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(दूसरा पुनरीक्षण)

Indian Standard

CRITERIA FOR DESIGN OF REINFORCED
CONCRETE CHIMNEYS

PART 1 ASSESSMENT OF LOADS

(Second Revision)

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FOREWORD

This Indian Standard (Part 1) (Second Revision) was adopted by the Bureau of Indian Standards, after the draft finalized by the Special Structures Sectional Committee had been approved by the Civil Engineering Division Council.

This standard was first published in 1968 as IS 4998 and subsequently revised in 1975 to cover the requirements of the structural design as well as assessment of loads for reinforced concrete chimneys. In this standard (Part 1) assessment of loads on reinforced concrete chimneys has been covered. Part 2 of this standard will cover design criteria of reinforced concrete chimneys. The recommendations of these standards apply only to chimneys of circular cross-section. Chimneys of non-circular cross-section may experience higher direct wind loads and more complex dynamic effects such as galloping. In such cases, specialist advice shall be obtained for estimating wind loads.

Design for dynamic effects of wind and seismic forces requires detailed investigation. When several chimneys are located close to each other, or when the chimney/chimneys are located close to other structures of comparable height, model tests in wind tunnels shall be carried out to assess the buffeting problems that may arise. The design provisions relating to seismic forces are covered in IS 1893 : 1984 'Criteria for earthquake resistant design of structures (*fourth revision*)'.

In the formulation of this standard the following publications have been consulted :

- ACI 307-88 Standard practice for the design and construction of cast-in-place reinforced concrete chimneys. American Concrete Institute, Detroit, Mich. 48219, USA.
- AS 1170.2-1989 SAA Loading code : Part 2 : Wind loads. Standards Association of Australia. Model code for concrete chimneys, Part A : The shell (October 1984) published by CICIND.
- Wind-induced loads on reinforced concrete chimneys by B.J. Vickery, National Seminar on Tall Reinforced Concrete Chimneys, April 1985, New Delhi.
- ESDU-70029, published by ESDU, London.
- Krishnaswamy T.N., Rao G.N.V., Durvasula S. and Reddy K.R. 'Model observations of interference effects on oscillatory response of identical stacks'. Proc. 4th Int. Conf. on Wind Effects on Blgs. and Str. Heathrow, pp. 209-214. 1975.
- Rao G.N.V., 'Wind effects on tall chimneys'. Asia Pacific Symposium on Wind Engineering, December 1985, University of Roorkee, India.
- Rao G.N.V., Durvasula S. and Reddy K.R. 'Model studies on wind effects on tall reinforced concrete chimneys'. National Seminar on Tall Reinforced Concrete Chimneys, April 1985, New Delhi.

*Indian Standard***CRITERIA FOR DESIGN OF REINFORCED
CONCRETE CHIMNEYS****PART 1 ASSESSMENT OF LOADS***(Second Revision)***1 SCOPE**

This standard (Part 1) covers the assessment of loads for reinforced concrete chimneys.

2 REFERENCES

The following Indian Standards are necessary adjuncts to this standard:

<i>IS No.</i>	<i>Title</i>
456 : 1978	Code of practice for plain and reinforced concrete (<i>third revision</i>)
1893 : 1984	Criteria for earthquake resistant design of structures (<i>fourth revision</i>)
875	Code of practice for design loads (other than earthquake) for buildings and structures :
(Part 1) : 1987	Dead loads
(Part 2) : 1987	Imposed loads
(Part 3) : 1987	Wind loads

3 SYMBOLS

Symbols used in this standard shall have the following meaning, unless otherwise defined elsewhere in this standard:

A_s	= Area of one discrete strake in m^2
B	= Background factor indicating the slowly varying component of wind load fluctuation
C_D	= Drag coefficient of the chimney to be taken as 0.8
C_L	= Peak oscillatory lift coefficient to be taken as 0.16
C_L	= RMS oscillatory lift coefficient to be taken as 0.12
d_z	= Diameter of chimney at height z in m

d	= Effective diameter taken as average diameter over the top 1/3 height of chimney in m
E	= A measure of the available energy in the wind at the natural frequency of chimney
e	= Distance between central line of the shell and the centre of gravity of the local load in m
f	= Natural frequency of the chimney in Hz
f_i	= Natural frequency of the chimney in the i^{th} mode of vibration in Hz
G	= Gust factor
g_r	= Peak factor defined as the ratio of the expected peak value to the RMS value of the fluctuating load
H	= Height of chimney in m
k_a	= Aerodynamic damping coefficient to be taken as 0.5
K_{si}	= Mass damping parameter for the i^{th} mode of vibration
L	= Correlation length in diameters to be taken as 1.0 in the absence of adequate field data
m_e	= Equivalent mass per unit length in the first mode of vibration in kg/m
m_{ei}	= Equivalent mass per unit length in the i^{th} mode of vibration in kg/m
m_z	= Mass per unit length of the chimney at section z in kg/m
M_x	= Moment due to corbel load in N-m
M_{oe} and M_{oi}	= External and internal ring moments due to circumferential wind forces in N-m/m
p_z	= Design wind pressure in N/m^2 at height z
\bar{p}_z	= Design pressure at height z , due to hourly mean wind, obtained as $0.6 V_z^2$ in N/m^2

