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# **Optimum Design of Single Layer Steel Domes using Non-Linear Constrained Technique**

#### Vijayakumar Anantpur

Assistant Professor, Department of Civil Engineering, Government Engineering College, Karwar, Karnataka, India

**ABSTRACT:** Weight optimization of trusses is so important due to economic and sustainability considerations. The present study aims at developing a suite of computer programs in Octave programming language that will generate geometry and loading data, analyze and design single layer spherical domes. Only gravity loads are considered in the present study. Design of members is done as per relevant Indian standard code. The validation of the results of the program are done using commercially available software. A computer program in Octave programming language to optimize the steel dome to carry given loads for given topology using nonlinear constrained optimization method is used for the minimum weight. The weight of the dome decrease as height of dome decreases from1/5th times the base diameter. It shows a maximum of 3.2% reduction in weight for height variation between 1/5th to 1/10th times the base diameters. The weight of dome reduces considerably if the number of sectors along plan is between 20 to 24 for all domes considered for gravity loading.

KEYWORDS: Weight, Area, Optimization, Spherical Dome, Space truss

#### **I.INTRODUCTION**

A dome is a structural system that consists of one or more layers of elements that are arched in all directions. The surface of a dome may be a part of a single surface such as a sphere or a paraboloid, or it may consist of patch work of different surfaces. Domes are characterized by the hinged joints with no moments or torsional resistance; therefore, all the members can only resist tension or compression. Domes are of special interest to engineers and architects as they enclose a maximum amount of space with minimum surface and have proved to be very economical in consumption of constructional materials. Domes are also exceptionally suitable for covering sports stadiums, assembly halls, exhibition centers, swimming pools and industrial buildings in which large unobstructed areas are essential and where minimum interface from internal support is required. The provision of unobstructed sight-lines for numbers is the primary requirement in sports halls and can easily be satisfied through the adoption of dome shape.

Optimization is the act of obtaining the best results under given circumstances. Optimization is being used in those design activities in which the goal is not merely to achieve a feasible design, but also a specified design objective. In the design of an engineering structure, engineer has to take many technical decisions at several stages. The ultimate goal of all such decisions is to either minimize the effort required or maximize the desired benefit. Now a days, a number of optimization techniques are available. The mathematical programming techniques for optimization of steel dome structures can be used. Since economy can be easily assessed by total weight of structure, an attempt is hereby made to reduce the total weight of the structure.

#### **II. LITERATURE SURVEY**

Isenberg, J., Pereyra, V., Lawver, D. (2002), consider the optimal design of steel structures. They attempt to minimize the total weight of the (frame) structure subject to various loads and constraints. They consider gravity and wind loads at first and the cross-sectional area (A) and bending moments (M) of groups of members as parameters for optimization. This limits the number of different member types, and thus makes the design more practical. They found that the performance of the method was not up to mark. It reduces the weight but violets the constraint. The method was not robust enough and they do not expect it to scale to larger problems. Thus, they use of an exact penalty method.



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And finally, they conclude that exact penalty method that seems to be more robust and extensible to more realistic, large-scale structures and further design constraints than the first one.

Pereyra, V., Lawver, D., Isenberg, J. (2003): In his paper an improved, faster and more robust algorithm was presented and applied to larger (frame) structures of practical interest. Gravity, wind loads, and stress constraints are considered. Other reasonable building constraints considered include grouping the members, so that a unique section can assigned to all the members of a group. Also, the size or variety of sections that can be used for certain groups are kept limited, thus reducing the number of parameters and the variety of sections. They said optimization method like stochastic search algorithm method is not appropriate for problems with a large number of variables, since they require a very large number of function evaluations to converge. In order to extend the applicability of search methods to problems with many parameters and constraints a block decomposition approach is considered. In this approach the parameters are partitioned into blocks and the sub-problems are optimized for the parameters within the active block, while the remaining parameters are kept fixed

