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CODE OF PRACTICE FOR CONSTRUCTION OF REINFORCED CONCRETE SHELL ROOF

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BUREAU OF INDIAN STANDARDS
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

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Indian Standard

CODE OF PRACTICE FOR CONSTRUCTION OF REINFORCED CONCRETE SHELL ROOF

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Indian Standard

CODE OF PRACTICE FOR CONSTRUCTION OF REINFORCED CONCRETE SHELL ROOF

0. FOREWORD

0.1 This Indian Standard was adopted by the Indian Standards Institution on 22 October 1962, after the draft finalized by the Building Construction Practices Sectional Committee had been approved by the Building Division Council.

0.2 Reinforced concrete shell roofs are chosen commonly for covering large clear areas using the minimum of intermediate supports, such as in factory buildings, godowns, power stations, garages, island platforms of railway stations, stadia, etc.

0.2.1 This standard is intended to give a general guidance to those engaged in the construction of reinforced concrete shell roofs. Because of the multiplicity of shapes employed in modern shell construction, it is difficult to lay down rules which will have a universal application. It needs hardly be emphasized that the design and construction of shell roofs is a specialized job and the specifications of the designer shall always prevail over the general regulations laid down in this standard.

0.3 The Sectional Committee responsible for the preparation of this standard has taken into consideration the views of builders and technologists and has related the standard to the building practices followed in the country in this field. Due weightage has also been given to the need for international co-ordination among standards prevailing in different countries of the world.

0.4 Wherever a reference to any Indian Standard appears in this code, it shall be taken as a reference to the latest version of the standard.

0.5 Metric system has been adopted in India and all quantities and dimensions in this standard have been given in this system.

0.6 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 Rules for Rounding Off Numerical Values (*Revised*). The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

0.7 This standard is intended chiefly to cover the technical provisions relating to reinforced concrete shell roof construction, and it does not cover all the necessary provisions of a contract.

1. SCOPE

1.1 This standard covers the *in-situ* construction of reinforced concrete shells of single and double curvature.

1.2 Precast and prestressed shells are not covered in this standard.

1.3 Shells of light weight concrete are also excluded from the scope of this standard.

2. TERMINOLOGY

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

2.1 Shell Dimensions

2.1.1 *Chord Width* (*see* B in Fig. 1) — The horizontal projection of the arc of the shell.

2.1.2 *Radius* — Radius at any point of the skin in one of the two principal directions in the case of cylindrical shells.

NOTE — If a circular arc is used, the radius of the arc is the radius of shell. In other cases, the radius R at any point is related to the radius R_o at the crown by $R = R_o \cos^n \phi$, where ϕ is the slope of the tangent to the curve at that point. The value of n is 1, -2 and -3 for the cycloid, the catenary and the parabola respectively. For an ellipse

$$R = \frac{a^2 b^2}{(a^2 \sin^2 \phi + b^2 \cos^2 \phi)^{\frac{3}{2}}}$$

where

a and b are the semi-major and semi-minor axes and ϕ is the slope of the tangent at the point.

2.1.3 *Rise* (*see* f in Fig. 1) — The rise of the shell at any section is the vertical distance between the lower springing level and the highest level or apex of the shell.

2.1.4 *Semi-central Angle* (*see* ϕ_c in Fig. 1) — This is half the angle subtended by the arc of a symmetrical circular shell at the centre.

2.1.5 *Span* (*see L* in Fig. 1) — As referred to a cylindrical shell, this is the distance between the centre lines of two adjacent end frames or traverses.

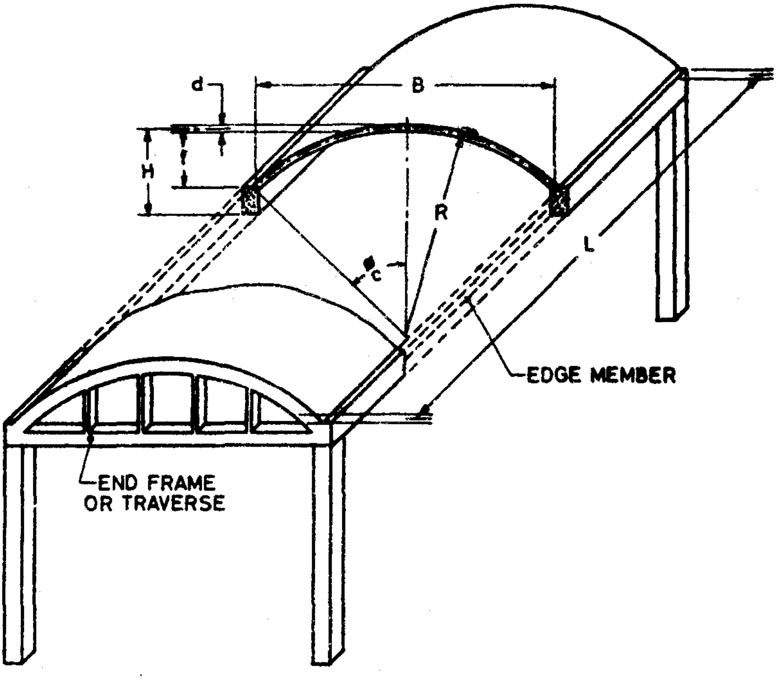


FIG. 1 SINGLE BARREL SHELL

2.2 Types

2.2.1 *Barrel Shells* — Cylindrical shells which are symmetrical about the crown.

