International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 7, July - 2014

Parametric Study and Optimization of Steel Dome

Deepti Kumari
Department of Civil Engineering
SDMCET
Dharwad, India

Basavaraj Gudadappanavar
Department of Civil Engineering
SDMCET
Dharwad, India

***Abstract*— Domes are space structures which provide economical solution for covering large column free net precious area for utilization. Sports stadiums, assembly halls, exhibition centers, shopping malls, industrial structures etc. are the some examples where dome is used. This feature provides economy in terms of consumption of constructional material and elegant structures with their splendid aesthetic appearance. In this paper the dome is taken as space truss in which all joints are pinned joints, resulting in to torsion and moment free structure. Thus all members are subjected to tensile and compressive forces only. Even though dome has to be designed only for axial forces, the manual calculations involved is very complex and error prone. Hence an attempt has been made to develop a software in Octave 3.6.4. The software can be used for configuration, analysis, design and weight Optimization of steel dome. The members are designed with tubular steel sections and the effect of dead load and live load has been considered.**

A parametric study has also been done to establish the variation in weight with height of the dome. This study is extended for the domes with bracings in one and both directions. Parametric study for optimization of dome using different approaches i.e. with discrete and continuous variables is also done. The variation in weight with number of segments along plan has also been done.

Keywords—3Dtruss; weight optimization; direct stiffness method; parametric study

I. INTRODUCTION

Architects and engineers are always seeking new ways of solving the problem of space enclosure. A space structure is a structural system in the form of a three dimensional assembly of elements, resisting loads which can be applied at any point, inclined at any angle to the surface of the structure and acting in any direction. Domes are a prominent example of space frame structure. Domes have been of a special interest in the sense that they enclose a maximum amount of space with a minimum surface. This feature provides economy in terms of consumption of constructional materials. The development of domes has been closely associated with the development of available materials. Great improvements in dome structures commenced with the development of the steel industry beginning in the 19th century. Design of steel structures is a traditionally sub-optimal process, because it normally relies on the experience of an engineer who uses a computer to iterate through several possible choices of shapes and sizes for each one of the elements of a certain structure. Nevertheless, most of the new methods developed have a common problem: they are based on linear programming techniques, and therefore tend to treat structural optimization as a problem in which the search space is continuous, where as it is really discrete. The mathematical programming techniques for optimization of steel dome structures can be used to resolve these difficulties. Since economy can be easily accessed by total weight of structure, an attempt is hereby made to reduce the total weight of the structure.

This thesis focuses on the use of a search technique for constrained problem through mathematical programming technique. The software developed can be used for various configurations of steel truss dome structures with little change.

II. ANALYSES OF DOME

A. Loads on domes

Dome structure are subject to various kinds of loads like dead load, imposed loads, wind loads, snow loads etc. Dead load on the dome structure includes the weight of the roof covering, purlins and self weight of the structure. To calculate the self weight of the structure, initially truss area is assumed and the self weight is calculated by knowing the density of the material and length of the member. It is then applied as gravity load to the end nodes of the members. For calculation and estimation of imposed loads IS:875 (Part 2)-1987 is referred

The loads specified above is combined in accordance with the stipulation in relevant design codes. The combination which produces the most critical case is considered.

B. Matrix method for analysis of dome

The use of matrix methods makes it possible to establish the most general form of the load-displacement relationships of linearly elastic structures. Matrix methods are computer oriented methods. There are in general two methods of analysis in matrix analysis methods namely stiffness matrix method and flexibility matrix method. Direct stiffness matrix method is used for the analysis of dome, which is a 3D truss structure . In this method of analysis, equations of equilibrium are set up in terms of the nodal displacements as unknowns. These equations are solved to evaluate the nodal displacements and from the displacements, member forces are calculated using the force-displacement relationships for each element. General procedure of solution consists of the following steps:

(i) Forming local and global stiffness matrices,

(ii) Decomposing stiffness matrices (by Choleski method or Gauss-Jordan elimination),

(iii) Forming load vector,

(iv) Solving system and evaluating displacements,

(v) Evaluating member forces and reaction with the help of detected displacements,

The preceding steps can be performed by a computer software very easily and in a short time.