Gero, Maria Belen Prendes, Garcia, A.B., Diaz, Juan Jose Del Coz (2006): They said that the optimization process may be used to group together the elements of structures in group with the same section. The optimum individual given in each optimization process could be a local optimal solution. Since it is impossible to know that beforehand, it is necessary to run several processes and choose the best among all of the intermediate optimum structures. In the selection of the final optimum individual, however, not only do the sections assigned to the groups have an influence, but also their final weight, understood as the weight of all the sections that make up the structure, the penalty that resulting safety coefficients produce, because they are taken into account by the modified objective function as another weight and lastly the number of evaluations that must be carried out to reach the said optimum individual; a value that indicates how many structures are generated throughout optimization and therefore how many are analyzed, with the corresponding computational cost.

Itti, S.V. (2006): He said for shape optimization of steel dome a constrained optimization method can be used. He used a sequential linear programming technique for optimization. While getting the solution of original nonlinear programming problem he solves a series of linear programming problems and each LP problem is generated by approximating the nonlinear objective and constraint functions using first-order Taylor series expansions about the (current) design vector.

From the literature of Isenberg J., Pereyra V., Lawver D. (2002, 2003), I got the idea as total weight of structure can be minimized by controlling the area and length of an individual member of structure easily and to handle dome like space structure problems penalty function method of an optimization can be used effectively.

#### III. METHODOLOGY

To develop the software, Octave 3.1.50 has been used. The analysis of the dome structure is carried out by direct stiffness method, design is done by limit state method and optimization is done by exact penalty method. All IS code provisions are incorporated in design process.

In this section, the methodology adopted in data generation, analysis, design and optimization of dome structure has been discussed. The functions developed to construct the programs, their logic and flow charts have been detailed. The flow chart diagrammatically represents the steps involved in the program as well as the flow of control between the various steps. The flow chart for the entire program is shown in the Fig 3.1. In subsequent sections, the flow charts for the individual steps, namely, data generation, analysis, design and optimization of structure will be elaborated.



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Fig. 3.1 Master flow chart



Fig. 3.2 Typical steel dome

The various flow charts for data generation, analysis, design and optimization are shown below.





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Fig. 3.3 Flow charts for (a) Data Generation (b) analysis (c) Design (d) optimization

**OPTIMIZATION:** The output from the design program is input to 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.

The first task in optimization is to write a statement of the optimization problem. The statement includes the objective function and the various constraints (equality constraints are not being used in problem formulation). This type of problem is called as (in this case non-linear) constrained problem. The penalty method requires converting a constrained problem into an unconstrained one using suitable transformation techniques. The developed unconstrained problem is solved by any unconstrained optimization technique like simplex method.

While forming the 'step length' in penalty method, the initial penalty parameter is kept constant as 1. Then each next penalty parameter generated by multiplying the previous penalty value by 0.1.

Problem Formulation

Weight = density × volume = density × area × length

 $W = \rho \times V = \rho \times A \times I$ 

To reduce weight, the optimization problem is derived as below.

Objective function: To minimize the objective,

$$f(x) = \sum_{i=1}^{n} \rho A_i l_i$$



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where, n is the number of members. 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 earlier in 3.5.1.1.

$$f(x, R^{(0)}) = \sum_{i=1}^{n} \rho A_{i} l_{i} + [\Omega] \left\{ \left[ \sigma_{max} - \left| \sigma_{ij}(x) \right| \right] + \left[ P_{i}(x) - \sigma_{ij}(x) \right] + \left[ \delta_{max} - \delta_{ij}(x) \right] + \left[ x_{i} - x_{i}^{(l)} \right] + \left[ x_{i}^{(u)} - x_{i} \right] \right\}^{2}$$

Here ' $\Omega$ ' is the penalty term and R<sup>(0)</sup> is the initial penalty parameter.

