3050.kN.m$

Design moment due to resonance: $F_{0m} := \sqrt{F_{res.0m}{}^{2} + \left(F_{st.0m} + F_{dyn.0m}\right)^{2}} = 211.kN.m$

Design moment due to resonance: $M_{0m} := \sqrt{M_{res.0m}{}^{2} + \left(M_{st.0m} + M_{dyn.0m}\right)^{2}} = 5005kN.m$

Check for stress at 15m level due to resonance: $f_{0m} := f_{st4} + f_{pl4} + \left(\frac{M_{0m}}{Z_4}\right) = 56.574MPa$

$f_{allowC4} = 107.MPa$ Therefore, safe

3.7. SUMMARY

This Chapter presents a step by step procedure for designing self supporting Steel chimney though example calculations. The chimney is first designed for static wind force and then the design is checked for seismic load, dynamic wind force and for possible resonance.

CHAPTER 4

EFFECT OF GEOMETRY ON THE DESIGN OF SELF SUPPORTING STEEL CHIMNEY

4.1 INTRODUCTION

This Chapter deals with the analysis of steel chimneys. The chimney is idealized as cantilever column with tubular cross section for analysis. As explained in the previous chapter the main loads to be considered during the analysis of chimneys are wind loads and seismic loads in addition to the dead loads. Basic dimensions of a self supporting steel chimney is generally obtained from the environmental consideration. Other important geometrical considerations are limited by design code IS 6533 (Part 1 & 2): 1989 to obtained preferred mode of failure. Section 4.2 discusses the geometry limitations recommended by IS 6533 (Part 1 & 2): 1989. This chapter attempts to assess these limitations through analysis of different chimney geometries. Section 4.3 presents the different chimney geometry considered for this study. Also, a study is carried out to understand the chimney behaviour with inspection manhole at the lower end of the chimney. Last part of this chapter presents the difference of chimney behaviour with and without the inspection manhole. Analysis is carried out through manual calculations using MathCAD as well as finite element analysis using commercial software ANSYS.

4.2 LIMITATIONS ON CHIMNEY GEOMETRY

Steel Chimneys are cylindrical in shape for the major portion except at the bottom where the chimney is given a conical flare for better stability and for easy entrance of flue gases. Height of the flared portion of the chimney generally varies from one fourth to one third of the total height of the chimney. Design forces in a chimney are very sensitive to its geometrical parameters such as base and top diameter of the chimney, height of the flare, height of the chimney and thickness of the chimney shell. Design codes consider two modes of failure to arrive at the thickness of chimney shell: material yielding in tension and compression and local buckling in compression. Height of the chimney obtained from environmental conditions. As per notifications of the Ministry of Environment and Forests (MEF Notification 2002), Govt. of India, height of a self supporting steel chimney should be as follows:

$$h = \max \begin{cases} 14Q^{0.3} \\ 6m + Tallest\ Building\ Height\ in\ the\ location \\ 30m \end{cases}$$

Where Q = total SO_2 emission from the plant in kg/hr and h = height of the steel chimney in m. Height of steel chimney as per IS-6533 (Part-1): 1989 also a function of environmental condition as follows:

$$h = \left[\frac{AMFD}{8CV} \right]^{\frac{3}{4}}$$

Where

A = coefficient of temperature gradient of atmosphere responsible for horizontal and vertical mixing of plume

M = estimated mass rate of emission of pollutants in g/s

F = dimensionless coefficient of rate of precipitation

C = maximum permissible ground level concentration of pollutant in mg/m^3

V = estimated volume rates of emission of total flue gases, m^3/s

D = diameter of stack at the exit of the chimney in m.

Also, inside diameter of the chimney shell at top as per IS 6533 (Part 1): 1989 is given by:

$$D = \sqrt{\frac{4Q_t}{\pi V_{exit}}}$$

Where

D = inside diameter of the chimney at top in m,

Q_t = Quantity of the gas in m^3/s, and

V_{exit} = Velocity of the flue gas at exit point of chimney in m/s.

However, the diameter shall be so chosen that velocity of the flue gas at exit point of chimney will not exit, under any circumstances, 30 m/s. As per IS 6533 (Part 1): 1989, velocity may be taken as 15 – 20 m/s.

It is clear that the height of the chimney and diameter of the chimney at top is completely determined from the dispersion requirement of the flue gases in to the atmosphere. Because of this IS 6533 (Part 2): 1989 limits the proportions of the basic dimensions from structural engineering considerations as follows:

i) Minimum outside diameter of the unlined chimney at the top should be one twentieth of the height of the cylindrical portion of the chimney.

ii) Minimum outside diameter of the unlined flared chimney at the base should be 1.6 times the outside diameter of the chimney at top.