C. Limit state method for design of dome

The limit state method philosophy uses a multiple safety factor format that attempts to provide adequate safety at ultimate loads as well as serviceability at service loads. The members of dome i.e. 3D truss structure is designed as tension members and compression members. The strength of compression member is function of the effective slenderness ratio KL/r. Since the radius of gyration r depends upon the section selected, the design of compression is an iterative process. The design of tension member is also iterative, involving a choice of trial sections and an analysis of its capacity.

III. OPTIMIZATION OF DOME STRUCTURE

Optimization is the selection of a best element (with regard to some criteria) from some set of available alternatives. In the simplest case, an optimization problem consists of maximizing or minimizing a real function by systematically choosing input values from within an allowed set and computing the value of the function. There are various methods for optimization. The optimum seeking methods are also known as mathematical programming techniques. Mathematical programming techniques are useful in finding the minimum of a function of several variables under a prescribed set of constraints. Some of the mathematical programming methods are calculus method, nonlinear programming method, geometric programming, quadratic programming, network methods like CPM and PERT, simulated annealing, neural network etc..

As the construction materials are getting extinct day by day it is important for the structural engineers to concentrate on optimum designing of the structures. In Mathematical programming method, the problem is formulated as the determination of a set of design variables for which the objective of the design is achieved without violating the design constraints. In this method search for finding optimum design starts from a set of designs to proceed towards optimum. There are various techniques in this method to go on getting better designs.

The goal of an optimization problem can be stated as to find the combination of parameters (independent variables) which optimize a given quantity, possibility subject to some restrictions on the allowed parameter ranges. The quantity to be optimized (maximized or minimized) is termed the objective function; the parameters which may be changed in the quest for the optimum are called control or decision variables; the restrictions on allowed parameter values are known as constraints. An optimization or a mathematical programming problem can be stated as follows.

$$\text{Find } X = \begin{pmatrix} x_1 \\ x_2 \\ . \\ . \\ x_n \end{pmatrix}$$

which minimizes f(x) (1)

Subject to the constraints

$g_j(x) \leq 0, j=1,2,\ldots m$ inequality constraint
$h_j(x) = 0, j=1,2,\ldots p$ equality constraint

Where, X is an n-dimensional vector called the designed vector, f(x) is termed the objective function. The number of variables n, the number of constraints m and p need not be related in any way. The problem stated is called a constrained optimization problem. Some optimization problem does not involve any constraints. Such problems are called as unconstrained optimization problems.

A. Constrained Optimization technique

Constrained optimization problem is converted in to unconstrained one by exact penalty method. In this method the problem is converted into an unconstrained minimization problem by constructing a function of the form as given in equation (2)

$$P(x, R) = f(x) + \Omega\{R, g(x), h(x)\} \quad (2)$$

Where, R is a set of penalty parameters, Ω is the penalty term chosen to favor the selection of feasible points over infeasible points. The change of penalty parameter in successive sequence of the penalty function method depends on whether an exterior or an interior penalty term is used. If the optimum point of the unconstrained objective function is the true optimum of the constrained problem, an initial penalty parameter will solve the constrained problem. Otherwise, if the constraints make the optimum of the unconstrained objective function infeasible, a number of sequences of the unconstrained optimization algorithm must be applied on a penalized objective function.

The unconstrained optimization methods act as a direction finding technique for penalty method. Simplex method which was originally given by Spendley, Hext and Himsworth and was developed later by Nelder and Mead is used here. The geometric figure formed by a set of (n+1) points in an ‘n’ dimensional space is called a simplex. The basic idea in this method is to compare the values of the objective function at the (n+1) vertices of a general simplex and move the simplex gradually towards the optimum point during iteration process. The movement of this simplex is achieved by using three operations known as reflection, contraction and expansion.

IV. OPTIMIZATION PROBLEM

For this optimization of steel dome, Octave 3.6.4 programming language has been used. The data are generated, analysis and designing of structure is done through the set of programs developed and optimization is done by the program in same programming language incorporating the exact penalty method as shown in fig. 1.

