IS 11504 (1985): Criteria for structural design of reinforced concrete natural draught cooling towers [CED 38: Special Structures]

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Indian Standard

CRITERIA FOR STRUCTURAL DESIGN OF REINFORCED CONCRETE NATURAL DRAUGHT COOLING TOWERS

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Indian Standard

CRITERIA FOR STRUCTURAL DESIGN OF REINFORCED CONCRETE NATURAL DRAUGHT COOLING TOWERS

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AMENDMENT NO.1 OCTOBER 1988

TO

IS:11504-1985 CRITERIA FOR STRUCTURAL DESIGN OF REINFORCED CONCRETE NATURAL DRAUGHT COOLING TOWERS

(*Page* 7, *clause* 5.1.3, *second sentence*) - Substitute the following for the existing sentence:

'As this is not normally practicable the wind pressure distribution suggested in Appendix A may be used for cooling towers not more than 100 m in height and not more than 120 m in base diameter built singly or in groups spaced in accordance with 6.2.'

(BDC 38)

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Indian Standard

CRITERIA FOR STRUCTURAL DESIGN OF REINFORCED CONCRETE NATURAL DRAUGHT COOLING TOWERS

0. FOREWORD

0.1 This Indian Standard was adopted by the Indian Standards Institution on 29 November 1985, after the draft finalized by the Criteria for Design of Structures Sectional Committee had been approved by the Civil Engineering Division Council.

0.2 Reinforced concrete cooling towers are extensively used in thermal power stations and other heavy industries such as steel plants. This standard is intended to provide unified approach for analysis, design and construction considerations of hyperbolic cooling towers, giving basic data regarding various loads and their design provisions.

0.3 Provisions of this standard are also applicable to cooling towers of other shapes formed by conic sections. However, structural studies carried out elsewhere on ellipsoidal, truncated cone, cylindrical and hyperboloid shell show that the hyperboloid offers very substantial material economies compared with other shapes. The hyperboloid shell is, therefore, recommended at present for cooling tower shells.

0.4 For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS : 2-1960*. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

1. SCOPE

1.1 This standard essentially deals with the structural design and construction considerations of cast *in-situ* reinforced concrete hyperbolic natural draught cooling tower shells.

*Rules for rounding off numerical values (*revised*).

1.2 The requirements of number, size, structural layout, location and spacing of towers arising out of thermal design considerations are not covered by this standard.

1.3 This standard also does not deal with the packing material, types, spacing of towers from buildings, water distribution system and the method of testing the performance requirements of cooling towers.

1.4 Provisions of IS : 2210-1962* and IS: 2204-1962† shall also apply to the design and construction of cooling tower shells wherever they are not covered in this standard.

2. TERMINOLOGY

2.0 For the purpose of this standard, the following definitions shall apply.

2.1 Air Flow — Total quantity of air including associated water vapour flowing through the tower.

2.2 Basin Sill Level — The datum level for the cooling towers.

2.3 Distribution System — Those parts of a tower beginning with the inlet connection which distribute the hot circulating water within the tower to the point from where it is allowed to fall in the packing material.

2.4 Packing Material — Material placed within the tower to increase heat and mass transfer between the circulating water and the air flowing through the tower.

2.5 Shell — The part of a natural draught cooling tower, above the air inlet.

3. SYMBOLS

3.1 For the purpose of this standard, the following letter symbols shall have the meaning indicated against each:

r_{th} — throat radius

r_{th}/b — slope of the asymptote of the generating hyperbola

D — base diameter at basin sill level

E_c — modulus of elasticity of concrete (short term modulus)

F_n — Fourier coefficient of n^{th} term

d — thickness of the shell

*Criteria for the design of reinforced concrete shell structures and folded plates.

†Code of practice for construction of reinforced concrete shell roof.