With this background this paper attempts to check the basis of design code limitations with regard to the basic dimensions of a self supporting unlined flared steel chimney. Two parameters: (i) top-to-base diameter ratio and (ii) height-to-base diameter ratio were considered for this study. A numbers chimneys with different dimensions analysed for dynamic wind load.

4.3 DESCRIPTION OF THE SELECTED CHIMNEYS

From the discussions in the previous section it is clear that top-to-base diameter ratio and height-to-base diameter ratio are the two important parameters that define the geometry of a self supporting chimney. In the present study a total of 66 numbers of Chimney were selected with varying top-to-base diameter ratio and height-to-base diameter ratio. The thickness and the diameter of flared base of the chimney were kept constant for all the cases. Fig.4.1 presents the different parameters of the selected chimneys. The shaded portion in the figure represents the region acceptable by the design code IS 6533 (Part 2): 1989. Design code limits minimum base diameter as 1.6 times the top diameter of the chimney. This gives maximum limit of top-to-base diameter ratio as $1/1.6 = 0.625$. Also, as per IS 6533 (Part 2): 1989, minimum top diameter of the chimney should be one twentieth of the height of the cylindrical portion of the chimney, *i.e.*, $(2h/3)\times(1/20) = h/30$ (considering the flare height of the chimney as one third of the total height).

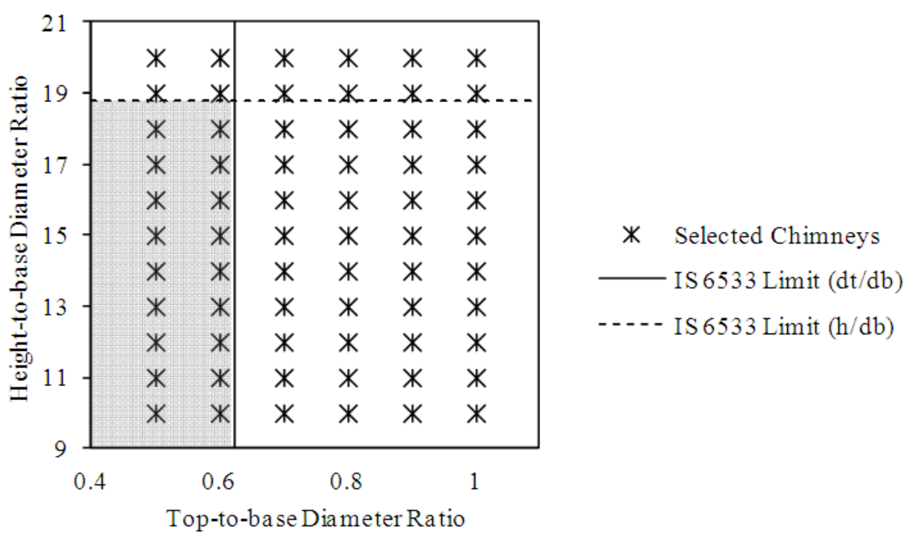

Fig. 4.1: Geometrical distribution of selected chimney models

Therefore the height-to-base diameter ratio as per the code limits to $30/1.6 = 18.75$ (for a maximum top-to-base diameter ratio of 0.625). This figure shows that the selected chimneys cover a wide range of geometry. Here, top-to-base diameter ratio is one means self-supporting chimney without flare. The chimney models were considered to be located at costal Orissa area with a basic wind speed of 210 km/h. Safe bearing capacity of the site soil at a depth 2.5m below the ground level is assumed to be 30 t/m^2. Fixity at the base of the chimney is assumed for the analysis.

4.4 DYNAMIC WIND LOAD AS PER IS 6533 (PART-2): 1989

IS 6533 (Part-2): 1989 requires design wind load to consider dynamic effect due to pulsation of thrust caused by wind velocity in addition to static wind load when the fundamental period of the chimney is less than 0.25s. The fundamental period of vibration for a self supporting chimney can be calculated as per IS-1893 Part-4:2005[6] as follows:

$$T = C_T \sqrt{\frac{W_T h}{E_s A_{base} g}}$$

Where, C_T = Coefficient depending upon slenderness ratio, W_T = Total weight of the chimney, h = total height of the chimney. E_s = Modulus of elasticity of the material of structural shell and A_{base} = Area of cross section at base of chimney shell. Stiffness of the flared chimney is generally approximated as two times the prismatic chimney. Therefore a conservative estimate of fundamental period for flared chimney considered to be one half the period of given in the previous equation. Fundamental period of the chimney is also determined from finite element software STAAD-Pro and compared with that obtained from the empirical equation. Assuming the fundamental mode shape of the chimney is represented by second degree parabola whose ordinate at the top of the chimney is unity. So, the ordinate, *y* (in m) of the mode shape at a height '*x* (in m)' from the ground is as follows (where *h* = total height of the chimney in m).

$$y = \left(\frac{x}{h}\right)^2$$

This assumption holds good for the type of chimney considered in the present study. Fig. 4.2 shows the fundamental mode shape of a typical chimney as obtained Eigen value analysis using STAAD-Pro.