- r = Twice the turbulence intensity
- r_m = Mean radius of shell at the section under consideration in m
- S = Size reduction factor
- S_n = Strouhal number to be taken as 0.2
- $$t = \left\{ \frac{-\delta}{\delta_z} d_z + \frac{\alpha d_z}{z} \right\} z = z_{ei}$$
- t_s = Thickness of shell at the section under consideration in m
- u = Wind speed in m/sec
- \bar{V}_{10} = Hourly mean wind speed in m/sec at 10 m above ground level = $V_b \cdot \bar{k}_2$ where V_b and \bar{k}_2 are as defined in IS 875 (Part 3) : 1987
- V_{crit} = Critical wind speed for i^{th} mode of vibration in m/sec
- W = Load on corbel in N
- z = Height of any section of the chimney in m measured from the top of foundation
- z_{ei} = Height at which $d_z^4 \phi_{z1} / \sqrt{t}$ is a maximum, in the i^{th} mode of vibration, in m
- α = Power law exponent
- β = Structural damping as a fraction of critical damping to be taken as 0.016
- δ_s = Logarithmic decrement of structural damping = $2\pi\beta$
- σ = Density of air to be taken as 1.2 kg/m³
- η_{oi} = Peak tip deflection due to vortex shedding in the i^{th} mode of vibration in m
- Ω = Equivalent aspect ratio
- ϕ_{z1} = Mode shape function normalized with respect to the dynamic amplitude at top of the chimney in the i^{th} mode of vibration

4 LOADS

4.1 Dead Loads

Dead loads shall include the weight of chimney shell, liners, liner supports, other accessories and load of ash and soot as applicable. Unit weight of the materials shall be taken in accordance with IS 875 (Part 1) : 1987.

4.2 Imposed Loads

Imposed loads shall be taken in accordance with IS 875 (Part 2) : 1987. The imposed loads on internal platform and hood of multi-flue chimneys shall include appropriate loads during construction.

4.3 Wind Loads

4.3.1 Wind loads shall conform to IS 875 (Part 3) : 1987.

4.3.2 The procedure for estimating loads on chimneys due to wind shall be as given in Annex A.

4.4 Earthquake Loads

Earthquake loads on chimneys shall be computed in accordance with IS 1893 : 1984 using the frequencies calculated as per provision in Annex A.

4.5 Temperature Effects

Thermal loading depends upon the individual requirements of chimneys and they should be considered accordingly.

5 ASSESSMENT OF LOADS

5.1 Load to be Considered

The various loads to be taken into account for design of chimneys shall be as follows:

- a) Dead loads including imposed loads;
- b) Lateral and circumferential wind loads;
- c) Earthquake loads; and
- d) Effect of temperature, both vertically and circumferentially.

5.1.1 For the overall design of chimney shell and foundation, imposed loads need not be considered. However, for design of individual structural elements such as platforms, etc, and for local strengthening of the shell, appropriate imposed loads shall be considered.

5.1.2 Wind and earthquake loads shall not be considered as acting simultaneously.

5.2 The foundation design should also be checked with minimum weight of chimney under shell alone condition combined with coexisting lateral loads.

For a lined chimney, the factor of safety against overturning of foundation shall not be less than 1.5 for shell alone case and shall not be less than 2.0 for the completed chimney.

5.3 Loading Conditions

The various load conditions for the design of chimney shell shall be :

- a) Dead loads
- b) Dead loads + wind loads
- c) Dead loads + earthquake loads
- d) Dead loads + temperature effect
- e) Dead loads + wind loads + temperature effect
- f) Dead loads + earthquake loads + temperature effect
- g) Circumferential effect due to wind
- h) Circumferential effect due to temperature
- j) Circumferential effect due to wind + temperature (g+h)

NOTES

1 Across-wind loads shall be combined with the co-existing along-wind loads. The combined design moment at any section shall be taken as the root sum square of the moments due to the across-wind loads and the co-existing along-wind loads.

2 Loading conditions (b) and (c) shall be considered for shell alone case also.

3 Secondary effects due to deflection shall be considered for one cycle.

4 Design should also consider effects due to local loads, if any, on the shell.

5.4 Circumferential Wind Moments

The circumferential ring moments due to wind are calculated by the formula:

$$M_{0e} \text{ or } M_{0i} = 0.33 p_z \cdot r_m^2 \text{ in N-m/m height}$$

where

M_{0e} and M_{0i} = external and internal ring moments

p_z = design wind pressure at height z in N/m^2 , and

r_m = mean radius of the shell at the section under consideration in m.

The design wind pressure (p_z), for the circumferential ring moments, shall be obtained in accordance with IS 875 (Part 3) : 1987, treating the chimney as Class A structure.

The hoop force and shear due to ovaling need not be considered.

5.5 Moment Due to Corbel Loads

Moment due to loads on corbels, M_k is :

$$M_k = \pm \frac{1}{2} W \cdot e$$

where

M_k = moment due to corbel in N-m,

W = load on corbel in N, and

e = distance between central line of the shell and the centre of gravity of the load in m.

Whenever the corbel is above or below an opening, the moment, M_k shall be taken = $\pm W \cdot e$.

In the above formula (+) and (-) refer to tension on inner face of the shell above the corbel and outer face of the shell below the corbel respectively. The effect of this may be taken as distributed over a length equivalent to the depths of the corbel at the junction with the shell or $0.76\sqrt{(r_m t_s)}$, in m whichever is greater, and t_s is the thickness of the shell at the section under consideration.

ANNEX A

(Clauses 4.3.2 and 4.4)

WIND LOAD CALCULATION FOR REINFORCED CONCRETE CHIMNEYS

A-1 WIND EFFECT ON CHIMNEYS

A-1.1 Static or Along-Wind Load with or Without Aerodynamic Interference

The wind load on an isolated chimney in the direction of wind at any height may be estimated by multiplying the design wind pressure at that height by the drag coefficient (C_D) and

diameter. The result will give the wind load per unit height. When a cluster of chimneys is present, aerodynamic interference between them may increase the total wind load. Aerodynamic interference shall be considered for along-wind load only if the spacing between the centre lines of the chimneys is less than 3 times the effective diameter of the largest

chimney. The enhancement in wind loads will be due to an increase in the value of C_D . The value of C_D for each chimney located within a distance of 3 times the effective diameter, may be calculated by assuming the value of C_D to be increasing linearly from 0.8 (for a spacing of 3 effective diameters) to a value of 2.0 (for a hypothetical spacing of 1 effective diameter which implies that the two chimneys touch each other if they are cylindrical and identical). These values of C_D apply up to the height of the nearest interfering chimney, if the chimneys are of unequal height. It is permissible to obtain more accurate values of C_D by carrying out properly conducted model tests in wind tunnels.

