EXPERIMENTAL AND ANALYTICAL STUDY ON FUNICULAR CONCRETE SHELL FOUNDATION UNDER ULTIMATE LOADING

T.M. Jeyashree, C. Arunkumar* and S. Ashok Kumar
Department of Civil Engineering, SRM University, Chennai, India

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ABSTRACT

Shell foundations are economical alternatives to the conventional flat shallow foundation, regarding material-saving technique. Shell foundation comes under the category of the shallow foundation. Concrete funicular shells of square plan, double curvature with various thicknesses are analyzed for the concentrated load. Specimens of size 680 × 680 mm are prepared using cement M30 concrete grade for which the mix design is carried by IS method. Formwork is prepared by concrete above which test specimen is prepared. The specimens are prepared with various thicknesses of 40 mm, 50 mm, 60 mm. The specimens are moist cured for 28 days before testing. The concentrated load over the column is applied, and the corresponding deflections and settlement characteristics are measured within elastic range. Beyond elastic range specimens are subjected to fail, and the ultimate loads are determined. The experimental result shows that load carrying capacity for 60 mm thick specimen (8 mm $\phi$ bar) is more compared to 40 mm and 50 mm thick specimen. Also by increasing the area of steel of edge beam reinforcement by 40% causes the increase in ultimate load carrying capacity by 15% and it also reduces the maximum settlement by 26%. A comparative study of the flat foundation and shell foundation shows that ultimate load carrying capacity for shell foundation increases by 50%. Finite element analysis was done using SAP 2000. Using the finite element model, a parametric study was conducted to determine the changes in stress level in the funicular shell. The magnitude of concentrated load used for the FEM analysis is same as the ultimate load of experimental work.

Keywords: Funicular shell; double curvature; deflections; ultimate load; shell foundation.

1. INTRODUCTION

1.1 General

Many studies are carried out to understand the behaviour of shell foundation. The behaviour

*E-mail address of the corresponding author: arun.zealous@gmail.com (C. Arunkumar)
of shell foundations like conical, hyperbolic paraboloidal, cylindrical, inverted dome, pyramid have been investigated by many researchers, and however study on the funicular type of foundation is limited [1]. For conventional shells like conical pyramidal, the traditional practice is to opt geometry of shell first after which stress analyses will be carried. But in funicular shell foundation end product of the analysis is their geometrical shape [2].

Shells of double curvature with the catenary shape in both axes are called funicular shells. The shape of a freely hanging rope is a catenary. The funicular shell may be used either with its convexity facing upward or with its cavity facing upward as a foundation. Due to its stiffness, the funicular shell is particularly suitable for the foundation [3].

The funicular shell is one such compression structure, which ensures conservation of natural resources and optimizing the use of expensive steel and cement. Further, the point load is distributed by the arch in all direction equally, so it can withstand impact loading at any point. The funicular shell has larger space because of the diagonal grid. As far as foundations are concerned, since a funicular shell is not limited by plane shape, it can serve for the inverted dome and elliptical paraboloid, either in single or multiple units [4]. It would be of considerable interest to investigate funicular footing for single column under a variety of loading and soil condition [5].

1.2 Objective

The objectives of this present study are

I. To obtain the ultimate load bearing capacity of the shell by varying their thickness.
II. To study the deflection characteristics of funicular shell foundation
III. To experimentally study the behaviour of settlement characteristics of funicular shell foundation.
IV. To compare the behaviour with flat foundation.
V. To study the variation of stress level in the funicular shell using finite elemental analysis.

2. MATERIAL PROPERTIES

Following are the materials which are used for the present investigation to meet out the objectives and scope of this study. The following Table 1 shows the material properties.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Parameters</th>
<th>Results Obtained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>Fineness modulus</td>
<td>10 %</td>
</tr>
<tr>
<td></td>
<td>Standard consistency</td>
<td>31%</td>
</tr>
<tr>
<td></td>
<td>Initial setting time (min)</td>
<td>31.30</td>
</tr>
<tr>
<td></td>
<td>Specific gravity</td>
<td>3.12</td>
</tr>
<tr>
<td>Fine aggregate</td>
<td>Fineness modulus</td>
<td>3.12</td>
</tr>
<tr>
<td></td>
<td>Specific gravity</td>
<td>2.5</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>Specific gravity</td>
<td>2.7</td>
</tr>
</tbody>
</table>
2.1 Cement
The cement used for this study is Ordinary Portland Cement (Dalmia cement) and is conforming to Indian Standard IS: 12269 of Grade 53 [6].

2.2 Fine aggregate
The sand is collected from Palar River nearby SRM University. The sand has been sieved in 4.75 mm sieve before it is used.