A. *Master Flowchart*

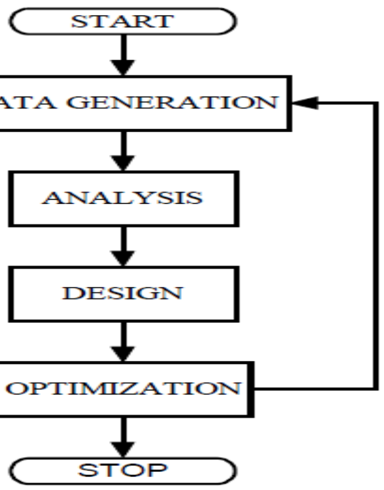

Fig. 1 Master flowchart

1) Modelling: For the required model, the inputs required are base diameter, height, geometry of dome, number of segments along height and plan, loading on dome(DL&LL) and member properties like Modulus of Elasticity, density. The output obtained are generation of information pertaining to nodes(numbering, co-ordinates, degree of freedom), members(member numbering, connectivity, length), restraints (number of joints restrained and their degree of freedom) and loads(nodal loads)etc..

2) Analysis: Includes the calculation of forces due to applied loads. The analysis program is based on the direct stiffness method as explained before. It takes the output of the data generation program as its input. After carrying out the direct stiffness analysis it gives the member force envelope, along with the length of all the members of the group, the number of members in the group and the group identification number.

3) Design of Dome: The design of each member of dome is done as tension or compression members only by limit state method of designing of steel structures as per IS 800:2007 and 10% over strength factor is also considered.For designing flowchart as shown in fig. 2 is followed.

4) Optimization of Dome: The output from the design program is input for the optimization program. The optimization program is based on the interior penalty method. The direction finding within the penalty method is carried out by Simplex method. This type of problem is called as (in this case non-linear) constrained problem. While forming the 'step length' in penalty method, the initial penalty parameter is kept constant as 1. Then each next penalty parameter is generated by multiplying the previous penalty value by 0.1. The cross-section remains same for each group. hence the number of variables is equal to the number of groups. The grouping technique is as shown in fig 3.

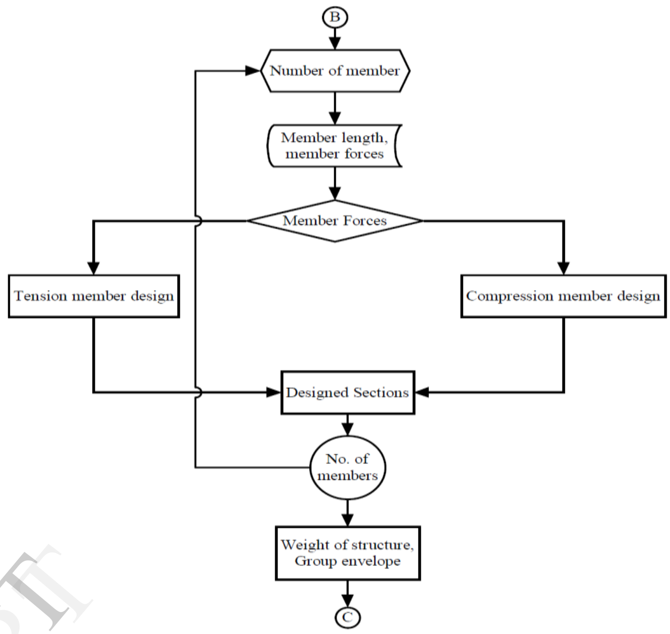

Fig. 2 Design of dome

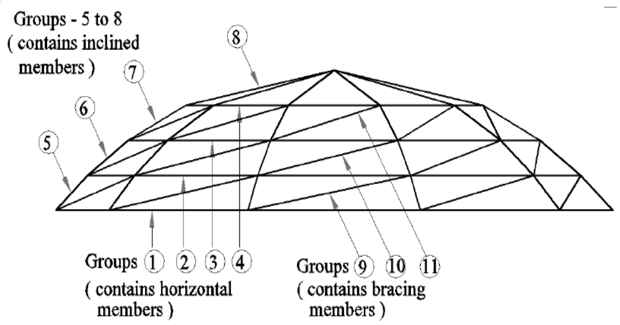

Fig. 3 Grouping technique for dome

a) Problem formulation: To reduce weight, the optimization problem is derived as below. To minimize the objective function:

$$W=\sum_{i=1}^{n} \rho \times A_i \times l_i \quad (3)$$

where, n- number of members , ρ- density, *Ai* - cross-sectional area of " i" th member, *li* - length of "i" th member

