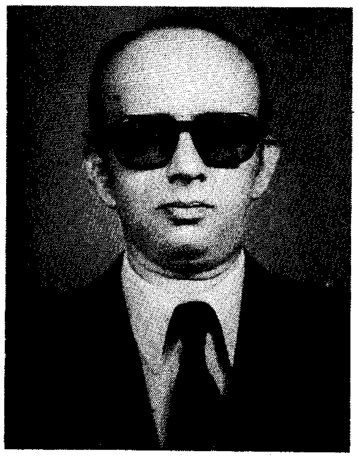
Reprinted from the Publication of the ING/IABSE, for the Seminar on Tall Structures and use of Prestressed Concrete in Hydraulic Structures, held in Srinagar in 1984.



TALL CHIMNEYS — THE PRESENT TREND

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SYNOPSIS

In recent years, there has been an increased demand for tall chimneys due to setting up several large thermal power stations in the country. In view of stricter control on air pollution, the trend is towards constructing taller chimneys, and many chimneys in the range of 220 m height have already been built. The Paper reviews external applied loadings that affect chimney structures, namely wind, seismic and temperature, with reference to the Indian Codes. The influence of design parameters in the aero-dynamic analysis, and current design practices are discussed. It also deals with use of refractory and insulation materials to protect concrete from thermal and corrosive effects, and other appurtenances which are special problems relevant to chimney design and construction. Finally, present day methods of construction including slipform technique are briefly looked at.

1. INTRODUCTION

Chimneys are a symbol of industrial growth in any country. In recent years there has been an increased demand for tall chimneys due to setting up several large thermal power stations in the country. With increased recognition that flue gases from large plants such as power stations, must be discharged at very high elevations in order to meet the demands of air pollution control, the trend is towards constructing taller chimneys. In the early 1960s a 122 m (400 ft) high chimney was considered to be very tall, and nowadays many chimneys in the range of 220 m height have been built in our country. In the USA several chimneys in the range of 380 m (1250 ft) already exist, and this trend toward constructing taller chimneys will continue. Construction of such tall chimneys has been possible with the better understanding of loads acting on them and of the structural behaviour, above all with the utilisation of modern construction plant, equipment and techniques such as slip-form. Reinforced concrete has been the most favoured material for chimney construction since it has the advantage to resist wind load and other forces acting on them, as a self standing structure. With the experience gained in the chimney design and construction over the years, the country has been able to meet the present day challenges of designing and constructing other similar tall structures such as television towers, urea prilling towers, silos etc. One of the early specifications for the design of chimneys was prepared by the American Concrete Institute in 1936 which has undergone revisions subsequently and the latest being ACI 307-79[1]. The Indian Code of practice for the design of reinforced concrete chimney IS : 4998[2], was first published in 1964 which has since been revised in 1975. In this Paper, an attempt has been made to review applied loadings, influences of various design parameters, and specialised problems associated with the design and construction of circular reinforced concrete chimneys.

2. CHIMNEY TYPES

There are mainly two types of reinforced concrete chimneys commonly employed at present, namely Single Flue Chimney and Multi-flue Chimney. The single flue chimney, Fig. 1 con-

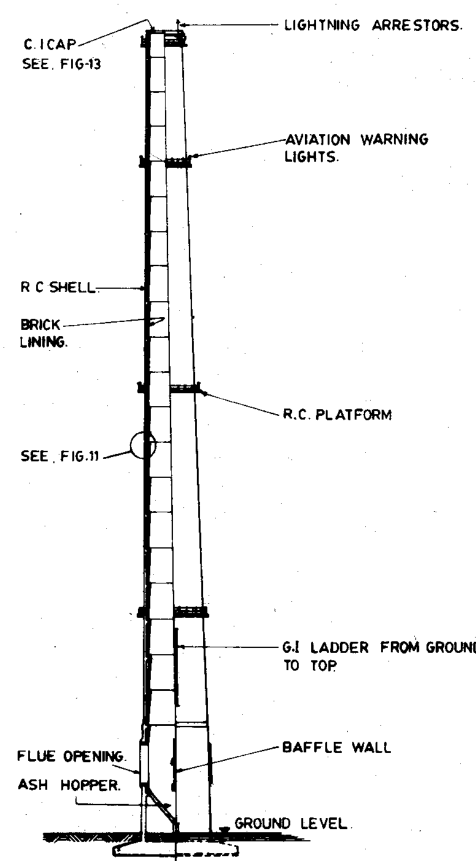

FIG.1 : SINGLE FLUE CHIMNEY

sists of an outer shell in reinforced concrete which support flue lining on corbels spaced at intervals along the chimney height. Usually, ventilated air space is provided between the shell and the lining. Many single flue chimneys in the range of 80 m to 160 m height, are in extensive use at power stations, cement factories and oil refineries, each serving one or two boilers of the plant. The multi-flue chimney consists of an outer wind-shield in reinfored concrete which support internal refractory flues, usually two or three in number, on platforms spaced at intervals along the chimney height, Fig. 2. Each flue of the multi-flue chimney generally serves only one boiler, and thus they are not affected by high ratios of maximum to minimum loading fluctuations. Although the cost of multi-flue chimney is usually more than that of the single flue type of a similar flue area, but it has its own advantage in operation and maintenance. Many multi-flue chimneys, height ranging from 160 m to 225 m height, have been built in the country in recent years for super thermal power stations.

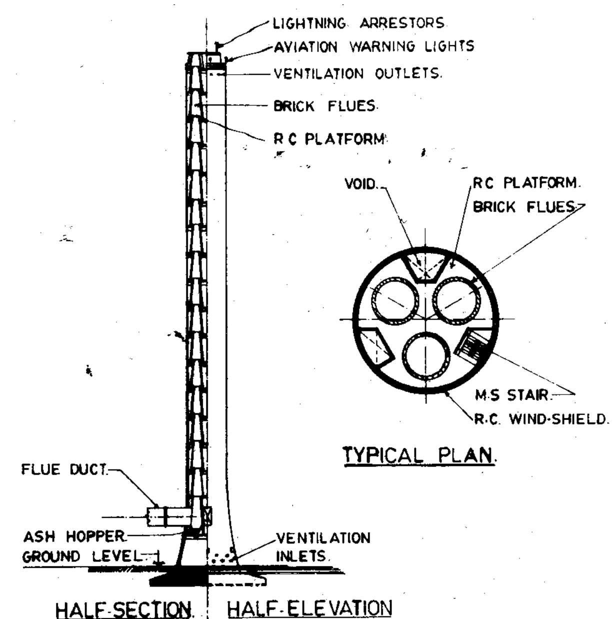

FIG-2. : MULTI-FLUE CHIMNEY.

3. CHIMNEY SIZING

The chimney height and top diameter are governed by exit velocity of gas and dispersion of effluent to a larger area within specified limits of ground level concentration. The dispersion of effluent is dependant on plume rise which are controlled by the following factors :

(1) The temperature and volume of gas leaving the chimney.
(2) The wind speed at top of the chimney.
(3) The effect of surrounding topography and buildings.