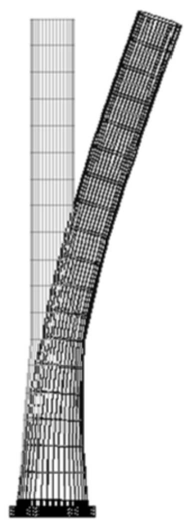

Fig. 4.2: Fundamental mode shape of a typical chimney as obtained from finite element analysis

Fig. 4.3 presents the comparison of the fundamental mode shapes of a typical chimney obtained from empirical equation and Eigen value analysis. This figure shows that the empirical equation for fundamental mode shape is closely matching the actual mode shape. Therefore, the use of this empirical equation in the present study is justified. Dynamic effect of wind is influenced by a number of factors, such as, mass and its disposition along chimney height, fundamental period and mode shape. Values of dynamic components of wind load should be determined for each mode of oscillation of the chimney as a system of inertia forces acting at ‘centre of mass’ location.

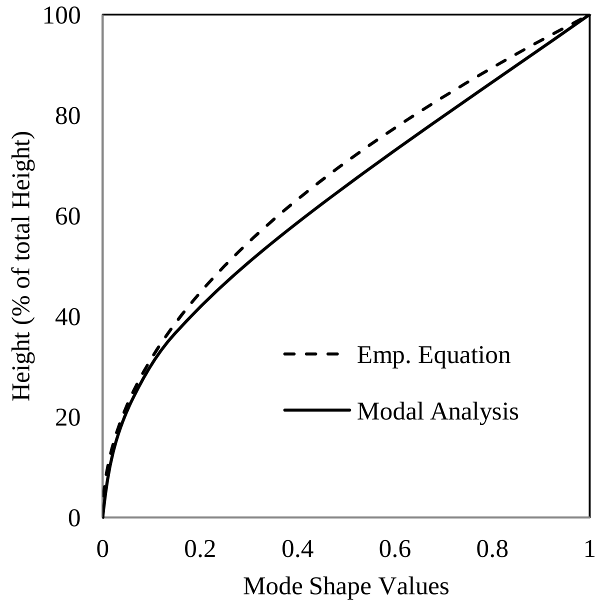

Fig. 4.3: Comparison of fundamental mode shape obtained different analysis

As per IS 6533 (Part-2): 1989 Inertia force, dP_{dyn}, for i^{th} mode for an infinitesimal height dx at a height x from the base of the chimney is as follows:

$$dP_{dyn} = dm \times \xi_i \times \eta_i \times \nu$$

Where dm = mass of the chimney for an infinitesimal height dx at height x from the base of the chimney, $\xi_i = (T_i V_b)/1200$ is the dynamic coefficient for the i^{th} mode of vibration, T_i = the period of i^{th} mode and V_b = basic wind speed in m/s, ν = coefficient which takes care of the space correlation of wind pulsation speed, and η_i = deduced acceleration in m/s^2 for i^{th} mode at height h. For the first mode deduced acceleration can be as follows:

$$\eta_1 = \frac{\int_0^h \left(\frac{x}{h}\right)^2 m_k dP_{st}}{\int_0^h \left(\frac{x}{h}\right)^4 dm}$$

Where, m_k = coefficient of pulsation of speed thrust at a height x from the base of the chimney and dP_{st} = static wind force for an infinitesimal height dx at height x from the base of the chimney.

4.5 RESULTS AND DISCUSSIONS

66 selected chimneys with different dimensions as explained in the previous section were analysed for dynamic wind load as per IS 6533 (Part-2): 1989 using MathCAD software to calculate base shear and base moment for each chimney as follows:

Base Shear: $P_{dyn} = \int_0^h dP_{dyn}$ and Base Moment: $M_{dyn} = \int_0^h x \times dP_{dyn}$