H — total tower height above basin sill level

M_{ϕ} — meridional moment per unit length of the middle surface

M_{θ} — circumferential moment per unit length of the middle surface

$M_{\phi\theta}, M_{\theta\phi}$ — twisting moments per unit length of the middle surface

n — n^{th} harmonic

N_{ϕ} — meridional stress resultant per unit length of middle surface

N_{θ} — circumferential stress resultant per unit length of middle surface

$N_{\theta\phi} N_{\phi\theta}$ — shearing stress resultants per unit length of middle surface

p' — design wind pressure coefficient

p — a constant reference load intensity per unit area of middle surface

p_{cr} — critical buckling pressure

$p_{\phi}, p_{\theta}, p_{z}$ — load components per unit area of middle surface

Q_{ϕ}, Q_{θ} — transverse shear stress resultants per unit length of middle surface

R_{0} — horizontal radius

r_{b} — base radius

H_{b} — vertical distance from the throat to basin sill level

r_{t} — top radius

H_{t} — vertical distance from the throat to the top of the shell

Y — vertical coordinate

ϕ — angle between vertical and the normal to an element of the shell

θ — the circumferential angle

γ — Poisson's ratio of concrete

4. MATERIALS

4.1 Concrete — The materials for concrete shall conform to the requirements specified in IS : 456-1978*.

4.2 Steel — The steel for reinforcement shall be any of the following:

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*Code of practice for plain and reinforced concrete (*third revision*).

a) Mild steel and medium tensile steel bars and hard-drawn, steel wire conforming to IS : 432 (Part 1)-1982* and IS : 432 (Part 2) -1982*,
b) Hot-rolled mild steel and medium tensile steel deformed bars conforming to IS : 1139-1966†,
c) Hard-drawn steel wire fabric for reinforcement conforming to IS : 1566-1982‡, or
d) Cold-worked steel high strength deformed bars conforming to IS : 1786-1979§.

4.3 Concrete Mix — Structural concrete shall be of designed mix complying with the relevant provision of IS : 456-1978‖. The minimum grades of concrete for structural components shall be as follows:

a) M25 — for raker columns, shell and ring beams
b) M20 — for all other members.

4.4 Steel Work (Exposed) — In view of particularly severe corrosive conditions in and around cooling towers, exposed steel work should be used only for minor components and fixtures such as doors, access ladders, handrail and the like. Such exposed steel work shall be given suitable and adequate protective treatment.

5. LOADING

5.1 The following loads shall be considered:

a) Dead loads;
b) Wind loads;
c) Earthquake forces;
d) Thermal restraint loads;
e) Construction loads; and
f) Any other loads such as snow loads, foundation settlement, etc.

5.1.1 *Dead Load* — Dead load shall be assessed carefully in accordance with IS : 1911-1967¶. It is desirable to minimize the loading upon the

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*Specification for mild steel and medium tensile steel bars and hard-drawn steel wire for concrete reinforcement :

Part 1 Mild steel and medium tensile bars (*third revision*).

Part 2 Hard-drawn steel wire (*third revision*).

†Specification for hot rolled mild steel, medium tensile steel and high yield strength steel deformed bars for concrete reinforcements (*revised*).

‡Specification for hard drawn steel wire fabric for concrete reinforcement (*second revision*).

§Specification for cold-worked steel high strength deformed bars for concrete reinforcement (*second revision*).

‖Code of practice for plain and reinforced concrete (*third revision*).

¶Schedule of unit weights of building materials (*first revision*).

shell due to permanent fixtures. Secondary stresses if any due to permanent fixtures on the shell shall be investigated.

5.1.2 *Wind Pressure* — The basic wind pressure shall, in general, conform to IS : 875-1964* excepting in places where local conditions warrant special investigations.

5.1.3 The wind pressure coefficient distribution on the shell should preferably be derived from wind tunnel tests of a model of the proposed tower shell shape. As this is not normally practicable, the wind pressure distribution suggested in Appendix A may be used for cooling towers more than 120 m in height and not more than 100 m in base diameter, built singly or in groups spaced in accordance with **6.2**.

5.1.4 It is recommended that for towers of greater height or built at closer spacings, wind pressure distribution shall be determined by model tests in a wind tunnel offering appropriate aerodynamic similitude. Such models shall include all adjacent topographical features, buildings and other structures which are likely to influence the wind load pattern on the tower significantly.