It is a fact that the higher the temperature of gases leaving the chimney, the higher they will rise. It is also known that larger the volume of hot gases leaving the chimney, higher the effluent rises, consequently the concentration of flue gas which reaches the ground is smaller. For this reason it is advantageous if gases from a group of boilers are discharged through one chimney instead of having separate independant chimneys to have a lesser ground level concentration for the same effective height of chimney. It is known by tests that downwash can be avoided if efflux velocity is greater than 1.5 times the wind speed, whereas at high wind speeds and low volume of gas it is less critical due to better dispersion with high wind speeds and a lower mass emission. For this reason, the chimney flue at top is based on a minimum exit velocity between 15 and 20 m/sec. Where sharp changes in land configuration or tall buildings exist in the surrounding, it is recommended[3] that chimney height should be at least two and a half times the height of the attached building to avoid formation of strong turbulance on the leeward side of the building causing down-draughts of the flue gases, Fig. 3. The maximum ground level concentration is known to occur[4] at a critical speed of 6 to 8 m/sec irrespective of the chimney height, and maximum deposition of gas particles of 30-120 microns takes place at a distance of 8 to 10 times the chimney effective height. Particles above 75 microns are known to cause irritation to human beings. Sulphur dioxide is the most common pollutant, and generally a ground level concentration of 0.5 mg/m^3 for half-hour period excluding background pollution, is considered to be the acceptable limit. There are several analytical methods[3,4] to calculate the chimney height. The Indian Code IS : 4998[2] gives an emperical formula to calculate the chimney height based on sulphur dioxide and ash contents which is very similar to the formula given by the 1975 French regulations relating to chimney construction for combustion installations. There seems to be an error in the unit of term 'Q' in the IS Code equation which should be gm/sec instead of mg/sec, to arrive at a reasonable value of chimney height. The bottom diameter of chimney is normally governed by structural requirements. For single flue chimneys, an outside batter of 1 in 50 or 60, and a ratio of height to base diameter in the range of 12 to 15 are usually provided.

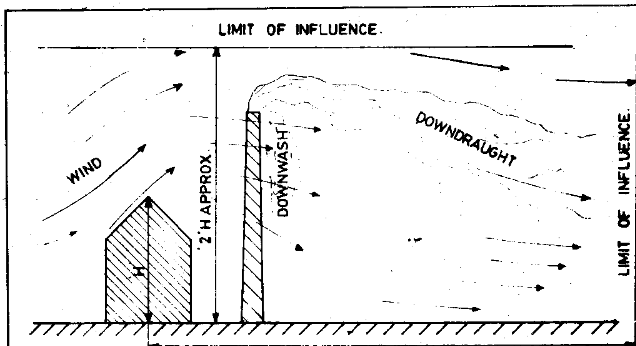

FIG.3

DIAGRAMMATIC REPRESENTATION OF DOWNDRAUGHT AND DOWNWASH.

4. LOADS

The external applied loadings that affect chimney structure are:

(1) Wind forces
(2) Earthquake forces
(3) Liner loads
(4) Temperature

4.1 Wind

Wind force forms the major external applied loading in the design of chimneys. The safety of chimney, its economy and accuracy of the analysis depend to a large extent on the knowledge of the nature of wind forces. It has been proved that wind is not uniformly distributed shear force as assumed in the building codes of various countries. Fluctuations in the anemometer readings indicate that considerable dynamic forces are produced by gusts of wind superimposed on a mean-steady pressure. The Indian Standard Code of Practice IS : 875-1964[5] adopts wind pressure as static loads, the intensity of which varying with height and the zone at which the structure is located. The Code considers two cases of basic wind pressure depending on wind duration. In the absence of meteorological data, the Code suggests the case with short duration as in squalls for design which are based on higher wind velocities. The Code gives basic pressure values of 100, 150 and 200 kg/m², for three zones covering the country, starting with a uniform value upto 30 m height and there above increasing in value with height upto 150 m, Fig. 4. These pressures are

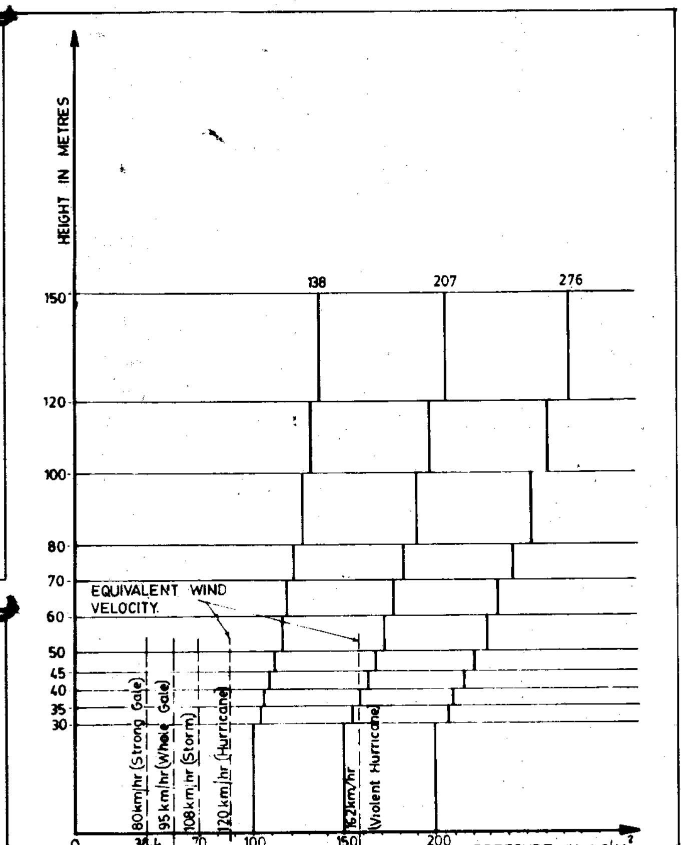

FIG. 4
BASIC WIND PRESSURE BASED ON SHORT DURATION AS IN SQUALLS (IS-875-1964).

based on a formula, $P = 0.006\ V^2$ where P is the pressure in kg/sq m and V is wind speed in km/hour. This formula gives pressure value of about 25% more than those calculated by the theoretical pressure equation, $P = \frac{1}{2} \rho V^2$, where ρ = density of air. This increase in pressure may be to allow for the effect of topography, ground roughness, gust duration etc. It is gratifying to note that the proposed revision of the Code which is in the draft stage, considers the above mentioned factors separately while assessing the basic wind pressures.

Having established the basic wind pressures along the chimney height, it is now necessary to consider the structural response under the action of wind flow. It is well known that an obstacle placed in a stream will disturb the flow pattern leading to changes of pressure. Magnitude and direction of these forces depend on the disturbance, shape of the obstacle, conditions at the boundary and nature of the flow. If the viscous forces in the flow are predominant, the action is smooth sliding of layers, and a laminar boundary is produced. But if the inertia forces are of sufficient magnitude, the flow becomes turbulent, and turbulent boundary is produced. In comparing the inertia and viscous forces, Reynolds number R is used as a parameter which is defined as $R = \frac{V \rho D}{\mu}$, where V is velocity, D is representative dimension, ρ is density and μ is viscocity. When R is low, the inertia forces are small and the flow past boundary can be expected to be laminar. A high value of R is usually associated with turbulent boundary layer. A body in an air-stream of velocity V results in a force F made of along-wind and cross-wind components defined as the Drag and the Lift respectively, Fig. 5.