2.2.2 *Butterfly Shells* — Butterfly shells are those which consist of two parts of a cylindrical shell joined together at their lower edges (*see* Fig. 2).

2.2.3 *Continuous Cylindrical Shells* — Cylindrical shells which are longitudinally continuous over the traverses (*see* Fig. 3).

2.2.4 *Corrugated Shells* — Shells which have corrugations on their surface (*see* Fig. 4).

2.2.5 *Cylindrical Shells* — Shells generated by a curve moving on a straight line or vice versa. Barrel shells (*see* Fig. 1), north light

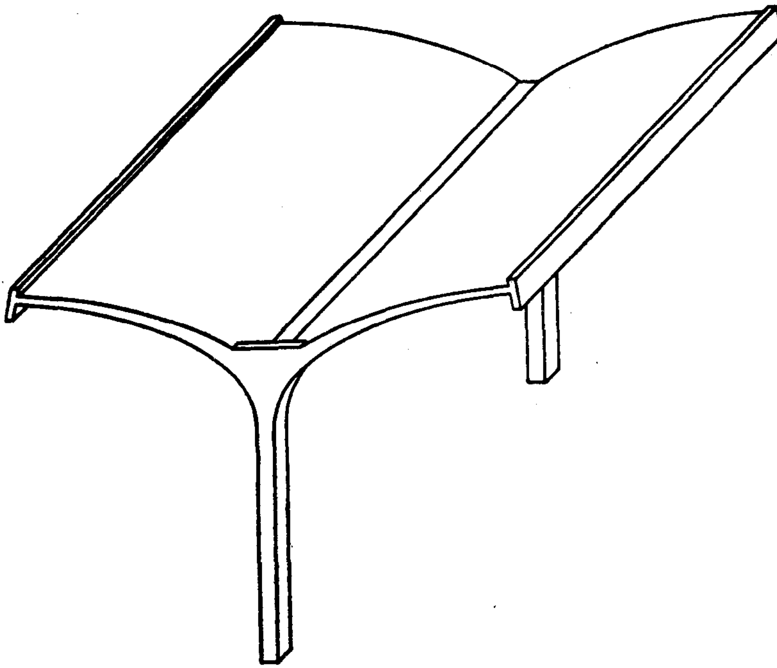


Fig. 2 Butterfly Shell

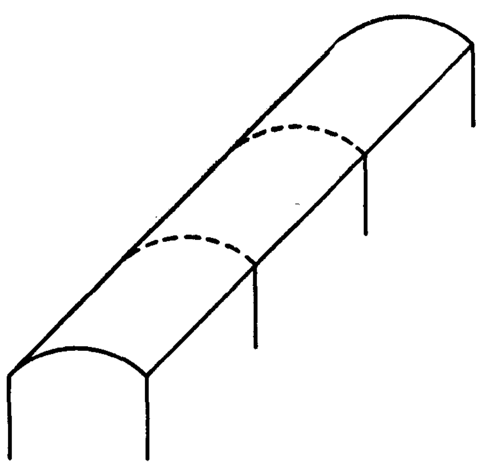


Fig. 3 Continuous Barrel Shells

cylindrical shells, and butterfly shells are common examples of this type.

The common curves employed for the cross section of cylindrical shells are (a) arc of a circle, (b) semi-ellipse, (c) parabola, (d) catenary and (e) cycloid (*see* Fig. 5).

NOTE — The semicircle, the semi-ellipse and the cycloid have the advantage that the tangents at the ends are vertical and hence the horizontal thrusts transferred

