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Parametric Study and Optimization of Steel Dome Structure

Praveen Belligatti
Student
Dept. of Civil Engineering,
SDMCET, Dharwad, India

Dr. D. K. Kulkarni
Professor,
Dept. of Civil Engineering,
SDMCET, Dharwad, India

***Abstract*— Domes are space constructions that offer an affordable way to cover a lot of valuable, column-free space. The utilization of domes can be seen in places like sports arenas, assembly halls, exposition centers, malls, industrial complexes, etc. This feature offers efficiency in the use of building materials and attractive appearance. The dome is used as a space truss in this article, with all joints being pinned to provide a torsion- and moment-free structure. As a result, only tensile and compressive forces are applied to all members. Even though only axial forces considered when designing a dome. So an effort to create software in Octave has been made. The program can be used to configure, analyze, design, and optimize the weight of a steel dome. The effects of the dead load and live load have been taken into account when designing the members, which are made of tubular steel sections.**

To establish the relationship between weight variation and dome height, a parametric analysis was also conducted. For the domes with bracings in one or both directions, this analysis is expanded. It is also done a parametric analysis for the optimization of the dome using various methods, such as with discrete and continuous variables. Weight variation according to the number of plan segments has also been done.

Keywords:- Dome, Optimization, Octave, Bracings, etc..

I. INTRODUCTION

Architects and engineers are constantly looking for new ways to solve the problem of space enclosure. Because of their diversity and flexibility, In their search for novel forms, architects and engineers might use space structures as a useful tool.. A three-dimensional collection of components known as a space structure is capable of withstanding loads that can be applied from any location. The proliferation of the space frame in recent decades has been primarily due to its great structural potential and visual beauty. Sports stadiums, exhibition pavilions, assembly halls, transit hubs, aviation hangars, workshops, and warehouses are just a few of the building types that utilize space frames. They have been utilized for mid- and short-span enclosures in addition to long-span roofs as roofs, floors, exterior walls, and canopies. A well-known illustration of space is a dome.

Domes have stimulated people's interest because they enclose the most space with the least amount of surface area. This feature saves money by reducing the consumption of building materials. Despite the fact that stone was the only structural material used in ancient times, brickwork gradually replaced stone masonry. Timber was used for the same purpose in Middle Ages. However, significant advancements in dome structures began with the development of the steel industry in the nineteenth century. This allowed the engineers to design large spanned and multi-story steel structures. Steel is now widely used to enclose large spans of length.

Because it depends on an engineer's skill to iteratively consider several feasible shapes and sizes for each component of a certain construction using a computer, structural design has historically been a less-than-ideal procedure. This is just a fast variation of the same computations performed by engineers of the last century, but not a real improvement to the design process. During the last few years, a lot of work has been done to fully automate the design of structures. Nonetheless, most of the new methods developed share a common flaw: they are based on linear programming techniques, and thus treat structural optimization as if the search space is continuous, when it is actually discrete due to the limited number of structural shapes available on the market. These issues can be resolved using mathematical programming techniques for optimizing steel dome structures. Because total weight of structure is easily accessed by economy, an attempt is made here to reduce total weight of structure.
The utilization of a constrained issue search technique via mathematical programming is the main topic of this thesis. With minimal modification, the created code can be applied to a wide range of steel truss dome construction configurations.

II. OBJECTIVES

- To develop software of computer programs in Octave programming language that will generate configuration and loading data, analyze the structural response, design and optimize the weight of domes. Only dead load and live load are considered in the present study. Design of members is done as per IS: 800-2007 code.
- Weight Optimization is done through the process non linear constrained optimization method.
- Parametric study for weight variation of dome considering various parameters like height, number of sectors in plan and different variable approaches.

III. METHODOLOGY

The Octave programming language was utilized to optimize the steel dome. The data is generated, the structure is analyzed and designed using a set of programs developed, and optimization is performed using the same programming language and the precise penalty approach.

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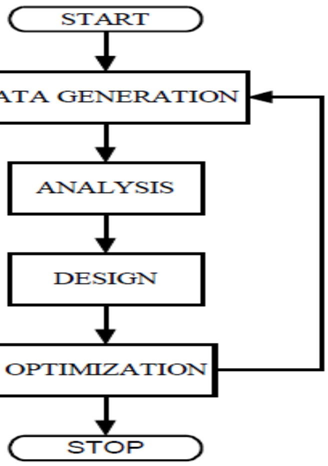
In this chapter, the methodology adopted in data generation, analysis and optimization of dome structure has been discussed. The codes developed to construct the programs, their logic and flow charts have been detailed.