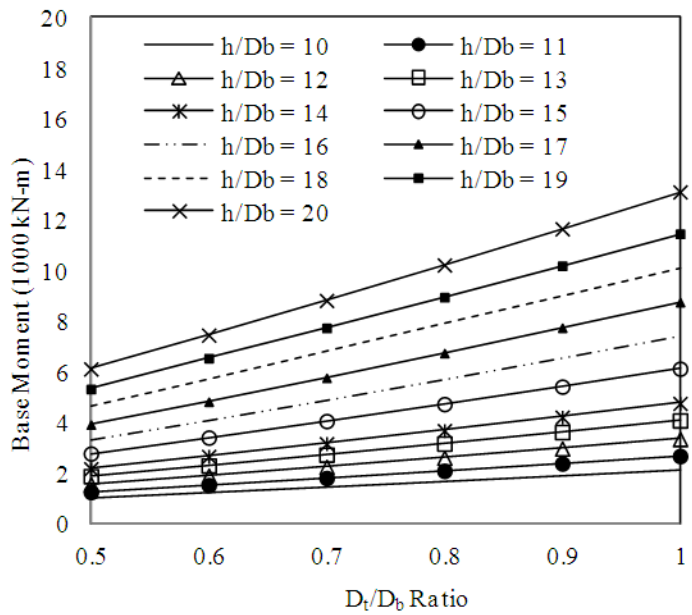

Fig. 4.4: Base moment of the chimney as a function of top-to-base diameter ratio

Fig. 4.4 presents the bending moment at the base of the chimney for dynamic wind load as a function of top-to-base diameter ratio for different height-to-base diameter ratio. This figure shows that the base moment increases with the increase of top-to-base diameter ratio almost proportionally.

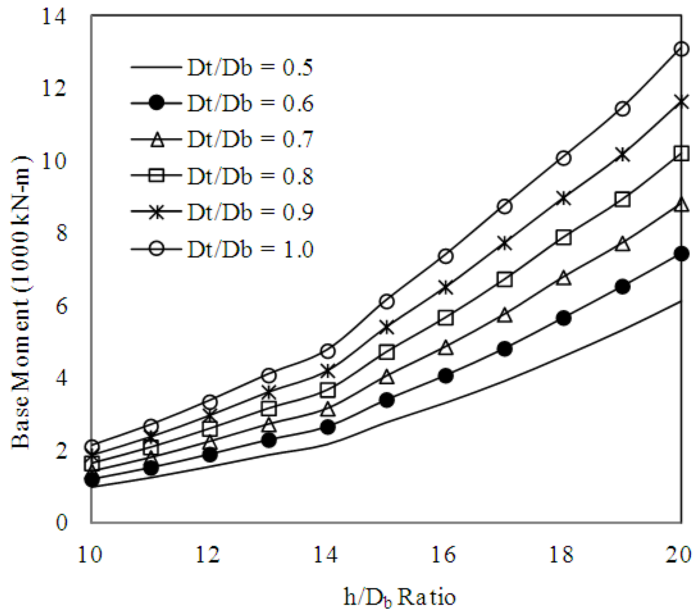

Fig. 4.5: Base moment of the chimney as a function of height-to-base diameter ratio

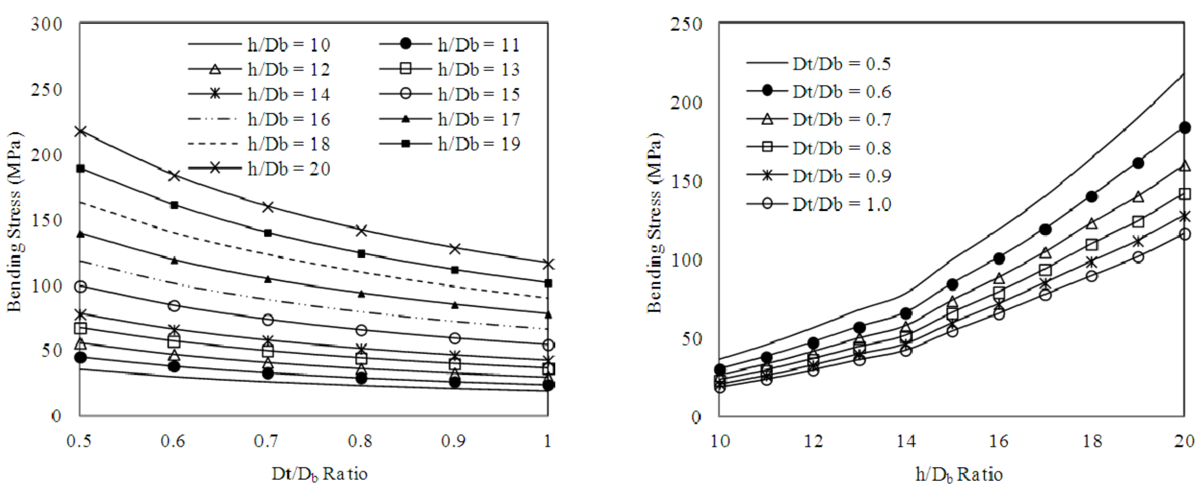

Fig. 4.6: Variation of bending stress as a function of geometry

Fig. 4.5 presents the base moment as a function of height-to-base diameter ratio for different top-to-base diameter ratio. This figure also shows similar results, *i.e*., that base moment increases with the increase of height-to-base diameter ratio. However, the rate of increase in base moment is slightly less for lower value of height-to-base diameter ratio. There is a sudden increase of the gradient of the base moment curve for height-to-base diameter ratio = 14.