5.1.5 *Earthquake Forces* — Earthquake forces shall conform to IS : 1893-1984†. It is recommended that for towers with more than 120 m height or more than 100 m base diameter analysis and design of tower shell, shell supporting structure and its foundation shall be carried out on the basis of model analysis.

5.2 Load Combinations — The combination of different loads for design purposes shall be in accordance with IS : 875-1964*.

5.3 Permissible Stresses — The permissible stress shall be in accordance with IS : 456-1978‡.

6. TOWER DESIGN CONSIDERATIONS

6.1 Size and Shape — The base diameter, air intake, opening height, tower height and throat diameter are basically determined by thermal design considerations.

6.1.1 As the range of possible hyperbolic shell shapes is infinite it is recommended that the designs be confined to the following major proportions

*Code of practice for structural safety of buildings : Loading standards (*revised*).
†Criteria for earthquake resistant design of structures (*fourth revision*).
‡Code of practice for plain and reinforced concrete (*third revision*).

which have been extensively adopted in cooling tower constructions. Other proportions shall be carefully studied before adoption:

$$H/D = 1{\cdot}20 \text{ to } 1{\cdot}55$$

$$H_b/H = 0{\cdot}75 \text{ to } 0{\cdot}85$$

6.1.2 The minimum thickness of the shell shall not be less than 140 mm for towers of height 75 m and above; for towers less than 75 m height the minimum thickness shall not be less than 100 mm.

6.2 Spacing — It is recommended that the cooling towers in a group be spaced at clear distance of not less than 0·5 times the base diameter of the largest cooling tower in the group. Even at this spacing, aerodynamic interference occurs and the design recommendations given in Appendix A takes this into account (*see* **5.1.3**).

6.3 Tower Shell

6.3.1 *Shell Analysis* — Analysis shall be in accordance with general accepted principles of structural mechanics and sound engineering practices. The following stipulations are made:

a) Analysis shall be as per the accepted theories of elasticity applicable to thin shell of revolution.

b) For elastic analysis concrete may be assumed to be uncracked, homogenous and isotropic.

c) Attention is drawn to the possibility of wind induced vibrations in the shell but no recommendations are made at present due to insufficient information available.

Though both the membrane and bending analysis of shells of revolution give similar results of stress resultants and also show that meridional stress resultants are not materially influenced with the normal range of boundary conditions found in practice, the use of bending analysis is recommended.

The following boundary conditions may be assumed for the normal range of provisions in the design of cooling tower shells:

a) *At upper edge* — The top edge of the shell is often thickened to form a ring beam, but is generally considered as a free edge in the analysis. It is recommended that the thickness transition from shell to upper ring beam should be smooth.

b) *At lower edge* — The lower edge of the shell is always thickened to form a substantial lower ring beam. It is recommended that the thickness of the transition from shell to lower ring beam is smooth and considered as an intergral part of the shell. It is recommended that the lower boundary of the shell may be considered as elastically supported by the columns.

The stress functions and equilibrium equations for membrane analysis and bending analysis for cooling tower shells is given for guidance in Appendix B.

6.3.2 *Temperature and Moisture Variations* — Consideration should be given in the analysis for the strain resulting from temperature gradient across the shell thickness or from variation of moisture content through the shell or from temperature/moisture variations over the shell caused by sunshine, rain or partial operation of tower.

6.3.3 *Buckling of Tower Shells* — Critical dynamic pressure (wind pressure) at buckling from tests on hyperbolic shell models may be approximated by equation given below:

$$p_{cr} = 0{\cdot}07 E_c \left(\frac{d}{r_{th}} \right)^{7/3}$$

A factor of safety of 5 is recommended for critical buckling pressure.

Vertical cracking shall not be allowed as this reduces the bending stiffnesses and hence the critical stress. For this reason, provision of reinforcement at both faces of the shell is preferred to single layer at the centre of the shell.