Flow Chart



PROCEDURE FOR DATA GENERATION

FORMULAE USED IN DATA GENERATION

In following fig.6.2, the label 'B' shows the base diameter and 'h' is the height of the dome. Few used in data generation process are listed below.

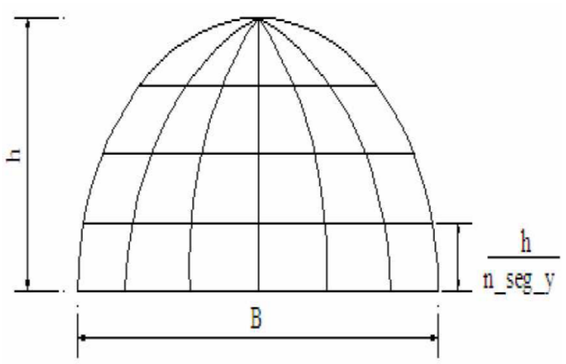


Fig. 1.1 Data generation for steel dome

Radius of curvature of the dome

$$R = \frac{B^2}{8h} + \frac{h}{2}$$

Distance from center of curvature to base ring of dome

$$p = \sqrt{R^2 - \left(\frac{B^2}{2}\right)^2}$$

Radius at the i th segment level

$$r_i = \sqrt{R^2 - \left(\frac{p + {y_i}^2}{2}\right)^2}$$

Slope (in degrees) of segment considered,

$$\text{slope} = \tan^{-1}\left[\left(\frac{r}{p + y_i}\right)\left(\frac{180}{3.142}\right)\right]$$

where y_i, is height of the segment considered from base .

$$y_i = i \times \frac{h}{n\_sec\_ht}$$

where i is the i *th* segment along height

The coordinates of nodes can be calculated by using the formula

$$X_{ij} = r\cos\theta_j$$

$$Y_{ij} = r\sin\theta_j$$

$$Z_{ij} = y_i$$

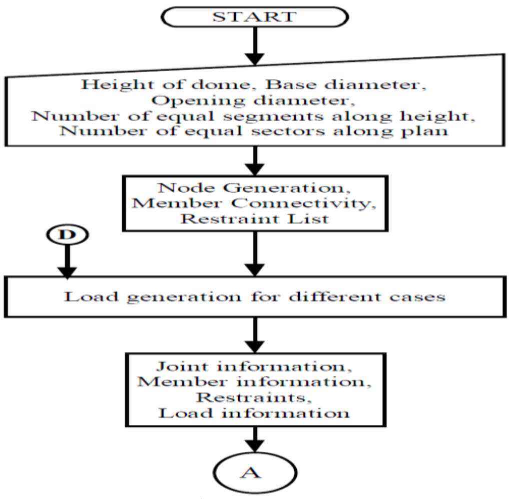
where j is *jth* sector along plan,

$$\theta_j = \frac{360}{n\_sec\_plan}$$

where n_sec_ht is number of segment along height
n_sec_plan is number of segments along plan

FLOW CHART FOR DATA GENERATION

The flow control between various steps involved in data generation of dome is shown in fig 6.3. The connector 'D' shown indicate the modification in the material properties of the member within optimization process. The optimization flowchart in Fig. 6.6 shows linking of 'D'.



Flowchart for data generation program

PROBLEM FORMULATION

The optimization problem is derived as follows to reduce weight.

Weight = density × volume
=density × area × length
W = ρ × V =ρ × A × l

Objective function:

To minimize the objective function:

$W=\sum_{i=1}^{n} \rho \times A_i \times l_i$

where, n - number of members
ρ -density
A_i-cross-sectional area of "i" th member
l_i -length of "i"th member

Subjected to constraints,

1) For maximum tensile and compressive stress

$$|\sigma_{ij}(x)| \le \sigma_{max} \quad (6.7)$$

where,

i = 1, 2, 3….n = no. of members
j = 1, 2, 3….m = indicates loading conditions
σ_{max} = allowable stress in tension and compression

2) For maximum buckling stress (slenderness ratio)

σ_{ij} (x) ≤ P_i (x)

where,

Pi (x) = bulking stress in member i
p=buckling load= $\frac{\pi^2}{L^2} EI$

3) For maximum deflection

δ_{ij}(x) ≤ δ_{all}

where ,

δ_{all} = maximum allowable deflection (span/360)....[IS:800-2007]