2.2.1 Sieve analysis for sand
The Percentage of various sizes of the particle in a dry soil sample is found by a particle-size analysis or mechanical analysis. Sieve analysis is carried out to determine the fineness modulus and grading curve of fine aggregates. The sieve analysis is carried out for sand, as per IS 383-1970 and it belongs to grading zone II conforming river sand [7]. The sieve analysis results identified is given in Table 2.

<table>
<thead>
<tr>
<th>Sieve number</th>
<th>Sieve size (mm)</th>
<th>Weight retained (gram)</th>
<th>% of weight retained</th>
<th>Cumulative weight retained (gram)</th>
<th>% finer</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4.75</td>
<td>30</td>
<td>3</td>
<td>3</td>
<td>97</td>
</tr>
<tr>
<td>8</td>
<td>2.36</td>
<td>70</td>
<td>7</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>16</td>
<td>1.18</td>
<td>350</td>
<td>35</td>
<td>45</td>
<td>55</td>
</tr>
<tr>
<td>30</td>
<td>0.60</td>
<td>200</td>
<td>20</td>
<td>65</td>
<td>35</td>
</tr>
<tr>
<td>50</td>
<td>0.30</td>
<td>260</td>
<td>26</td>
<td>91</td>
<td>9</td>
</tr>
<tr>
<td>100</td>
<td>0.15</td>
<td>70</td>
<td>7</td>
<td>98</td>
<td>2</td>
</tr>
<tr>
<td>PAN</td>
<td>0</td>
<td>20</td>
<td>2</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

2.3 Coarse aggregate
Crushed granite stone is used as the coarse aggregate of maximum size 12.5 mm, conforming to IS: 2386 (Part I) 1963 and the surface texture characteristic of the aggregate is good [8].

2.4 Water
Available portable water in University premises which was free from all impurities are used for the entire work whenever it is required.

3. EXPERIMENTAL INVESTIGATION

3.1 Formwork
Special formwork is required for casting shell foundation. The Funicular roof is used as a formwork for the foundation. The form work in concrete was meticulously made with a leather rexine sheet held tightly on all four sides by a wooden frame and side cover is provided with plywood to the depth of 60 mm. Then concrete is poured to the thickness of about 50 mm throughout the surface [9].
The mesh is placed after bottom layer is laid and then the top layer of concrete is poured. It is then allowed to cure for some days, and it is inverted to use as a formwork for shell foundation. Leather rexine sheet is pasted on the form work to separate the cured concrete and fresh concrete as shown in Fig. 1.

Figure 1. Formwork without side cover

Plywood is used to make side cover. The size of the edge beam is 75 mm × 75 mm and square plan of the shell is 600 × 600 mm and the central rise of the shell is 10 mm [10]. Formwork required for shell foundation are shown in Fig. 2.

Figure 2. Formwork with side cover

3.2 Detailing of shell
Special detailing is required for funicular shell foundation. By considering the type of loading and behaviour, shell detailing is provided. For main specimen anchorage bar of 8 mm $\phi$ is provided diagonally to resist the punching shear. For edge beam 8 mm $\phi$ bar runs throughout the beam. For column, anchorage bar is extended and circular stirrups are used to
holds the main anchorage bar in position [11]. The mesh of 25 mm c/c is used throughout the shell as shown in Fig. 3.

For trial specimen anchorage bar and edge beam of 6 mm φ bar are provided. For surface reinforcement mesh of 25 mm c/c is used. Fig. 4 shows the actual reinforcement detailing of shell foundation.

Figure 3. Detailing diagram

Figure 4. Detailing of shell
3.3 Concrete mix
Conventional concrete specimens for M30 mix were cast and tested for the 28th day strength. Mix design ratio for the trial mix is 1: 1.6: 2.5. Shell foundation concrete specimens are cast with M30 grade concrete [12].

3.4 Method of casting
M30 grade concrete is used for casting of the shell. The Cover is used to maintain the thickness of the shell. Concrete is poured and compacted by hand compaction. First, the bottom layer is laid and compacted well. After placing a reinforcement, the top layer is laid and it is compacted well.

![Figure 5. Method of casting](image1)

After shell surface is laid, the column is cast by using PVC pipe of 100 mm diameter which is used as a mould for column. The height of the column is 100 mm. The pipe is cut vertically for the easy removal after hardening, and it is tied with steel wire to maintain the diameter of the column [13]. The figure of method of casting specimens is shown in Fig. 6.

