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FINITE ELEMENT MODELING OF RECTANGULAR FUNICULAR SHELL USING SAP2000

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ABSTRACT

A shell structure covers the space without beams and columns within the buildings. Thin shells as structural elements occupy a leadership position in engineering. Shell forms are adopted in long span roofing systems, Liquid retaining structures, Pressure vessels, cooling towers. Shells of eggs, nuts and the human skull are thin and hard to crack or break. Thin shells are an example of strength through from as opposed to strength through mass. A minimum of materials is used to the maximum structural advantage. Shells by virtue of their spatial curvature and less flexural rigidity tend to carry applied loads mainly by direct stresses in their plane with little bending. It is possible to span as large as 30m with 75mm thick shells. This paper gives complete guidelines for Finite Element modelling of Rectangular funicular shells with IS code parameters, Calculation of Z coordinates and obtaining the membrane stress and deflection of shell.

KEYWORDS: *Deflection, Edge beam, Funicular shell, Membrane thickness, Rise, SAP2000*

I. INTRODUCTION

Funicular shells are a class of doubly curved shells, the shape of which satisfies the desired state of stress in its body for the given loading and boundary conditions. The state of stress desired in an unreinforced concrete thin shell will be pure compression unaccompanied by shear and bending stresses. In funicular shells, the shape of the shell is such that under a particular loading condition, the shell is subjected to pure compression unaccompanied by bending and shear stresses. Under other conditions of loading, bending moments would develop and the shell will no longer behave purely as a funicular element. Analytically, it is possible to compute the funicular surface of any ground plan for the given loading conditions. The funicular shell is constructed as per the configuration obtained from the analysis. By using simple techniques like the use of a sagging fabric, funicular shells can be cast to satisfy simp1e loading and boundary conditions (Rama swamy and Chetty, 1960).

Funicular shells are not limited by plan, shape or size. It can be triangular, square, rectangular, circular or elliptic of required dimensions. Models can be cast to scale and its ordinates measured to be used for casting the prototype. The shells can be cast either using the formula for the ordinates of the shell from computations or by using the simple sagging fabric technique developed by the Structural Engineering Research Centre, Roorkee, India.

For many structures, funicular shells of different sizes and shapes have been tried as roof element and many publications on their use have been brought out. An important case was that of a heavy duty platform built of precast funicular shells for unloading cargo from the ships for the use of Madras Port. A single funicular shell roof over an oval ground plan was built as roofing for the Municipal Corporation Conference Hall at Kanpur, India. Other notable funicular shells designed by Structural

Engineering Research Centre were the roof for their testing laboratory at Madras, brick shell roofs at the National Institute of Design, Ahmedabad, the concrete shell roof of the Cathedral at Lucknow, the roofs for the schools at Roorkee and Chaibassa, the roofs for 600 units of houses for Bharat Heavy Electricals, Thiruchirappalli, and the roofs for the tenements of Tamil nadu Slum Clearance Board and the housing project of Andhra Pradesh Police Housing Corporation.

II. GENERAL CLASSIFICATION OF SHELLS

A concrete shell generally includes single curved shells such as cylinders & cones & double curved shells such as domes. These shells are either synclastic (curves running in the same direction) or anticlastic (curves running in opposite directions).Shells are widely classified as 'singly-curved shell' and 'doubly-curved shell'. These classifications are based on Gauss curvature. In case of singly curved shell gauss curvature is equal to zero because one of their principal curvatures is zero. Doubly-curved shells are non developable and based on their positive and negative Gauss curvature they are classified as synclastic or anticlastic. The other special cases of doubly curved shells are funicular shells, which are synclastic & anticlastic in parts & the other is corrugated shells which are alternately synclastic & anticlastic. This kind of shells has positive gauss curvature when they are synclastic & negative when they are anticlastic.

The classification of shell structures is given in detail in Fig 1.

Generally shells are classified into the following classes.

1. Shells of revolution
2. Translational shells
3. Ruled surfaces
4. Composite shells

Each class of shell is discussed in the following sections.

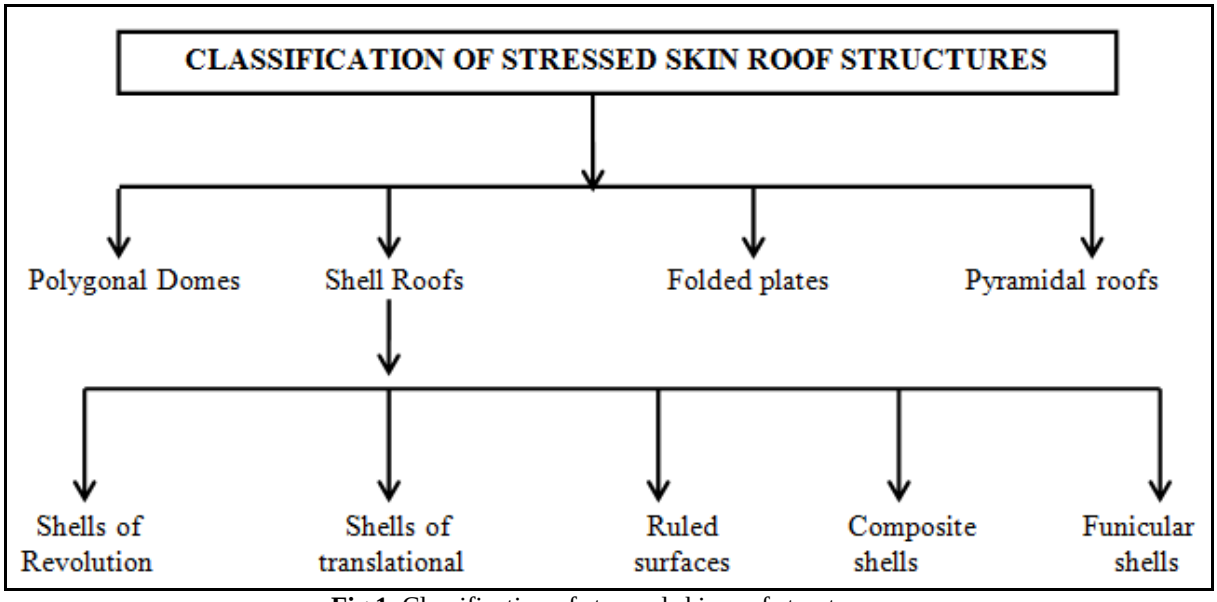
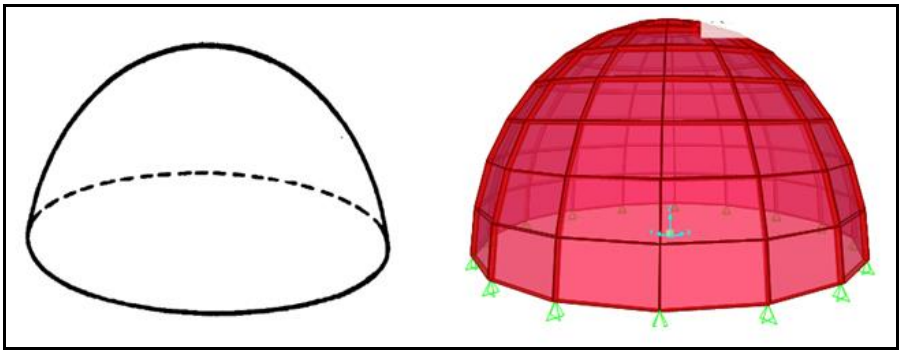


