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Wind induced torsion in chimney structures

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Abstract: *Chimneys are the essential part of industrial buildings provided for dissolution of combustion byproducts, smokes and gases to the atmosphere and thereby protecting the public and the environment .Chimneys with circular cross sections are mostly used owing to the aerodynamic and structural advantages. Chimneys are long cylindrical shell structures in vertical configurations and are of masonry, reinforced cement concrete or steel. Steel chimneys are preferred owing to the advantage of higher strength, fabrication and maintenance. Chimney structure can be idealized as a vertical cantilever beam with bottom end fixed and top end free and subjected to distributed load over the length. Torsion induced in the cylindrical shell structure cause out of plane displacement of the cross section in the longitudinal direction (warping). Once restrained, this will introduce stresses and displacements in the longitudinal direction along with bending stress and displacement. Hence the need to investigate the wind induced torsion bahaviour of chimneys has been felt and is addressed in the present study. Scope of application of strength of material concepts for estimating the torsional response has been limited to selected loading and boundary conditions. This paves the way for finite element method.*

Keywords: *steel chimney, wind load, torsion, finite element analysis*

I. Introduction

Chimneys are the essential part of an industrial building and are provided for dissolution of combustion byproducts, smokes and hazardous gases to the atmosphere and thereby protecting the public and the environment. Chimneys are long cylindrical shell structures that are placed in vertical configuration to ensure the smooth flow of gases and smokes to the desired height and drawing air into the combustion in. Chimneys with rectangular and circular cross sections are used in industry but circular sections are common owing to the aerodynamic and structural advantages. Prismatic and nonprismatic cylindrical shell structures are used as chimneys but nonprismatic structures tapering in the upward direction are common considering the structural stability, economy and aesthetics.

Chimneys are made up of various types of materials. Brick chimneys are suitable in clay industries. They are cheaper for small heights, but maintenance cost is high. Reinforced cement concrete chimneys are expensive than other forms upto a height of 45 meter, but above this height they are competitive. Above 65 meter height they are more readily acceptable because of their flexibility of shape and flue layouts, in addition to the absence of any limitation on the size. Guyed steel chimneys are better suited where the supporting capability of the soil is low whereas it involves regular maintenance of guy wires anchor points and other fittings in addition to difficulty in finding suitable anchor points of guys at ground. Steel chimneys are ideally suited for process work where a short heat up period and low thermal capacity are required. Whereas it encourages acid condensation and corrosion hence reduction in the life of chimney. Steel chimneys are considered commonly with reference to overall economy, higher strength, fabrication and maintenance [2].

II. Design Loads

Chimney structures are subjected to wind load, self weight, earthquake load etc. The relevant codes considered for the design of steel chimneys are IS6533 part1; 1989, IS6533 part2;1989 and IS875(part3);1987.

Dead loads are calculated based on the unit weight of the material. If the unit weight of the material is not known the dead load shall be calculated according to IS875 (part1):1987. The wind load shall be calculated in accordance with the provisions contained in IS875 (part3): 1987.
Design wind speed is given by (1).

$$Vz = Vb\ k1\ k2\ k3 \qquad (1)$$

Design wind pressure at any height above mean ground level shall be obtained by the following relationship between wind pressure and wind velocity.

$$P_z = 0.6\,V_z^2 \qquad (2)$$

Wind force acting on a structure is calculated using pressure coefficients. The pressure coefficients are always given for a particular surface of a structure. The wind load acting normal to a surface is obtained by multiplying the area of that surface or its appropriate portion by the pressure coefficient (Cp) and the design wind pressure at the height of the structure from the ground. Average values of pressure coefficients are given for critical wind directions in one or more quadrants. In order to determine the maximum wind load on the structure the total load should be calculated for each of the critical directions shown from all quadrants.

When calculating wind load on individual structures it is essential to take account of the pressure difference between opposite faces of such structures. Therefore it is necessary to know the internal pressure as well as the external pressure. The wind load F acting in a direction normal to the individual structural element is given by (3).

$$F = (C_{pe} - C_{pi})\,A P_z. \qquad (3)$$

III. Structural Behaviour

Chimney structures can be idealized as a vertical cantilever beam with bottom fixed and top end free and subjected to distributed load over the height. Structural behaviour of chimney structures includes buckling, bending, torsional, dynamic & thermal behaviour.

Self weight of the structure induces compressive stresses and it may cause buckling of the structure. Wind load distributed over the length will induce bending shear stresses. Chimney structures are subjected to continuously changing wind load and also they are erected on very tall heights. Due to these reasons chimney structures undergo dynamic vibrations. Dynamic behaviour of the structure is generated due to the phenomena such as gusts, vortex shedding and buffeting. The shell of chimney is always subjected to hot flue gases. Due to thermal gradient vertical and circumferential stresses are developed.