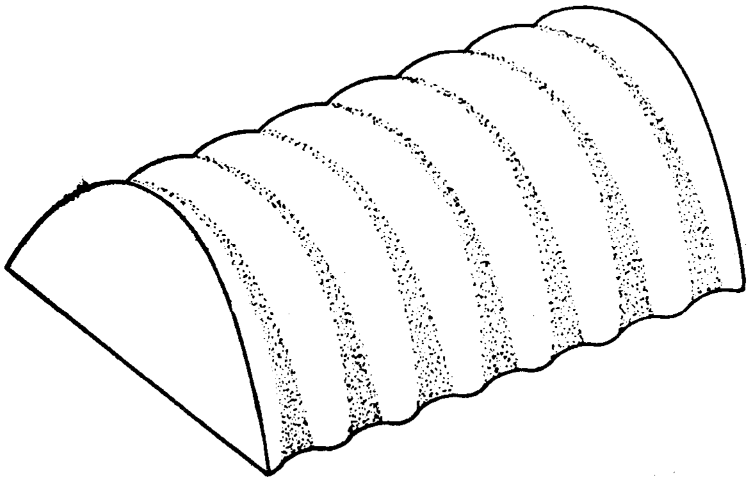


FIG. 4 CORRUGATED SHELL

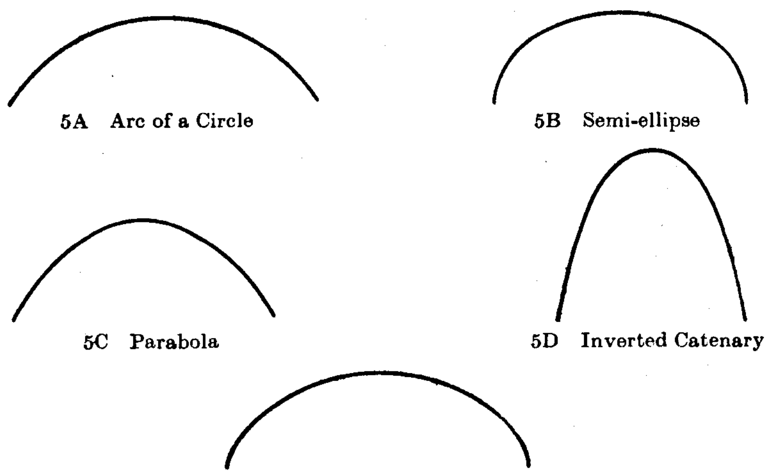


FIG. 5 COMMON CURVES USED FOR 'DIRECTRICES' OF CYLINDRICAL SHELLS

to the edge members are negligible, but these shapes are somewhat difficult to construct. By far the most common curve employed in modern cylindrical shell construction is the segment of a circle.

2.2.6 *Multiple Cylindrical shells* (*see* Fig. 6) — A series of parallel cylindrical shells which are traversely continuous.

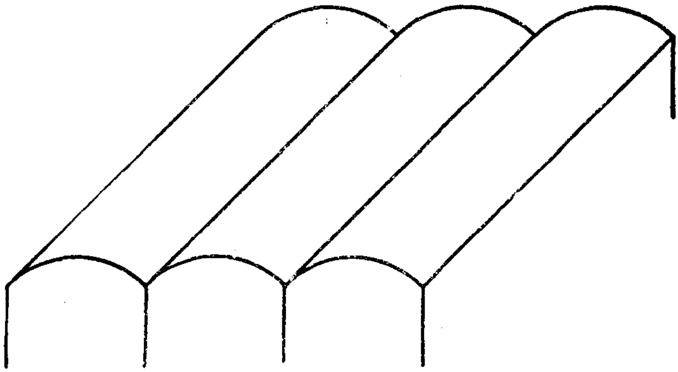


FIG. 6 MULTIPLE BARREL SHELLS

2.2.7 *North-Light Cylindrical Shells* — Cylindrical shells with the two springings at different levels and built in single or multiple bays and having provisions for north-light glazing (*see* Fig. 7).

2.2.8 *Ruled Surfaces* — A surface which can be generated entirely by a straight line. The surface is said to be singly ruled if at every point a single straight line only can be ruled and 'doubly ruled' if at every point two straight lines can be ruled. Cylindrical shell and conoid (*see* Fig. 8) are examples of singly ruled surfaces, and hyperbolic paraboloid (*see* Fig. 9A *and* 9B) and inverted umbrella (*see* Fig. 10) are examples of doubly ruled surfaces.

Ruled surfaces have a practical advantage that they can be formed by straight plank shuttering. Doubly ruled surfaces obviously have greater advantage for shuttering than singly ruled surfaces.

2.2.9 *Shells of Revolution* — Those generated by curves revolved about their axis of symmetry. Examples are segmental domes (*see* Fig. 11), paraboloids of revolution and hyperboloids of revolution. The term 'hyperboloid of revolution', unless otherwise qualified, will mean hyperboloid of revolution of one sheet.

2.2.10 *Shell Roof* — Curved surfaces in which the thickness is small as compared to the radius and other dimensions.