#### **IV. RESULTS & DISCUSSION**

In the subsequent sections the results obtained from the program, the graphs plotted for different base diameters and heights of the dome have been presented and discussed.

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. Any of these configurations can be generated either with an opening at top or without an opening at top. The analysis program performs the complete analysis of dome for individual independent load cases, which are chosen in load generation program. Currently, the program only generates dead load and live load. The analysis program gives the envelope of member end forces for all the load combinations considered. The program then carries out the design of the members using steel tube sections and forwards the results to the optimization function.

The results obtained from the program are compared with the output from STAAD.Pro 2006. A parametric study has been carried out by varying the height of the dome for four selected base diameters, different number of sectors in plan ,and different number of segments along the height of the dome. Results are presented in the form of tables and graphs and a discussion of the results is presented.

For the study of domes without an opening at top, the base diameters 20m, 30m, 40m, 50m and 60m are considered. The height is varied from 1/5th to 1/10th of the base diameter is considered. 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 and maximum crown displacements are tabulated in Table 4.3 for single braced domes.

Considering the base diameter 20m and different configurations; the weight of the dome is 32.942 kN, 32.514 kN, 32.196 kN, 31.887 kN, 31.925 kN and 32.925 kN for dome height equal to 1/5th to 1/10th of base diameter i.e. varies from 4 m to 2 m as shown in Table 4.3. 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. Similar trend in weights of the domes is exhibited for other diameters and respective heights.

The weight of the dome decrease as height of dome decreases from 1/5th times the base diameter to height equal to 1/8th times the base diameter. It shows a maximum of 3.2% reduction in weight for height variation between 1/5th to 1/10th times the base diameters. The maximum crown displacement increases for 20 m base diameter dome from 0.9 mm to 2.407 mm as the dome height decreases from 4 m to 2 m. similar trend of variations in crown displacements of the domes is exhibited for other diameters and respective heights. The maximum crown displacement increases as the height of the dome decrease from 1/5th to 1/10th times the base diameter. The maximum crown displacement occurs for a height of B/10 and is 62.1% more than that for B/5 for 20 m diameter domes. This variation is 62.95% for 60 m diameter dome.

The minimum weight total weight of dome structure corresponds to B/8 and is 3.2% lesser than the dome with B/5, and the corresponding crown displacement is up to 46% greater than the crown displacement for B/5 for the different domes considered.



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#### A. Optimization of Areas

Dome of diameter 40 m with height 5 m, single bracing, 20 numbers of sectors along plan and 4 numbers of segments along height is considered. The program directly gives the envelope for grouping of members as per length and level of member. In Table 4.2 and Table 4.3, 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.

The optimization process is begun by assigning assumed cross section areas to each group of members and the dome is analyzed and the members are designed. The optimization function now optimizes the cross-section areas as described in 3.5. The modified cross section values are then given to the data generation function and data is modified. 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. However, in subsequent examples, this process has been carried out three times and has been found to be satisfactory. It is seen that after the second iteration, the cross-section areas have converged.

It can be seen that in the second iteration, areas are modified for groups 5 and 6 (see Fig. 4.1). In third and fourth iterations areas remain constant. It can be clearly seen that for all members the cross-sectional area optimized in three iterations. The maximum area is assigned to the members at top which are having maximum length compared to others.



Fig. 4.1 Grouping technique for dome

<b>Table 4.1 O</b>	ptimization of	cross-sectional	areas starting	with	uniform	initial	areas
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Group number	Assumed areas	Areas after 1 <sup>st</sup> iteration	Areas after 2 <sup>nd</sup> iteration	Areas after 3 <sup>rd</sup> iteration	Areas after 4 <sup>th</sup> iteration
1	500	182	182	182	182
2	500	830	830	830	830
3	500	660	660	660	660
4	500	430	430	430	430
5	500	910	880	880	880
6	500	780	750	750	750
7	500	650	650	650	650
8	500	2080	2080	2080	2080