Subjected to constraints:

1) For maximum tensile and/or compressive stress

$$|\sigma ij(x)| \leq \sigma max \quad (4)$$

where i = 1, 2, 3….n = no. of members and
j = 1, 2, 3….m = indicates loading conditions
σmax = allowable stress in tension and compression

2) For maximum buckling stress (slenderness ratio)

$\sigma ij(x) \leq Pi(x)$ (5)

where, $Pi(x)$ = bulking stress in member i

p=buckling load= $\frac{\pi^2}{L^2} EI$ (6)

3) For maximum deflection

$\delta ij(x) \leq \delta all$ (7)

where δall = maximum allowable deflection = (span/360)....[IS:800-2007]

4) For upper and lower limit of cross sectional area

$$x_i^{(l)} \leq x_i \leq x_i^{(u)} \quad (8)$$

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

b) Unconstrained problem: For penalty the constrained problem is required to convert in to unconstrained one. The following equation shows the formulation of unconstrained equation for problem defined.

$$f(x, R^{(0)}) = \sum_{i-1}^{n} \rho A_i l_i + [\Omega]\{[\sigma_{max} - |\sigma_{ij}(x)|] + [P_i(x) - \sigma_{ij}(x)] + [\delta_{all} - \delta_{ij}(x)] + [x_i - x_i^{(l)}] + [x_i^{(u)} - x_i]\}^2 \quad (9)$$

Here Ω is the penalty term and $R^{(0)}$ is the initial penalty parameter.The optimization is done as mentioned in flowchart in fig. 4.

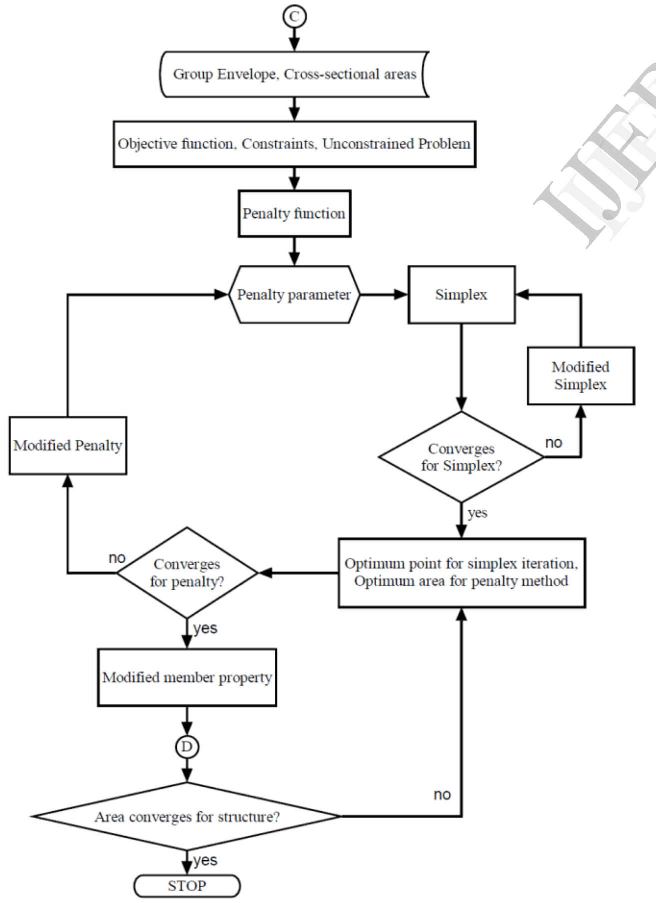

Fig. 4 Optimization flowchart

V. RESULTS AND CONCLUSIONS

A. Optimization Results

The use of programs developed for the optimum structural design of 3-D dome structures has been explored in this paper. The program is capable of generating the configuration of four types of domes, namely, dome without bracing, dome with right bracing, dome with left bracing and dome with both left and right bracings. Currently dead load and live load have been considered. The analysis program gives the envelope of member end forces for all the load combinations considered.

Dome of diameter 40 m with height 6 m, single bracing, 20 numbers of sectors along plan and 4 numbers of segments along height is considered. In Table 1 and Table 2, the first column shows the group number for a member. Second column gives the cross section areas assumed initially and subsequent columns give the areas for different iterations. Last column results obtained by SAP 2000 using auto select option for assigning sections for members.