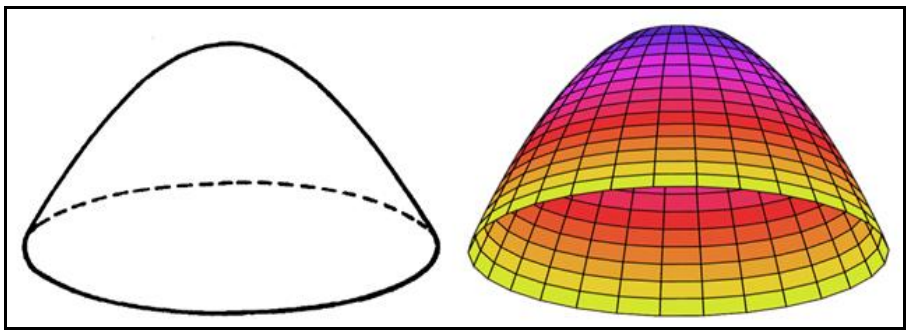
Fig 1. Classification of stressed skin roof structures

2.1. Shells of revolution:

Shells which are obtained when a plane curve is rotated about the axis of symmetry. Examples are segmental domes, cones, paraboloids of revolution, hyperboloids of revolution, etc (Fig.2.)



Segmental domes

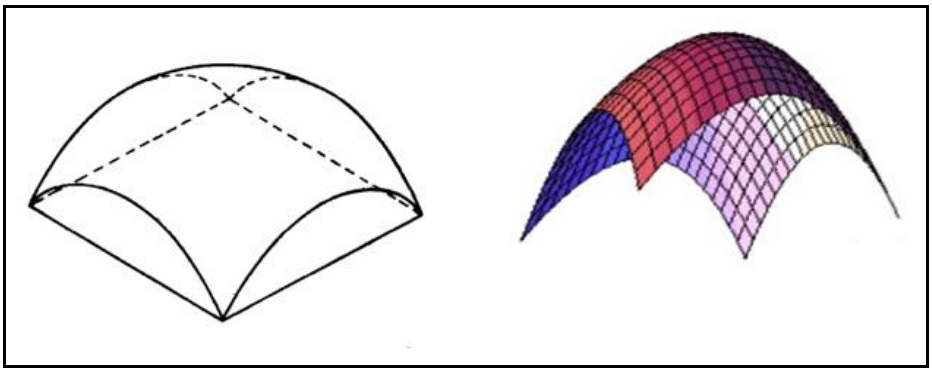


Paraboloid of revolution

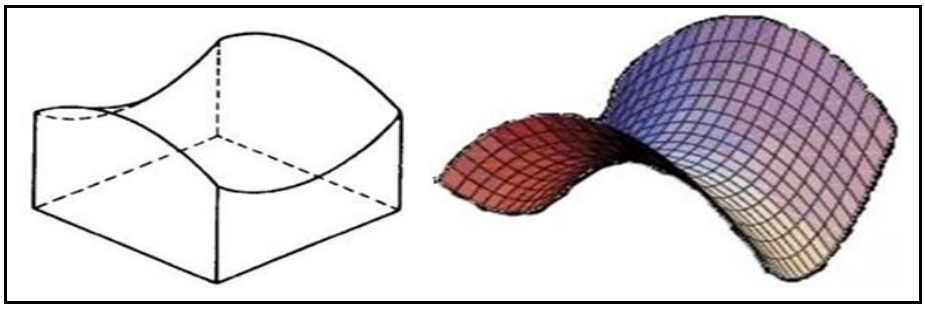
Figure 2. Shells of revolution

2.2. Shells of Translation

Shells which are obtained when the plane of the generatrix and the directrix are at right angles. Examples are cylindrical shells, elliptic paraboloids, hyperbolic paraboloids, etc (Fig.3).