A-1.2 Unsteady Forces on a Single Chimney

A single isolated chimney will experience unsteady wind forces due to two main causes, namely (i) periodic vortex shedding, and (ii) unsteady force caused by atmospheric turbulence and/or wake from structures of comparable height. It may be assumed that every chimney with a height more than 3 times its effective diameter, will shed vortices of opposite sign alternately from opposite sides. The periodic vortex shedding is very marked at sub-critical Reynolds numbers. When the surface of the chimney is even slightly rough, distinct periodic forcing is not present in the critical Reynolds number range from 3×10^5 to 2×10^6 . The alternate shedding of vortices from the two sides of the chimney will result in periodic forces both in the direction of wind and perpendicular to it. The force that is generated in the direction of wind is called, "Oscillatory Drag Force" and the force that is generated perpendicular to the direction of wind is called, "Oscillatory lift force". The frequency of oscillating drag force is twice that of the oscillatory lift force. Of these two, the oscillatory lift force is very much larger than the oscillatory drag force. Their relative magnitude is about 1 : 10 and they are both functions of Reynolds number, amplitude of oscillation, surface roughness and height to diameter ratio. When the atmospheric wind has high levels of turbulence (greater than about 5 percent), reinforced chimneys are observed to vibrate with amplitudes containing both a periodic and a random component. The force in the direction of wind is called, "Along-wind force" and that perpendicular to the direction of wind as, "Across-wind force".

A-1.2.1 The frequency of shedding of vortices has been found to be directly proportional to

wind speed and when this frequency coincides with the natural frequency of the structure, the periodic forcing function will be in resonance with the natural frequency of the structure and oscillations of large amplitudes can take place, sometimes at quite low wind speeds. Generally, this shedding does not take place all along the height of the structure in a correlated manner. Such correlated shedding takes place at the most over the top half of the chimney. A large number of experiments on models in wind tunnels, and observations on full scale chimneys have shown that periodic shedding of vortices is related to the average wind speed by the formula $S_n = fd/u$, where f is the natural frequency of the chimney, d is its average diameter over the top 1/3 height and u is the wind speed at the level where the diameter is d . S_n is the Strouhal number the value of which is to be taken as 0.2. Although it may appear that resonance will take place at a particular wind speed called the "Critical wind speed", in practice, it is found that resonant oscillations persist over a wider range of wind speeds around the value corresponding to $S_n = 0.2$, due to a phenomenon termed as "Vortex locking". This locking, which depends on the amplitude of oscillations, may extend for up to ± 10 percent of the critical wind speed. Therefore, the structure can be expected to continue to undergo resonant oscillations for wind speeds up to about 10 percent above the critical wind speed.

A-1.2.2 Because of the relatively small thickness of the chimney at the top compared to its diameter, possibilities of "ovalling" oscillations will have to be examined if the diameter of the chimney exceeds 75 times the wall thickness at the top.

A-1.2.3 When the height to top diameter ratio of the chimney exceeds about 20, the possibility of second and higher modes of oscillations being excited due to vortex excitation can be expected. Since the dynamic stresses due to higher modes of oscillations can be much higher than that due to the first mode of oscillation, it is important that the design be checked for higher modes of oscillations, if found necessary.

A-1.2.4 When identical chimneys are spaced at less than 20 times the diameter at 2/3rd height, the amplitudes of oscillation of the downstream chimneys are found to be magnified due to aerodynamic interference. This magnification is a function of the Reynolds number, taper, surface roughness and possibly, structural damping. Although many model

studies have been carried out there does not seem to be any systematic full scale measurements which would throw light on the effect of various parameters. The reported model studies show wide variations in magnification of the amplitudes of oscillation due to aerodynamic interference, and it has therefore been decided to present one set of consistent data in this code as a guideline. This guideline is to be used to assess only the importance of the phenomena but the actual magnifications on the full scale structure may be less than the values indicated here due to the factors mentioned above. The term 'magnification' is used to denote the ratio of the amplitude of across-wind oscillations when there is periodic vortex induced aerodynamic interference to the amplitude of across-wind oscillations when there is no aerodynamic interference.

A-1.2.5 The turbulence in the atmosphere around a mean wind speed consisting of fluctuations of large magnitude in velocity can also be a source of large deflections and stresses in chimneys. This is termed as atmospheric buffeting. Such buffeting may also be caused by large structures of comparable height which are located nearby such as clusters of cooling towers. The design of chimneys should also consider such buffeting effects. Modern design practices tend to find the random response of a chimney both along and across the wind, due to a turbulent atmosphere, and compute the resultant load along and across the wind.

A-1.2.6 When the cross-sectional shape of the chimney is not circular, such as in some multi-flue chimneys, it is necessary to examine the possibility of "galloping instability" which is another type of structures to wind. In all galloping oscillations, the amplitude of the response continues to increase with wind speed and this can, therefore, be highly dangerous. The existence of galloping oscillations does not preclude the prior excitation of vortex excited oscillation. Thus, typically, a chimney of non-circular cross-section will first go into resonance due to vortex excitation, which becomes negligible outside a small range of critical wind speed, but at a still higher wind speed, galloping oscillations will start and the amplitude of oscillations continue to increase with wind speed. It is recommended that when chimneys of non-circular cross-section are used, the possibility of galloping instability and preventive measures, if any, be investigated by model studies in a wind tunnel before the design is committed to execution.

A-2 ESTIMATION OF WIND LOADS

A-2.1 Two methods of estimating of wind loads are given in A-4 and A-5. The first is a simplified method and is likely to yield slightly conservative results as far as across wind loads are concerned. The reason for this, as explained earlier, is the paucity of basic fluid-elastic interaction information, sufficiently acceptable data on atmospheric turbulence in several parts of our country and absence of any systematic full scale investigation on tall structures in our country. The second method is based on random response method.