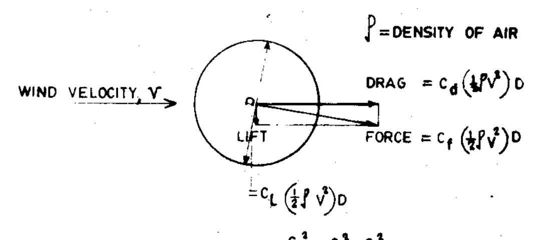

FIG. 5
WIND FORCES ON CIRCULAR SECTION.

For circular and rounded sections, force coefficient C_f vary with Reynolds number since the point at which the flow becomes turbulent is controlled in part by the velocity, whereas for angular sections such as squares and triangles, force coefficients are independant of the Reynolds number, and are wholly determined by the angularity of the shape.

In static analysis, the design force is calculated by considering the force coefficient C_f ignoring aero-dynamic considerations such as mass distribution, flexibility and damping. Model tests[6] have shown that along-wind oscillations occur at a round one-half of the critical wind speed for cross-wind oscillations. Moreover, along-wind oscillations are generally weak and are easily damped out. At high Reynolds number of 10^6 to 10^8 force coefficient for circular sections are known to vary between 0.6 to 0.8 depending on the roughness of the section. The value of C_f as per IS : 875-1964 which calls it as shape factor, is 0.7 for circular sections. This value needs to be reviewed in the proposed revision of the Code.

In aero-dynamic analysis, cross-wind oscillations caused by the oscillating lift force are by far the most important which must be checked. These transverse oscillations are caused by the alternate shedding of vortices from the airflow at opposite sides of the chimney, Fig. 6. The vortices are of equal strength but of opposite rotation and it is the alternate shedding of each of

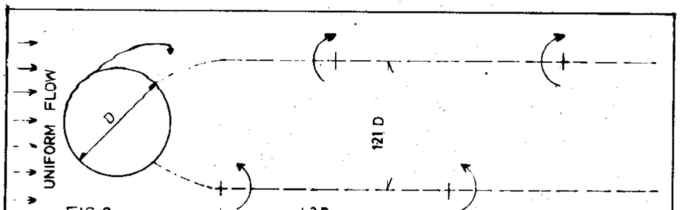

FIG.6
GENERATION OF VORTICES FROM A CYLINDRICAL MEMBER

these vortices when released from the side of the chimney, inflict a periodic transverse lift force which causes the oscillation. At the critical wind velocity, the frequency of vortex shedding coincides with the natural frequency of the chimney, and hence resonant oscillation begins. If the chimney is flexible with low damping, oscillation starts as the critical wind approaches and it continues through a zone of wind speed, and eventually the structure becomes stable again. For most chimneys, only the first mode of oscillation need be considered, but chimneys having a high degree of taper with small tip diameters, investigation for higher modes would be necessary. The amplitude of these oscillations is dependant on the mass, diameter of the chimney, the amount of damping inherent in structure and its foundations, and the natural frequency of the chimney. The frequency of vortex shedding depends on the wind speed, the shape of the structure and on Reynolds number. This is defined by the non-dimensional Strouhal number $S = \frac{fD}{V}$, where f is the frequency of shedding of vortex pairs, D is the typical dimension of the chimney and V is the wind speed. For circular sections, S varies with Reynolds number. Generally, a Strouhal number of 0.2 is used in the analysis, and this figure is known to be accurate by wind tunnel tests for Reynolds number upto 3×10^5. Experiments show that S value for Reynolds number between 3×10^5 and 3.5×10^6 is random and irregular (Fig. 7). No observations

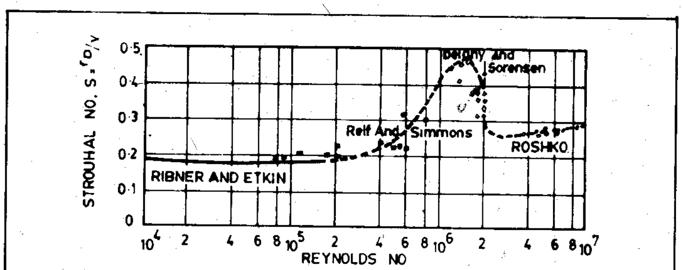

FIG.7 STROUHAL NUMBER.

have been made for values of R more than 10^7 in view of the difficulty in relating model test results to full scale structures. The draft revision to IS : 875-1964 suggests a Strouhal number of 0.25 which if finally adopted will have a significant effect in the dynamic analysis in that resonant moments will be reduced by 36 per cent from those corresponding moments calculated $S = 0.2$.

The simplest method of calculating natural frequency is by Rayleigh's principle which can be easily used for hand computations for the first mode of vibration. In this method, horizontal forces equivalent to inertia loads which are gravity loads times the assumed deflection under the first mode of vibration, are assumed concentrated at regular intervals. Deflection under these loads is calculated by area-moment method or by Newmark's numerical procedure, and the fundamental frequency of vibration is then calculated from $f = \frac{1}{2\pi}\sqrt{\frac{g}{y_t}}$ Fig. 8. In order to obtain an accurate value of 'f', the shape of

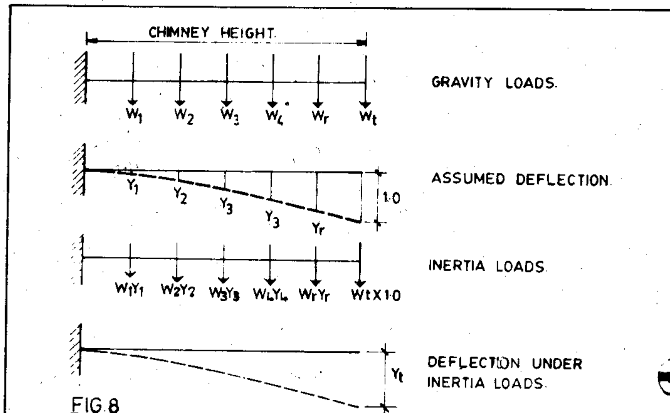

FIG.8
RAYLEIGH'S PRINCIPLE.

the assumed deflection should be close to that of the calculated deflection shape. For higher mode frequencies, a stiffness matrix method using computers can be used with great speed and accuracy.