NOTE — It is further pointed out that the above value of p_{cr} can be reduced by a maximum of 50 percent in severe vertical cracking.

6.3.4 *Vibration Characteristics* — Natural frequencies of vibration of a structure are inversely proportional to its mass and height. Taller the tower greater is the attention required to design against the wind-induced vibration.

6.3.5 *Openings in Shells* — Opening through the shells should be avoided as far as possible. They should be of smallest required dimensions and shall be shaped such that stress concentration is minimized at the boundary of the opening. Should thickening of the edges be necessary, it shall be smoothly tapered back to the shell thickness.

Openings shall be provided with additional edge reinforcements of a minimum cross-sectional area at each edge equal to 75 percent of the reinforcement intercepted by the openings in the direction parallel to the edges. In addition, diagonal reinforcement shall be provided at each corner as close as possible. The total cross-sectional area in cm^2 of this reinforcement shall be $0{\cdot}5d$, at each corner where d is the shell thickness in cm.

No horizontal thrust due to inlet piping shall be transmitted to the shell.

6.3.6 *Minimum Reinforcement Spacing and Placement* — The minimum reinforcement to be provided in each direction shall be as follows:

> 0·35 percent of gross cross-sectional area when mild steel bars are used, and
>
> 0·25 percent when cold-worked steel high strength deformed bars are used.

The maximum spacing shall be restricted to twice the thickness of the shell in either direction. It is preferable to provide reinforcement at both faces of the shell. For shells of thickness 175 mm and above two layers of reinforcement shall invariably be provided.

6.3.7 *Cover* — Where two layers of reinforcement are provided, the clear cover to reinforcement shall not be less than 25 mm. This cover of minimum 25 mm needs rigorous control on steel positioning, concrete quality and concrete compaction. In special cases of aggressive conditions the cover shall be increased as per **25.4** of IS : 456-1978* or suitable and adequate protective treatments shall be provided.

6.4 Shell Supporting Structure — The dead weight of the integral shell and the wind or seismic forces induced in it are usually transmitted to the foundation system through a series of raker columns spanning air intake openings.

It is recommended that the inclination of these columns closely matches the meridional slope at the base of the integral shell so that the load transfer to foundation takes place through predominantly axial forces in columns. The columns shall be designed as per IS : 456-1978*.

6.5 Foundations and Auxiliary Structures — Analysis, design, and construction of foundation and auxiliary structures such as basin, supporting structures for packing, platforms, internal grillage, etc, shall be in accordance with the following Indian Standards as may be applicable.

Foundations	IS : 2911 (Part 1/Sec 1)-1979†, IS:2911 (Part 1/Sec 2)-1979† and IS : 2911 (Part 1/Sec 3)-1979†
	IS : 2950 (Part 1)-1981‡

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*Code of practice for plain and reinforced concrete (*third revision*).

†Code of practice for design and construction of pile foundations: Part 1 Concrete piles,

Section 1 Driven cast *in-situ* concrete piles (*first revision*).
Section 2 Bored cast *in-situ* piles (*first revision*).
Section 3 Driven precast concrete piles (*first revision*).

‡Code of practice for design and construction of raft foundations: Part 1 Design (*second revision*).

Platforms/internal grillage	IS : 456-1978*
Basin distribution ducts	IS : 3370 (Part 1)-1965†
	IS : 3370 (Part 2)-1965†
	IS : 3370 (Part 3)-1967†
Steel structures	IS : 800-1984‡

6.5.1 When the tower is supported on pile foundation, the necessity or otherwise of providing raker piles to resist horizontal forces may be investigated.

Influence of foundation settlement, if any, shall be taken into account while designing the tower shell, raker columns and foundations. It is recommended that in the analysis soil structure interaction may be taken into account.

6.5.2 If the tower is more than 75 m high, continuous foundations or continuous annular pile cap may be provided. For smaller towers, individual isolated foundations may be adopted.