Elliptic Paraboloid

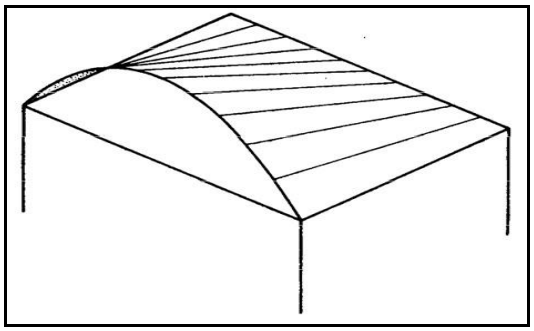


Hyperbolic Paraboloid

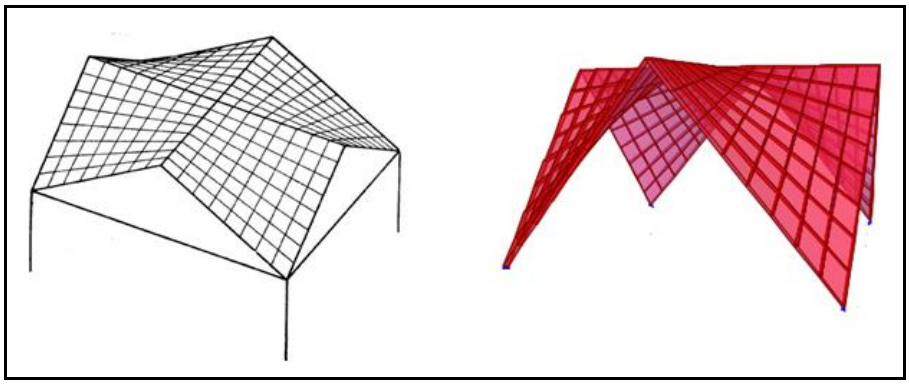
Figure 3. Shells of translation

2.3. Ruled surfaces

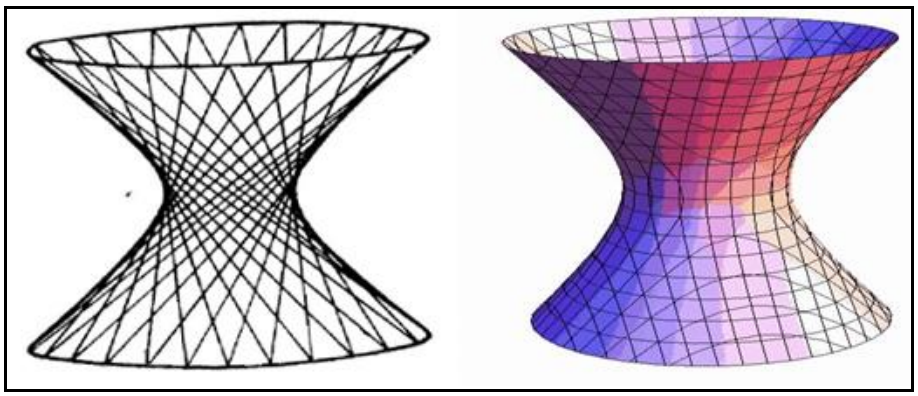
Surfaces which can be generated entirely by straight lines. The surface is said to be 'singly ruled' if at every point, a single straight line only can be ruled and 'doubly ruled' if at every point, two straight lines can be ruled. Cylindrical shells, conical shells and conoids are examples of singly ruled surfaces; hyperbolic parabolids and hyperboloids of revolution of one sheet are examples of doubly ruled surface (Fig.4).



Conoid



Hyperbolic Paraboloid



Hyperboloid

Figure 4. Ruled surfaces

III. BASIC DEFINITIONS

Shells - Thin shells are those in which the radius to thickness ratio should not be more than 20.
Span - The span of a cylindrical shell is the distance between the centre lines of two adjacent end frames of traverses.
Gauss Curvature - The product of the two principal curvatures 1/R1 and l/R2 at any point on the surface of the shell.

Generatrix & Directrix - A curve which moves parallel to itself over a stationary curve generates a surface. The moving curve is called the generatrix and the stationary curve the directrix. One of them may be a straight line.
Radius - Radius at any point of the shell in one of the two principal directions.
Edge Member - A member provided at the edge of a shell.
End Frames or Traverses - End frames or traverses are structures provided to support and preserve the geometry of the shell.

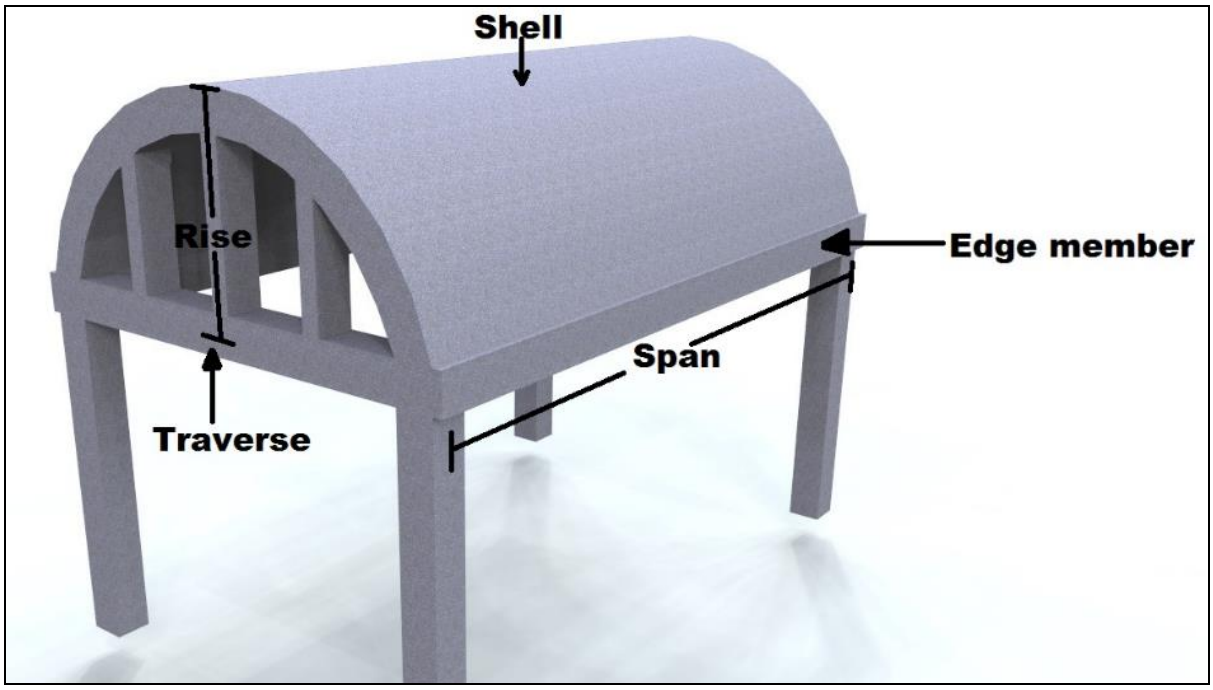


Figure 5. Single Barrel shell

IV. PARAMETERS FOR FUNICULAR SHELLS

Parameters for Funicular Shells According to the Code "**IS 2210 (1988)**: Criteria for design of reinforced concrete shell structures and folded plates" and "**IS 6332 (1984)**: code of practice for construction of floor and roof using precast doubly-curved shell units".

4.1 Geometry

A shell is a 3D structure; it is thin in one direction & long in the other two directions. The length of the shell is along X & Y directions, and the thickness is along Z directions. The shell considered for the case study is doubly curved shell, with varying size.

4.2 Materials

Controlled concrete shall be used for all shell and folded plate structures. The concrete is of minimum grade M20. The quality of materials used in concrete, the methods of the concrete proportioning and mixing shall be done in accordance with the relevant provisions of IS: 456-1978. High cement content mixes are generally undesirable as they shrink excessively giving rise to cracks. The maximum size of the aggregate for the Concrete shall not exceed 8 mm or l/3 of the thickness of shell, whichever is more. The workability of the mix is to be assured as small thicknesses are being cast.