Maximum bending stresses in the chimney also calculated and presented in Fig. 4.6 for different height-to-base diameter ratio and top-to-base diameter ratio. a typical chimney model It is clear from these figures that base moment (maximum moment) and the maximum bending stress due to dynamic wind load are continuous function of the geometry (top-to-base diameter ratio and height-to-base diameter ratio). Therefore this study does not support the limitations imposed by IS 6533 (Part-2): 1989 with regard to the selection of basic dimensions of self supporting steel chimneys.

4.6 EFFECT OF INSPECTION MANHOLE ON THE BEHAVIOUR OF SELF SUPPORTING STEEL CHIMNEY

Manholes are generally provided at the bottom of the chimney for maintenance and inspection purpose. The standard dimension of the manhole is 500mm×800mm according to Indian standard IS 6533 (Part-2):1989. These manholes are at generally located at minimum suitable distance from the base of the chimney. Two chimney models, one with the manhole and other without manhole, are analysed using finite element software ANSYS for static wind load. Fig. 4.7 presents the Von-Mises stress for chimney model without manhole whereas Fig. 4.8 presents the same for chimney with manhole. These results show that the maximum stress in the chimney with manhole is increased 55.6% as compared to the maximum stress in chimney without manhole.

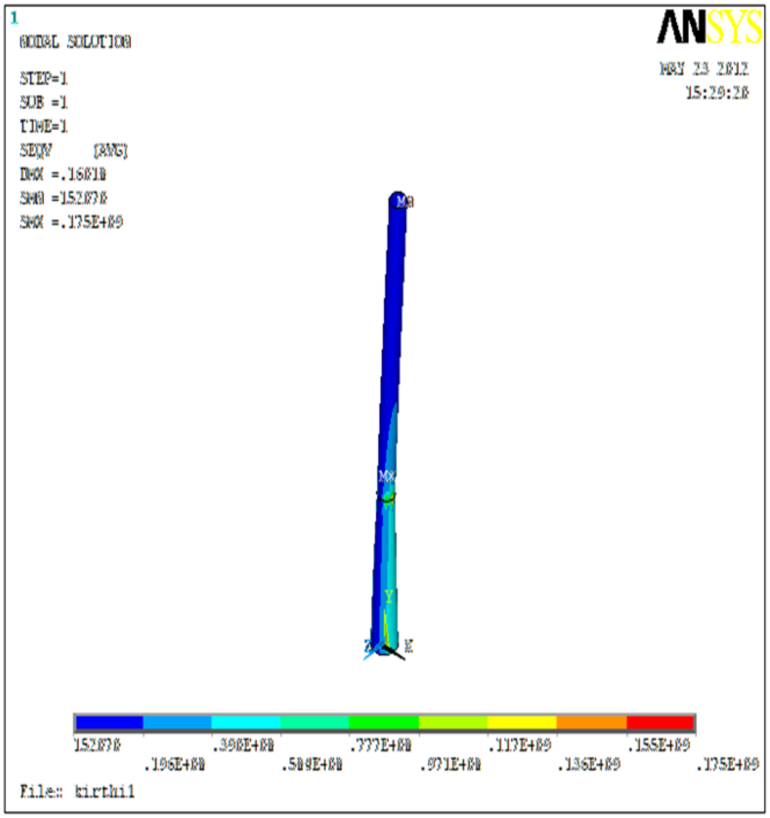

Fig.4.7: Von Mises stress for chimney without manhole

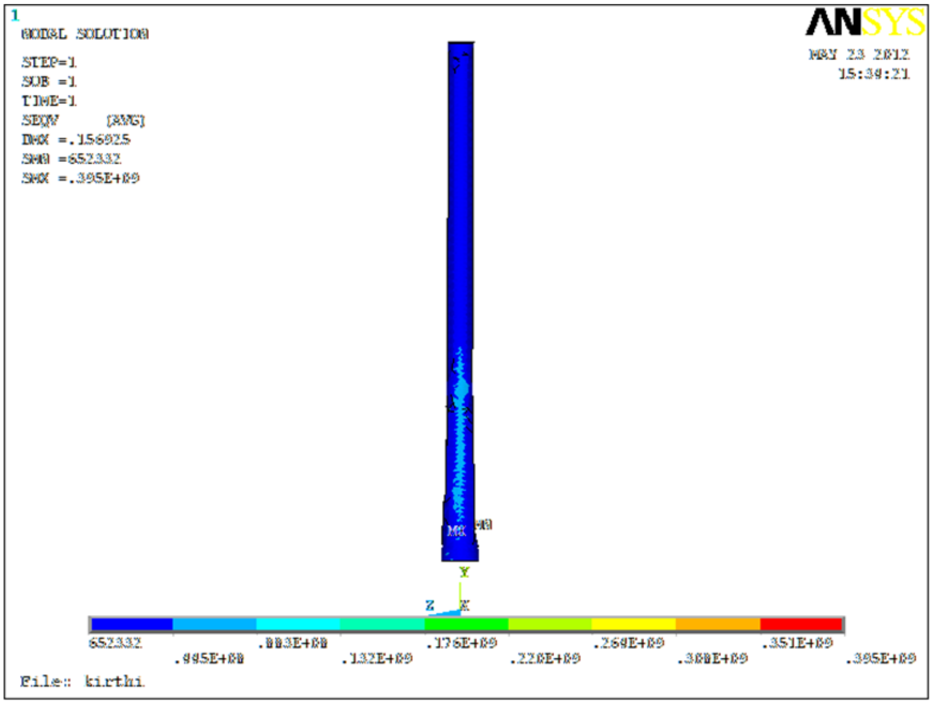

Fig.4.8: Von Mises stress for chimney with man hole

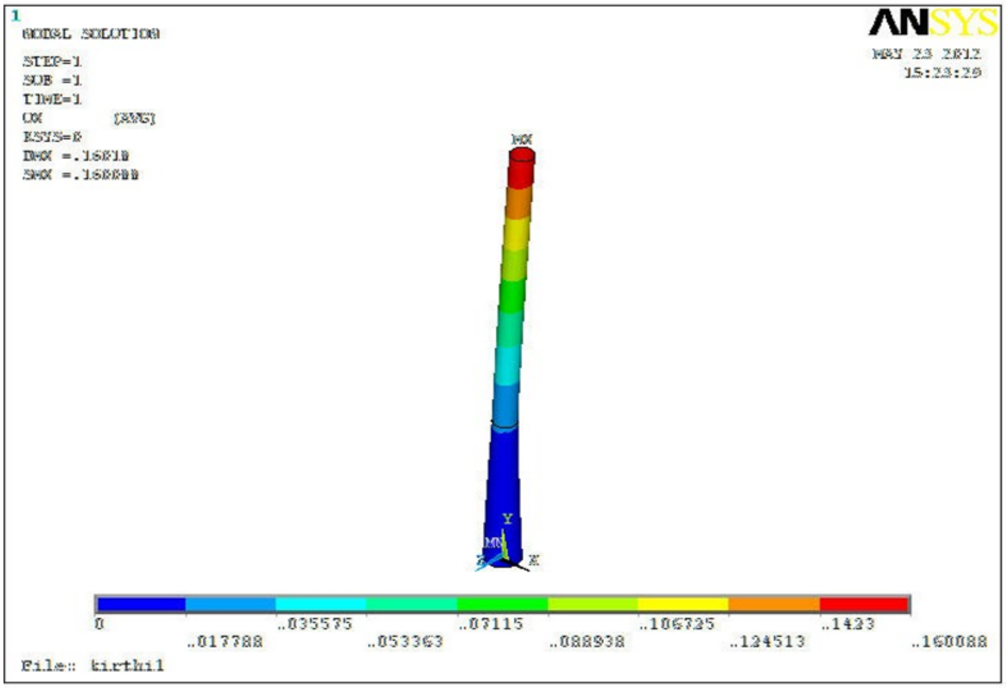

Fig.4.9: Top deflection of the chimney without manhole

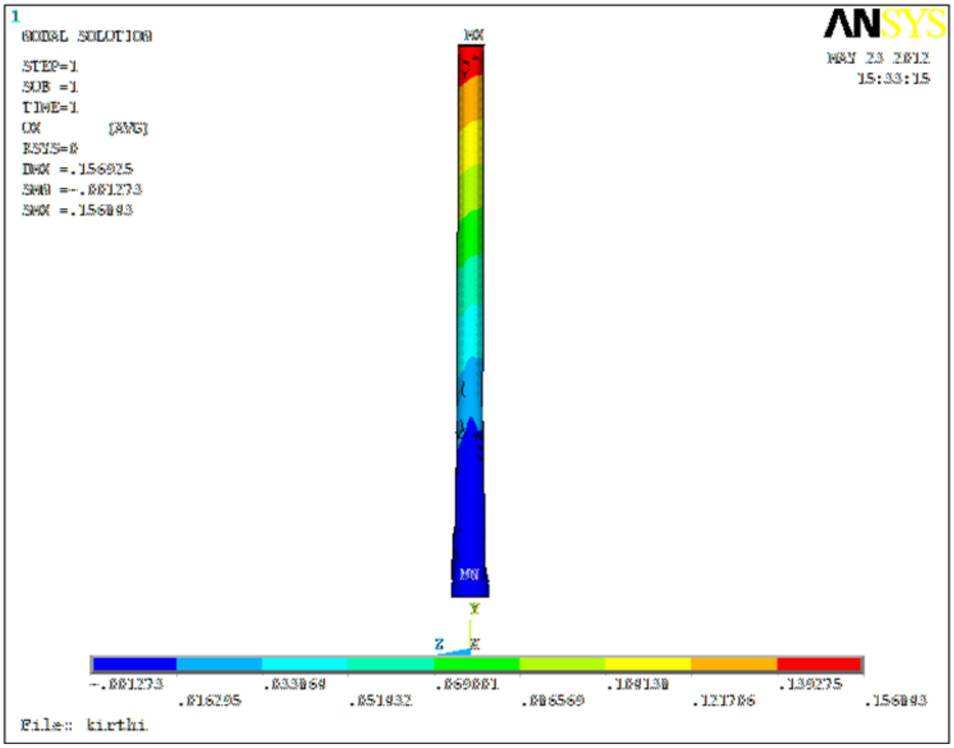

Fig.4.10: Top deflection of the chimney with manhole

Figs. 4.9 and 4.10 present the displacement response of the two chimneys under static wind force. These two figures show that higher deflection is occurred at the top of the chimney with manhole as compared to chimney without manhole.

Fig. 4.11 and 4.12 presents the fundamental mode shape of the two chimney models. Chimney without manhole is found to have higher fundamental frequency compared to the chimney with manhole. This is because chimney without manhole is stiffer than chimney with manhole.