7. CONSTRUCTIONAL ASPECTS

7.1 General — The setting out, checking and formwork system should be intended to produce smooth surface, without geometrical deformities. It shall also produce a high degree of dimensional accuracy to ensure the design considerations originally envisaged.

7.2 Shell Formwork -- The formwork for shell shall be capable of adjusting to shell profile and thickness accurately, and rigidly braced to prevent deflection or movement during concreting.

To achieve high dimensional accuracy, the formwork shall be rigid, shape preserving, tight fitting and easy to construct. The use of steel formwork is recommended at present. Except where recommended otherwise in this standard, provisions of IS : 456-1978* shall apply to formwork for cooling towers.

*Code of practice for plain and reinforced concrete (*third revision*).
†Code of practice for concrete structures for the storage of liquids:
Part 1 General requirements.
Part 2 Reinforced concrete structures.
Part 3 Prestressed concrete structures.
‡Code of practice for general construction in steel (*second revision*).

7.3 Tolerances — Dimensional tolerances within which the construction be carried out shall be as follows:

a) Shell wall centre line in horizontal plane measured radially at mid point on a 3 m wide chord	±15 mm
b) Shell wall centre line in meridional plane over a height of 1 m	±10 mm
c) Thickness of shell	+10 mm or −5 mm
d) Horizontal radius of shell at any section other than shell base	±50 mm
e) Horizontal radius at shell base	±40 mm

7.4 Checking of Shell Geometry — Checks for absolute positions may be carried out from ground stations arranged at not more than 10 degrees plan angle apart. Readings of horizontal radius taken at every 6 m height or weekly during constructton period whichever is more frequent. The following allowance survey inaccuracies shall be provided for readings taken between the following heights:

Up to 30 m	± 15 mm
30 to 60 m	± 40 mm
60 to 120 m	± 60 mm
Above 120 m	± 80 mm

7.5 Fittings and Fixtures

7.5.1 Every cooling tower shall have a complete system of lightening protection in accordance with the provision of IS : 2309-1969*. In addition, it is recommended that vertical bars be tied to horizontal bars and the system suitably earthed.

7.5.2 *Aviation Warning Lights* -- Towers are usually tall and necessary aviation obstruction lighting and marking should be provided.

7.5.3 *Access Ladder* — Access ladder shall be provided as far as possible independent of the main structure. Where fixtures are provided, the effect of stress concentration shall be taken into account.

*Code of practice for the protection of buildings and allied structures against lighting (*first revision*).

APPENDIX A

(*Clauses* 5.1.3 *and* 6.2)

WIND PRESSURE DISTRIBUTION

A-1. GENERAL

A-1.1 This appendix describes the wind pressure distribution for cooling towers not more than 120 m in height and not more than 100 m in base diameter built singly or in groups in accordance with **6.2**.

A-2. PRESSURE DISTRIBUTION

A-2.1 The wind pressure distribution on the outside of the shell is assumed to be symmetrical about the centre line in the direction of wind. For practical design these values may be increased by 10 percent to take into account geometrical imperfections.

A-2.2 The wind pressure coefficient distribution around the shell is defined by the following equation and shall be of the form indicated in Fig. 1.