4.3 Thickness

Normally in case of singly curved shell the thickness of shells shall not be less than 50mm and in case of doubly-curved shell 40mm. The thickness may be less than that specified above in case of small

precast concrete shell units but it should not be less than 25mm and the reinforcement shall have a min clear cover of 15mm or its nominal size whichever is greater.

4.4 Loads

Unless otherwise specified, shells and folded plates shall be designed to resist the following load combinations:
a) Dead load,
b) Dead load + appropriate live load or snow load,
c) Dead load + appropriate live load -I- wind load, and
d) Dead load + appropriate live load + seismic load.
Dead loads shall be calculated on the basis of the unit weights taken in accordance with IS: 875 (Part I)-1987. Live loads, wind loads and snow loads shall be taken as specified in IS: 875 (Parts 2 to 4)-1987.
Seismic loads shall be taken in accordance with IS: 1893-1984t. Where concentrated loads occur, special considerations should be given in analysis and design.

4.5 Edge beam

A width of two to three times the thickness of shell subject to a min of 15 cm is usually necessary for the edge beams. The minimum thickness of edge beam shall be 25 mm in normal condition and 35 mm in corrosive atmosphere. In the edge beams of the shells the minimum reinforcement shall be one 6mm diameter mild steel bar.

4.6 Diameters of Reinforcement Bars

The following diameters of bars may be provided in the body of the shell. Larger diameters may be provided in the thickened portions, transverse and beams:
a) Minimum diameter: 8 mm, and
b) Maximum diameter: 4 of shell thickness or 16 mm whichever is smaller.

4.7 Spacing of Reinforcement

The maximum reinforcement spacing in any direction in the body of the shell shall be limited to 5times the thickness of shell **1** area of unreinforced panel shall in no case exceed 15times the square of thickness.

4.8 Boundary conditions

In general, in the membrane analysis of synclastic shells, only one boundary condition is admissible on each boundary. For an anticlastic shell, the boundary conditions have to be specified in a special manner as the characteristic lines of such surfaces plays a significant role in membrane theory. The types of boundary conditions that can be specified depend on whether or not the boundaries of the shell are characteristic lines.
Further, a membrane state of stress can be maintained in a shell only if the boundaries are such that the reactions exerted by the boundary members on the shells correspond to stresses in the shell at the boundaries given by the membrane theory. It is seldom possible to provide boundary conditions which would lead to a pure membrane state of stress in the shell. In most practical cases, a resort to bending theory becomes necessary. Only deep doubly-curved shells behave like membranes and it is only for such shells that a membrane analysis is generally adequate for design. Bending analysis is necessary for all singly-curved shells and shallow doubly-curved shells

V. METHODS OF CASTING SHELLS

5.1 Sagging Fabric Mould

- A level platform in masonry or timber shall be built up.
- A square frame with hessian, canvas or cloth stretched and tucked to it shall be placed over a masonry platform so that the inside surface of the frame snugly fits into the outside of the

platform. The fabric is thus fully supported from sagging. A frame equal to the shell thickness shall be set up on the platform. Concrete of the specific mix shall be poured inside the frame and compacted. The mould shall next be lifted off the platform and supported at 4 corners. The hessian sags and the shell gets itself cast . Ensure that shell is finished smooth as for ceiling finish.

- The mould for the edge beam shall be next set up. The reinforcement cage shall be placed in position and the edge beam concreted.
- The edge beams shall be demoulded 3 hours after casting.
- The shell should be inverted and cured in the normal way 24 hours after casting.

5.2 Masonry Mould

- The surface of the shell cast by itself adopting the method is defined by the equation given in a various plan shapes. For any desired raise of the shell of rectangular or square plan the ordinates on various points can also be calculated using approximate formula,

$$Z = \frac{Z_{Max}}{a^2 b^2}\left(a^2 - x^2\right)\left(b^2 - y^2\right)$$

Where Z is the vertical ordinate at point x & y

Z_{max} is the max central rise which may be $\frac{L}{10}$ to $\frac{L}{20}$ $(L = \text{shell size})$

'a' is half of the length of shell

'b' is half of the width of shell

X and Y are the co-ordinates of grid point from the origin, which is taken as centre of the shell unit. The ordinates thus obtained shall be set off from a level platform and the surface concreted and finished smooth.

- The finished surface shall be coated with oil, grease or any other releasing agents.
- Outer mould for the edge beams shall be set up.
- The designed reinforcement for the edge beam shall be placed between the outer edge beam mould and the masonry platform built up.
- Concrete of the specified mix shall be laid in the edge beam and over the shell mould. The thickness over the shell mould equal to the designed thickness of the shell shall be controlled by thickness gauges. The shell is thus cast in the erect position. Ensure that finished concrete is rough enough to bond with screed concrete.
- The edge beam mould should be released 3 hours after casting.
- The shell should be lifted off the mould using levers at the four corners 24 to 48 hours after casting. Longer time up to 72 hours may be necessary in cold climates (below 25°C) as also when pozzolana cement is used. In using levers ensure that the 'levers are operated only on one side at a time and never at the end at diagonals.
- The shell should be kept stacked and cured in the normal way. The stacking of the shells may be done one above the other supported at four corners only, in piles of 8 to 10 shells.
- Shell units up to 1.5m in size may be handled manually. Shells heavier than this will need the help of hoisting equipment and appliances. For small size shells where handling is done manually, provision of lifting hooks are not necessary.

5.3 Mechanized Process

- The mechanized process may be normally adopted when the size of the shell exceeds 1.5 m and where reinforcement is provided in the body of the shell.
- Surface of the shell may be calculated using the equations.

- The ordinates thus obtained shall be laid out to form a steel, timber, or plastic mould. The mould for the shell and the inner surface of the edge beam may be fabricated as a monolithic block.
- A level platform 600 to 1000 mm above the ground level shall be made in timber or RCC with openings equal to the size of internal dimensions of the shell unit. Four to five openings may be provided in platform.
- The fabricated mould shall be mounted on a trolley with jacking arrangements for lifting and lowering the mould to the level of the casting platform.
- The trolley may be positioned below the opening and the mould raised to the appropriate levels. The outer edge beam mould shall then be positioned over the casting platform. The designed reinforcement in the edge beam and in the shells, if any, are then placed.
- Concrete of the specified mix shall be laid in the edge beam and over the shell mould. The thickness over the shell mould shall be controlled by thickness gauges. The shell is thus cast in the erect position.
- Outer edge beam mould may be released 3 hours after casting. Twenty-four to forty-eight hours after casting the shell, the mould may be lowered and the cast shell is left on the platform for a further period of 24 to 48 hours.
- The mould may then be moved to the next opening in the casting platform and set for the casting of the next shell. The shells thus cast may be lifted off the casting platform after 48 to 96 hours after casting.
- Lifting hooks shall be provided at corners of the shell within the edge beam thickness.
- The shell may then be kept stacked and cured in the normal way.