Oscillations occur when the energy input from wind exceeds that dissipated by damping. At critical wind speed when the motion has reached equilibrium, the energy input per cycle due to vortex shedding force is equal to the energy absorbed per cycle by the structural aero-dynamic damping. Rumman[7] has proposed the following expression by which the maximum displacements, shears and moments are obtained by multiplying their respective modal values by the multiplier 'q' which is equal to

$$\frac{\rho}{16\pi^2 S^2} \cdot \frac{C_L}{\beta} \cdot \frac{D_c^2 \int_0^H D\phi\,dx}{\int_0^H m\phi^2\,dx}$$

where C_L = lift coefficient, β = fraction of critical damping, ρ = density of air, D_c = critical diameter which is considered at ⅓ height from the top, S = Strouhal number, m = mass per unit length and ϕ is the modal shape. In the above expression, the most uncertain values are C_L, β and S. The lift coefficient normally varies between 0.12 to 0.15, and $\beta = \frac{\delta}{2\pi} = 0.0095$ considering logarithmic decrement of structural damping δ equal to 0.06. S could vary between 0.2 to 0.28 depending on Reynolds number, and which reference is used.

The 1977 National Building Code of Canada has incorporated the following design parameters based on results obtained from wind tunnel tests and measurements on full scale structures :

$C_L = 0.2$ for circular cylinders, $S = 0.25$ for $R_e > 2 \times 10^5$ which cover most cases in practice, $R_e = \frac{V_c D}{16} \times 10^5$, and $\beta = 0.02$

Using this approach, Cassidy and Hartstein[8] find that the vortex shedding effect do not normally control the chimney design.

The structural damping of a chimney is usually expressed as a dimensionless coefficient K_s equal to $\frac{2M\delta}{\rho D_c^2}$, where M = equivalent mass per unit length, and the other terms being same as above. For a particular chimney profile, it is possible to assess the probability of stability by considering relationship between non-dimensional reduced wind velocity $\frac{V}{fD}$ and non-dimensional K_s. It has been found[9] that unacceptable amplitudes of oscillation do not occur when K_s is more than 20 for cylindrical chimneys, and about 25 for tapered chimneys. The aspect on K_s is incorporated in the Indian Code IS : 4998[2], and the Code recommends value equal to 0.05 for single flue chimneys and 0.03 for the multi-flue type. These damping values are based on full scale measurements in UK, but the value for multi-flue chimneys seems to be comparatively low and is debatable. It is also found that for multi-flue chimneys which usually have large diameter windshields, it is rather difficult to satisfy the minimum requirement of K_s value in practice, particularly under unlined condition i.e. without internal floors and flue linings, which occur during construction. It may however be possible by providing very thick shells and/or with thick internal floors and roof at top elevations in order to increase the equivalent mass per unit length, but such a proposition would not make multi-flue chimneys economically viable. The Indian Code IS : 4998 also recommends maximum values of height to diameter ratio to prevent oscillation due to vortex shedding, and minimum values of thickness to base diameter ratio for different taper ratio. These recommendations are based on a Paper by Irish and Cochrane[10] which should be used for general guidance and preliminary calculations only. The author has come across a few instances where these recommendations have been misused with the belief that aero-dynamic stability is deemed to have been satisfied by providing the recommended taper and the minimum shell thickness.

In large power stations, it is a common practice to locate two or more chimneys in a line, serving separate units of the station. Research[18] has shown that vortex-induced lateral movements in such a case are increased in the upstream chimney due to very strong interference effect on the downstream chimneys. The maximum increase in amplitude over that of an isolated chimney is when spacing of chimneys is at 4.3 times the chimney diameter which coincides with the distance between pairs of vortexes, Fig. 6, and the magnitude of this increase in amplitude is about 10 for 1 in 50 taper chimney, and about 5 for 1 in 40 taper. The interference effect becomes negligible at spacings greater than 20 times the chimney diameter. To alleviate the effect of interference, provision of discrete helical strakes specially designed for each case can be adopted, Fig. 9.

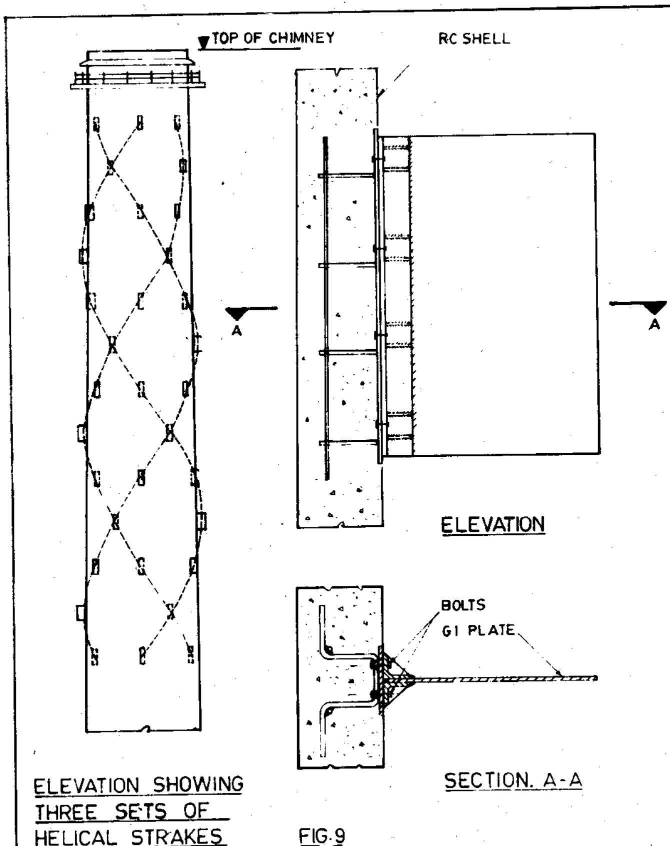

FIG.9
DETAILS OF STRAKES

Many chimneys, both single flue chimneys and the multi-flue type, in the country have been provided with such strakes at the advice of the Indian Institute of Science, Bangalore, following their model testing in wind tunnel.

Ovalling of circular shells and plan deformations are governed by the distribution of wind pressure on the shell as a ring. Fig. 10, shows the shape of such pressure distribution at a high

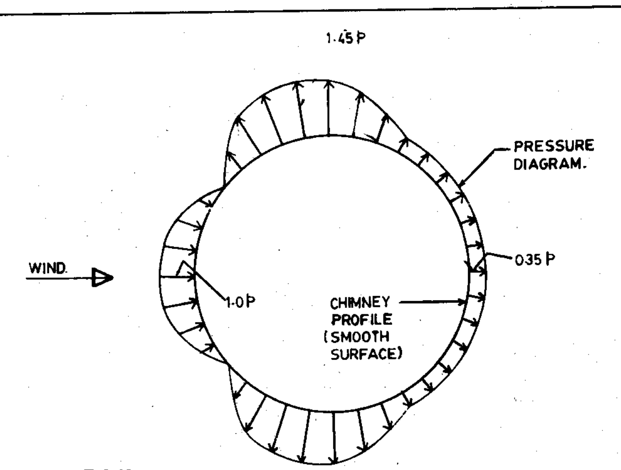

FIG.10
POLAR PRESSURE DISTRIBUTION AT HIGH REYNOLDS NUMBER.

