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Research Article

THE SIZE OPTIMIZATION OF STEEL BRACED BARREL VAULT STRUCTURE BY USING RAO-1 ALGORITHM

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ABSTRACT

The barrel vault structures are built by using enough aches side by side along with the distance. This type of structure has been preferred to construct from past to present. In the last century, the barrel vault structure frequently used to cover large span areas by using steel structural elements. The aim of this study is to present the optimization of steel double barrel vault structures without violating ~~the~~ some structural constraints such as nodal displacement, stresses and the buckling of the compression line element according to the AISC-ASD. For this purpose, a 384-bar double-layer barrel vault structure was selected as an example. The three dimensional (3D) finite element model (FEM) of the double-layer barrel vault structure was created with SAP2000. Analysis of the 3D FEM was conducted under the vertical concentrated loads which ~~is~~ are applied to the non-supporting joints of top barrel vault. In the optimization process a new proposed algorithm named Rao 1 is preferred. The MATLAB programming is used the data transfer from the SAP2000 for sending design variables and getting the stresses and nodal displacement of the structure. The efficiency of the optimization process was shown by comparisons with the available results in the literature.
Keywords: Barrel vault, double-layer, optimization, rao, buckling analysis, AISC-ASD, SAP2000-OAPI.

1. INTRODUCTION

The first examples of barrel vault structures (BVS) date back to ancient civilizations such as Ancient Egypt and Mesopotamia. This type of structure firstly used to cover masonry buildings with burnt bricks, stone bricks and timber materials. In the last century, BVS can be considered as a special roof to cover large span areas such as stadiums, shopping centers, and exhibition halls by using steel structural elements. With the help of this structural system, it is possible the cover span in more than 100 m [1, 2]. The shape of this system can be a circular arc, an ellipse, a cycloid, a parabola or a catenary. Generally, steel braced barrel vault structures are designed to double or single layer geometry in one direction curve form. Double layer systems are more

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capable to cover large span than single layer systems. In the case of the double layer barrel vault structures, the bottom and top barrel vaults are connected to each other by braced line elements keeping the symmetry of the structure. The double layer braced barrel vault (DLBBV) structures can be a circular arc, an ellipse, a cycloid, a parabola or a catenary in shape. Due to the pinned joints connections, all members ~~is~~ are exposed only to tension or compression forces. There are different types of DLBBV structures according to the arrangement of members. Jadhav and Patil [3] compared to the behavior of 4 different types of geometric patterns such as square on square, lattice structure (two way grids), diagonal on diagonal and square on diagonal under the effects of dead load. They concluded that square geometry and latticed truss are optimum due to the minimum deflection and axial forces.

Like the other civil engineering structures, the barrel vaults are optimized for the minimum weight of the total structure without violating some structural constraints such as nodal displacement, stresses and the buckling of the compression line element. In the literature, there are some papers related to the barrel vaults structures. Kaveh et al. [4] used the metaheuristic algorithm to solve single layer barrel vault framed structures. In that study, the authors used applicable programming interface properties of SAP2000 to realize the finite element analysis of single layer barrel vault frame structures. Kaveh et al. [5] used improved magnetic charged system search for shape-size optimization of single-layer barrel vaults by taking into account the dead load, snow load and the wind load. Kaveh and Moradveisi [1, 6] used two different optimization methods, colliding bodies (CBO) and its enhanced version (ECBO), for DLBBV structures under the static loads. They used the strength constraints of AISC-LRFD specifications. They also examined the effect of support location on the optimization of selected structures. Kaveh et al. [7] used an improved magnetic charged system search for the optimal design of the double layer barrel vaults. They used an open application programming interface (OAPI) for the optimization of double layer barrel vaults. They used discrete set design variables for the cross sectional area of the frame elements. Tunca et al. [8] made a study on optimum design of braced barrel vault systems using cold-formed steel sections. The authors of that paper used the Artificial Bee Colony algorithm to optimize the structure. They used the allowable stress according to AISC-ASD and nodal displacement as constrained for the optimization problem. Hasançebi and Kazemzadeh [9] used the Big Bang-Big Crunch algorithm for discrete structural design optimization of barrel, grill and 3D framed structures. They used AISC standard sections for design variables and taken into account stress, stability and geometric constraints according to AISC-ASD. Hasançebi et al. [10] presented a conference paper on large scale structural optimization by using ant colony optimization. They optimized 693-bar braced barrel vault structure with the discrete set design variables and compared their optimal results with those of other methods, such as particle swarm optimization (PSO), harmony search optimization (HSO) and genetic algorithms (GAs). Hasançebi and Çarbaş [11] made a study using the Ant Colony Search method for barrel vault structures. Grzywiński [12] used optimization algorithm available in Autodesk Robot Structural Professional for design of the double layer barrel vaults.