The wind loads shall be estimated by both the methods and the loading which yields higher moments shall be considered for design of chimneys.

A-3 CALCULATIONS OF NATURAL FREQUENCY OF CHIMNEY IN BENDING

A-3.1 The natural frequency of the chimney is to be calculated by using any of the standard methods involving discretization of the structure and assuming it to be made of a homogeneous material with a suitable value of the elastic modulus. The following values of the modulus of elasticity of concrete shall be considered for calculating the natural frequencies:

Grade of Concrete	Modulus of Elasticity (N/m^2)
M 25	$3 \cdot 20 \times 10^{10}$
M 30	$3 \cdot 35 \times 10^{10}$
M 35	$3 \cdot 50 \times 10^{10}$
M 40	$3 \cdot 60 \times 10^{10}$

The above values of modulus of elasticity take into account the dynamic behaviour of the chimney.

A-4 SIMPLIFIED METHOD

A-4.1 Along-Wind Load or Drag Force

The along-wind load or drag force per unit height of the chimney at any level shall be calculated from the equation :

$$F_z = p_z \cdot C_D \cdot d_z$$

where

p_z = design wind pressure obtained in accordance with IS 875 (Part 3) : 1987

z = height of any section of the chimney in m measured from the top of foundation

C_D = drag coefficient of the chimney to be taken as 0.8

d_z = diameter of chimney at height z in m

The design wind pressure (p_z), for the along-wind response, shall be obtained in accordance with IS 875 (Part 3) : 1987, taking the appropriate factor depending upon the class of the structure as defined in that standard.

The chimney shall be divided into ten or more sections along its height and the load at any section shall be calculated by suitably averaging the loads above and below it. The moments are calculated from the sectional forces treating the chimney as a free standing structure.

A-4.2 Across-Wind Loads

The amplitude of vortex excited oscillation perpendicular to direction of wind for any mode of oscillation shall be calculated by the formula:

$$\eta_{01} = \left\{ \frac{\int_0^H d_z \phi_{z1} dz}{\int_0^H \phi_{z1}^2 dz} \right\} \times \frac{C_L}{4 \pi S_n^2 K_{s1}}$$

where

- η_{01} = peak tip deflection due to vortex shedding in the i^{th} mode of vibration in m
- C_L = peak oscillatory lift coefficient to be taken as 0.16
- H = height of chimney in m
- K_{s1} = mass damping parameter for the i^{th} mode of vibration
- S_n = Strouhal number to be taken as 0.2
- ϕ_{z1} = mode shape function normalized with respect to the dynamic amplitude at top of the chimney in the i^{th} mode of vibration

The recommended value of the peak oscillatory lift coefficient accounts for the Reynolds number, partial correlation of vortex shedding over the height of the chimney, effect of amplitude of oscillation and typical value of surface roughness. Calculations based on this value are acceptable for oscillatory amplitudes of up to 4 percent of the effective diameter. If the so computed value of the amplitude of oscillation η_{01} exceeds 4 percent of the effective diameter, the amplitude of oscillation shall be increased as follows :

Amplitude of oscillation η_{01} (for computed value of $\eta_{01} > 0.04 d$) = (computed value of η_{01})³ / (0.4d)².

A-4.2.1 Calculation of Shear Force and Bending Moment

The sectional shear force (F_{z0i}) and bending moment (M_{z0i}) at any height z_0 , for the i^{th} mode of vibration, shall be calculated from the following equations :

$$F_{z0i} = 4\pi^2 f_1^2 \eta_{01} \int_{z_0}^H m_z \phi_{z1} dz$$

$$M_{z0i} = 4\pi^2 f_1^2 \eta_{01} \int_{z_0}^H m_z \phi_{z1} (z - z_0) dz$$

where

- f_1 = natural frequency of the chimney in Hz in the i^{th} mode of vibration
- m_z = mass per unit length of the chimney at section z in kg/m

A-4.2.2 Calculation of Mass Damping Parameter K_{s1}

Periodic response of the chimney in the i^{th} mode of vibration is very strongly dependent on a dimensionless mass damping parameter K_{s1} calculated by the formula:

$$K_{s1} = \frac{2m_{ei} \delta_s}{\sigma \cdot d^2}$$

where

- m_{ei} = equivalent mass per unit length in kg/m in the i^{th} mode of vibration, as defined in A-4.2.3
- δ_s = logarithmic decrement of structural damping = $2\pi\beta$
- β = structural damping as a fraction of critical damping to be taken as 0.016
- σ = mass density of air to be taken as 1.2 kg/m³
- d = effective diameter taken as average diameter over the top 1/3 height of chimney in m

A-4.2.3 Calculation of Equivalent Mass per Unit Length (m_{ei})

The equivalent mass per unit length in i^{th} mode of vibration (m_{ei}) shall be calculated by the formula :

$$m_{ei} = \frac{\int_0^H m_z \phi_{z1}^2 dz}{\int_0^H \phi_{z1}^2 dz}$$

When the mass per unit length has to be used in a numerical method of integration, it is recommended that the mass of the segment above the section considered be added to the mass of the segment below the section and the total mass so obtained divided by the total length of the two segments.

A-4.3 Calculation of Critical Wind Speed

The critical wind speed (V_{crit}) for vortex shedding for the i^{th} mode of vibration shall be calculated from the equation:

$$V_{crit} = f_1 d / S_n$$

A-4.4 The critical wind speeds for exciting the fundamental and higher modes of vibration of the chimney shall be calculated by substituting the relevant modal frequencies in the equation given in A-4.3. All the modes which can be excited up to wind speeds 10 percent above the maximum expected at the height of the effective diameter shall be considered for subsequent analysis. If the critical wind speed calculated for any mode of oscillation exceeds the limits specified earlier, it is permissible to assume that problem of vortex excited resonance will not be a design criterion for that and the higher modes. In such cases across-wind analysis is not required.