TABLE I. OPTIMIZATION OF CROSS SECTIONAL AREAS STARTING WITH SAME ASSUMED AREA

Group No.	Areas per iterations in sq mm					
	Assumed	Ist	2nd	3rd	4th	SAP
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

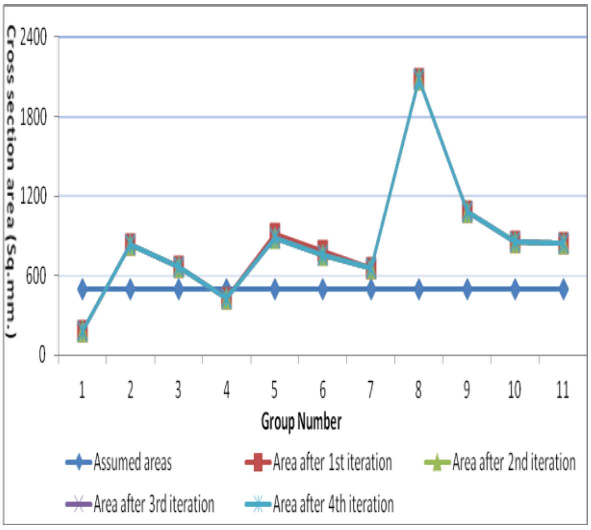

Fig.5 Optimization of cross sectional area applying uniform initial area

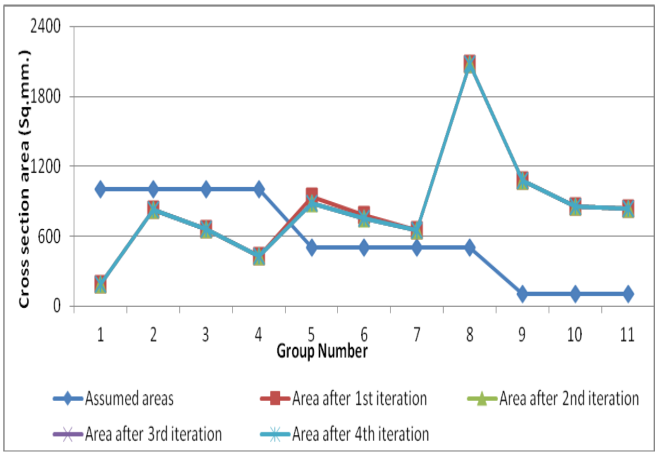

Fig. 6 Optimization of cross sectional area applying different initial area

OPTIMIZATION OF CROSS SECTIONAL AREAS STARTING WITH DIFFERENT INITIAL AREAS

Group No.	Areas per iterations in sq mm				
	Assumed	1st	2nd	3rd	4th
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

B. Parametric Study

1) Variation of weight of dome with height

In order to carry out the parametric study, base diameters, 20m, 30m, 40m, 50m, 60 m and 70m are considered. The height is varied from 1/5th to 1/10th of the base diameter. The number of sectors in plan is 16 and number of segments along height is 8. For these various heights, the total optimized weight of structure are tabulated in TABLE III for single braced domes

TABLE II. VARIATION OF TOTAL WEIGHT WITH DIFFERENT HEIGHTS OF THE DOME

Base diameter (Meter)	Height (meter)	Height	Optimum weight of the structure (KN)
20	4.00	B/5	32.942
	3.33	B/6	32.514
	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

2) Variation of weight of dome for different design approaches

In the first approach, it is assumed that cross sections available are continuous in the sense that any cross section required is available. In the second approach, it is assumed that only discrete cross sections are available and after determining the required cross section, the next available section is chosen from the pool of available sections. To compare the results obtained by the two approaches, a 40 m diameter dome with 5 m height, 20 number of sector in plan, and 4 numbers of segments along height without bracings, with single bracings and with bracings in both directions are considered. The results obtained are as shown in fig. 7.