VI. GENERATING 'Z' CO-ORDINATES

The coordinates of funicular shells can be determined by developing a computer program or by Excel program using formula.

$$Z = \frac{f}{a^2 b^2}(a^2 - x^2)(b^2 - y^2)$$

Where Z is the vertical ordinate at point x & y

f = Z_{max} is the max central rise which may be $\frac{L}{10}$ to $\frac{L}{20}$ $(L = \text{shell size})$

'a' is half of the length of shell

'b' is half of the width of shell

X and Y are the co-ordinates of grid point from the origin, which is taken as centre of the shell unit.

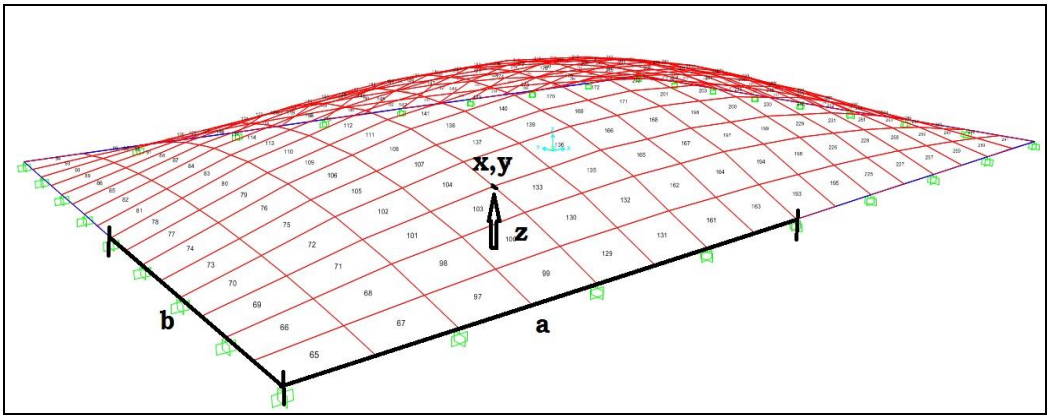


Figure 6. Shell showing x, y, a and b

6.1 Generating Co-ordinates Using Computer Program

By developing a computer program the coordinates of funicular shells are determined. B**y** using Turbo C as compiler to compile the program the following steps should be carried out,

- Values of x, y integer are declared.
- The integer values of f, a, b is Initialized.
- Then declare float value 'Z'.
- Take choice from user whether to continue or to stop by pressing 1 or 0.
- Then enter the value of x & y by user.
- Then by using formula calculate the value of Z.
- Then print the value of Z.
- Take choice of user whether to continue or not.

Program to calculate Z co-ordinates.

Type the program as shown in Figure 7.

```
#include <stdio.h>
#include <conio.h>
int main()
{
    float h,Z,Zmax,a,b,x,y,e,f,g;
    printf("Enter Zmax value \n");
    scanf("%f",&Zmax);
    printf("Enter value of 'a' \n");
    scanf("%f",&a);
    printf("Enter value of 'b' \n");
    scanf("%f",&b);
    printf("Enter value of 'x' \n");
    scanf("%f",&x);
    printf("Enter value of 'y' \n");
    scanf("%f",&y);

    printf("Entered values are \n");
    printf("Zmax=%f \n",Zmax);
    printf("a=%f \n",a);
    printf("b=%f \n",b);
    printf("x=%f \n",x);
        printf("c=%f \n",y);
        e=(a*a)-(x*x);
        f=(b*b)-(y*y);
        g=(a*a)*(b*b);
        h=Zmax/g;
```

```
        Z=h*f*e;
        printf("Z=%f \n",Z);
    return 0;
}
```

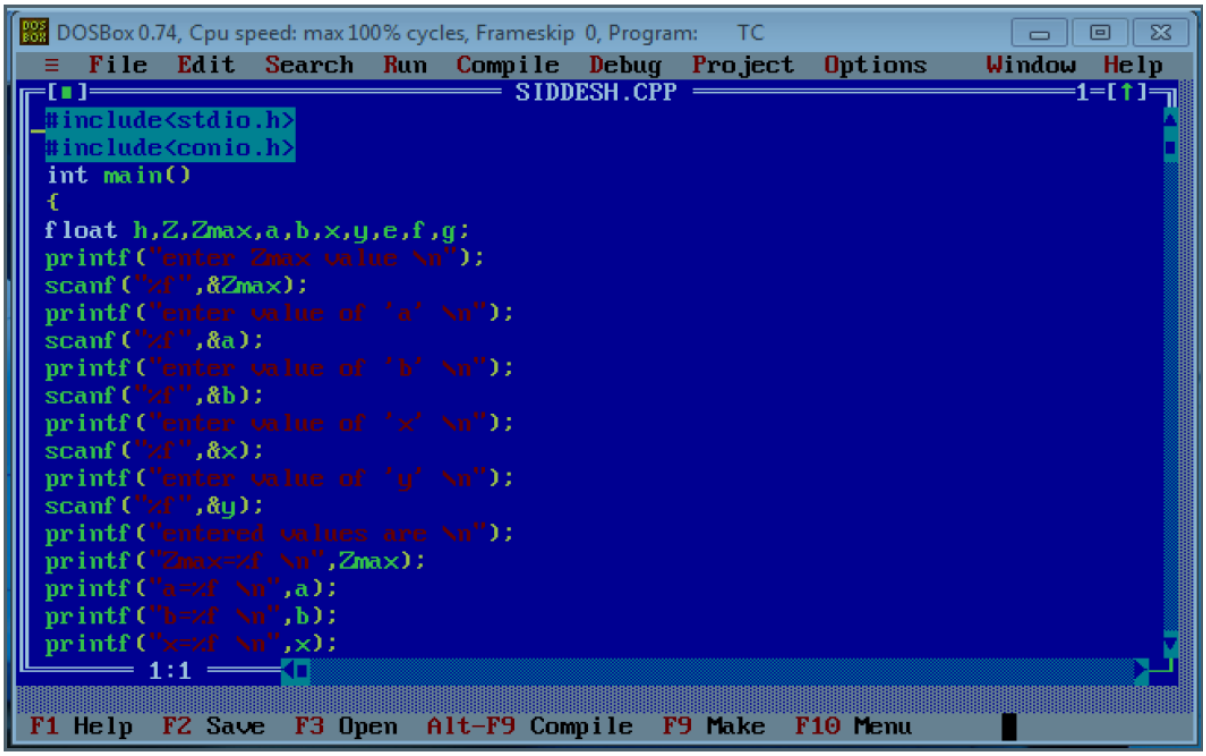


Figure 7. Computer program to calculate Z co-ordinates.