A-5 RANDOM RESPONSE METHOD

A-5.1 Along-Wind Response

The along-wind response of a chimney shall also be calculated by the Gust Factor method as described below. The use of the Gust Factor method requires a knowledge of Hourly Mean Wind Speed (HMW). Hourly mean wind speed at any height (z), shall be obtained as per IS 875 (Part 3) : 1987.

A-5.2 Along-Wind Load on a Chimney

The along-wind load per unit height at any height z on a chimney shall be calculated from the equation:

$$F_z = F_{zm} + F_{zf}$$

where, F_{zm} is the wind load in N/m height due to HMW at height z and is given by :

$$F_{zm} = \bar{p}_z \cdot C_D \cdot d_z$$

F_{zf} is the wind load in N/m height due to the fluctuating component of wind at height z and is given by:

$$F_{zf} = 3 \cdot (G-1) / H^2 \cdot (z/H) \int_0^H F_{zm} \cdot z \cdot d_z$$

\bar{p}_z = design pressure at height z , due to HMW is obtained as $0.6 \bar{V}^2 z$ (N/m²)

G is the Gust Factor which shall be calculated from the equation:

$$G = 1 + g_T \cdot r \sqrt{B + SE/\beta}$$

where

g_T = peak factor defined as the ratio of the expected peak value to RMS value of the fluctuating load

$$= \sqrt{(2 \log_e vT) + 0.577} / \sqrt{(2 \log_e vT) \text{ and } vT = 3600 f_1 / (1 + B\beta/SE)^{\frac{1}{2}}}$$

r = twice the turbulence intensity

$$= 0.622 - 0.178 \log_{10} H$$

B = background factor indicating the slowly varying component of wind load fluctuation

$$= [1 + (H/265)^{0.63}]^{-0.88}$$

E = a measure of the available energy in the wind at the natural frequency of chimney

$$= [123 (f_1/\bar{V}_{10}) H^{0.21}] / [1 + (330f_1/V_{10})^2 \cdot H^{0.42}]^{0.83}$$

S = size reduction factor

$$= [1 + 5.78 (f_1/\bar{V}_{10})^{1.14} \cdot H^{0.98}]^{-0.88}$$

\bar{V}_{10} = hourly mean wind speed in m/sec at 10 m above ground level = $V_b \cdot \bar{k}_2$ where, V_b and \bar{k}_2 are as defined in IS 875 (Part 3) : 1987

f_1 = natural frequency of chimney in the first mode of vibration in Hz

NOTE — For design, higher of the along-wind loads obtained from the simplified method in A-4.1 and the random response method in A-5.1 shall be used.

A-5.3 Across-Wind Load on a Chimney

Calculation of across-wind load is made by first calculating the peak response amplitude at the specified mode of vibration (usually the first or second). The relevant expressions for chimneys with taper less than or equal to 1 in 50 and those with taper more than 1 in 50 are given in (a) and (b) below respectively. Taper is defined as $\{2(d_{av} - d_{top})/H\}$ where d_{av} is the average outer diameter over the top half of chimney and d_{top} is the outer diameter at top.

a) For Chimneys with Little or No Taper (That is, If the Average Taper Over the Top One-Third Height is Less Than or Equal to 1 in 50) — The modal response, at a critical wind speed $V_{crit} = f_i \cdot d/S_n$, shall be

calculated by the formula :

$$\eta_{01} = \frac{1.25 \bar{C}_L d \phi H_1}{\pi^2 S_n^2} \times \frac{\sigma d^2 \sqrt{\{\sqrt{(\pi L)/2}(\Omega + 2)\}}}{m_{e1}} \frac{H}{[1/H \int_0^H \phi^2 d_z]^{1/2}} (\beta - k_a \sigma d^2 / m_{e1})^{1/2}$$

where

Ω = equivalent aspect ratio = H/d

\bar{C}_L = RMS lift coefficient to be taken as 0.12

L = correlation length in diameters, which may be taken as 1.0 in the absence of field data

k_a = aerodynamic damping coefficient to be taken as 0.5

b) *Chimneys which are Significantly Tapered (That is, If the Average Taper Over the Top One-Third Height is More Than 1 in 50)*—The modal response shall be calculated by the formula :

$$\eta_{01} = \frac{\sigma \bar{C}_L d^4 z_e \phi_{zei} \phi H_1 (\pi L / 2t)^{1/2}}{2\pi n^2 S^2 m_{e1} \int_0^H \phi^2 d_z (\beta - k_a \sigma d^2 / m_{e1})^{1/2}}$$

where

z_{ei} = height in m at which $d_z^4 \phi_{z1} / \sqrt{t}$ is a maximum in the i^{th} mode of vibration

and $t = \begin{cases} -\delta & \alpha d_z \\ -d_z + & \\ \delta_z & z \end{cases} z = z_{ei}$

α = Power law exponent shall be taken as given below for each terrain category as defined in IS 875 (Part 3) : 1987:

Terrain Category	α
1	0.10
2	0.14
3	0.18
4	0.34
3 km from sea shore	0.12

The values of α do not exactly match the variation of K_2 factors of IS 875 (Part 3) : 1987. However, they have been chosen to be slightly conservative and should be used only in A-5.3(b) and nowhere else.

The critical wind speed at z_{ei} for exciting the mode of vibration is determined from the equation :

$$V_{crit} = f_1 d_{zei} / S_n$$

Calculations should begin by first taking $z_{ei} = H$ and progressively decreasing z till a maximum in η_{01} is observed for each mode. However, if V_{cr} for any mode is more than the maximum wind speed expected at site for $z_e = H$ for the first mode of vibration itself, the chimney will not experience any significant across-wind load in that mode. For very tall chimneys η_{01} may not show a maximum, either in first or the second mode at speeds less than the maximum expected at site. In that case, the value of z_e shall be taken as the value at which the calculated V_{cr} equals the maximum expected velocity V_z at z_e .