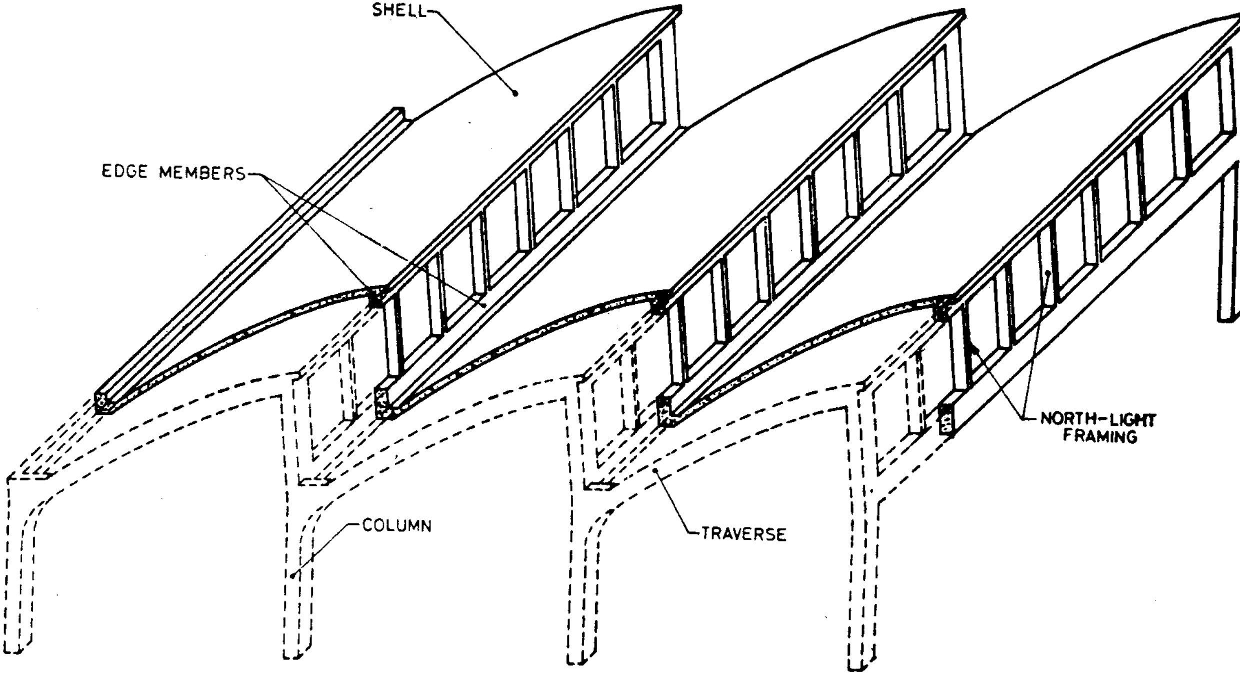


Fig. 7 North-Light Cylindrical Shells

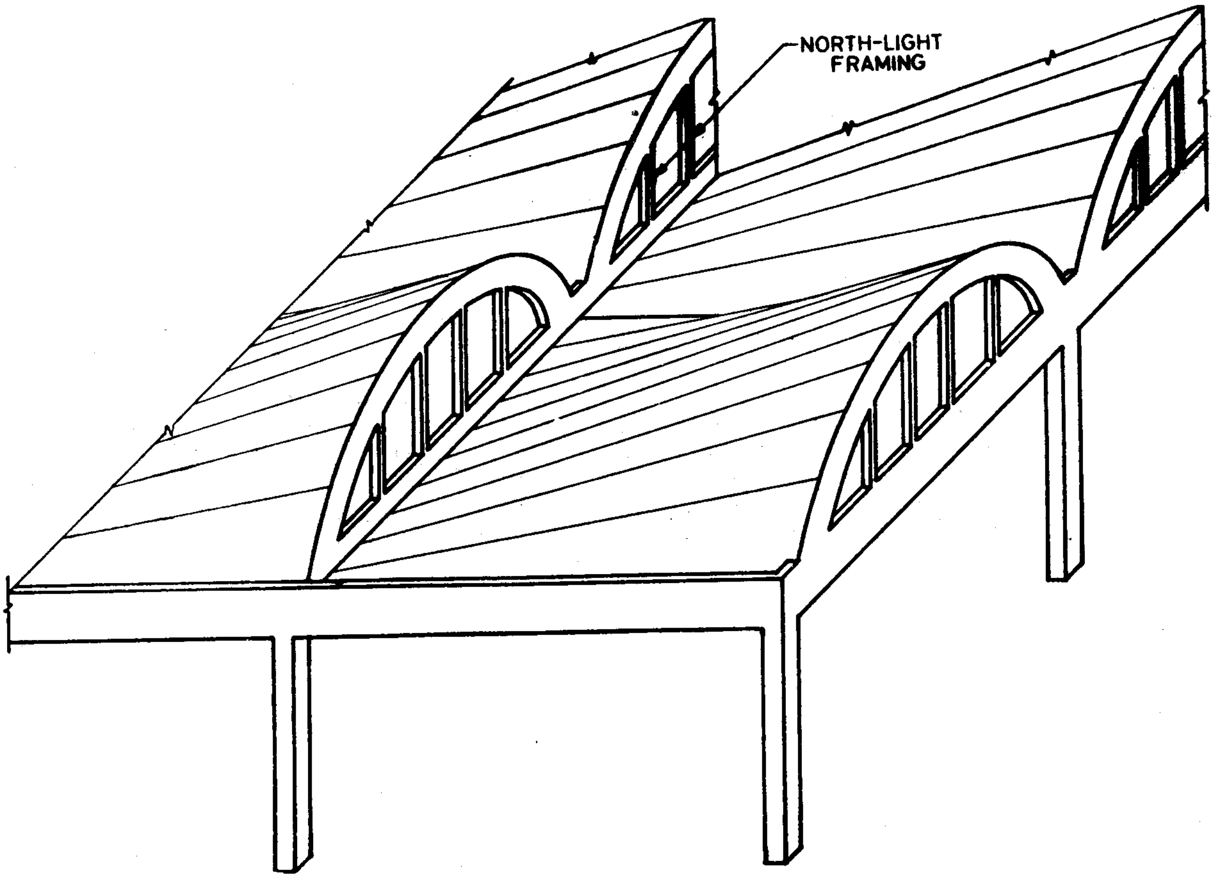
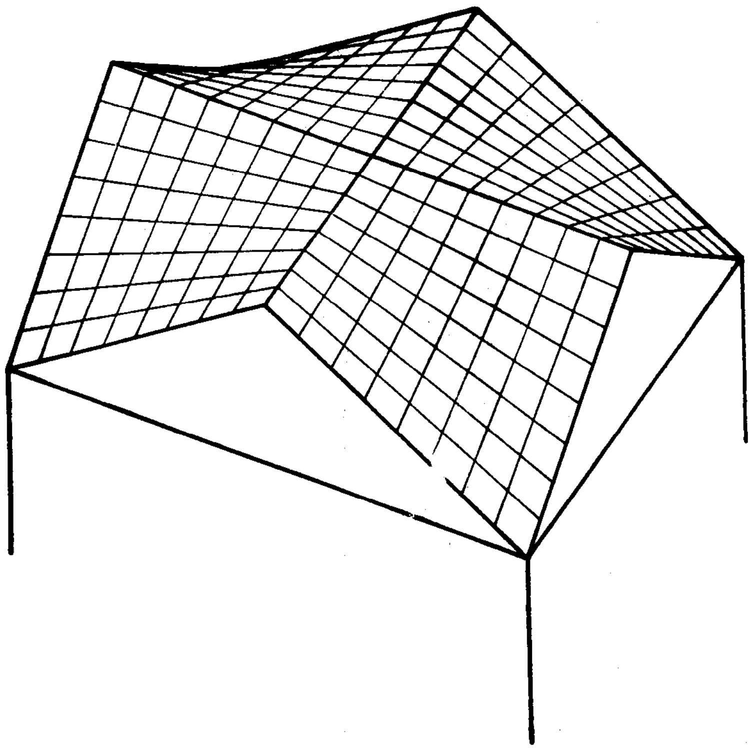
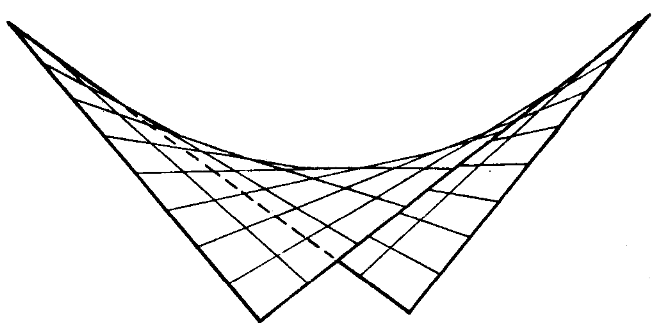