After compiling the program enter the values of Z_{max}, a, b, x and y and output is obtained as shown in figure 8.

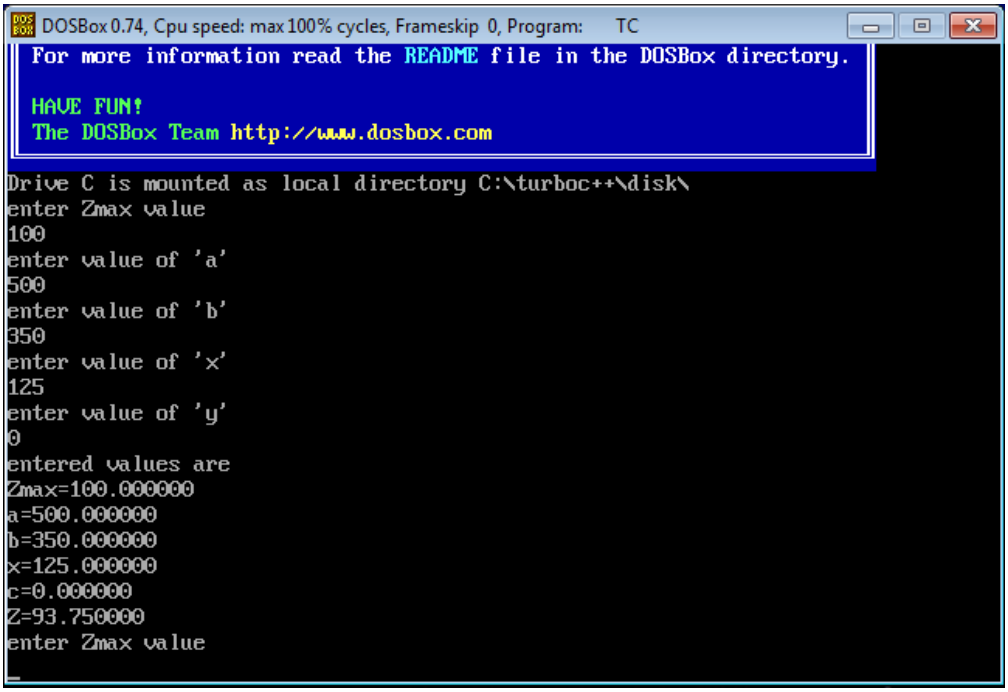


Fig 8. Output of the program

6.2 Generating Coordinates Using MS Excel

The coordinates of funicular shells can be determined by using an Excel worksheet also. Table 1 shows the calculation of Z co-ordinates using excel sheet.

Steps to be followed in the calculation are,

- Enter the values of Zmax, a, b and X Y coordinates in separate column.
- By using formula of

$$Z = \frac{f}{a^2 b^2}(a^2 - x^2)(b^2 - y^2)$$

Where Z is the vertical ordinate at point x & y

- Enter the formula in formula bar in excel format

*f*x =(A2/(B2^2*C2^2))*(B2^2-D2^2)*(C2^2-E2^2)

Where A2, B2, C2, D2 and E2 are the cell numbers.

Table 1: Z coordinates calculated in MS excel.

F2 =(A2/(B2^2*C2^2))*(B2^2-D2^2)*(C2^2-E2^2)

	A	B	C	D	E	F	G	H
1	Zmax,f	a in mm	b in mm	x	y	Z in mm		
2	100	500	350	0	0	100		
3	100	500	350	125	0	93.75		
4	100	500	350	250	0	75		
5	100	500	350	375	0	43.75		
6	100	500	350	500	0	0		
7	100	500	350	0	87.5	93.75		
8	100	500	350	125	87.5	87.89063		
9	100	500	350	250	87.5	70.3125		
10	100	500	350	375	87.5	41.01563		
11	100	500	350	500	87.5	0		

VII. FE MODELING OF FUNICULAR SHELL IN SAP2000

The analysis and the computation of funicular shell over rectangular ground plan are done using the standard program, by following the steps mentioned below.

- Click on File menu and then select 'New Model' command to create New Model.
- Then click the drop-down list and set the units as N, mm, C.
- Select the Shells option to access the Shells form.
- In that Select *Hyperbolic Paraboloid* type in the *Shell Type* option.
  - Enter length in the *Span length* L_x edit box.
  - Enter width in the *Span length* L_y edit box.
  - Enter 0 in the *Height*, H_1edit box.
  - Enter max rise in the *Height*, H_2 edit box.
  - Enter the *Number of Divisions* as 4, *X* edit box.
  - Enter the *Number of Divisions* as 4, *Y* edit box.

- Click in the "X" in the upper right-hand corner of the X-Y Plane @ Z=0 window to close it. Change Z coordinates at all the points by using shell surface co-ordinate equation.

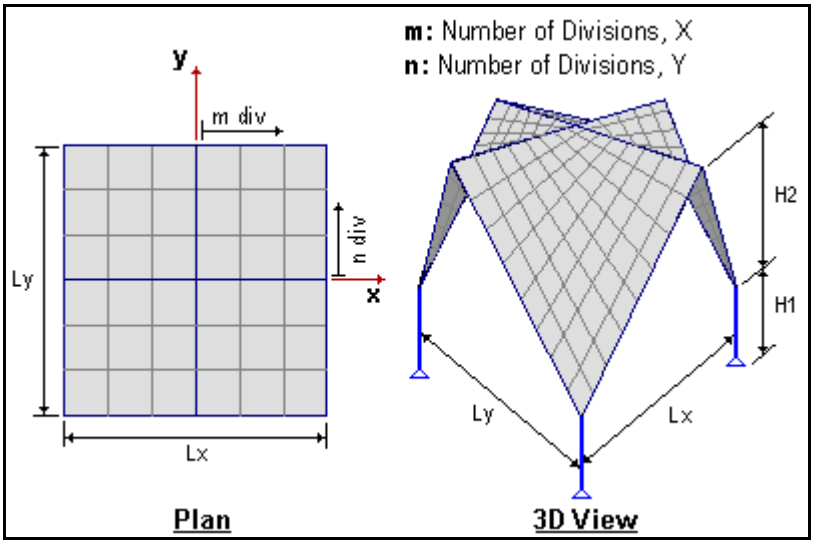


Fig 9. Parametric definitions of Hyperbolic Paraboloid shell.