The sectional shear force (F_{z01}) and the bending moment (M_{z01}) at any height z_0 shall be calculated from the respective equations given in A-4.2.

A-6 AERODYNAMIC INTERFERENCE OF TWO OR MORE CHIMNEYS

A-6.1 When two or more nominally identical chimneys are located within 20 times their diameter at 2/3rd height, adverse aerodynamic interference between them can be expected. Figure 1 is to be used as a guide for assessing this aerodynamic interference. This figure gives the magnification factor by which the amplitude of transverse oscillations may increase, as a function of spacing and chimney taper and has been obtained by model experiments at Reynolds numbers of about 10^6 with laminar boundary layer separation.

A-6.2 When chimneys in a cluster are of different sizes, the magnification factors shall be established by model tests or on the basis of observations on closely spaced dissimilar chimneys. Such interference in dissimilar chimneys need not be considered if the smaller chimney is at a distance of more than 20 times the diameter at 2/3rd height of the nearest larger chimney. For a given configuration of identical chimneys, the magnification factor obtained from Fig. 1 indicates a measure of the seriousness of the increased amplitude of oscillations due to aerodynamic interference, although the actual magnification at full scale Reynolds Numbers, of the order of 10^7 , are likely to be lower.

A-7 AERODYNAMIC REMEDIAL MEASURES FOR SUPPRESSING OR ALLEVIATING VORTEX EXCITED OSCILLATION

A-7.1 The vortex excited oscillations can be suppressed or substantially alleviated by incorporating discrete strakes on the chimney as shown in Fig. 2. The strakes are to be

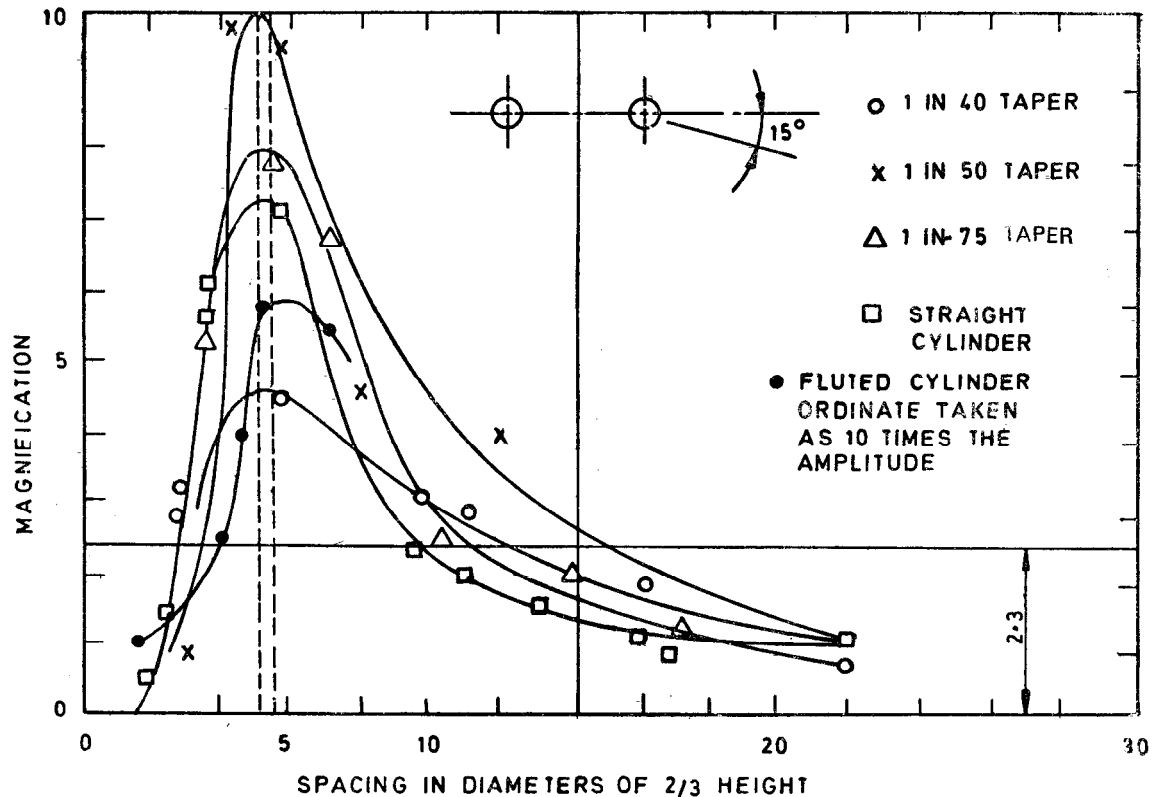


FIG. 1 MAGNIFICATION FACTOR AS A FUNCTION OF SPACING IN TERMS OF REPRESENTATIVE DIAMETER AT 2/3 HEIGHT

mounted along three helices with the strakes along each helix being displaced in azimuth by 30° and spaced vertically centre to centre by a distance of $5d/12$. The strakes are to be provided over the top 1/3 height of the chimney if the magnification given by Fig. 1 is less than 6 and over the top half of the chimney if the magnification given by Fig. 1 is greater than 6.

Table 1 gives the minimum area of each strake A_s to be used depending on the magnification as given by Fig. 1.

Table 1 Minimum Area of Strake, A_s

Magnification	$A_s/(\pi d^2/4)$	Additional Equivalent Drag Coefficient Over the Region of Strakes
1.1-1.5	0.005	0.05
1.5-2.5	0.010	0.10
2.5-5.0	0.020	0.20
5.0-7.5	0.025	0.25

The provision of discrete strakes increases the drag coefficient over the height where they are mounted. The incremental drag coefficient is given in the last column of Table 1 for different strake areas (A_s) and they should be added to the basic drag coefficient $C_D=0.8$.

