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Continuous size optimization of large-scale dome structures with dynamic constraints

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Abstract. In this study size optimization of large-scale dome structures with dynamic constraints is presented. In the optimal design of these structure, the Jaya algorithm is used to find minimal size of design variables. The design variables are the cross-sectional areas of the steel truss bar elements. To take into account the constraints which are the first five natural frequencies of the structures, the finite element analysis is coded in Matlab programs using eigen values of the stiffness matrix of the dome structures. The Jaya algorithm and the finite elements codes are combined by the help of the Matlab - GUI (Graphical User Interface) programming to carry out the optimization process for the dome structures. To show the efficiency and the advances of the Jaya algorithm, 1180 bar dome structure and the 1410 bar dome structure were tested by taking into the frequency constraints. The optimal results obtained by the proposed algorithm are compared with those given in the literature to demonstrate the performance of the Jaya algorithm. At the end of the study, it is concluded that the proposed algorithm can be effectively used in the optimal design of large-scale dome structures.

Keywords: Jaya; optimization; finite element analysis; dynamic analysis; dome structure; large-scale structure

1. Introduction

In order to control the dynamic response of a structure, the natural frequency of its can be taken as a constraint in the optimization problem. Therefore, the cross-sectional area of each structural elements which effects the mass of structure becomes a design variable. In the mass minimization, some natural frequencies should be little than the lower bounds when the others should be greater than the upper bound of frequency constrains.

The different types of mass minimization problem can be carried out by size, shape and the topology optimization. In this study to keep symmetry the size optimization of dome structure is taken into account. The size optimization of the large-scale structure takes many CPU times and the computational volume when the traditional mathematical is preferred. To overcome this difficulty, a metaheuristic algorithm called Jaya is used in this study.

When the literature is searched, it can be seen that many metaheuristic algorithm were used for the optimal design of the structures by using different types of constraint and design variables. Optimum design of steel bridges including corrosion effect using TLBO is made by Artar *et al*. (2017). Optimum design of steel space frames under earthquake effect using harmony search is presented by Artar (2016). Another study by Artar and Daloğlu (2015) for the optimum design of steel frames with semi rigid connections and composite beams is carried out by using GA. The topology and the cross-sectional size optimization of the structural member for the cold-formed steel portal frames buildings are presented by the Phan *et al*. (2013). A cuckoo search algorithm used by Kaveh *et al*. (2014) for the optimal design of multi-span composite box girder. A Colliding Bodies Optimization (CBO) for the optimal design of the laterally-supported castellated beams is presented by Kaveh and Shokoh (2015). Dede (2018) presented a study using the Jaya algorithm for the size optimization of the steel grillage structures. Eirgash *et al*. (2019) made a study about the time-cost trade off problems by using TLBO algorithm. Optimal design of truss tower is made by Musa and Daloğlu (2019) by using Jaya algorithm.

The studies related to the optimization of truss structures using frequency are sorted by date. Bellagamba and Yang (1981) presented the first problem of structural optimization with frequency constraints on the truss structures taking into account the mass minimization. A static and dynamic constraints used by Lin *et al*. (1982) for the studies on geometrical and element sizing optimization of the structures. Topology and sizing optimization of truss structures with frequency constraints is studied by Gomes (2011) using particle swarm optimization (PSO) algorithm. Topology and geometry optimization of geodesic domes was presented by Kaveh and Talatahari (2011) by using charged system search algorithm. A harmonics search algorithm (HS) and firefly (FA) are proposed by Miguel and Miguel (2012) to optimize the size and layout truss with frequency constraints. Baghlani and Makiabadi (2013) used TLBO algorithm for the size and shape optimization of truss structures taking into account the dynamic constraints. To optimize the shape and size of trusses Kaveh and Javadi (2014) have developed a hybrid algorithm (HRPSO) with frequency constraints. Dede and Toğan (2015) presented a

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study on mass optimization of the truss structures under frequency constraints using Teaching learning based optimization. Topology and geometry optimization of different types of domes using ECBO was studied by Kaveh and Rezaie (2015). An optimization algorithm (VPS) the vibrating particles system is proposed by Kaveh and Ghazaan (2017) for optimization of truss with frequency constraints. A review study is made by Kaveh and Zolghadr (2018) using meta-heuristic methods for optimization of truss structures with frequencies constraints. A new hybrid meta-heuristic algorithm for optimal design of large-scale dome structures was presented by Kaveh and Ghazaan (2018). Grzywiński *et al.* (2019) presented a study for the middle-size of dome structure by using Jaya algorithm with the frequency constraints.