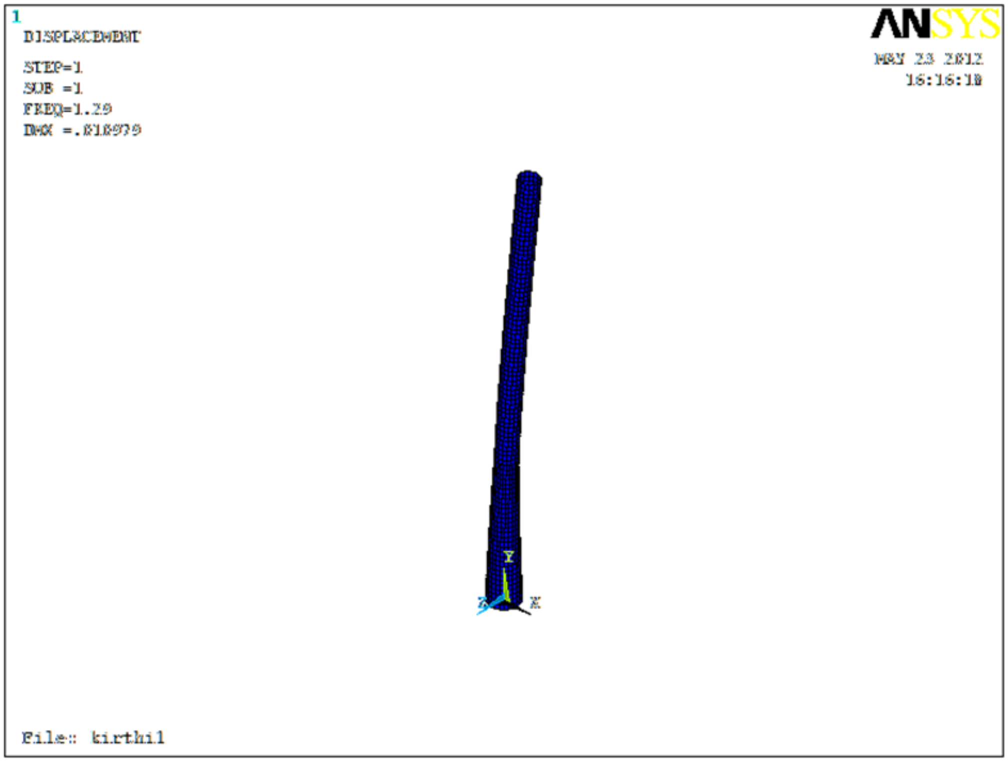

Fig. 4.11: Mode shape without manhole consideration

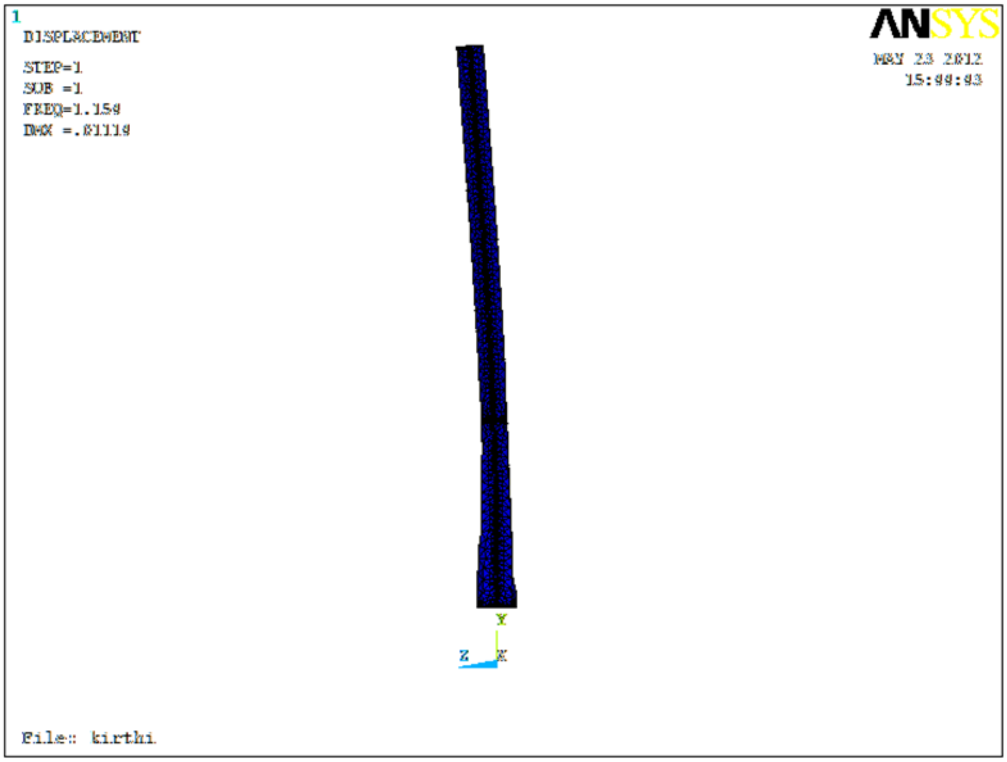

Fig. 4.12: Mode shape consideration with hole consideration

4.7 SUMMARY AND CONCLUSIONS

The objective of this chapter was to check the basis of design code limitations with regard to the basic dimensions of a self supporting unlined flared steel chimney. Two parameters: (i) top-to-base diameter ratio and (ii) height-to-base diameter ratio were considered for this study. A numbers chimneys with different dimensions analysed for dynamic wind load. A total of 66 numbers self supporting steel flared unlined chimneys were analysed for dynamic wind load due to pulsation of thrust caused by wind velocity. It is found from these analyses that maximum moment and the maximum bending stress due to dynamic wind load in a self supporting steel chimney are continuous function of the geometry (top-to-base diameter ratio and height-to-base diameter ratio). This study does not support the IS 6533 (Part-2): 1989 criteria for minimum top diameter to the height ratio of the chimney and minimum base diameter to the top diameter of the chimney.

Last part of this chapter presents the effect of inspection manhole on a self supporting steel chimney. This results show that manhole increases the von-mises stress resultant and top displacement in a chimney. This is because manhole reduces the effective stiffness of a chimney as evident from the modal analysis results.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1. SUMMARY

The main objective of the present study was to explain the importance of geometrical limitations in the design of self supported steel chimney. A detailed literature review is carried out as part of the present study on wind engineering, design and analysis of steel chimney as well as concrete chimney. Estimation of wind effects (along wind & across wind), vortex shedding, vibration analysis, and gust factor are studied. There is no published literature found on the effect of geometry on the design of self supporting steel chimney.