FIG. 8 NORTH-LIGHT CONOIDAL SHELLS



9A



9B

FIG. 9 HYPERBOLIC PARABOLOID

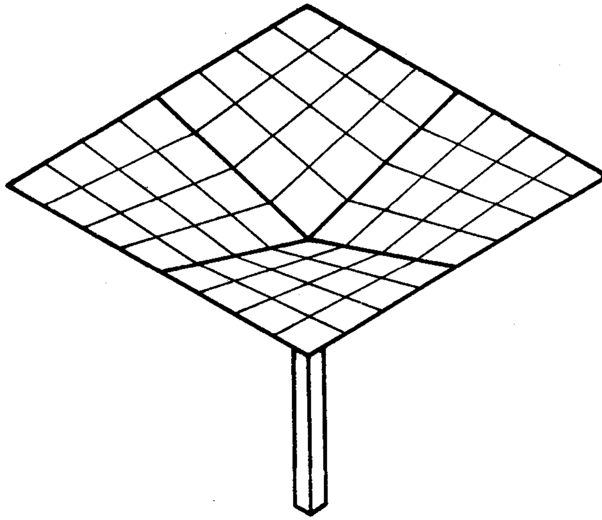


Fig. 10 Inverted Umbrella

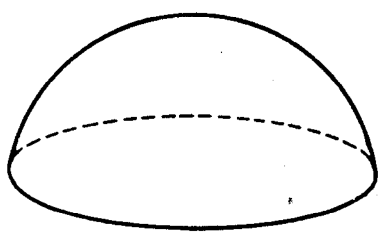


Fig. 11 Segmental Dome

2.2.11 *Translational Shell* — This is the surface generated when one curve moves parallel to itself along another curve, the planes of the two curves being at right angles to each other. As a special case, one or both the curves may be straight lines. Examples are ' hyperbolic paraboloids ' (generated by a convex parabola moving over a concave parabola or vice versa), ' elliptic paraboloids ' (*see* Fig. 12) (generated by one parabola moving over another parabola, both being convex), and 'cylindrical shells '.

2.3 Components of Shell Roof — *See* Fig. 1.

2.3.1 *Common Edge Member (Intermediate Beam or Rib)* — The common edge member provided at the junction of two adjacent multiple shells.

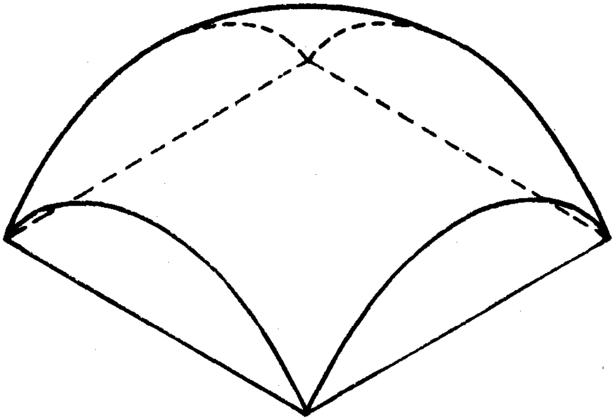


Fig. 12 Elliptic Paraboloid

2.3.2 *End Frames or Traverses* — End frames or traverses are structures provided to support and preserve the geometry of the shell.