4) For upper and lower limit of cross sectional area

$x_i^{(l)} \le x_i \le x_i^{(u)}$

where,

$x_i^{(l)}$ = Lower bound area
$x_i^{(u)}$ = Upper bound area

UNCONSTRAINED PROBLEM

For penalty, the limited problem must be converted to an unconstrained one. The formulation of an unconstrained equation for the problem outlined in Chapter 4 is shown in the following equation.

$$f(x, R^{(0)}) = \sum_{i-1}^{n} \rho A_i l_i + [\Omega]\{[\sigma_{max} - |\sigma_{ij}(x)|] + [P_i(x) - \sigma_{ij}(x)] + [\delta_{all} - \delta_{ij}(x)] + [x_i - x_i^{(l)}] + [x_i^{(u)} - x_i]\}^2$$

Here 'Ω' is the penalty term and $R^{(0)}$) is the initial penalty parameter.

DESIGN OF DOME

Each dome member is designed as a tension or compression member using the limit state method

FLOWCHART FOR DESIGN OF DOME

The flow control between various steps involved in design of dome is shown in following chart

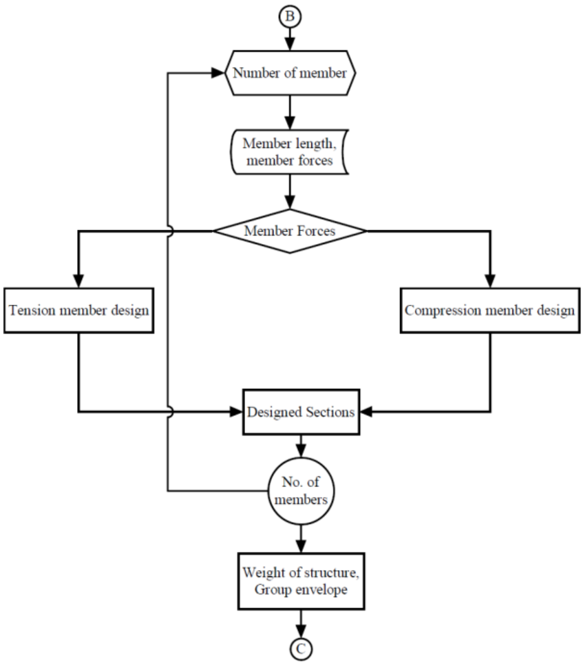


Fig. 6.5 Flowchart for Design

IV.RESULTS AND DISCUSSION

This thesis investigated the use of programs developed for the optimum structural design of 3-D dome structures. These strategies have been studied in terms of their application, efficiency, and success in solving dome structural challenges.

A parametric study has been carried out by varying the height, approaches for optimization (discrete and continuous variable), varying the number of sectors along plan of the dome for selected base diameters. Results are in the form of tables and graphs and a discussion of the results is presented.

PARAMETRIC STUDY

A detailed parametric evaluation of the various factors affecting the behavior of the dome structure is carried out. The program developed can analyze design and optimize the dome members without user interaction. In order to carry out the parametric study, base diameters, 20m, 30m, 40m, 50m, 60 m and 70m are considered. The study is conducted for domes without bracings, domes with single bracings and domes with double bracings.

VARIATION OF WEIGHT OF DOME WITH HEIGHT

The height is changed between 1/5th and 1/10th of the base diameter. There are 16 sectors in the plan and 8 segments along the height. The total optimum weight of structure for these various heights is for single braced domes.