![Figure 6. Casting of column head](image2)

Totally four specimen is cast, three main specimens and one trial specimen. Geometric and details of reinforcement are shown in Table 3 and Cast main specimens are shown in Fig. 7.
Table 3: Geometry and details of reinforcement

<table>
<thead>
<tr>
<th>Type</th>
<th>Thickness(mm)</th>
<th>Edge</th>
<th>Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial</td>
<td>50</td>
<td>6 mm $\phi$ rod all round</td>
<td>25 mm c/c mesh</td>
</tr>
<tr>
<td>I</td>
<td>40</td>
<td>8 mm $\phi$ rod all round</td>
<td>25 mm c/c mesh</td>
</tr>
<tr>
<td>II</td>
<td>50</td>
<td>8 mm $\phi$ rod all round</td>
<td>25 mm c/c mesh</td>
</tr>
<tr>
<td>III</td>
<td>60</td>
<td>8 mm $\phi$ rod all round</td>
<td>25 mm c/c mesh</td>
</tr>
</tbody>
</table>

3.5 Testing of specimen

The concentric load is applied on the specimen by using hydraulic jack. Specimen is fitted with strain gauge to measure the deflection of the shell and dial gauge to measure the settlement of the foundation [13]. Loads are applied gradually by increment of 250 N as shown in Fig. 8.

Load vs. Deflection graph is plotted, and Load vs. Settlement graph is drawn. Actual Test Assembly are shown in Fig. 9 & 10.
4. ANALYTICAL STUDY

4.1 Calculation of coordinates
The coordinates for developing the funicular shell with square plan are arrived using the following Equation [14].

\[ Z = \frac{Z_{\text{max}}}{a^2b^2} (a^2 - b^2)(a^2 - b^2) \]  \hspace{1cm} (1)

where,
\( Z \) – Vertical ordinate at point \( x, y \)
\( Z_{\text{max}} \) – Maximum central rise which may be \( L/10 \) to \( L/20 \)
\( a \) – \( \frac{1}{2} \) (length of the shell)
\( b \) – \( \frac{1}{2} \) (width of the shell)
\( x, y \) – Coordinates of the grid point from the origin
4.2 Model dimensions
The funicular shell profile is modelled and analysed using SAP 2000. The dimensions of funicular shell are taken as same as in the experimental work. The length of the shell is 680 mm in X direction and width is 680 mm in Y direction. The thickness of the shell is varying as 40 mm, 50 mm, 60 mm in Z direction. The central rise is given as 100 mm. The shell is divided into 6 parts equally in x, y directions. The coordinates are calculated by using the Equation (1). The following Fig. 11 shows the modeled funicular shell profile in SAP.

Figure 11. Modelled funicular shell with edge beam

4.3 Material properties
The edge beam is modelled for M30 grade of concrete and Fe 415 grade of steel. The funicular shell is created as area section of thin-shell type. The membrane thickness is varying as 40 mm, 50 mm and 60 mm for different models [15].

4.4 Meshing
The modelled shell is finely divided into several equal parts using area meshing. The following Fig.12 shows the shell after meshing.

Figure 12. Funicular shell model after meshing
4.5 Assigning of spring
The area spring is given for the modelled shell. The spring is assigned in the each joint coordinate. The stiffness of the spring for per unit area is $2.714 \times 10^{-4}$ kN/mm. The following Fig. 13 shows the assigned spring in the model.

![Assigned spring at the bottom of the shell](image)

4.6 Loading
The model is analysed by applying dead load and live load alone. The live load is given as concentrated load at the centre joint. The magnitude of live load is same as the ultimate load of experimental work. The magnitude of live load is given as 40 kN, 47.5 kN and 50 kN for 40 mm, 50 mm and 60 mm thicknesses respectively.

5. RESULTS AND DISCUSSION

5.1 Trial specimen
The Trial specimen is first tested to study the behaviour of the shell foundation with maximum capacity of 200 kN. The test result of funicular shell foundation for 28 days curing is tabulated in Table 4 and Fig. 14 shows the crack pattern of trial specimen.

<table>
<thead>
<tr>
<th>Mix Ratio</th>
<th>Loading type</th>
<th>Specimen Plan Dimension (mm)</th>
<th>Thickness (mm)</th>
<th>28 Days strength (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1.9:1.7</td>
<td>Concentrated loading</td>
<td>680 × 680</td>
<td>50</td>
<td>40</td>
</tr>
</tbody>
</table>
5.2 Main specimens

From the trial specimen, behaviour testing arrangements are slightly modified to test the main specimen. The behaviour of the shell foundation is studied with maximum capacity of 200 kN. The test result of funicular shell foundation for 28 days curing is tabulated in Table 5 and Fig. 15 shows the crack pattern of main specimen No. 1.