In this paper, Jaya algorithm is preferred to optimize large-scale braced dome structures. The original study for the Jaya algorithm was developed by Rao (2016, 2018). For this aim, 1410 bar dome structures and 1180 bar dome structure with different grouping is investigated. In the optimization of this large-scaler dome structures, the natural frequencies of the structures are taken for the constraints. The main parts of this paper are; finite elements analysis of the dome structures, statements of the optimization problem, the Jaya algorithm and the numerical examples to show the performance of the proposed algorithm.

To carry out the optimization process, a computer program coded in Matlab–GUI (Graphical User Interface) is developed. This visual program has the ability to take into account the two and three dimensional truss and dome structures. For the design of structure, the displacement, stress and frequencies can be selected as a constraint in this developed program. Also, this program gives an opportunity to user for selecting the optimization type as a size and shape optimization. The general viewing of this program is given in the section “numerical examples”.

2. Statement of the optimization problem

In the case of the size optimization of structure, for minimizing the total weight of the structure, the steel profiles with small cross-sectional area are preferred. For this aim, the general objective function is written as given in the Eq. 1.

$$W_{\min} = \sum_{i=1}^{n} \rho (L.A)_i \tag{1}$$

Where, ρ is the density of the structural material, L is the length of the bar element, A is the cross-sectional area of the bar 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. These constraint can be the nodal displacements, strength of the bar elements and natural frequency of the structural. In this study, natural frequencies of the structure are taken into account as dynamics constraints.

$$\omega_i \le \omega_{upper} \qquad i = 1,...,k \tag{2}$$

$$\omega_j > \omega_{lower} \qquad j = k+1,...,n \tag{3}$$

Where, n is the number constraints and ω_i is the natural frequency of the structure. Some of the frequencies should be smaller than the upper bound of the specified frequency, while others should be larger than the lower bounds of the specified frequency. The specified frequency is determined according to the problem. To calculate the value of constraints C in the optimization problem, the following constraint equations are written.

$$g_i(x) = \frac{\omega_i}{\omega_{upper}} - 1 \le 0 \qquad i = 1,...,k \tag{4}$$

$$g_j(x) = \frac{\omega_{lower}}{\omega_j} - 1 \le 0 \qquad j = k+1,...,n \tag{5}$$

$$\text{if} \quad g_m(x) > 0 \quad c_m = g_m(x) \tag{6}$$

$$\text{if} \quad g_m(x) < 0 \quad c_m = 0 \tag{7}$$

$$C = \sum_{m=1}^{n} c_m \tag{8}$$

The objective function is written in terms of the constraint to take into the constraints. Thus, the penalized objective function φ is given in Eq. (9).

$$\varphi = W(x).[1 + P.C] \tag{9}$$

Where, the P is a constant value which is determined according to the problem. At the end of the optimization process, the penalized objective function must be equal to the objective function.

3. Finite element analysis of dome structures

Dome structures can be analysis like a 3D truss structures. A bar element for dome structure is given in the Fig. 1. As seen from this figure, 3D bar element has two nodal points and three degree of freedom in each node. These freedoms are the displacements in x, y and z directions.