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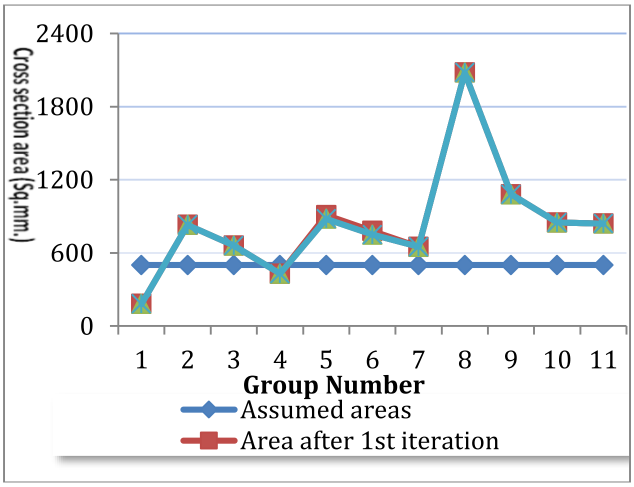
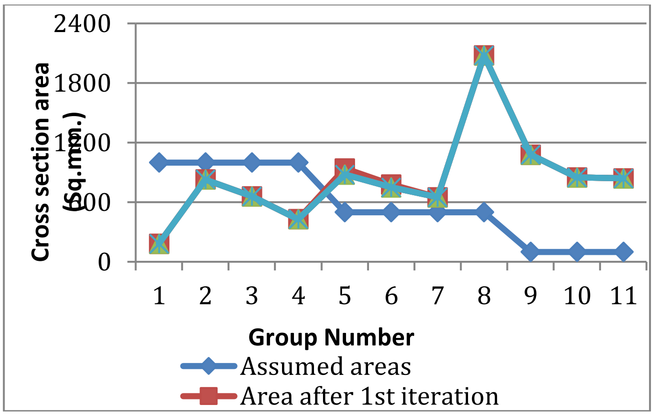
	Assumed areas (in mm^2)	Area after 1st iteration (in mm^2)	Area after 2nd iteration (in mm^2)	Area after 3rd iteration (in mm^2)	Area after 4th iteration (in mm^2)	Area(in mm^2) obtained by auto select list option
1	500	182	182	182	182	732
2	500	830	830	830	830	861
3	500	660	660	660	660	788
4	500	430	430	430	430	254
5	500	910	880	880	880	861
6	500	780	750	750	750	861
7	500	650	650	650	650	861
8	500	2080	2080	2080	2080	861
9	500	1080	1080	1080	1080	1730
10	500	850	850	850	850	1250
11	500	840	840	840	840	1110



Optimization of cross sectional area applying uniform initial area (area in mm^2)

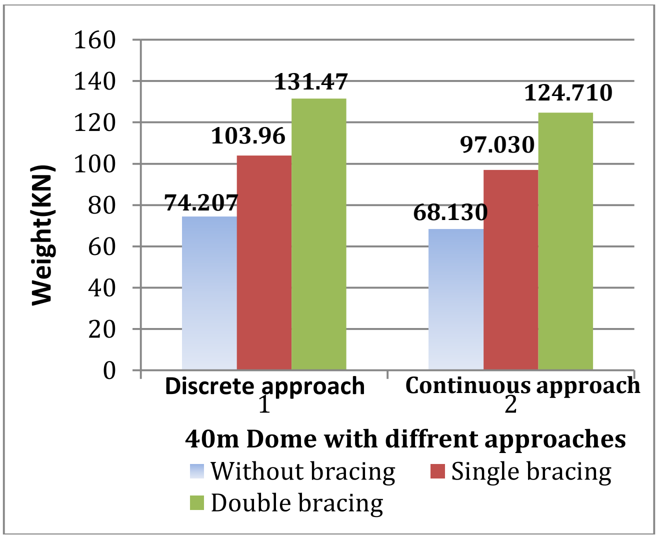
Group Number	Assumed areas (in mm^2)	Area after 1st iteration (in mm^2)	Area after 2nd iteration (in mm^2)	Area after 3rd iteration (in mm^2)	Area after 4th iteration (in mm^2)
1	1000	182	182	182	182
2	1000	830	830	830	830
3	1000	660	660	660	660
4	1000	430	430	430	430
5	500	940	880	880	880
6	500	780	750	750	750
7	500	650	650	650	650
8	500	2080	2080	2080	2080
9	100	1080	1080	1080	1080
10	100	850	850	850	850
11	100	840	840	840	840



Optimization of cross sectional area applying different initial area (area in mm^2)