2.3.3 *Edge Member* — A member provided at the edge of the shell.

2.3.3.1 An edge member or traverse or a portion thereof is said to be '*up-stand*' when it projects above the extrados of the shell and '*down-stand*' when it projects below intrados of the shell.

3. NECESSARY INFORMATION

3.1 For the efficient construction of shell roofs, detailed information with regard to the following shall be furnished by the designer to the builder:

Working drawings showing the orientation and arrangement of shells, dimensions, details of reinforcement including exact positioning, and other salient features, such as arrangement of north lighting, skylight, roof drainage, construction joints and expansion joints, etc.

3.2 Before the construction, the builder shall give detailed consideration to the design and fabrication of formwork and centering. The details of formwork and the sequence of erection and release of formwork used in shell construction shall be as approved by the designer.

4. DESIGN CONSIDERATIONS

4.1 Slope — Generally, if the slope of the shell exceeds 45°, it will be too steep for easy concreting and will necessitate the use of backforms (*see* Note).

NOTE — It is the experience of some builders that concreting can be done without the use of backforms up to a slope of 60° if it is for short distances, and with cautious tamping, satisfactory compaction of concrete even up to a slope of 65° would be possible without backforms.

4.2 Thickness

4.2.1 The thickness of singly-curved shells shall, in no case, be less than 5 cm. It is the usual practice to thicken the shells near the edges and the traverses.

4.2.2 The thickness of shells of double-curvature shall, in no case, be less than 4 cm. This minimum thickness is adequate, as shells of double curvature are non-developable and hence are more resistant to buckling. Moreover, flexural stresses are small.

4.3 End Frames or Traverses — An 'end frame' or 'traverse' is provided to preserve the shape of the shell. It may be a solid diaphragm, an arch rib, a portal frame or a bowstring girder. Where a clear soffit is required, especially where travelling formwork is employed, the end frames may consist of up-stand ribs.

4.4 Reinforcement

4.4.1 The diameter of reinforcement shall not be less than 5 mm in the unthickened portion of the shell, and shall not be greater than the following limits:

10 mm dia	For shells from 4 cm up to less than 5 cm thick
12 mm dia	For shells from 5 cm up to less than 6·5 cm thick
16 mm dia	For shells 6·5 cm and over in thickness

4.4.1.1 The maximum diameters specified in **4.4.1** apply only to the unthickened portion of the shell. Larger diameters for reinforcement will be permissible subject to the approval by the designer.

4.4.2 The maximum spacing of reinforcement in any direction shall be limited to five times the thickness of the shell and the area of unreinforced panel shall in no case exceed 15 d^2 where d is the thickness of the shell.

4.4.3 The total depth occupied by reinforcement in the direction of thickness in the unthickened portion of the shell shall not exceed three times the maximum permissible diameter for reinforcement as specified in **4.4.1**.

4.5 Mix Proportions for Concrete

4.5.1 Generally, a nominal mix of 1 : 2 : 4 (by nominal volumes) may be used for shells of medium dimensions and a nominal mix by volume of 1 : $1\frac{1}{2}$: 3 for very large shells. In no case shall the nominal mix for concrete used in shell construction be lower than 1 : 2 : 4. It is, however, desirable that the required strength for concrete is arrived at from considerations of stresses in the shell and its elastic stability, and the mixes specified by strength rather than by nominal volumes. Rich mixes will be generally undesirable as the concrete shrinks more, giving rise to cracks.

4.5.2 Wherever feasible, the maximum size of aggregate shall be 20 mm. If there are difficulties in placing such a concrete, the maximum size may be restricted to 12 mm provided the requirements for strength are satisfied.

NOTE — ' 20 mm maximum size ' of aggregate corresponds to ' 12 mm nominal size ' according to *IS : 383-1952 Specification for Coarse and Fine Aggregates from Natural Sources for Concrete.

4.5.3 It is advisable to use an air-entraining agent so that satisfactory workability is obtained without increasing the water content of the mix. Concrete having excessive water contents should be avoided as it is likely to slip down steep slopes.

5. SEQUENCE OF CONSTRUCTION

5.1 Shells may have edge members which are designed to act in unison with the shells; adjacent shells may also have been designed to take the loads in unison. For ease and economy of construction, however, it is generally necessary to construct the various elements separately. In order that the final stress pattern in the completed structure may conform as closely as possible to that assumed by the designer, it is necessary that the designer should specify the essential conditions governing the sequence of construction. The actual sequence proposed by the builder shall be subject to the designer's approval before construction starts on any of the elements of the shell structure and this sequence shall not be varied without the designer's approval.