Design of a self supporting steel chimney as per IS 6533 (Part-1 and 2): 1989 is discussed through example calculations. A study is carried out to understand the logic behind geometrical limitations given in Indian Standard IS 6533 (Part-1 and 2): 1989. The relation between geometrical parameters and corresponding moments and shear is developed by using MathCAD software. Two parameters: (i) top-to-base diameter ratio and (ii) height-to-base diameter ratio were considered for this study. A numbers chimneys with different dimensions analysed for dynamic wind load. A total of 66 numbers self supporting steel flared unlined chimneys were analysed for dynamic wind load due to pulsation of thrust caused by wind velocity.

To explain the effect of inspection manhole on the behaviour of self supporting steel chimney, two chimney models one with the manhole and other without manhole are taken into consideration. These models are analysed by finite element software ANSYS.

5.2. CONCLUSIONS

It is found from these analyses that maximum moment and the maximum bending stress due to dynamic wind load in a self supporting steel chimney are continuous function of the geometry (top-to-base diameter ratio and height-to-base diameter ratio). This study does not support the IS 6533 (Part-2): 1989 criteria for minimum top diameter to the height ratio of the chimney and minimum base diameter to the top diameter of the chimney.

Inspection manhole increases the von-mises stress resultant and top displacement in a self supporting steel chimney. This is because manhole reduces the effective stiffness of a chimney as evident from the modal analysis results. Therefore it is important to consider manhole opening in the analysis and design of self supporting steel chimney.

5.3. SCOPE FOR FUTURE WORK

i) The effect of across-wind can be analysed through computational fluid dynamics using finite element software ANSYS.

ii) The present study considers only self supporting steel chimney .This study can be further extended to guyed steel chimney as well as concrete chimney.

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