<table>
<thead>
<tr>
<th>Mix Ratio</th>
<th>Loading type</th>
<th>Specimen Plan Dimension(mm)</th>
<th>Thickness (mm)</th>
<th>Compressive strength (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1.9:1.7</td>
<td>Concentrated loading</td>
<td>680 × 680</td>
<td>40</td>
<td>32.5</td>
</tr>
<tr>
<td>1:1.9:1.7</td>
<td>Concentrated loading</td>
<td>680 × 680</td>
<td>50</td>
<td>47.5</td>
</tr>
<tr>
<td>1:1.9:1.7</td>
<td>Concentrated loading</td>
<td>680 × 680</td>
<td>60</td>
<td>50</td>
</tr>
</tbody>
</table>

Figure 14. Tested trial specimen

Figure 15. Tested main specimen No. 1
5.3 Ultimate load carrying capacity of square footing

Size of the footing = \(0.68 \times 0.68\) m
Depth of footing = 50 mm = 0.05 m
Liquid Limit (W<sub>L</sub>) = 47% = 0.47
Water content (w) = 19.80% = 0.198
Specific gravity (G) = 2.23

Saturated unit weight (\(\gamma_{\text{sat}}\)) = 93.14 kN/m<sup>2</sup>
Factor of safety (F) = 3
Unconfined compressive strength (\(q_u\)) = 30 kN/m<sup>2</sup>
\(\phi\) = 0
\(N_c\) = 5.7
\(N_q\) = 1
\(N_y\) = 0
\(\alpha = \gamma_{\text{sat}} D\)
\(c = q_u/2 = 15\) kN/m<sup>2</sup>
\(q_s = 1/F [1.3 c N_c +\alpha (N_q - 1) +0.04 B \gamma N_y] = 42.4384\) kN/m<sup>2</sup>
\(Q_s = q_s B^2 = 19.716\) kN

5.4 Comparative study of funicular foundation with flat foundation
The settlement characteristic of specimen of 40 mm, 50 mm and 60 mm thickness are shown in Fig. 16. Comparative study of shell foundation with flat foundation is shown below Fig. 17.

5.5 Stress distribution in funicular shell by FEM analysis
The magnitude of concentrated load is taken from the ultimate load of experimental work. The above Fig. 18 shows the deformed shape of the specimen after the concentrated load of 32.5 kN was applied at the centre. The significant displacement was found at the loaded point.

![Figure 16. Load vs. settlement of main specimens](image-url)
Figure 17. Comparative study of shell foundation with flat foundation

Figure 18. Deformed shape of the funicular shell loaded at 32.5 kN

Figure 19. Variation of the stress in funicular shell of thickness 40 mm loaded at 32.5 kN
The above Fig. 19 shows the variation of the stress in funicular shell under static loading was obtained by Finite element analysis. The contour scale is at its default setting which will take the maximum and minimum stress. The magnitude of stress variation is represented by blue, green, yellow and red colour. Pink colour (red shade) usually represents the lowest stress, and it is gradual increases for the highest stress range is in blue colour. The colour yellow represents the average stress.

The variation of the stress in funicular shell of thickness 40 mm loaded at 32.5 kN is shown in Fig. 19. It is fully in pink colour shows the equal distribution of stress and the level of stress is also minimum. It is partially having red in colour represents the small incremental of stress in that portion [14].

![Figure 20. Variation of the stress in funicular shell of thickness 50 mm loaded at 47.5 kN](image)

The above Fig. 20 shows the variation of the stress in funicular shell of thickness 50 mm loaded at 47.5 kN. It is fully in yellow colour with small shades of red. So the level of stress is average.

![Figure 21. Variation of the stress in funicular shell of thickness 60 mm loaded at 50 kN](image)
The above Fig. 21 shows the variation of the stress in funicular shell of thickness 60 mm loaded at 50 kN. It is also having average level of stress.

From the FEM analysis, it is observed that the shell with thickness of 50 mm and 60 mm showing average level of stress and shell with thickness of 40 mm having very low-stress level.

6. CONCLUSION

Concrete funicular shells of square plan, double curvature with $680 \times 680$ mm of various thicknesses of 40 mm, 50 mm and 60 mm are prepared using cement M30 concrete are tested by applying concentrated load.

i. From the experimental results, it is observed that load carrying capacity for 60 mm thick specimen (8mm $\phi$ bar) is more compared to 40 mm & 50 mm thick specimen.

ii. When compared to 40 mm thickness shell with 50 mm thickness, ultimate load increases by 46% and 60 mm thickness shell by 54%.

iii. The increase in area of steel of edge beam reinforcement by 40% causes increase in ultimate load carrying capacity by 15%, and it also reduces the maximum settlement by 26%.

iv. Comparative study between flat foundation and shell foundation shows that ultimate load carrying for shell foundation increases by 50%.

v. From FEM analysis, increase in the thickness of the funicular shell showed low level of variation in the stress and reduction in the deflection.

REFERENCES


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New Delhi, 1963.