Discrete strakes can also be used to suppress or minimize large across-wind amplitudes in single chimneys. In such cases, magnification in Table 1 shall be taken as the ratio of the calculated across-wind amplitude to the along-wind amplitude.

The radial depth of each strake shall not in any case be less than $0.1d$ and not more than $0.125d$. The vertical height of each strake should be between 1.0 and 1.5 times the radial depth (see Fig. 2). Occasionally, it may be found that the strake area estimated from Table 1, is less than that required to meet the geometric constraints stated here. In such cases, the area required to meet the geometric constraints shall govern and the incremental drag coefficient shall be taken from Table 1 by interpolation for the actual area ratio.

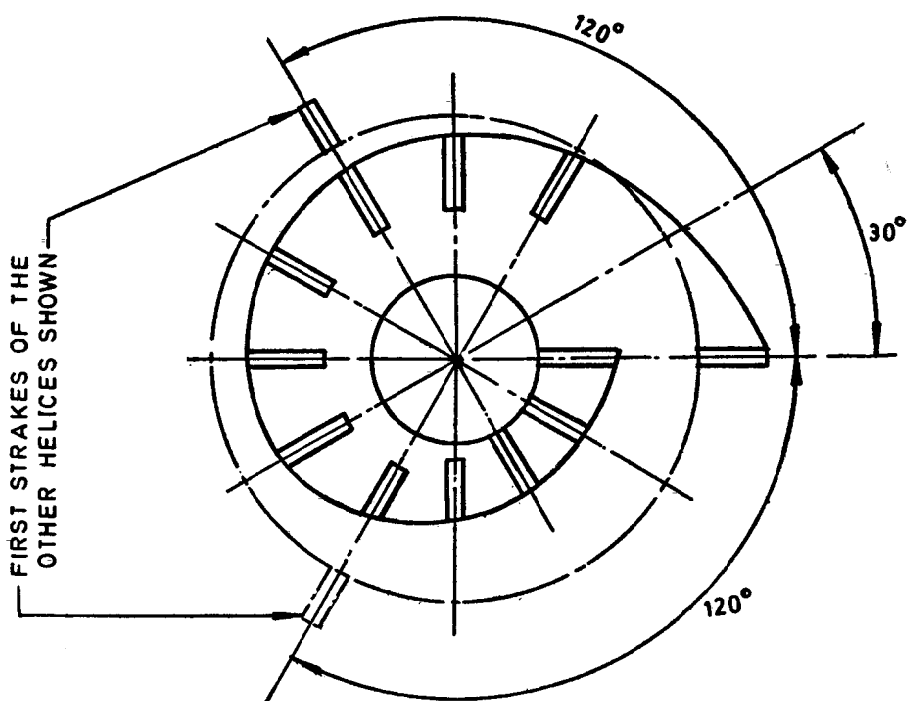
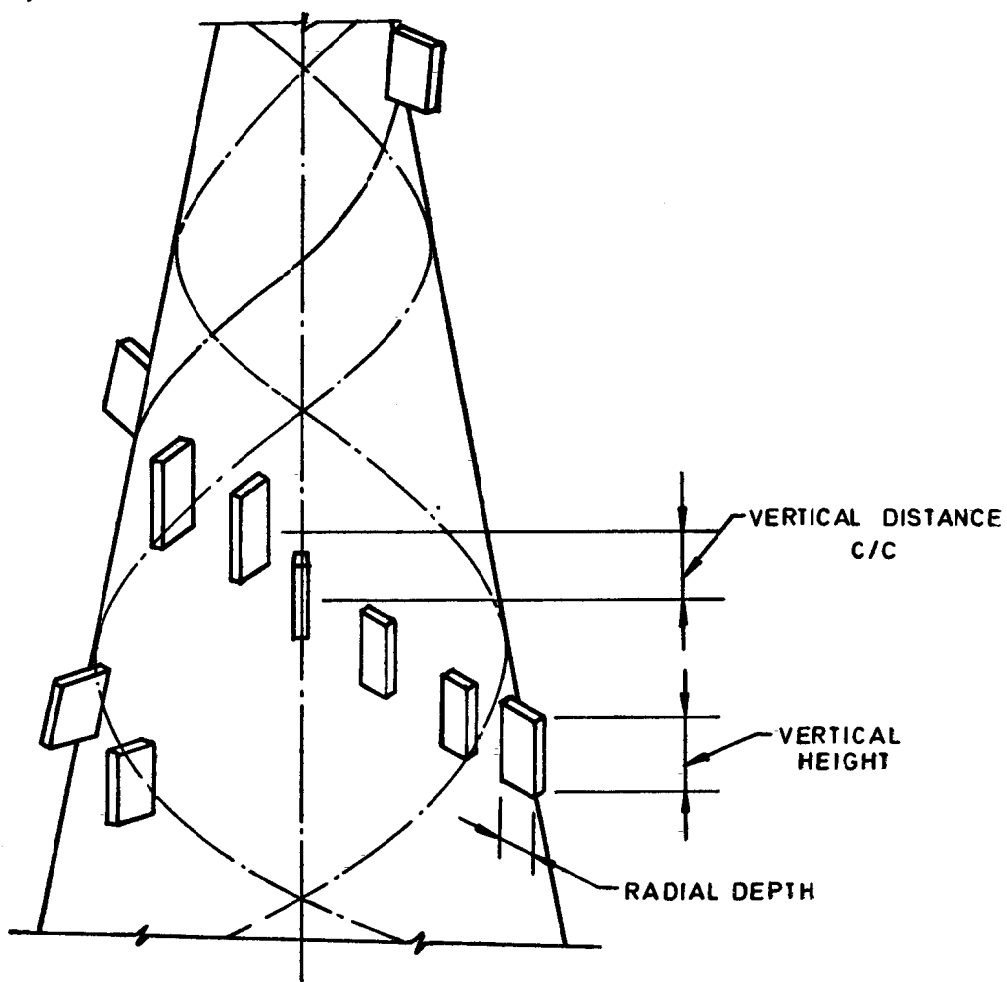


FIG. 2 DISCRETE STRAKES

The strake assembly shall be designed for a direct wind pressure of 3 times the maximum wind pressure expected at top of the chimney. The complete strake assembly shall be protected against corrosion.