Reynolds number. The Indian Code IS : 4998 gives an emperical formula for the calculation of bending moments in the horizontal plane for a circular shaft considering these pressure variations, and the Code also recommends minimum shell thickness in relation to the chimney diameter to avoid ovalling effect.

4.2 Earthquake

In zones where there are known geological faults, the chimney should be designed for the effects of earthquake forces. Earthquake force attracted by a structure is dynamic in nature and is governed by the ground motion and the properties of the structure itself. The effect of this force is equivalent to a horizontal force varying over the chimney height.

The basis for earthquake design in the country is IS : 1893-1975[11,12] which gives specific recommendations for tall slender structures such as chimney, to adopt Response Spectral method for the analysis. The chimney is considered as a flexible structure fixed at the base, with lumped masses having one degree of freedom that of lateral displacement in the direction under consideration. The natural period for completing one cycle of vibration depends on the structural characteristics and the distribution of structural masses. Earthquake force on the structure depends on the type of soil as well as the type of foundation. Although forces transmitted through softer soil is of lesser magnitude, the strains underneath the foundation will be quite large enough to cause excessive deformation and subsequent damage to the structure. Formulae given in the Code in regard to period of vibration, base shear and base moments are based on the research work by Chandrasekaran[13]. It considers slenderness ratio from 5 to 50 which relates to short, stout to long and slender type, and for varying taper ratio of 1 to 0.2 which covers most cases of chimney profile in practice. Recorded ground motion corresponding to actual earthquakes at El Cento in May 1940 and at Taft in July 1952 have been used to compute the various response. First three modes of vibration have been used for mode superimposition purposes, considering two cases of damping, namely with uniform damping for all modes which is conservative and the other case with damping increased with increase in order of modes. Distribution of shear forces are based on Housner's paper[14]. The American Code ACI 307-79 recommends a slightly different method of distributing the base seismic shear in that it considers 15 per cent of the base shear to act at the top of chimney and the balance shear is distributed along the chimney height in proportion of their weights. The design horizontal seismic coefficient as per IS : 1893, is calculated by the equation $\beta I \frac{F_o S_a}{g}$, where β is a coefficient depending upon the soil-foundation system, I is a coefficient depending upon the importance of the structure, F_o is seismic zone factor, and $\frac{S_a}{g}$ is the average acceleration coefficient. The Code recommends values of β for different soil-foundation systems which is 1.0 for raft foundation generally adopted in practice, and for F_o for five different zones covering the country which varies from 0.05 in zone *I* to a maximum value of 0.40 in zone *V*. The value of I is usually taken as 1.5 for power station chimneys. $\frac{S_a}{g}$ value is read from a figure given in the Code for appropriate natural period and damping of the structure which is usually considered as 5 per cent. It is found that the period of acceleration is usually of the order of 1.5 to 3 seconds in single flue chimneys, and of 1.5 to 2 seconds in multi-flue chimneys. The earthquake effect do not normally govern the chimney design for zones *I* to *III*. In cases where the effect governs, bending moments in the top half height are usually higher than those due to wind, and these become critical in the design. It is a common practice to consider the effects of wind and earthquake separately in the design.

4.3 Temperature Effects

The effect of temperature gradients is to produce compressive stresses on the inside of shell and tensile stresses on the outside of shell, and they act both in horizontal and vertical directions. The early reinforced concrete chimneys built in the USA and Europe were directly exposed to heat of the hot gases without any lining, and were insufficiently reinforced to resist temperature stresses. This resulted in severe cracks on the outer surface of concrete shell. The present day chimneys are usually lined with refractory bricks so that the chimney shell is not subjected to high temperatures. Apart from lining, a ventilated air space is provided between lining and shell which is normally 100 mm wide. The fall of temperature across the lining and shell depends on thermal conductivity of the materials, heat transfer by conduction/convection and radiation at the surface of lining and shell, and how well the air space is ventilated. The thermal conductivity of concrete is normally taken as 1.488 kcal/mh°C, and of refractory bricks vary between 1.0 and 1.25 kcal/mh°C. The Indian Code IS : 4998[2] recommends values of heat transfer coefficents which are related to the gas velocity, temperature and diameter of lining. It is considered that 50 per cent of the heat transmitted into and through the lining is removed by the air in cavity. It is recommended that temperature gradient across the chimney shell is limited to 80°C since thermal expansion is same for both concrete and reinforcement upto this temperature range. For higher temperature gradient, a reduction in permissible stresses in concrete would be necessary to limit crack widths in concrete. The design temperature of flue gases of the present day chimneys of thermal power stations, are usually in the range of 150°C to 180°C, and the temperature gradient in the chimney shell where air space with refractory lining is provided, is in the order of 20°C to 50°C. The temperature of flue gases in chimney for oil refineries are usually high, in the range of 800°C to 1000°C, for which chimney is lined with an additional layer of insulation bricks such as mica bricks which has a low value of thermal conductivity, and also insulated with 50 mm to 100 mm thick mineral wool or glasswool mattress in order to bring down the temperature gradient in the shell to an appreciably low value.

5. LINERS AND INSULATION

The primary function of the lining is to protect the concrete shell from corrosive, abrasive and temperature effects of the flue gases. The choice of material depends on factors, principally on temperature at lower elevations, and combined with corrosion factors at the top elevations where the gas temperature is likely to fall below acid dew point and condenses as acid on the lining. The most extensively used chimney lining in the country has been fire clay bricks conforming to IS : 195-1963, the principal constituents of which are 30 per cent alumina (minimum) and 65 per cent silica (maximum), which can protect upto a temperature of 1200°C. In the top elevations where the gas temperature is likely to fall below dew point, acid resistant bricks conforming to IS : 4860-1968 are used. There are two classes of these bricks, class I being used in severe corrosive environment whose resistance to acid is restricted to 1.5 per cent loss by weight, whereas the corresponding figure for class II type is 4 per cent. Fire bricks are laid in fire clay mortar conforming to IS : 6-1967, and the acid resistant bricks are laid in acid resistant mortar conforming to IS : 4832 (Part I)-1969, either of sodium silicate or potassium based. Potassium silicate mortar is used where resistance to mixture of sulphuric and other acids is required. The mortar consists of mixture of a solid filler with a setting agent usually contained, and a liquid silicate binder. When these are mixed at ordinary temperature, a trowelable mortar is formed which subsequently hardens. Working time of the mortar is usually 15 to 20 minutes. The thickness of mortar joints is limited to 2 to 3 mm. The lining is supported on Corbels, Fig. 11, which are spaced at

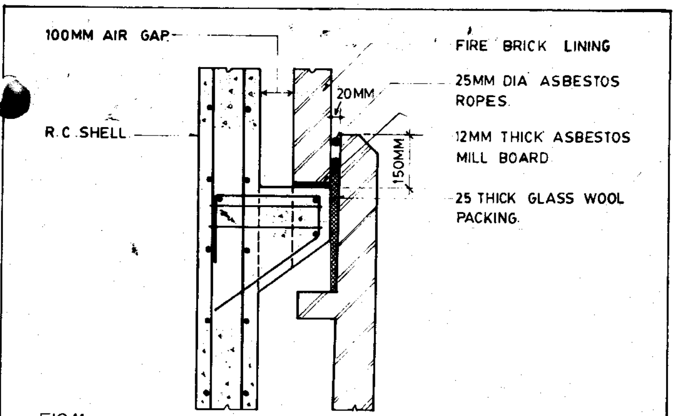

FIG.11

TYPICAL DETAILS AT CORBEL.