As seen in literature, some studies were optimized single layer barrel vault framed structures and double layer barrel vaults with different gradient-based methods and metaheuristics algorithm. The new proposed algorithm named Rao-1 presented by Rao [13] was used to optimize DLBBV in this study to expand to knowledge of this topic in the literature. This new algorithm is similar the Jaya algorithm which also proposed by the same author. The main objective function of the optimization process is to minimize the total weight of DLBBV structure. The design variables for the size optimization were the cross-sectional area of steel pipe members of selected structures. The allowable steel pipe sections for the cross-sectional areas of the bar elements of barrel vault structure are taken from AISC-LRFD code [14]. Some constraints were considered to minimizing the objective function of optimization problem. These are nodal displacement and the tension or compression stresses of structural system and members, respectively. The allowable tensile and compressive stresses are calculated using the AISC-ASD code [15]. To realize the optimization of the DLBBV struct ure the Rao-1 algorithm and FEM analysis were combined with the help of MATLAB programing. To overcome difficulties of subsequent 3D FEM analysis of DLBBV structure, Open Applicable Programming Interface (OAPI) properties of SAP2000 [16] was preferred in this study.

2. OPTIMIZATION OF DOUBLE BARREL VAULT STRUCTURES

The aim of the optimization used in this study is to find minimum weight for the double layer barrel vaults without violating the constraint of the optimization problems. In the other words, to find the minimum total weight of structure, the cross-sectional areas of line element which are the design variables must be small size. The design variables of the optimization problem are represented as given below.

$$X=\left[X_1,X_2,X_3,...,X_n\right] \tag{1}$$

When "n" is the number of design variables. In the term of these design variables, the objective function is written as given in Eq. (2).

$$W_{\min}=\sum_{i=1}^{nm}\rho_i x_i l_i \tag{2}$$

Where, "nm" is the number of structural member, "ρ" is the density of the structural material, "l" is the length of the bar element, "x" is the cross-sectional area of the line element and the W is the total weight of the structure. Structural constraints should not be violated while reducing the total weight of the structure. In this study, the nodal displacement and the allowable stresses are taken as design constraints.

$$\delta_i<\delta_{\max} \quad \text{i=1,2,…, nn} \tag{3}$$

$$\left.\begin{array}{l}\sigma_j^t<\sigma_{j,all}^t\\ \sigma_j^c<\sigma_{j,all}^c\\ \lambda_j^t<\lambda_{j,all}^t\\ \lambda_j^c<\lambda_{j,all}^c\end{array}\right\} \text{j=1,2,…, nm} \tag{4}$$

Where "δ_i" is the nodal displacement, "$\delta_{\max}$" is the maximum displacement, "nn" is the number of nodes, "σ_j^t" is the tensile stress and "$\sigma_{j,all}^t$" is the allowable tensile stresses, "σ_j^c" is compression stress, "$\sigma_{j,all}^c$" allowable compression stress, "nm" is the number member and the "λ" is the slenderness ratio both tensile and compression members.