Chimney structures are always subjected fluctuating wind loads. Torsional moments occur if the point of application of the total wind load does not coincide with the shear centre of the chimney structure. According to IS875 (part3):1987 wind pressures and forces on buildings are calculated using pressure coefficients. These are always given for a particular surface or part of the surface of the building. The wind load acting normal to a surface is obtained by multiplying the area of that or its pressure coefficients and the design wind pressure at the height of the surface from the ground. Wind load acting on the structure will cause positive pressure distribution on the windward side and asymmetrical negative pressure distribution on the leeward side. This differential pressure distribution will cause twisting of the structure.

Torsion induced in the nonprismatic cylindrical shell structure cause out of plane distortion of the cross section in the longitudinal direction (warping). Once restrained this will introduce stresses and displacements in the longitudinal direction [6]. Functional openings such as breach openings and cleanout doors are provided in the chimney structure. Geometry of the opening distorted under torsion and stress concentrations will develop in the corners of the opening. Therefore the study of torsional stresses in chimney structures is relevant.

The present study aims to evaluate the wind induced torsion effects in steel chimney structures. Torsional stresses in chimney structures can be analyzed using classical methods and finite element method. Scope of application of strength of material concepts for estimating the torsional response has been limited to selected loading and boundary conditions. This paves the way for finite element method.

IV. Finite Element Analysis For Predicting Torsional Behaviour

Finite element analysis of chimney structure has been carried out to determine the wind induced torsion effects. The steel chimney structure presented by Kawecki et al (2007) [5] has been considered for the analysis. Structure is divided into 11 segments as given in figure1 and height and shell thickness of each segment is given in table1. 1615 nodes and 440 elements are assigned to the structure as a part of meshing and is given in figure2.Finite element analysis is carried out using the commercial software MSC Nastran. Quadrilateral surface element QUAD8 is selected as the finite element for the analysis. This isoparametric element has four corner and four midside nodal points.

Table1. height and shell thickness of segments of chimney structure

Segment No.	Height (m)	Shell thickness (mm)
1-6	10.32	10
7	7.618	8
8-10	7.618	7
11	7.618	5

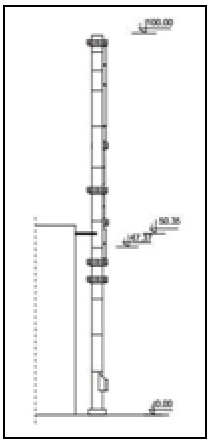

Fig1. An outline of the chimney structure.[5]

Unit torque is applied at the free end of the chimney structure and finite element analysis has been carried out. Maximum shear stresses at different locations of the shell are given in table2.

Table2. Maximum shear stress in cylinder subjected to torsion

	Maximum shear stress (N/m2) FEM	Maximum shear stress (N/m2) Classical method
Middle	10.027	10.145
Bottom	10.909	10.145

Values obtained from the finite element analysis and that obtained from classical method are comparable.

Wind load is calculated using IS875 part3; 1987. Structure is divided into 11 segments and wind load is calculated for each segment and applied at the node at the middle of each segment. Wind loads are calculated around the circumference by treating as eight equal segments to account for the circumferential variation of wind load. Thus a total 88 set loads comprises the wind load.

Basic wind speed of 10m/s is selected and the design wind speed is calculated using (1). Design wind pressure is obtained from (2). Design wind speed and wind pressure at each segment obtained as given in the table 2 and 3.

Table3. Wind pressure distribution along the height of the chimney structure

Height (m)	Design wind speed Vz (m/s)	Design wind pressure Pz (N/m2)
10.32	10.5	66.15
20.63	11.2	75.26
30.95	11.5	79.35

41.27	12.0	86.40
51.60	12.0	86.40
61.91	12.1	87.84
69.53	12.2	89.30
77.15	12.3	90.77
84.76	12.4	92.25
92.38	12.5	93.75
100.00	12.6	95.25

Wind load is distributed symmetric to the plane of direction of wind. Distribution of wind load in the one half of cylinder circumference in table 7. Wind load distribution in another half is same as that in the first half. Where zero degree indicates the direction of wind. Calculations are done using excel worksheet.

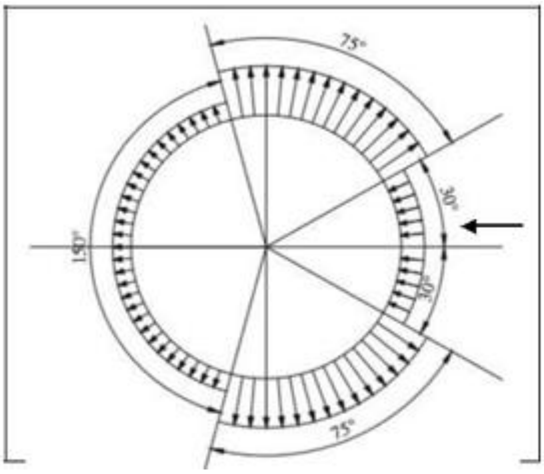

Fig2. Wind pressure distribution around the circumference of chimney structure. [1]