7 m to 10 m intervals, as a free standing brickwork of a minimum thickness of 115 mm, except at flue entry level where it is usually 230 mm thick. The lining thickness is based on the compressive stress permissible on the inside face and tensile stress that will occur due to temperature. In order to limit tensile temperature cracking, it is necessary to provide liner thickness based on the modulus of rupture of the material. To reduce the effect of tensile stresses, steel flat stiffeners are provided both in the horizontal and vertical directions at the outer face of lining. The effectiveness of these stiffners is debatable since the expansion coefficient of masonry lining is considerably less than that of steel, unless the steel flats are pre-tensioned into the lining. In multi-flue chimneys, the brick liners are supported on concrete platforms spaced at 7 m to 10 m interval along the chimney height. These liners are usually wrapped with 50 mm thick mineral wool or glasswool mattress, and pressurised fans are sometimes installed for effective control of temperature within the windshield.

In the USA, mild steel linings have been provided in fall chimneys with exceptional satisfactory service for many years. The advantage with steel flue linings are, firstly they are impermeable to flue gas, secondly being lighter than brick flues fewer internal platforms are required, and lastly they are preferred where earthquake effect governs the design. Steel liners are liable to corrosion attack unless adequate insulation is applied to prevent condensation of the flue gases. For this purpose, sometimes gunited concrete using calcium aluminate cement is provided within. Stainless steel flues made of grade AISI 316S/16 are provided in the top elevation for a length of 10 m to 15 m against acid corrosion. As insulation against temperature, steel liners are wrapped with 50 mm to 100 mm thick mineral wool or glasswool mattress at the outer face. In multi-flue chimneys, steel flues are supported either on intermediate steel floors or hung from the top in which case the intermediate floors provide only lateral restraint to flues.

In single flue chimneys, the provision of insulation in the form of mineral wool or glasswool mattress may be necessary where the temperature effect on the concrete shell is critical. The mattress of the rigid type such as resin bonded conforming to IS : 8183-1976 should be preferred instead of the loose wool type as the latter tends to settle down in course of time and affect its insulation performance. These mattresses are fixed at the inner face of concrete shell with galvanised lugs provided in the shell at regular intervals and tied to galvanised chicken mesh provided at the front face of the mattress. Insulation directly behind brick lining should be avoided since most linings are to some extent permeable to gas, and a clear gap should be provided between the brick lining and the insulation. Insulation bricks conforming to IS : 2042-1972 which are of light density and with low thermal conductivity, are used as a backup lining with fire bricks or acid resistant bricks, particularly in ash collection hoppers.

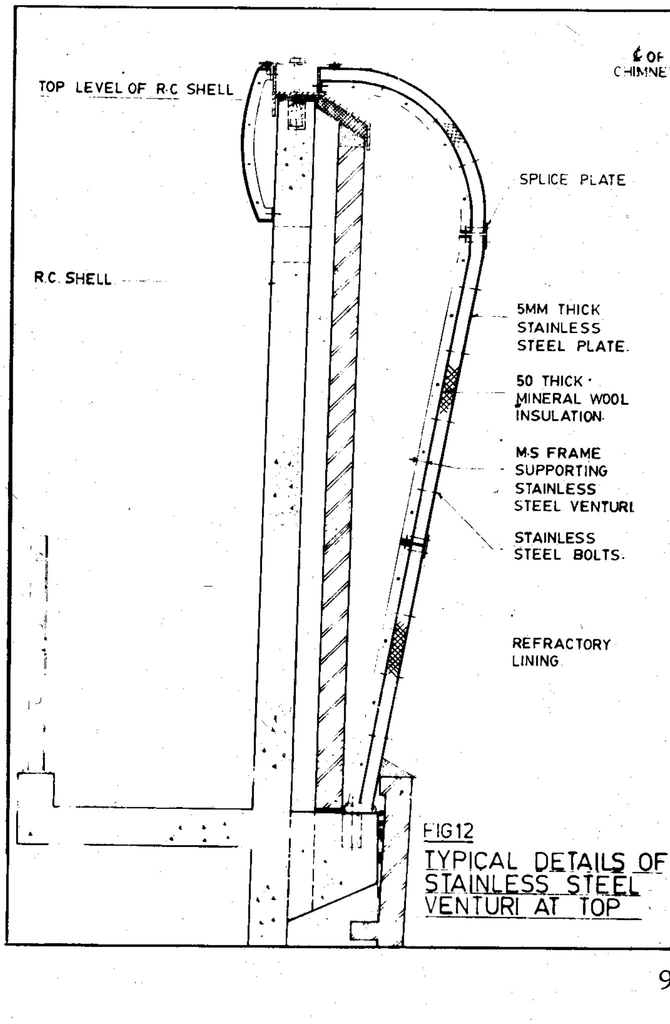

FIG12

TYPICAL DETAILS OF STAINLESS STEEL VENTURI AT TOP

At low loads of the boiler, the volume of gas at the chimney top is low, consequently lower gas efflux temperature possibly below dew point and lower exit velocity. This results in a gas column which is inadequate in cross section to fill the chimney, and will allow cold air by inversion to penetrate down into the chimney along the inner perimeter, chilling the inner surface. To minimise this effect, stainless steel venturi, Fig. 12, is provided at the top section designed to give the maximum gas velocity. The extent of reduction should be small with a slope no greater than 1 horizontal to 4 vertical to avoid the possibility of creating an unacceptable back pressure within the flue.

6. DESIGN PRACTICE

For chimney design, IS Codes IS ; 4998-1975[2] and IS : 456-1978[15] are used in the country. IS : 4998 is very similar to the American Code ACI 307-69 except for slight modifications in regard to permissible stresses in concrete and reinforcement for various loading conditions. The basis of design is by elastic method. The design requires calculation of stresses under wind and earthquake load cases separately, and a check is made in combination of these load cases with temperature. The Code does not recommend permissible stresses for the load case with aerodynamic resonance moment, but it is an accepted practice to consider this case equivalent to earthquake load case. The value of modular ratio 'm' is worked out on the basis of an emperical equation given in IS : 456-1978, whereas 'm' in the American Code is based on E_s/E_c which gives slightly a lower value. It is found that this small variation in the value of 'm' results in higher stresses due to temperature by the IS Code. Under dead load and wind/earthquake moments, the chimney shell of circular section is wholly under compression if the ratio of eccentricity and shell radius is less than 0.5. For higher values of this ratio, the Code gives equations to work out the stresses in concrete and steel. The equations given to calculate stresses due to temperature in the Indian Code as well as ACI 307-69 consider only one layer reinforcement at the outer face of shell, and this aspect has not been spelt out in the Code. The current American Code ACI 307-79 which supersedes ACI 307-69 now considers reinforcement at each face of shell, of any proportion. Pinfold[16] gives equations to calculate stresses for two layer reinforcement with equal proportion at each face which gives slightly leser values of stresses than those by the IS Code equations. It is interesting to note that thinner the shell and lesser the reinforcement is, there is least effect of temperature on the shell. But providing such thinner shells may not be possible considering other load cases particularly for resonance moment condition and at flue-opening sections. Cassidy and Hartstein[8] are of the opinion that the use of instantaneous value of the modulus of elasticity in the calculation of temperature stresses is considered to be conservative in view of the fact that thermal gradient across the shell is a long term load, and the modulus of elasticity for long time loads may be reduced by a factor of two or three.