If the design variables violate the constraint, the penalty function in terms of the total weight and the violated constraints are calculated as given below.

$$f_{penalty}=W\left(1+\varepsilon_1 C\right)^{\varepsilon_2} \tag{5}$$

$$\varepsilon_1 = 1.0$$

$$\varepsilon_2 = 1.5 + 1.5\frac{Iter}{MaxIter} \tag{6}$$

Where "*Iter*" is the current iteration number and the "*MaxIter*" is the maximum iteration number. So, the "ε_2" will be gradually equal to 3. The penalty function "*C*" is calculated as given below.

$$C = C_\delta + C_\sigma + C_\lambda \tag{7}$$

$$C_\delta = \sum_{i=1}^{nn} \max\left(\left|\frac{\delta_i}{\delta_{\max}}\right| - 1, 0\right)$$

$$C_\sigma = \sum_{j=1}^{nm} \max\left(\left|\frac{\sigma_j}{\sigma_{all}}\right| - 1, 0\right) \tag{8}$$

$$C_\lambda = \sum_{j=1}^{nm} \max\left(\left|\frac{\lambda_j}{\lambda_{all}}\right| - 1, 0\right)$$

At the end of the optimization process, the penalized objective function must be equal to the objective function. That is, the penalty function must equal to zero.

The allowable tensile and compressive stresses are calculated based on the AISC-ASD code [15].

for tensile members;

$$\sigma_{all}^t = 0.6Fy$$

$$\lambda_{all}^t = 300 \tag{9}$$

for compression member;

$$\sigma_{all}^c = \begin{cases} \left[\left(1 - \dfrac{\lambda^2}{2Cc^2}\right)Fy\right] / \left(\dfrac{5}{3} + \dfrac{8\lambda}{8Cc} - \dfrac{\lambda^3}{8Cc^3}\right) & for \quad \lambda < Cc \\ \dfrac{12\pi^2 E}{23\lambda^2} & for \quad \lambda \geq Cc \end{cases} \tag{10}$$

$$\lambda_{all}^c = 200$$

Where E is the modulus of elasticity and Fy is the yield stress. The slenderness ratio for i[th] member is calculated as given below. The maximum slenderness (λ_{all}) ratio is limited to 300 for tension members, and it is taken as 200 for compression members

$$\lambda_i = k_i l_i / r_i \tag{11}$$

$$Cc = \sqrt{\frac{2\pi^2 E}{Fy}} \tag{12}$$

Where "*k*" is the effective length factor and its value is taken as 1 for the truss structures. l_i, r_i and *Cc* are the length of the truss member, minimum radius of gyration and the critical slenderness ratio parameter, respectively.

3. RAO-1 ALGORITHM

Let *Y* is the objective function to be minimized (or maximized). At any iteration *i*, assume that there are '*d*' number of design variables, '*s*' number of solutions (i.e. population size, *k*=1,2,…,s). Let the best candidate *best* obtains the best value of *Y* (i.e. Y_{best}) in the entire solutions and the worst candidate *worst* obtains the worst value of *Y* (i.e. Y_{worst}) in the entire candidate solutions. If $X_{d,k,i}$ is the value of the d^{th} variable for the k^{th} candidate during the i^{th} iteration, then this value is modified as per the following equation [13].