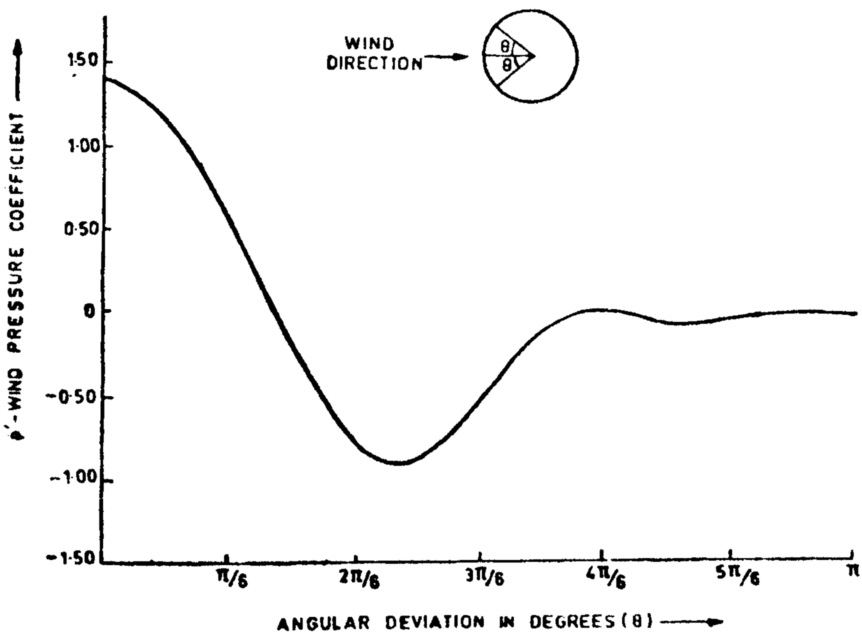

FIG. 1 CIRCUMFERENTIAL NET WIND PRESSURE DISTRIBUTION

The distribution shall be used at all heights of the tower and includes an allowance for internal suction.

$$p' = \sum_{n=0}^{7} F_n \cos n\theta$$

where

p' = design wind pressure coefficient,

F_n = Fourier coefficient of n^{th} term, and

θ = angular position measured from the incident wind direction in degrees.

Values of F_n for various values of n are tabulated below:

n	F_n
0	−0·000 71
1	+0·246 11
2	+0·622 96
3	+0·488 33
4	+0·107 56
5	−0·095 79
6	−0·011 42
7	+0·045 51

NOTE — The series have been given only up to 7 terms as it is found to be sufficiently accurate.

The actual design wind pressure on the shell is obtained by multiplying the basic wind pressure as given in IS : 875-1964* by the coefficient p' obtained above.

A-2.3 Pressure Fluctuations — The steady pressure coefficients given in **A-2.2** are for uniform pressure distribution in laboratory conditions and further allowances should be made in assesing the wind loading for:

a) load intensification due to natural turbulence in the incident wind, and

b) load intensification due to turbulence induced in the incident wind by adjacent cooling towers in a group or of the structures of significant dimension in the vicinity.

*Code of practice for structural safety of buildings: Loading standards (*revised*).

APPENDIX B

(*Clause* 6.3.1)

ANALYSIS OF SHELL

B-1. SHELL ANALYSIS

B-1.1 Except for moderately sized towers where membrane analysis gives sufficiently satisfactory results, bending analysis should be carried out as per the elastic theory for thin shells either by classical methods or by numerical methods like finite differences or finite elements.

It should include the following information at 10° plan angle and not more than 0·05 of the shell height:

a) Meridional and circumferential direct stress resultants and tangential shear stress resultants,

b) Meridional and circumferential bending moments, and

c) Displacements normal to shell midsurface.

B-2. The geometry of the hyperboloid of revolution shown in Fig. 2 is given by:

$$\frac{r^2 + y^2}{r_{th}^2 b^2} = 1$$

$$b = \frac{r_{th} H_t}{\sqrt{r_t^2 - r_{th}^2}} = \frac{r_{th} H_b}{\sqrt{r_b^2 - r_{th}^2}}$$

The coordinate system is also shown in Fig. 2 where the positive directions of ϕ and θ as well as the load components per unit area of middle surface, p_θ, p_ϕ and p_s are indicated. The principal radii of curvature R_θ and R are given by:

$$R_\theta = r \operatorname{cosec} \phi = \frac{r_{th}^2}{\sqrt{r_{th}^2 \sin^2 \phi - b^2 \cos^2 \phi}} = \frac{r_{th} \sqrt{k^2 - 1}}{\sqrt{k^2 \sin \phi - 1}}$$

$$R = \frac{-r_{th}^2 b^2}{(r_{th}^2 \sin^2 \phi - b^2 \cos^2 \phi)^{3/2}} = \frac{-r_{th} \sqrt{k^2 - 1}}{(k^2 \sin^2 \phi - 1)^{3/2}}$$