- To draw edge beam define the section property as frame section. Select frame section property as concrete then select rectangular concrete section. Specify depth and width of edge beam.
- To add the details of reinforcement in edge beam, in rectangular section select concrete reinforcement then select design type as beam. Specify the cover to longitudinal rebar center as 20 mm in top and bottom edit box. Click OK button. Select draw frame or cable element command draw the edge beam along the four sides by connecting to each element.
- Select all edge joints in opposite directions. Click the Assign menu and click on Joint and select Restraints command to access Joint Restraints form and select Pinned: All three translational degrees of freedom are restrained.
- Then define material properties of the model, click on the Define menu and select Materials command to access Define Materials form.
    - Select Add New Material Quick option to access Quick Material Definition form. In that form: Select *India* in the *Region* drop-down list.
    - Select *concrete* in *Material type* drop-down list.
    - Select *Indian code* in *Standard* drop-down list.
    - Select *M20 grade concrete* in *Grade* drop-down list.
- Name the newly defined material as M20 in *Materials* display list & click the option Modify/Show Material button to display & Material Property Data,
    - Then verify that the *Units* are set to N, mm, C
    - Enter *Modulus of Elasticity* as 5000 √fck.
    - Enter the *Poisson's Ratio* as 0.17.
    - Type 20 in the Specified Compressive Strength, f^1c
    - Click the *Units* drop-down list change units as KN, m, C
    - Type 25 in the *Weight per Unit Volume* edit option box.
    - Click OK option to accept these values.

- Then Click Define menu & select Section Properties and select Area Sections command to access Area Sections form
    - In *Select Section* select the *Shell* option.
    - Then select the Add New Section option to access Shell Section Data. In that Verify the **Shell-Thin** option is selected in *Type area.*
    - Highlight **M20** definition in the *Materials* display list and click the Modify/Show Material option to access the Material Property Data form.

- Click OK option on Material Property Data and Define Materials forms to return to the Shell Section Data form.
- Verify that *Material Name* is **M20.**
- Verify that both the *Bending and Membrane thicknesses* are **same.**

- Click on the Define menu and select Load Patterns command to access Define Load Patterns form. In that,
  - Enter LIVE in *Load Pattern Name* edit box.
  - Select *LIVE* from *Type* drop-down list.
  - Verify that, *Self Weight Multiplier* is 0.
  - Click on Add New Load Pattern option.

- Select the shell model, Click Assign menu select Area loads and select Uniform to frame (shell) command to access the Joint Forces form. In that,
  - Select *LIVE* from *Load Pattern Name* drop-down list.
  - Enter the load in the *Force Global Z* edit box in *Loads* area.
  - Verify Add to Existing Loads is selected in *Options* area.
  - Verify Co-ordinate system is GLOBAL.
  - Verify Distribution is one way.
  - Click the OK option.

The finite element models which are developed by SAP 2000 finite element package are shown in below figure 10 and 11.

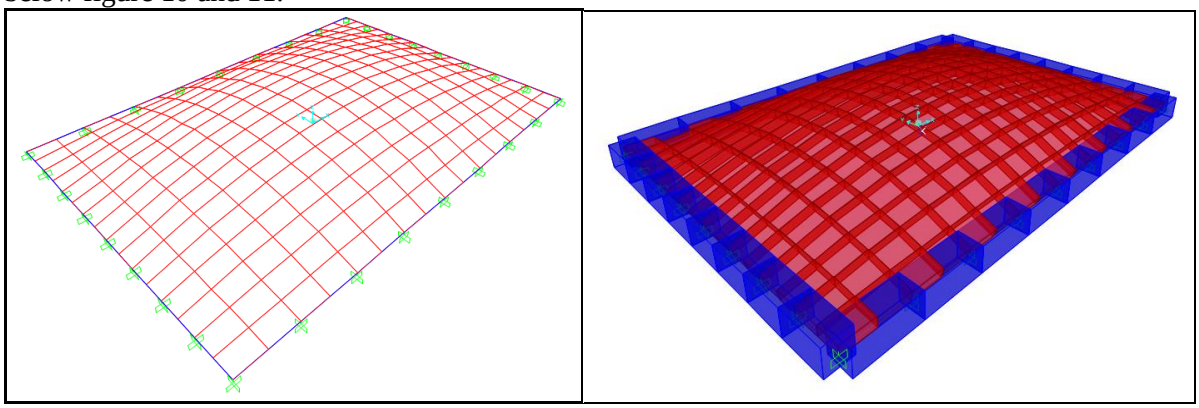


Figure 10. 3D model of Funicular shell

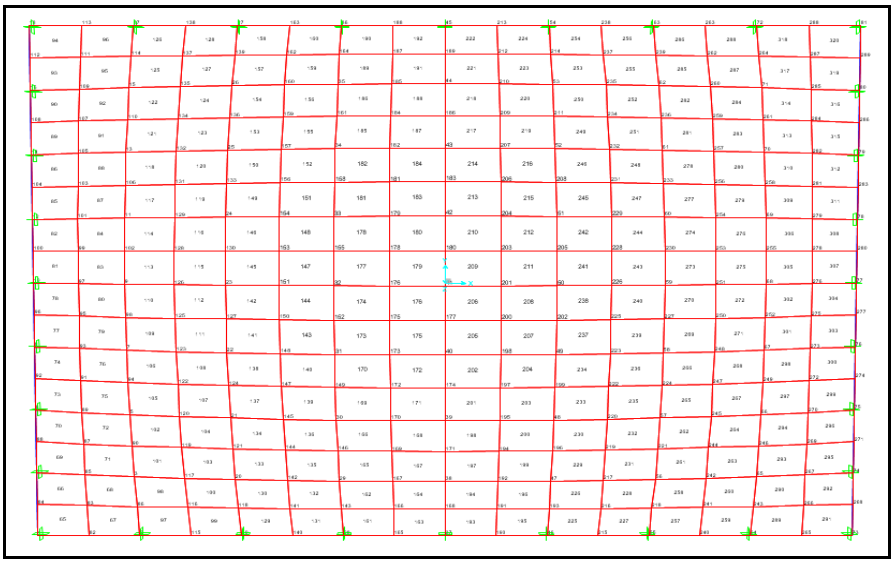


Figure 11. Discretized model and corresponding node numbers.