$$X'_{d,k,i} = X_{d,k,i} + r\,(X_{d,best,i} - X_{d,worst,i}) \tag{13}$$

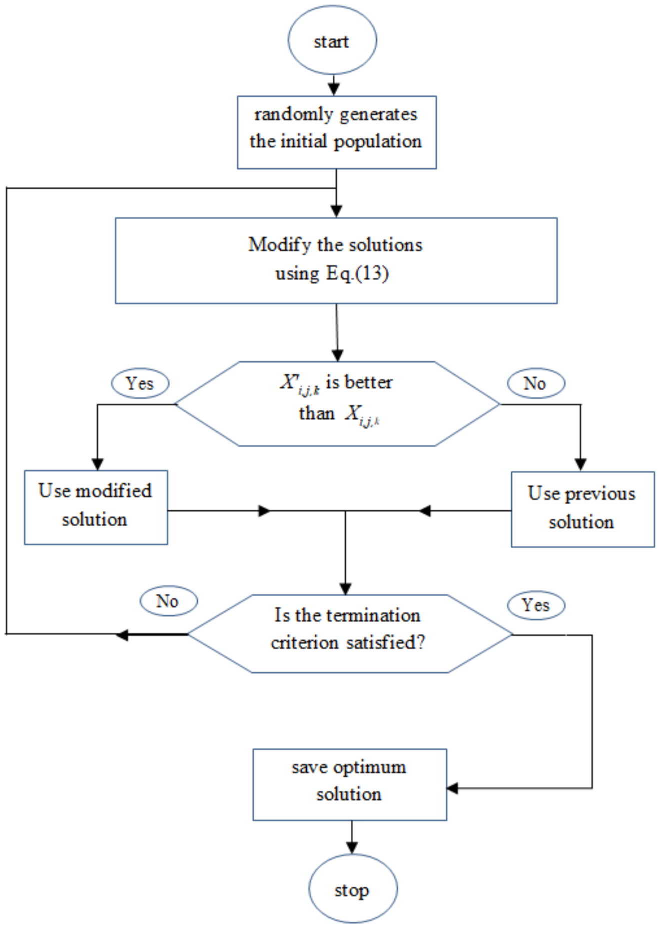

Figure 1. The flow chart for the Rao-1 algorithm

where, $X_{d,best,i}$ is the value of the variable *d* for the *best* candidate and $X_{d,worst,i}$ is the value of the variable *d* for the *worst* candidate during the i^{th} iteration. $X'_{d,k,i}$ is the updated value of $X_{d,k,i}$ and *r* is a random number in the range [0, 1]. In simple words, Eq. (13) may be written as,

New value of the variable = Old value of the variable + random number (Value of the variable corresponding to the best solution - Value of the variable corresponding to the worst solution)

It may be noted that Rao-1 algorithm, given by Eq. (13), is a very simple algorithm and is based only on the difference between the best and worst solutions. The general flow chart for the proposed algorithm is given in Fig.1.

4. APPLICABLE PROGRAMMING INTERFACE IN SAP2000

Writing computer codes for the finite element analysis of structure is so hard and not possible for the some type of complex structures. Instead of this, it will be better to call SAP2000 as a finite element function. SAP2000 offers opportunity for user to realize their finite element analysis. For this aim, it has a property called open applicable programming interface. The required codes are in available for different type of programming language like the MATLAB. In this study, the authors developed MATLAB codes to transfer data from the SAP2000. The general flowchart for this cooperation between MATLAB and OAPI-SAP2000 is given in Fig. 2.