Variation of total weight with different heights of the dome

Base dia (M)	Ht (m)	Ht	Optimum wt of the structure (KN)
20	4.00	B/5	32.942
	3.33	B/6	32.515
	2.86	B/7	32.196
	2.50	B/8	31.887
	2.22	B/9	31.925
	2.00	B/10	32.484
30	6.00	B/5	71.425
	5.00	B/6	70.924
	4.29	B/7	69.993
	3.75	B/8	64.494
	3.33	B/9	69.833
	3.00	B/10	70.011
40	8.00	B/5	132.253
	6.67	B/6	131.503
	5.71	B/7	130.614
	5.00	B/8	130.179
	4.44	B/9	131.19
	4.00	B/10	132.351
50	10.00	B/5	240.041
	8.33	B/6	238.282
	7.14	B/7	237.027
	6.25	B/8	235.572
	5.56	B/9	237.536
	5.00	B/10	239.899
60	12.00	B/5	375.097
	10.00	B/6	372.728
	8.57	B/7	370.124
	7.50	B/8	368.102
	6.67	B/9	374.020
	6.00	B/10	380.012
70	14.00	B/5	537.421
	11.67	B/6	539.890
	10.00	B/7	542.384
	8.75	B/8	544.416
	7.78	B/9	538.492
	7.00	B/10	532.516

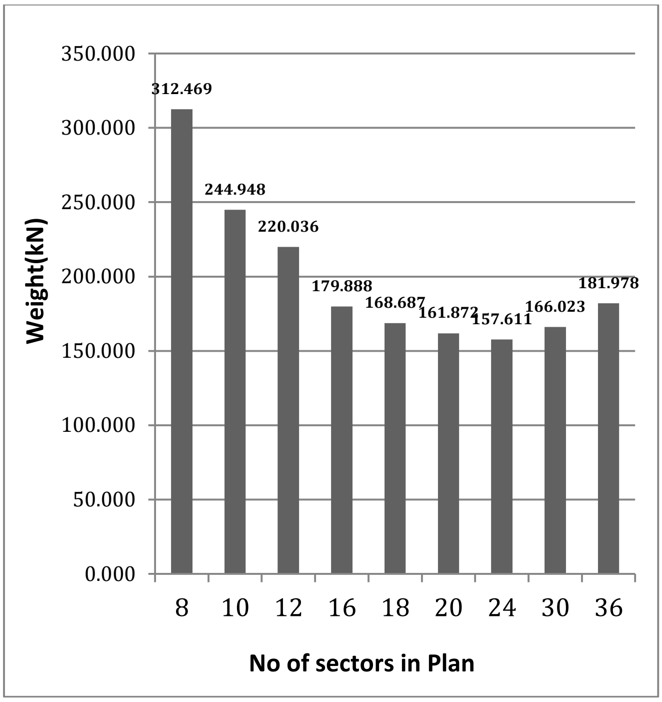


VARIATION OF WEIGHT OF DOME WITH NUMBER OF SECTORS IN PLAN

The number of sectors in plan and number of segments along height also have an influence on total weight of the structure For the study, 10° to 45° differences in angle between sectors in plan are studied, with the number of sectors varying between 8, 10, 12, 16, 20, 24, 30, and 36. During this parametric analysis, the number of segments along height is held constant at 5. The structure's weight varies as the number of sectors changes. First, it reduces the number of sectors by up to 24 for base diameters of 50m and 60m domes. This demonstrates that having 24 sectors reduces the weight of the dome structure. The variation of this number of sectors in plan and weight of structure is shown in Tables 7.9 to 7.10

Weight of dome for different no. of sectors in plan for base diameter of 50m

Base diameter (Meter)	No of sectors in Plan	θ (deg.)	No. of segments along height	Weight (KN)
50	8	45	5.00	312.469
	10	36	5.00	244.948
	12	30	5.00	220.036
	16	23	5.00	179.888
	18	20	5.00	168.687
	20	18	5.00	161.872
	24	15	5.00	157.611
	30	12	5.00	166.023
	36	10	5.00	181.978



Variation of weight of dome with number of sectors in plan for base diameter 50m

V. CONCLUSIONS

1. As only gravity loading is considered, total weight of the structure increase as bracing members are added to the domes.
2. The weight of the dome decrease as height of dome decreases from1/5th times the base diameter to height equal to 1/8th times the base diameter It demonstrates a maximum weight decrease of 3.2 percent for height variations ranging from 1/5th to 1/10th times the base diameters.
3. The wt of dome reduces considerably if the number of sectors along plan is 24 for domes of base diameter of 50m and 60m considered for gravity loading.
4. The difference in the weight by the 2 approaches (continuous variables and discrete variables) for dome without bracing is 8.19%, for domes with single bracing is 6.67% and for dome with double bracing is 5.14%.
5. The results obtained for cross sectional area of members by designing (auto select option) in SAP 2006 was greater than that obtained by software developed in Octave. This shows the efficiency of the software developed

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