5.2 In the type of shell roofs, covered by this standard, the following sequence of construction may generally be used at preliminary stages of planning the construction work:

Type	*Stage*	*Operation*	*Remarks*
a) Single shell	I	Erection of formwork for the edge members and the traverses, fabrication and placing of reinforcement and concreting with	Wherever economically feasible, consideration may be given to the erection of the formwork for the entire shell unit

*Since revised.

Type	*Stage*	*Operation*	*Remarks*
		such portion of shell reinforcement as shown in the drawings.	including the edge member and the traverse. However, it shall be ensured that the formwork for the edge member and traverse is not in any way connected with the formwork of the shell proper.
	II	Removal of formwork leaving required supports.	
	III	Erection of formwork for the entire shell, fabrication and placing of steel therein and concreting.	
	IV	Curing.	
	V	Removal of formwork.	
	VI	Waterproofing and insulating.	
	VII	Finishing.	
b) **Multiple shell**		Multiple shells do *not* generally exceed four or at the most five in number in one series depending on the designer's requirements for expansion joints. For multiple shells the stages of construction will be the same as those for single shells. However, unless otherwise provided for in the design, supports required for the edge beams, traverses and shells in one series shall remain till the entire series is completed.	

6. FORMWORK

6.1 Since shape is the essence of shell design and thicknesses are small, greater care shall be exercised in the design and erection of formwork and special attention shall be paid to minimizing the differential settlement of the centering and of the props supporting them. Where repetitions justify, formwork in panels or mobile units may be considered. Details for mobile units, if used, shall be worked out by the builder. If the formwork is to be used a great number of times, the surface of the forms shall be of firm construction to give the required repetitions. A hard and smooth surface for the form may eliminate the need for plastering, thus effecting economy. Where no additional decorative treatment is to be carried out, the designers may specify the general pattern to be left on the intrados by the formwork.

6.2 Formwork shall be designed and erected in such a manner as to lend itself to be removable as specified in **11**.

7. PLACING OF REINFORCEMENT

7.1 The reinforcement in shell structure including edge members, traverses, etc, shall be placed as shown in the drawing accompanying the design. To ensure monolithic connection between shell and the edge members, the shell reinforcement shall be adequately anchored into the edge members or vice versa, by providing suitable bond bars from the edge members to the shell.

7.1.1 *Reinforcement in the Shell* — As far as possible, hooks shall be avoided in the shell and adequate laps or welded joints as specified by the designer shall be provided in straight lengths. If at all hooks are to be provided for reinforcement in the shell, they shall be kept parallel to the plane of the shell. Only the minimum number of lengthening joints in the bars shall be used and the joints shall be staggered.

NOTE — Welding is rarely adopted in the case of reinforcement placed within the thickness of the shell. However, if it is required that the reinforcement shall be welded, only lap welding shall be adopted.

7.1.2 Reinforcement in edge members may be lapped, welded, or provided with special couplings with or without welding. If butt welding is used, it shall be done with extreme caution for successful results.

7.1.3 Provision of special couplings may be advantageous in edge members of large spans as it would avoid congestion of bars (*see* Note) due to laps and hooks. In such cases, the details and positioning of couplings shall be decided by the designer.

NOTE — The problem of congestion in reinforcement will, however, become less serious with the use of prestressed concrete construction.

7.2 A minimum cover of 12 mm shall be provided for the reinforcement. For regulating the cover, accurately made and matured precast mortar or concrete pieces shall be used. The reinforcement shall be correctly placed and firmly fixed. The reinforcement may be securely tied or welded so that the spacing of the bars is correctly maintained.

8. MIXING CONCRETE

8.1 The concrete shall be mixed in accordance with the requirements specified for concrete in*IS : 456-1957 Code of Practice for Plain and Reinforced Concrete for General Building Construction (*Revised*), and also the special instructions, if any, of the designer.

8.2 Unless otherwise specified by the designer, the maximum size of the aggregates shall be 20 mm and the aggregate shall conform to †IS : 383-1952 Specification for Coarse and Fine Aggregates from Natural Sources for Concrete.

9. CASTING OF THE SHELL

9.1 The full thickness of the shell shall be concreted in one operation. The positioning of the construction joints shall be as indicated by the designer.

The portion of an up-stand member, if any, shall be concreted as soon as possible after the concreting of the shell.

9.2 Edge members and end frames shall be concreted first. A slump of 4 cm for the concrete will be sufficient.

9.3 For casting the shell either hand tamping or mechanical compaction by vibrators may be used. The concrete shall have a slump of not less than 5 cm, if hand tamping is used. Concreting may be done in panels of convenient dimensions and shape. In the case of singly-curved shells, the panel should be laid parallel to the curved edge in order to limit the effect of shrinkage; each panel shall be started at the lowest level and worked upwards. In the case of doubly curved shells, the arrangement of panels shall be decided by the designer giving due consideration to shrinkage effects. Mechanical compaction shall be done by using screed vibrators generally. Needle vibrators may be used in thickened portions of the shell as advised by the designer; however, use of needle vibrators shall be restricted to edge members or thickened portions of the shell where the depth will be sufficient to accommodate these vibrators.

9.4 Concreting shall preferably be done in the cool hours of the morning or during the night in summer.

*Second revision in 1964.