For shell construction, M 25 grade concrete using ordinary portland cement is generally used. In sections where stresses are critical, it is advantageous to use a higher grade concrete although it is offset by higher temperature stresses due to higher Young's modulus of concrete. The Code specifies minimum reinforcement in both vertical and horizontal directions for both mild steel and high yield deformed bars, with limitations on bar diameter and spacings. The laps in reinforcement are staggered in groups of two or three to avoid concentration of stresses at one location. Where the shell thickness exceeds 250 mm two layer reinforcement is recommended. The other criteria for providing two layer reinforcement is when the tensile stress due to wind ovalling moment in the horizontal plane exceeds the permissible value of $0.07f_{cu}$, where f_{cu} is the 28 day crushing strength of concrete. With 50 mm cover to steel which the Code recommends, a minimum shell thickness of about 180 mm is required where two layers are to be provided, for practical considerations

The present IS and ACI Codes do not consider limit state philosophy in the chimney design, although ACI Code proposes to look into it in the next revision. Where the chimneys are sensitive of tensile stresses due to severe wind or earthquake loading condition, it is important to check the sections under ultimate load conditions. Pinfold [16] describes limit-state design applications for the chimney design which are generally in accordance with the recommendations of the British Standard Code of practice CP110–1972 for the structural use of concrete. The limit states are to satisfy safety and serviceability aspects. These limit states are checked using characteristic loads multiplied by appropriate load factors. For the Indian conditions, partial safety factors as given in IS : 456-1978 can be considered to evaluate limit-state loads. The limit-state method is incomplete if there is no check made on the limit state of cracking. Pinfold suggests that calculated crack widths should be limited between 0.1 and 0.3 mm depending on the location and environmental conditions. As far as deflection is concerned, it should be based on the elastic design considering uncracked sections, and a static wind deflection of height/500 at the top is considered to be within the acceptable limits.

Regarding effect of temperature under ultimate conditions, there is conflicting evidence on the strength of concrete at prolonged high temperatures. Brettle[17] suggests reduced cube strengths depending on the maximum concrete temperature anticipated. However, Pinfold suggests that temperature gradient of about 120°C which is much above the value generally encountered in practice, may generally be ignored at ultimate load in the vertical direction since concrete strain including this temperature gradient will be within the limiting concrete strain of 0.0035, and on the tensile side of the shell, once the reinforcement has become plastic any variations in strain do not affect the stress. In the horizontal direction, the effects of temperature and ovalling moments may be considered as being additive.

7. FOUNDATIONS

Chimney foundations are usually in the form of a solid raft or an annular ring. The ideal shape of the foundation is circular, but other polygonal shapes are provided for ease of construction and placing reinforcement. The size of foundation is governed by the safe bearing capacity of soil, permissible and differential settlement. Where the bearing capacity of soil is poor, piles are provided to resist the vertical and horizontal loads. Under wind/earthquake loading condition, a 25 per cent increase is allowed in the bearing pressures and in the capacity of piles. In most cases, the vertical piles are able to resist the horizontal loads which are usually within 5 per cent of the vertical load. However, where poor soil exists in the top strata, raker piles would be considered necessary. Under minimum load condition, tension in piles are not usually allowed to occur.

The foundations are designed for loading cases of both maximum and minimum dead loads in combination with wind/earthquake loads. For the strength requirements of foundations, IS : 456-1978 forms the basis for design. The vertical shearing force on the foundation at vertical section near the periphery of the shell should be investigated. For construction, usually M20 grade concrete with coarse aggregate size of 43 mm and under is used. Large size foundations are constructed in segments, divided in the radial direction, to suit construction facilities, with vertical keyed joints. The number of such construction joints should be kept to a minimum, and special attention should be given to preparation of the joint surface for proper bonding of old and new concrete.

8. MISCELLANEOUS ITEMS

Miscellaneous appurtenances such as lightning protection system, aviation warning lights, access and clean out doors, ash collection hopper, cast iron cap, ladder and hand rails, flue duct frames, etc. require special attention in detail and construction. The lightning protection system is provided in accordance with IS : 2309-1969. The lightning conductors and terminals in the top elevations are usually covered with 1.6 mm thick lead coating as a protection against corrosion. Temporary lightning protection is provided during construction by connecting shell reinforcement to permanent grounding cables. Chimneys located in the proximity of air-ports and in urban areas are provided with aviation warning lights to suit the requirements of the Civil Aviation Authorities. Usually three or four lights are provided at each platform on the outside which are spaced at not more than 45 mm long chimney height. Lightning conductors and lighting cables are fixed to the outer face of shell or embedded in the shell in which case it requires careful planning beforehand. The ladders are usually 450 mm wide, made of galvanised iron, with safety cages, and are fixed to the shell by using expanding type G. I. anchors. Cast iron caps are usually 12 mm thick, made in segments, fitted together and fixed to concrete shell at top with bronze rag bolts, Fig. 13. The inner surfaces of concrete shell and the top 10 to 15 m height of the outer surface are usually provided with a protective treatment against acid corrosion. Two or three coats of black bituminous acid and heat resisting paint

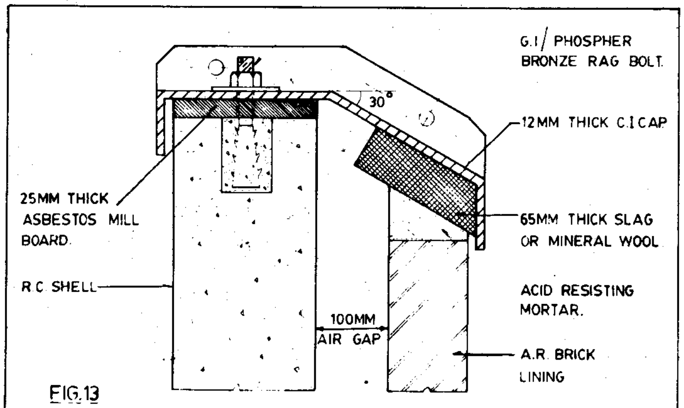

FIG.13

TYPICAL DETAILS OF C.I CAP

conforming to type 1 of IS : 158-1968 are applied for this purpose. Chimneys located near air-ports, are provided with a band of alternate colours in red and white colour paints to meet the regulations of the Civil Aviation Department.