A-7.2 Instead of discrete strakes, continuous strakes may also be used if feasible and economical. Figure 3 shows a sketch of this arrangement. The continuous strake should also be mounted over either the top one-third or top half height of the chimney, as indicated for discrete strakes. The radial depth of the rib shall be at least $0.1d$ and the drag coefficient over

the portion where the continuous strakes are mounted shall be taken as 1.23. The strakes shall be designed for a direct wind pressure of three times the maximum pressure expected at top of the chimney.

A-7.3 Other remedial measures may also be incorporated, provided their effectiveness have been adequately substantiated by model studies in wind tunnels.

A-7.4 Whenever model studies in wind tunnels are carried out, the scale of the models shall not be less than 1 : 250.

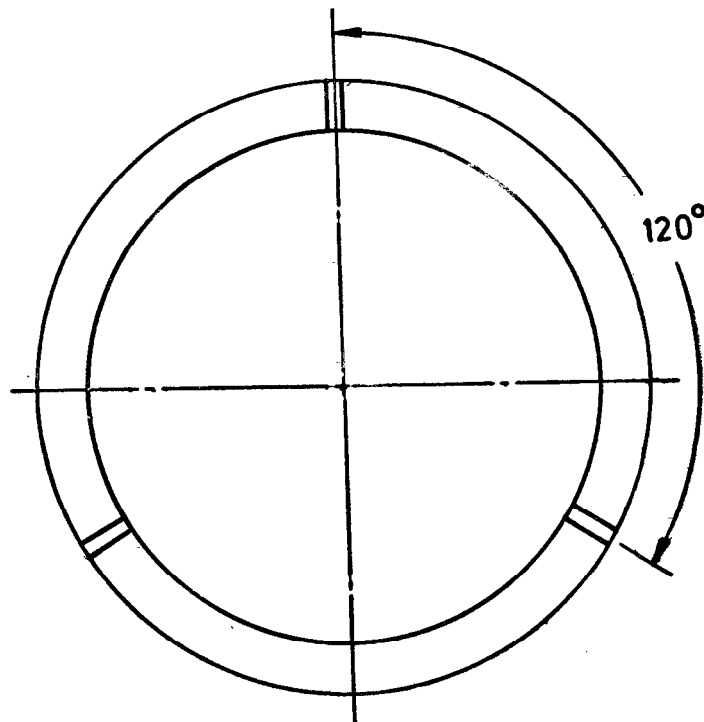
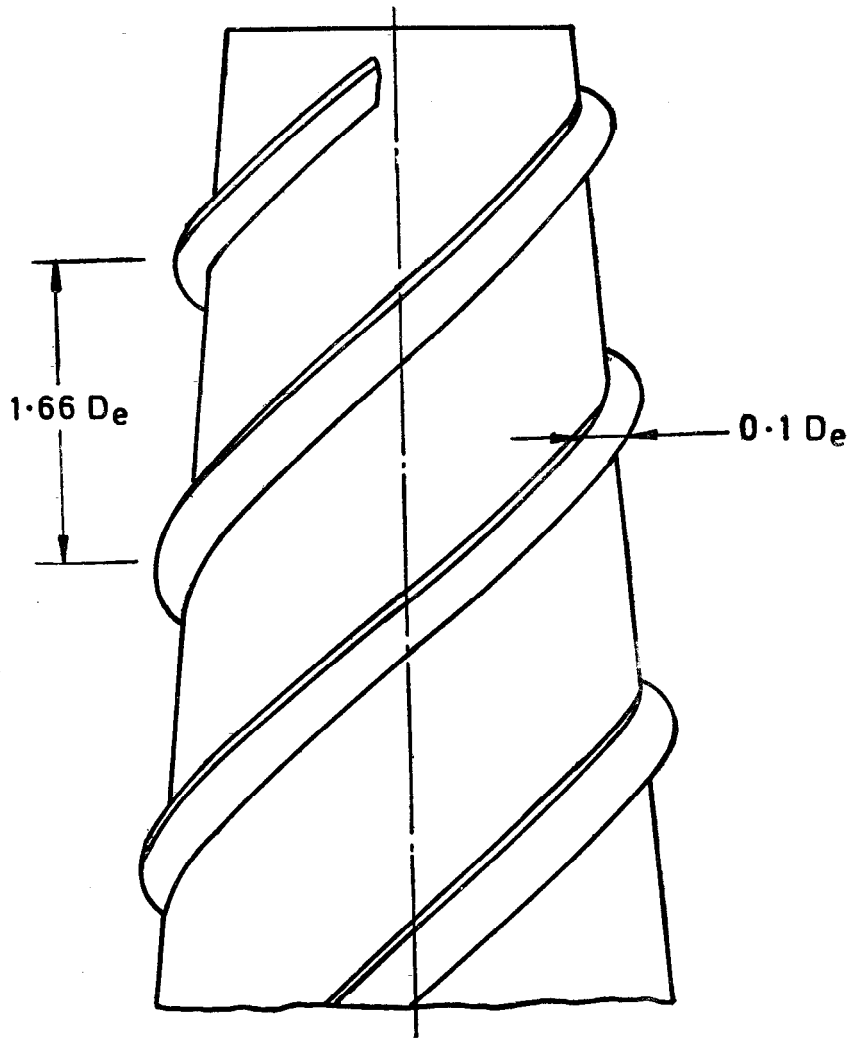


FIG. 3 CONTINUOUS STRAKES

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