† Since revised.

9.4.1 Special care shall be taken in tamping the concrete in downstand stiffening members which are usually deep.

9.5 Concrete shall be finished to the correct curve as set by template. This may be done either continuously or by alternate-bay method.

9.6 Thickness of the shell shall be regulated by using templates of corresponding thickness. This thickness of the shell shall also be accurately checked at typical points in between the thickness guides on the shell.

9.7 Proper arrangements shall be made to avoid displacement of steel during placing of concrete by providing walkways above the level of the finished concrete and supported and free from the reinforcement at intervals so as to avoid disturbance of the reinforcement.

9.8 Construction Joints — Construction joints shall invariably be along the curve. They shall preferably be located along a line of zero shear stress, as for example, along the directrix at mid-span. The construction joints shall be finished in such a way that new concrete will effectively bond with the old. When the work is commenced the next day, the joints shall be cleaned with wire brushes and slushed with cement slurry.

9.9 The surface of the concrete shall be finished with wooden floats.

9.10 The portions of the shell that are already cast shall be effectively protected from exposure to sudden rains by means of tarpaulins and similar coverings.

9.11 When concreting proceeds, cubes of concrete shall be taken out from each day's work for purpose of testing and verification of its quality.

10. CURING

10.1 In a shell roof, the ratio of the exposed area to the volume of concrete is relatively much larger in comparison with normal reinforced concrete structures. Hence, extreme care is required in keeping the surface sufficiently damp for curing. As soon as concrete has sufficiently hardened to prevent damage to it, it shall be kept continuously moist for the first 24 hours by covering the surface with wet canvas or gunny bags. Thereafter, the surface shall be kept continuously moist for a period of at least 10 days by sprinkling water or by covering it with gunny bags or similar materials which are sprayed over with water periodically; alternatively curing compounds may be used with the approval of the engineer in-charge.

11. DECENTERING

11.1 The process of decentering shall be gradual and without shock and so controlled that the overall stress pattern in the structure, at any stage of decentering is reasonably similar to the pattern expected in the design. Supports of adjacent edge members may have to be lowered simultaneously with those of the shell. The decentering procedure to be actually adopted shall be subject to the designer's approval.

NOTE 1 — As a general guide, the decentering may commence when concrete has attained a strength equal to twice the maximum dead load stress multiplied by a factor equal to Fc/Fb, where Fc = ultimate crushing strength of concrete, and Fb = ultimate buckling strength of the concrete in the shell.

NOTE 2 — Generally in the absence of test results on cubes, the centering of the shell may be removed at the end of 14 days, and the decentering the bottom shuttering of the edge members and the end frames may be done at the end of 21 days. By casting the latter a week in advance of the shell, it will be possible to strike the centering of the shell, the edge members and the end frames on the same day.

12. EXPANSION JOINTS

12.1 Expansion joints shall be provided in accordance with the design and specification of the designer (*see* relevant provisions of IS : 2210-1962 Criteria for the Design of Reinforced Concrete Shell Structures and Folded Plates). Complete structural isolation of the roof members shall be effected at the expansion joints with a clear gap of not less than 2 cm. It may also be necessary, sometimes, to have double columns. The gap shall be filled with an elastic filler, and the waterproofing carried across the joint without a break.

13. LIGHTING AND OTHER FIXTURES

13.1 Skylights, when provided, may be at the crown or on the slope of the shell very near the crown.

13.2 After completion of shells, no fittings shall be embedded or suspended from the shell without the approval of the designer.

14. THERMAL INSULATION

14.1 Thermal insulation may be provided by the following methods:

a) By application of light-weight insulating concrete, foam-concrete, cork, etc, over the shell roof;

b) By providing an air gap between the shell and any rigid form of waterproofing, such as asbestos sheets;

c) By casting the shell over rigid boards that provide thermal and acoustic insulation; and

d) By spraying on the underside of the shell a coating of insulating material, such as asbestos.

14.2 Whatever type of thermal insulation is adopted, the net weight of the insulation layer shall not exceed that assumed in the design, and the designer shall always specify this weight.

15. WATERPROOFING

15.1 Waterproofing of shell roofs may be carried out by any of the following methods or any other accepted method of flexible waterproofing.

a) By application of bitumen-hessian process, bituminous felts, or cold bitumen;

b) By lining with aluminium foils; and

c) By lining with asbestos sheets.

15.2 Adequate slope for drainage of water shall be made in the waterproofing.

15.3 Whatever method of waterproofing is adopted, the net weight of the waterproofing layer shall not exceed that assumed in the design and the designer shall always specify this weight.

16. FINISHING

16.1 After completion of the shell, the inside may be given a rubbed finish, if so required. The rubbing may be done with an abrasive stone.

BUREAU OF INDIAN STANDARDS

Headquarters:

Manak Bhavan, 9 Bahadur Shah Zafar Marg, NEW DELHI 110002

Telephones: 331 01 31, 331 13 75 Telegrams: Manaksanstha (Common to all Offices)

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*Sales Office in Calcutta is at 5 Chowringhee Approach, P. O. Princep Street, Calcutta 700072 27 68 00

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