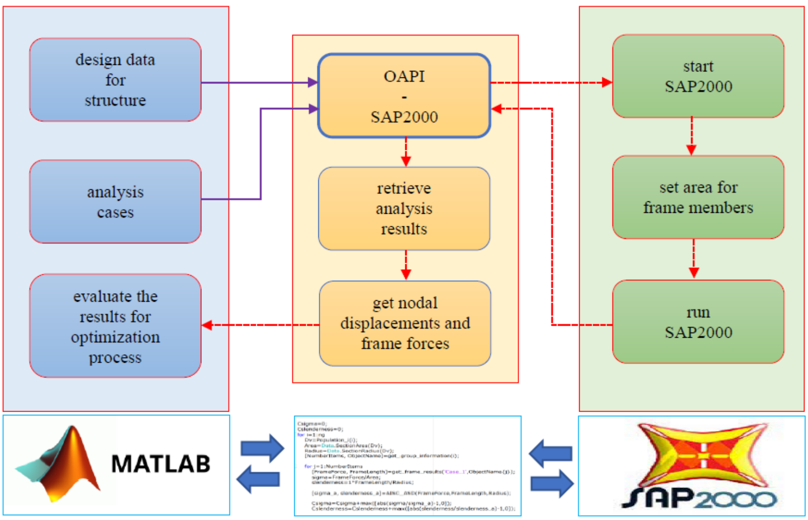

Figure 2. The cooperation between SAP2000 and MATLAB via OAPI-SAP2000

5. NUMERICAL EXAMPLE

In this study, 384-bar DLBBV structure was selected as a numerical example to illustrate the efficiency of the algorithm. This example was previously solved by Kaveh et al. [4]. The views of the selected DLBBV structure are given in Fig. 3. This barrel vault structure consists of two rectangular nets. The vertical distance between the bottom and top nets is 5.12 m. The bottom nets are placed between two top barrel nets by symmetrical. There are 31 design variables for this structure. That is the 384 bar elements are categorized 31 grouping. This groping can be seen in Fig. 3(a) with details. The 384 bar structures consist of 8 sub-structure given in Fig. 3(a) and modeled in SAP2000 by using parabolic curve. The material properties of members; the young modulus is 30450 ksi (210000 MPa), density of material is 0.288 lb/in^3 (7971.810 kg/m^3), yield stress is 58 ksi (400 MPa) and the maximum displacement in all direction is ± 0.1969 in (5 mm). As a design variables used for this example are the cross sectional areas of the pipe steel sections. These design variables given in Table 1 are not continuous and selected as discrete from the allowable set of steel pipe sections taken from AISC-LRFD code [14]. For the loading case 1, the non-supporting joints of top barrel vault (all free nodes) are loaded with the vertical concentrated loads of -20 ksi (-88.968 kN). The number of population size and the maximum generation are 20 and 1000, respectively. The optimal results are obtained as 61473.7 lb which is better than the optimal result given in literature. The obtained optimal design variables and the value of objective function are given in Table 2 by comparing the previous study given in literature.

Table 1. The allowable steel pipe sections

No	Type	Nominal Diameter (in)	Weight per ft (lb)	Area (in^2)	I (in^4)	Gyration Radius (in)	J (in^4)
1	ST	1/2	0.85	0.25	0.017	0.261	0.082
2	EST	1/2	1.09	0.32	0.2	0.25	0.096
3	ST	3/4	1.13	0.333	0.037	0.334	0.142
4	EST	3/4	1.47	0.433	0.045	0.321	0.17
5	ST	1	1.68	0.494	0.087	0.421	0.266
6	EST	1	2.17	0.639	0.106	0.407	0.322
7	ST	1 1/4	2.27	0.669	0.195	0.54	0.47
8	ST	1 1/2	2.72	0.799	0.31	0.623	0.652
9	EST	1 1/4	3	0.881	0.242	0.524	0.582
10	EST	1 1/2	3.63	1.07	0.666	0.787	1.122
11	ST	2	2.65	1.07	0.391	0.605	0.824
12	EST	2	5.02	1.48	0.868	0.766	1.462
13	ST	2 1/2	5.79	1.7	1.53	0.947	2.12
14	ST	3	7.58	2.23	3.02	1.16	3.44
15	EST	2 1/2	7.66	2.25	1.92	0.924	2.68
16	DEST	2	9.03	2.66	1.31	0.703	2.2
17	ST	3 1/2	9.11	2.68	4.79	1.34	4.78
18	EST	3	10.25	3.02	3.89	1.14	4.46
19	ST	4	10.79	3.17	7.23	1.51	6.42
20	EST	3 1/2	12.5	3.68	6.28	1.31	6.28
21	DEST	2 1/2	13.69	4.03	2.87	0.844	4
22	EST	5	14.62	4.3	15.2	1.88	10.9
23	EST	4	14.98	4.41	9.61	1.48	8.54
24	DEST	3	18.58	5.47	5.99	1.05	6.84
25	ST	6	18.97	5.58	28.1	2.25	17
26	EST	5	20.78	6.11	20.7	1.84	14.86
27	DEST	4	27.54	8.1	15.3	1.37	13.58
28	ST	8	28.55	8.4	72.5	2.94	33.6
29	EST	6	28.57	8.4	40.5	2.19	24.4
30	DEST	5	38.59	11.3	33.6	1.72	24.2
31	ST	10	40.48	11.9	161	3.67	59.8
32	EST	8	43.39	12.8	106	2.88	49
33	ST	12	49.56	14.6	279	4.38	87.6
34	DEST	6	53.16	15.6	66.3	2.06	40
35	EST	10	54.74	16.1	212	3.63	78.8
36	EST	12	65.42	19.2	362	4.33	113.4
37	DEST	8	72.42	21.3	162	2.76	75.2