VIII. OBTAINING RESULTS OF SHELL ANALYSIS

8.1 Membrane Stress of Shell

- Click on Analyze menu option and select Set Analysis Options command to access Analysis Options. Then, click the Plane Frame XZ Plane option to set available degrees of freedom & click the OK option.
- Click Run Analysis option to access the Set Load Cases to run. In that:
  - Click on Modal in *Case Name* list to highlight it.
  - Click the Run/Do Not Run Case option.
  - Click the Run Now option.
- After completion of analysis there should be no warnings or errors in analysis window.
- Then click the Display menu>Show Forces/Stresses>shells command to access the Joint Reaction Forces form. In that,
  - Select any one from *Case/Combo Name* drop-down list.
  - Click OK option. The resultant forces, shell stresses are displayed on the screen.
  - Move the cursor on the nodes to obtain stress in that node.

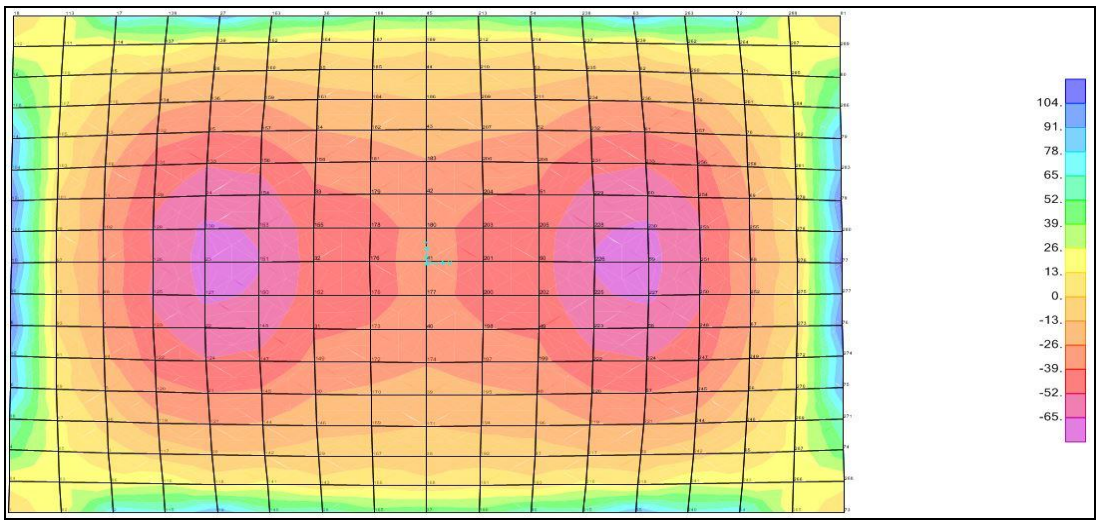


Figure 12. Stress contour of Funicular shell.

8.2 Deflection of the Shell

- Click on Display menu> Show Deformed shape
  - Select case/combo then click apply and ok.
  - Move the cursor on the nodes to obtain deflection in that node and note down the U3 reading.

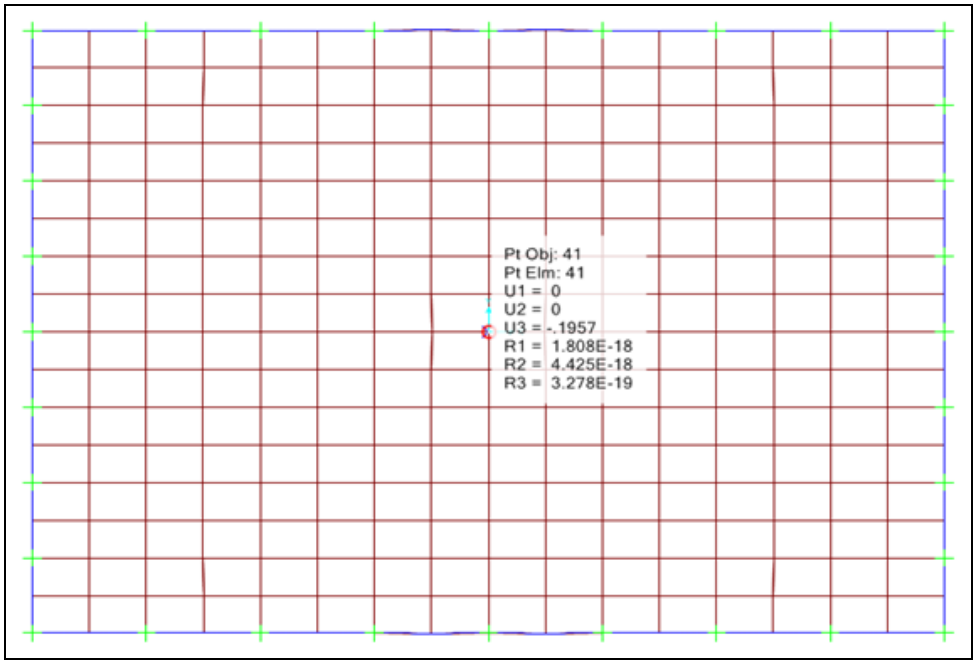


Figure 13. Deformed shape in XY plane showing deflection at centre.

IX. CONCLUSIONS

1. Funicular shells are doubly curved shells.
2. Shape of which satisfies the desired state of stress in its body for given loading and boundary condition
3. Funicular shells can take any shape, square, rectangle, triangular and trapezium.
4. The edge beam is required to hold stirrups only.
5. Funicular shell roof facilities in the installment of fixtures like ceiling fan, lighting fixtures.
6. Funicular shells act as an arch
7. There is decrease in deflection with increase in rise and thickness of shell.
8. There is decrease in membrane stresses with increase in rise and thickness of shell.
9. In case of uniformly distributed load there is a maximum tension at edges of the shells and compression at the region around the centre of the shell.
10. In case of concentrated load there is a maximum tension in between the edge beam and centre region of shell and maximum compression is at the centre of the shell. Commended it.
11. Doubly curved shell as an elastically supported plate has much to co
12. The rate of deflection is more in case of slabs when compared to shells.
13. The rate of membrane stresses is more in case of slabs when compared to shells.

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