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9	500	1080	1080	1080	1080
10	500	850	850	850	850
11	500	840	840	840	840

#### Table 4.2 Optimization of cross-sectional areas starting with different initial areas

Group number	Assumed areas	Areas after 1 <sup>st</sup> iteration	Areas after 2 <sup>nd</sup> iteration	Areas after 3 <sup>rd</sup> iteration	Areas after 4 <sup>th</sup> iteration
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



#### Fig. 4.2 Optimization of cross-sectional area applying uniform initial area

#### **B.** Domes Without Opening

Table 4.3 Variation of total weight and crown displacements with different heights of the dome

Base diameter (meter)	Height (meter)	Optimum weight of the structure (kN)	Crown displacement (mm)
	4.00	32.942	0.900
20	3.33	32.514	1.111
	2.86	32.196	1.365



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	2.50	31.887	1.670
	2.22	31.925	2.020
	2.00	32.484	2.407
	6.00	71.425	2.807
	5.00	70.914	3.466
20	4.29	69.993	4.271
50	3.75	69.494	5.230
	3.33	69.833	6.330
	3.00	70.011	7.540
	8.00	132.253	6.380
	6.67	131.503	7.880
40	5.71	130.614	9.750
40	5.00	130.179	11.910
	4.44	131.190	14.420
	4.00	31.887   31.925   32.484   71.425   70.914   69.993   69.494   69.833   70.011   132.253   131.503   130.614   130.179   131.190   132.351   240.041   238.282   237.027   235.572   237.536   239.899   375.097   372.728   370.124   368.102   374.020	17.190
	10.0	240.041	12.148
	8.33	238.282	15.026
50	7.14	237.027	18.561
50	6.25	235.572	22.697
	5.56	237.536	27.402
	5.00	239.899	32.761
	12.0	375.097	20.626
	10.0	372.728	25.509
60	8.57	370.124	31.523
60	7.50	368.102	38.567
	6.67	374.020	46.659
	6.00	380.012	55.681



Fig. 4.3 Variation of weight of structure and crown displacement with heights for base diameter of 20m



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#### Table 4.4 Weights of domes by discrete approach

Doma (40 m dia )	Total weight in kN (discrete approach)				
Dome (40 m dia.)	Without bracing	Single bracing	Double bracing		
Without opening	74.207	103.960	131.470		
With opening (of 5 m)	55.967	124.880	169.360		

#### Table 4.5 Weights of domes by continuous approach

Dome (40 m die )	Total weight in kN (continuous approach)				
Donne (40 m dia.)	Without bracing	Single bracing	Double bracing		
Without opening	68.130	97.030	124.710		
With opening (of 5 m)	33.438	97.392	141.370		





#### Table 4.6 Crown displacement of dome

	Crown displacement in mm (discrete approach)			
Dome (40 m dia.)	Without bracing	Single bracing	Double bracing	
Without opening	9.143	9.258	10.411	

#### V. CONCLUSION

• 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 shows a maximum of 3.2% reduction in weight for height variation between 1/5th to 1/10th times the base diameters.



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- The maximum crown displacement increases as the height of the dome decrease from 1/5th to 1/10th times the base diameter. The maximum crown displacement occurs for a height of B/10 and is 62.1% more than that for B/5 for 20 m diameter domes. This variation is 62.95% for 60 m diameter dome. The minimum weight total weight of dome structure corresponds to B/8 and is 3.2% lesser than the dome with B/5, and the corresponding crown displacement is up to 46% greater than the crown displacement for B/5 for the different domes considered.
- The weight of dome reduces considerably if the number of sectors along plan is between 20 to 24 for all domes considered for gravity loading.
- There is no particular pattern in reducing or increasing the total weight of dome structure while varying the number of segments along the height.
- As only gravity loading is considered, the crown displacement and total weight of the structure increase as bracing members are added to the domes.

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