As seen from the Table 2, the optimal result for the 384-bar DLBBV structure obtained from the proposed algorithm is better than the optimal results given in literature. The convergence history of the objective function of the optimization problem is shown in Figure 4. As mentioned before, the objective function is the total weight of the selected DLBBV structure. At the beginning of the optimization, the penalized objective function increased. Because, the randomly selected design variables violets the constraint of the structural limits which are the maximum nodal displacement and the allowable stressed. Then, the optimization algorithms find candidate solutions by the hope that they will not violates the constraints. At the end of the optimization process, the penalized objective function is equal to the weight of the structure. That is, the design variables in the final solution don't violate the constraint. As seen from the Fig. 4, after 300 generations the graphs has a convergence and has a constant value as 61473.7 lb.

Table 2. Optimal results for 384-bar double-layer barrel vault structure

Design variable no	Kaveh and Eftekhar [17] IBB-BC	Kaveh et al. [4] IMCSS	This study Rao-1
1	0.7750	0.7752	1.4800
2	1.0480	1.2515	0.6690
3	1.3990	0.7751	2.2300
4	0.7750	5.2906	0.6690
5	6.5230	0.7751	0.8810
6	0.7750	1.0878	0.8810
7	13.2880	13.4320	14.6000
8	10.3520	11.2207	15.6000
9	14.8250	16.2342	15.6000
10	15.3490	16.2034	12.8000
11	10.2190	10.6870	11.3000
12	13.7470	14.1700	11.3000
13	7.0330	6.4223	3.0200
14	4.7300	4.3321	21.3000
15	2.4970	2.3384	2.2500
16	5.0300	4.3778	4.0300
17	6.6920	6.6193	3.6800
18	0.7750	0.7750	0.6690
19	0.7750	0.7767	0.7990
20	0.7750	0.7785	1.0700
21	0.7750	0.7751	0.7990
22	0.7750	0.7750	1.7000
23	0.7750	0.7752	1.0700
24	3.0110	2.4360	1.7000
25	1.8110	1.1545	1.7000
26	1.7320	1.4576	0.6690
27	2.8240	2.7649	1.4800
28	1.2170	1.2236	1.0700
29	1.2790	1.3542	0.7990
30	1.2550	1.4034	0.7990
31	1.2310	1.2101	0.7990
Weight (lb)	**61972**	**62150.7**	**61473.7**