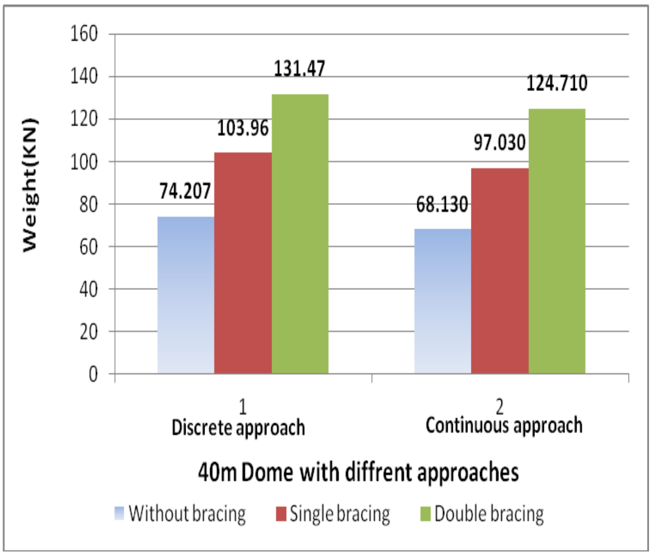

Fig. 7 Variation of weight of 40 m dia. dome for different approaches

3) Variation of weight of dome with number of sectors in plan

For the study, 10 to 45 degree variations in angle between the sectors in plan are considered and number of sectors is varied taking 8, 10, 12, 16, 20, 24, 30 and 36 sectors. The number of segments along height is kept constant at 5 during this parametric study. The results are as shown in fig .8 and 9.

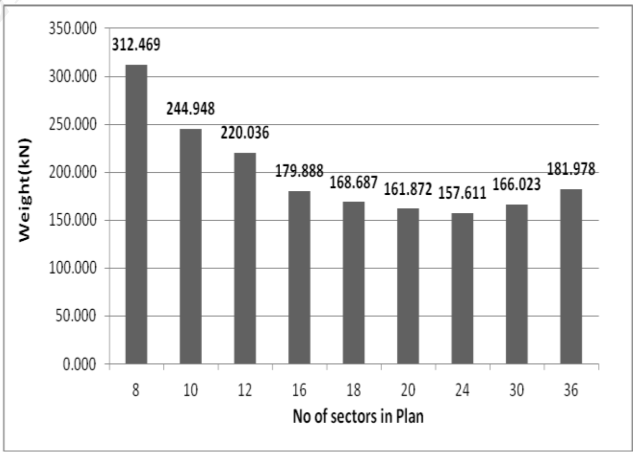

Fig. 8 Variation of weight of dome with number of sectors in plan for base diameter 50m

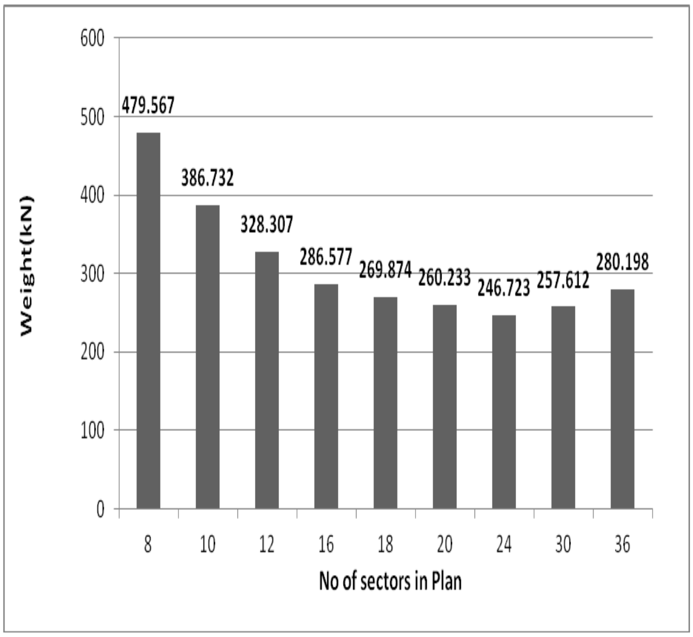

Fig. 9 Variation of weight of dome with number of sectors in plan for base diameter 60m