where $k = \sqrt{1 + \frac{r_{th}^2}{b^2}}$

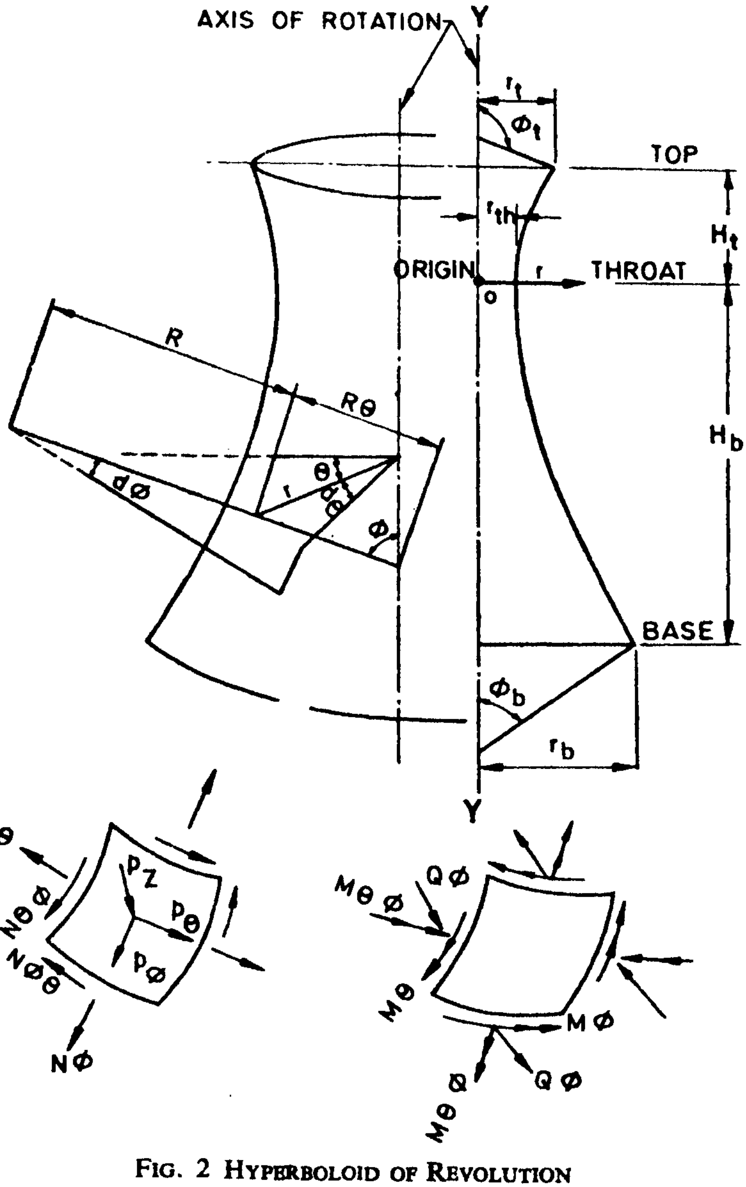

FIG. 2 HYPERBOLOID OF REVOLUTION

and R_θ and R are related by:

$$\frac{\partial}{\partial\phi}(R_\theta \sin\phi) = R\cos\phi$$

B-3. MEMBRANE ANALYSIS

The general equations of equilibrium for membrane analysis of a hyperboloid of revolution are:

$$\frac{\partial}{\partial\theta}(rN_{\theta\phi}) - \frac{\partial}{\partial\theta}(RN_\theta) + R\cos\phi N_{\theta\phi} - rRP_\theta = 0$$

$$\frac{\partial}{\partial\phi}(rN_\phi) - \frac{\partial}{\partial\theta}(RN_{\theta\phi}) - R\cos\phi N_\theta + rRP_\phi = 0$$

$$R\sin\phi N_\theta + rN_\phi + rRP_z = 0$$

B-4. BENDING ANALYSIS

The general equations of equilibrium in terms of the six quantities N_θ, N_ϕ, M_θ, M_ϕ, S and M_t are:

$$\frac{\partial}{\partial\phi}(rS) - \frac{\partial}{\partial\theta}(RN_\theta) + R\cos\phi S$$

$$+\frac{\sin\phi}{r}\left[2\frac{\partial}{\partial\phi}(rM_t) - \frac{\partial}{\partial\theta}(RM_\theta)\right] + 2M_t\cos\phi - rRP_\theta = 0$$

$$\frac{\partial}{\partial\phi}(rN\phi) - \frac{\partial}{\partial\theta}(RS) - R\cos\phi N_\theta$$

$$+\frac{1}{R}\left[\frac{\partial}{\partial\phi}(rM_\phi) - R\cos\phi M_\theta - 2\frac{\partial}{\partial\theta}(RM_t)\right] + rRP_\phi = 0$$

and

$$R\sin\phi N_\theta + rN_\phi + \frac{1}{r}\frac{\partial}{\partial\theta}\left[\frac{\partial}{\partial\phi}(rM_t) - \frac{\partial}{\partial\theta}(RM_\theta) + R\cos\phi M_t\right]$$

$$-\frac{\partial}{\partial\phi}\frac{1}{R}\left[\frac{\partial}{\partial\phi}(rM_\phi) - \frac{\partial}{\partial\phi}(RM_t) - R\cos\phi M\phi\right] + rRP_z = 0$$

in which

$$\left.\begin{aligned} M_t &= \tfrac{1}{2}(M_{\theta\phi} + M_{\phi\theta}) \text{ and} \\ S &= N_{\theta\phi} - \frac{M_{\phi\theta}}{R} = N_{\phi\theta} - \frac{M_{\theta\phi}\sin\phi}{r} \end{aligned}\right\}$$

To obtain a determinate problem, three more equations are required. These are provided by compatibility relations which exist between the strain and curvature parameters of the middle surface of the shell that is:

$$- R\frac{\partial K_\phi}{\partial \theta} - r\frac{\partial T}{\partial \phi} - 2R\cos\phi T + \omega\cos\phi$$

$$+ \frac{\sin\phi}{r}\left[r\frac{\partial \omega}{\partial \phi} + R\cos\phi\omega + R\frac{\partial \epsilon_\phi}{\partial \theta}\right] = 0$$

$$r\frac{\partial K_\theta}{\partial \phi} + R\cos\phi\,(K_\theta - K_\phi) + R\frac{\partial T}{\partial \theta}$$

$$- \frac{1}{R}\left[R\frac{\partial \omega}{\partial \theta} + r\frac{\partial \epsilon_\theta}{\partial \phi} + R\cos\phi\,(\epsilon_\theta - \epsilon_\phi)\right] = 0$$

and

$$rK_\theta + R\sin\phi K_\phi + \frac{1}{r}\frac{\partial}{\partial \theta}\left[R\frac{\partial \epsilon_\phi}{\partial \theta} + \frac{r}{2}\frac{\partial \omega}{\partial \phi}\ R\cos\phi\omega\right]$$

$$+ \frac{\partial}{\partial \phi}\frac{1}{R}\left[r\frac{\partial \epsilon_\theta}{\partial \phi} + R\cos\phi\,(\epsilon_\theta - \epsilon_\phi) + \frac{R}{2}\frac{\partial \omega}{\partial \theta}\right] = 0$$

The quantities ϵ_θ, ϵ_ϕ, ω, K_θ, K_ϕ and in the above equations are given by:

$$\epsilon_\theta = \frac{1}{E_c d}(N_\theta - \nu N_\phi)$$

$$\epsilon_\phi = \frac{1}{E_c d}(N_\phi - \nu N_\theta)$$

$$\omega = \frac{2(1+\nu)}{E_c d}S$$

$$K_\theta = \frac{12}{E_c d^3}(M_\theta - \nu M_\phi)$$

$$K_\phi = \frac{12}{E_c d^3}(M_\phi - \nu M_\theta) \text{ and}$$

$$T = \frac{12(1+\nu)}{E_c d^3}M_t$$

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