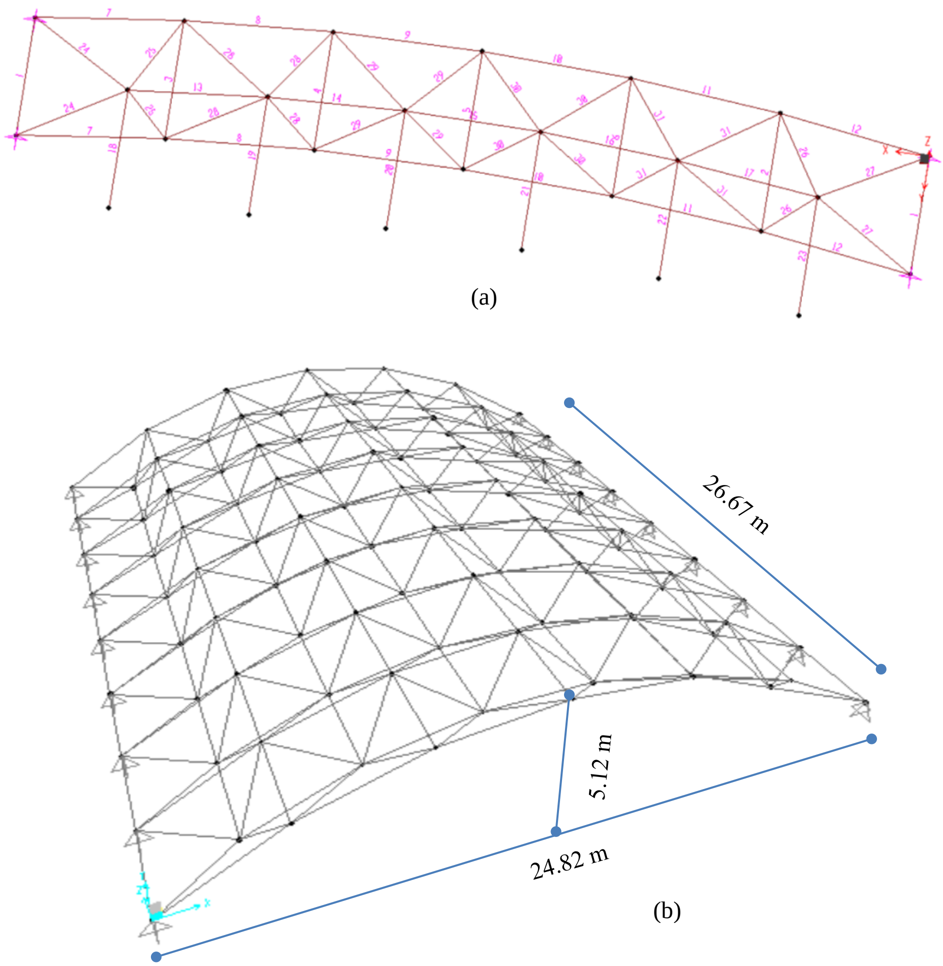

Figure 3. 384-bar double-layer barrel vault structure (b) 3D view and (a) details of grouping for sub-structure

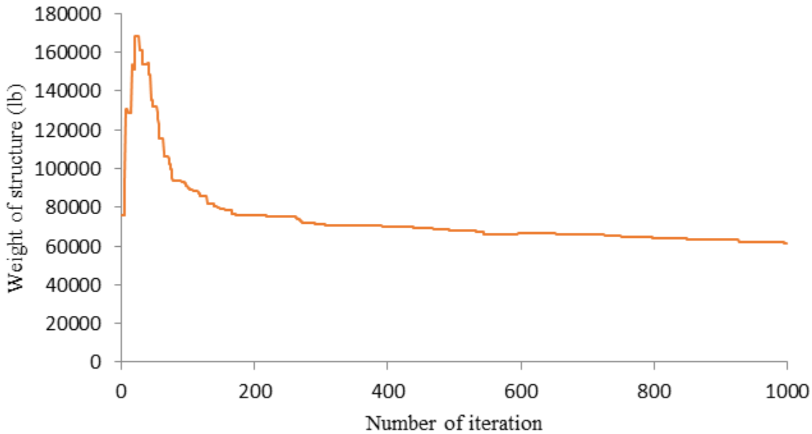

Figure 4. Convergence history of the total weight of the structure

6. CONCLUSION

The main purpose of this study is to present the optimal design of steel double barrel vault structures without violating the some structural constraints such as nodal displacement, stresses and the buckling of compression line element according to the AISC-ASD by using a metaheuristic algorithm named Rao-1. The main objective function of the optimization process is to minimize the total weight of DLBBV structure. The design variables for the size optimization were the cross-sectional area of steel pipe members of selected structures. The allowable steel pipe sections for the cross-sectional areas of the bar elements of barrel vault structure are taken from AISC-LRFD code. To illustrate the efficiency of the selected algorithm, 384-bar double-layer barrel vault structure used previous study in the literature was selected as an example. The three dimensional finite element model of the selected structure was created with SAP2000. Analysis of the model was conducted under the vertical concentrated loads applied the non-supporting joints of top barrel vault. The MATLAB programming is used the data transfer from the SAP2000 for sending design variables and getting the stresses and nodal displacement of the structure analysis. At the end of the optimization process, the penalized objective function is equal to the weight of the structure as 61473.7 lb after 300 generations. This result is better according to the result obtained as 61972 and 62150.7 in literature. The optimal result obtained from this study shows that the proposed algorithm can be effectively used for the optimization of the double barrel vault structures.

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