9. CONSTRUCTION

The construction of reinforced concrete chimneys is mainly undertaken by specialist contractors experienced in this type of work. It requires careful and detailed planning of various construction activities, particularly of temporary works, viz. formwork, scaffolding, means of access for men and materials. The common methods of formwork used in the construction are jump-form and slip-form.

9.1 Jump-form Method

This is the most conventional and commonly used method for chimney construction. The forms are usually made of steel sheets of 1.2 m to 1.5 m height, by which successive rings of equal height are cast. The speed of shell construction is usually three or four lifts per week. Some of the steel sheets lap one another, and as the construction proceeds up, the amount of lap increases with the reduction in shell diameter until one panel is removed, and this operation is continued. For construction of corbels and outside platforms, shutters are modified to suit at these locations. Tubular scaffolding is provided internally with working platforms and hoist for materials. The scaffolding is also made use of for the construction of flue lining.

9.2 Slip form Method

Slip-forming is a continuous process in which placing of concrete into forms is carried out 24 hours a day. This method has the advantage of speed over jump-form construction, and speed around 2.5 m to 3 m height can be accomplished in a day. There are a number of proprietory systems for tapered slip-forms, mainly available from Europe and the USA. Slip-forms for tapered concrete chimney require special design in that the outer and inner formwork panels of about 1 m height made in steel sheet slide over each adjacent panel which are continuously adjusted with the aid of screw jacks as sliding proceeds. The Jacks ride on steel jack rods of about 25 mm to 32 mm diameter embedded in the centre of concrete shell. The jacks each of 3 ton to 6 ton capacity, through which the jack rods pass, are fixed to yokes at regular spacing of about 1.5 m to 2 m along the circumference from which the forms and platforms are suspended Fig. 14. The entire construction systems, forms, working platforms climb up the jack rods about 25 mm to 30 mm at a time operated by a central hydraulic module. The reduction of diameter is done by manually operated radial screws and by operation of hydraulic panel jacks. Placing of reinforcement in position and pouring of concrete are carried out on a continuous basis. The rate of concrete filling should keep pace with the rate of rise, and generally keeping the concrete within 100 mm to 150 mm of the top of the formwork. For this purpose sufficient number of concrete mixers are to be installed, particularly at lower elevations where the volume of concrete poured is more. Similarly sufficient number of supervisory staff and workmen required to carry out the work in at least three shifts, should be planned well in advance. The setting time of concrete is important and

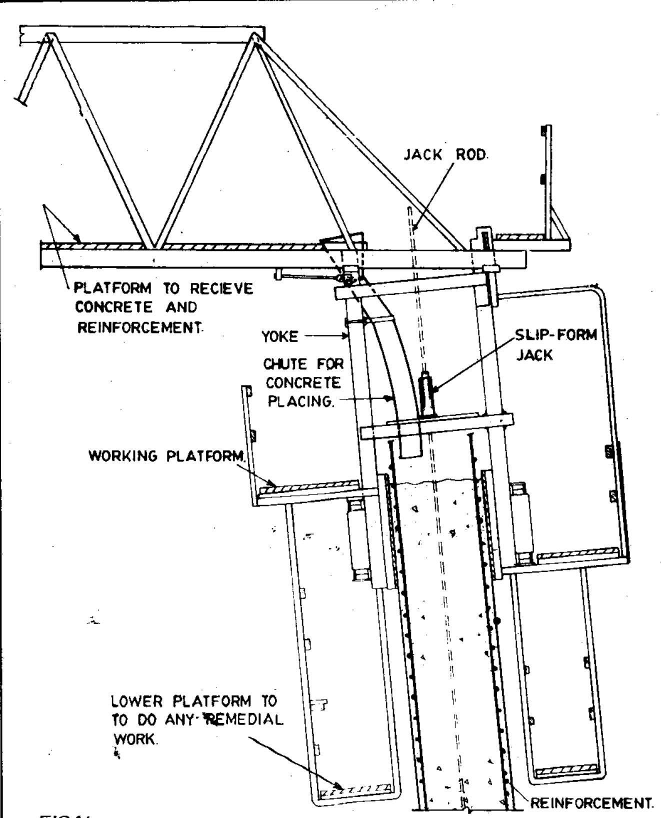

FIG.14.

TYPICAL SECTION THROUGH SLIPFORM FOR TAPERED CHIMNEY.

sometimes retarders are added to concrete to slow down setting time. For higher grades of concrete, extra care is necessary to maintain workability at low water/cement ratios. The minimum shell thickness for slip-forming should be 180 mm to 200 mm. It is preferable to provide reinforcement at each face of the shell to avoid any horizontal tension cracks developing due to frictional force that may arise between the shutter and concrete. The percentage of reinforcement should be kept low to avoid the difficulties of placing congested reinforcement during slipping operation. For the construction of corbels and platforms at a later date, mild steel dowel bars, preferably not more than 16 mm diameter, are provided at the surface of shell during slip-form construction, and these bars are pulled out while the concrete is still green. For slip-form work, construction tolerances as specified in ACI 341-78 is generally accepted in practice. Scaffolding system with hoists, as in the jump-form method, are provided to full height as the work proceeds.

10. MAINTENANCE

The most common instances of deterioration in chimneys are in its flue linings, and very few cases of failures of reinforced concrete shells have been known. These deteriorations occur due to interaction between the chimney shell and the lining, loss of material strength due to movement, thermal shock, acid attack, and these are commonly seen as cracking and flaking of brickwork or concrete, open joints in brickwork, irregularities in shape of the flues and discolouration of the flue surfaces. It is very much essential that the chimneys are examined from time to time, say every 2 or 3 years. Deterioration of a lining may give an indication of unfavourable conditions affecting the shell and corbels. If the lining is removed for replacement or repair opportunity should be taken to inspect the inside of shell. Provisions should be made in the top section of chimney to support temporary platforms which are lowered down for making visual inspection inside the lining. In some countries, closed circuit television cameras with wide angle lense are used to photograph the interior surface of the flues. If the chimney requires a major repair work which may take few months to do, it would be necessary to have a stand by chimney to avoid a situation of complete shut down of the main plant during such repair periods.

11. CONCLUSIONS

Chimneys are in a way special structures which require special expertise both to design and construct. Although in recent years lot of research has been carried out to determine various design parameters and applied loadings for aero-dynamic and seismic analysis, evidence to date indicates that there is yet ample scope for further research and instrumentation of full scale structures before more reliable values can be adopted in the structural design. Special attention is required in design detailing and construction in regard to thermal and corrosion problems associated with chimneys. If the fault lies in workmanship or in poor maintenance of lining work, gas leakage and consequent deterioration do take place which are not easily noticeable. There is a need for owner's awareness to inspect the lining from time to time, and maintain them like any other plant or structure in order to provide a satisfactory service to the industry.

ACKNOWLEDGEMENT

The author wishes to express his gratitude to Mr. T.N. Subba Rao, Managing Director, Gammon India Limited, Bombay, for his permission to publish the Paper.

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