C. *Conclusions*

- This process of data generation, analysis, design and optimization are repeated a prescribed number of times as specified in the input. In this particular example, this process has been repeated four times. The maximum area is assigned to the members at top which are having maximum length compared to others.
- The weight of structure first decreases as height of dome decreases from 1/5th to 1/8th of base diameter; after that weight begins to increase. This implies that further decrease in height less than 1/8th of base diameter will not cause any reduction in weight of the dome. It shows a maximum of 3.2% reduction in weight for height variation between 1/5th to 1/10th times the base diameters
- The total weight of structure given by the continuous approach is always lesser than the weight obtained by the discrete approach for the variables in all cases. The difference in the weight by the two approaches is 8.19% for dome without bracing, 6.67% for dome with single bracing and 5.14% for dome with double bracing.
- The weight of structure varies as number of sectors changes. First it decreases up to 24 numbers of sectors for base diameters 50m and 60m domes. This shows that 24 numbers of sectors will give lesser weight of dome structure.

REFERENCES

[1] Tugrul TALASLIOGLU, " Design optimisation of dome structures by enhanced genetic algorithm with multiple populations" , Scientific Research and Essays Vol. 7(45), pp. 3877 -3896, 19 November, 2012.

[2] S. Çarbaş and M.P. Saka, "Optimum design of single layer network domes using harmony search method", asian journal of civil engineering (building and housing) vol. 10, no. 1 (2009) Pages 97-112

[3] Wuxi, Jiang Su China, "Lectotype Optimization of Single-Layer Steel Reticulated Dome Based on Sectional Optimization", 2010 Third International Conference on Information and Computing

[4] H. S. Jadhav, Ajit S. Patil "Parametric Study of Double Layer Steel Dome with Reference to Span to Height Ratio", International Journal of Science and Research (IJSR), India Online ISSN: 2319-7064

[5] O. Hasançebi, F. Erdal, M. P. Saka, " Optimum design of geodesic steel domes under code provisions using metaheuristic techniques", International Journal of Engineering and Applied Sciences (IJEAS) Vol.2, Issue 2(2010)88-103

[6] Galawezh Saber, Nildem Tayşi, Ghaedan Hussein, "Analysis and Optimum Design of Curved Roof Structures", 2nd International Balkans Conference on Challenges of Civil Engineering, BCCCE, 23-25 May 2013, Epoka University, Tirana, Albania.

[7] J. Farkas, "Mathematical and technical optima in the design Of welded steel shell structures", international journal of optimization in civil engineering Int. J. Optim. Civil eng., 2011; 1:141-153

[8] Matteo Dini, Giovani Estrada2, Maurizio Froli, Niccolò Baldassini, " Form-finding and buckling optimization of gridshells using genetic algorithms", Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2013"BEYOND THE LIMITS OF MAN" 23-27 September, Wroclaw University of Technology, Poland

[9] Isenberg, J., Pereyra, V. and Lawver, D., "Optimal design of steel frame structure",Applied Numerical Mathematics, Volume No. 40, 2002, pp. 59-72

[10] Pereyra, V., Lawver, D., Isenberg, J., "An algorithm for optimal design of steel frame structures", Applied Numerical Mathematics, Volume No. 47, 2003, pp 503-514

[11] Itti, S. V., "Shape optimization of steel domes using sequential linear programming". Ph.D. thesis, Civil engineering department, NITK, Surthakal, 2006.

[12] Rajeev, S., and Krishnamoorthy, C. S.,"„Discrete optimization of structures using genetic algorithms"", J. Struct. Eng., Vol.118, No.5, May 1992, 1233–1250.

[13] Yavuz Saraç, "Optimum design of pin-jointed 3-D dome structures using global optimization techniques", A thesis submitted to The graduate school of natural and applied sciences Of Middle east technical university

[14] IS:800-2007 "Code of practice for general construction in steel", third revision, Bureau of Indian standards, New Delhi, 2007

[15] IS:806-1968 "Code of practice for use of steel tubes in general building construction", first revision, Bureau of Indian standards, New Delhi, 1968.

[16] IS:875-1987 (Parts 1 and 2) "Code of practice for design loads (other than earthquake) for buildings and structures", fourth revision, Bureau of Indian standards, New Delhi, 1987.

[17] IS:1161-1998 "Steel tubes for structural purpose - specifications", fourth revision, Bureau of Indian standards, New Delhi, 1998.

[18] Rao, S. S., "Engineering Optimization: theory and practice", New Age InternationalPublishers, revised 3 ed., 2006.