Table4. Wind load distribution around the circumference of chimney structure

Seg-ment No.	Wind load acting in the structure (N) in different positions in the periphery 'Θ' in degrees				
	0o	45o	90o	135o	180o
1	134.02	-1139.17	-2278.34	-1005.15	-938.14
2	154.40	-1296.08	-2592.16	-1143.60	-1067.36
3	160.76	-1366.46	-2732.92	-1205.70	-1125.32
4	174.64	-1487.84	-2975.78	-1312.80	-1225.28
5	174.64	-1487.84	-2975.78	-1312.80	-1225.28
6	177.97	-1512.79	-3025.58	-1334.82	-1245.83
7	133.24	-1132.54	-2265.01	-999.30	-932.68
8	135.32	-1150.22	-2300.44	-1014.90	-947.24
9	137.64	-1170.10	-2339.98	-1032.34	-963.50
10	139.87	-1188.93	-2377.87	-1049.06	-979.12
11	142.12	-1208.02	-2416.04	-1065.90	-994.84

Positive wind load indicates the force acting towards the structural element and negative away from it. Results obtained after the finite element analysis is given table 6 and 7. The maximum deflection at the top of the steel chimney produced by the wind load shall not be greater than h/200. Where h is the unsupported height of the chimney[3].

Table 5. Deflection of the structure

Allowable deflection	0.50 m
Actual deflection	0.618 m

To control buckling the compressive stress caused by the combination of extreme fiber stresses due to bending shall not exceed the permissible values [3].

Table6. Allowable and actual stresses in the structure

Segment No.	Allowable stress (MPa)	Actual stress in X direction (Mpa)	Actual stress in Y direction (Mpa)
1	126	3.27	4.34
6	40	2.18	5.41
11	36	0.95	1.64

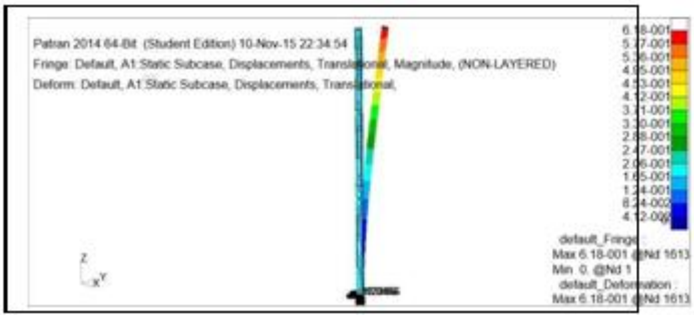

Fig3. Results showing the variation of deflection.

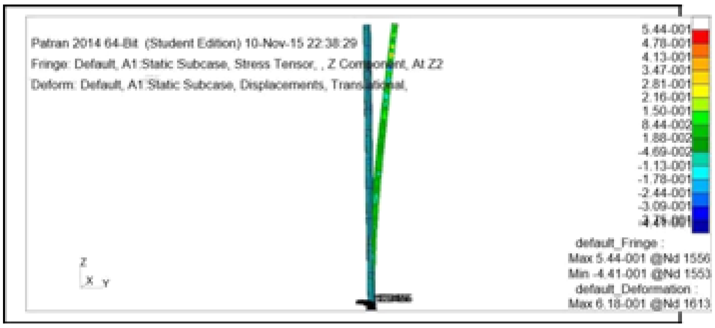

Fig4. Results showing the variation of longitudinal normal stress.

An opening of width 1m and height 1.5m is provided in the structure at the middle height and wind load is applied. Finite element analysis is carried out and stress concentrations and displacements are obtained at the corners of the opening. It is found that diagonal of the opening changed after the wind loading. Values of stress concentrations and change in diagonals are given in table 7 and 8.

Table 7. Stress concentrations in the corners of opening.

Corner No.	Stress (MPa) X component	Stress (MPa) Y component
1	61.04	938.7
2	-103.4	-103.3
3	317.4	-443.63
4	-288.5	384.8

Table8. Diagonal length before and application of loading

	Initial(m)	Final(m)
Diagonal 1	1.8027	1.7223
Diagonal 2	1.8027	1.7324

V. Conclusion

Finite element analysis for steel chimney structure subjected to unit torsion and wind load has been carried out. Values obtained for maximum shear stress in the middle and bottom portion of the chimney structure are comparable with that of classical solution. Deflections are not in the permissible range, hence redesigning of the structure is necessary. Stress concentrations at corner points of an opening provided at the middle height of the chimney structure and differential changes in diagonals of the opening proves the twisting of the structure along with bending. It is evident that torsion is introduced in chimney structures due to wind loading. Therefore study of torsion stresses in chimney structure has got importance.

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Nomenclature

A	Surface area of structural element
Cpe	External pressure coefficient
Cpi	Internal pressure coefficient
m	meter
mm	millimeter
N	Newton
k1	probability factor
k2	Terrain, height and structure size factor
k3	Topography factor
Pz	Design wind pressure in N/m^2 at height z.
Pz	Design wind pressure
Ri	Inside radius of the cylinder
Ro	Outside radius of the cylinder
T	Torsional moment
τ	shear stress
Vz	design wind speed at any height z in m/s. Vb Basic wind speed
Vz	Design wind velocity in m/s at height z.