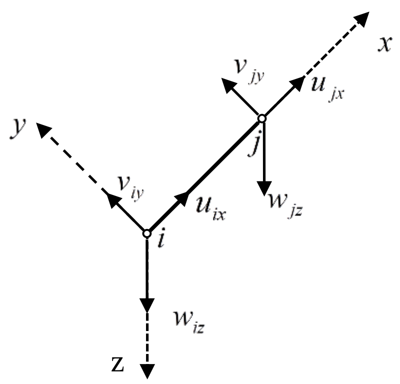


Fig. 1 A bar element in 3D for dome structure example 1

Where, i, j are the nodal points, x, y, z are the element axis sets, u_{ix}, v_{iy}, w_{iz} are displacements for node "i" in x, y, z direction, respectively. u_{jx}, v_{jy}, w_{jz} are displacements for node "j" in x, y, z direction, respectively. The nodal displacements are shown in the matrix form given below.

$$\{U\} = \begin{Bmatrix} u_{ix} \\ v_{iy} \\ w_{iz} \\ u_{jx} \\ v_{jy} \\ w_{jz} \end{Bmatrix} \qquad (10)$$

W

Where U is the nodal displacements vector for a bar element in 3D structures. Element stiffness matrix for the dome structure is calculated by the using Eq.11.

$$[K]_{ij}^{e} = \frac{EA}{L}\begin{bmatrix} 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (11)$$

$$[T] = \begin{bmatrix} \gamma_X & \gamma_Y & \gamma_Z & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \gamma_X & \gamma_Y & \gamma_Z \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (12)$$

Where, "E" is Young modulus, "L" is length of the element and A is the cross-sectional area of the bar element.

The element stiffness matrix created in the element axes must be transformed to the global axes by using the transformation matrix. To calculate the transformation matrix, direction cosines given in the Fig. 2 are used. Where X,Y,Z are the global axes, x,y,z are the local exes and α, β, γ are the angles for the bar element with the global direction X,Y and Z, respectively.

The transformation matrix is given in the Eq.12. where the γ_x, γ_y, γ_z are the cosine angles of the α, β, γ, respectively.

$$\gamma_x = \cos\alpha = \frac{x_j - x_i}{L} \qquad (13)$$

$$\gamma_y = \cos\beta = \frac{y_j - y_i}{L} \qquad (14)$$

$$\gamma_z = \cos\gamma = \frac{z_j - z_i}{L} \qquad (15)$$

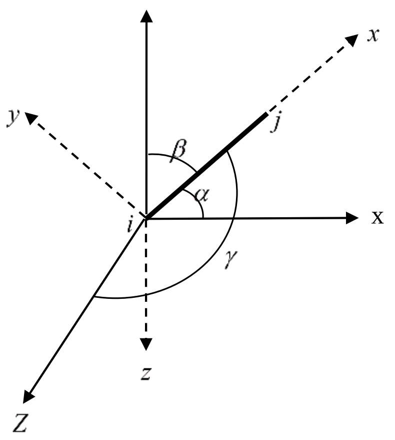


Fig. 2 Local and global axes for 3D truss element

The element stiffness matrix in the global axes can be formed by the following equation. Then, the stiffness matrix for all structure is created by assembling the element stiffness matrix.

$$[K]_{ij}^{s} = [T]^{T}.[K]_{ij}^{e}.[T] \qquad (16)$$

$$[K] = \sum_{k=1}^{n}[K]_{ij}^{s} \quad \text{k=1,...,n} \qquad (17)$$

Where "n" is the number element. The lumped mass matrix is given in the Eq. 18.

$$[M]_{i}^{e} = \frac{\rho LA}{6}\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{i=1,...,n} \qquad (18)$$

The structural mass matrix is created by assembling the element mass matrix.

$$[M] = \sum_{i=1}^{n}[M]_{i}^{e} \quad \text{k=1,...,n} \qquad (19)$$

After the assembling, structural stiffness matrix and mass matrix, the general equation for the natural frequency of the structures can be written as;

$$K\Phi - \omega^2 M\Phi = 0 \qquad (20)$$

Where "ω" is the frequency and "Φ" is the vibration modes. To solve this equation the "eigen" comments in Maltab is used in the developed program.

4. Jaya algorithm

Rao (2016) presented a metaheuristic optimization technique called Jaya not only constrained but also unconstrained optimization problems. Jaya uses a randomly

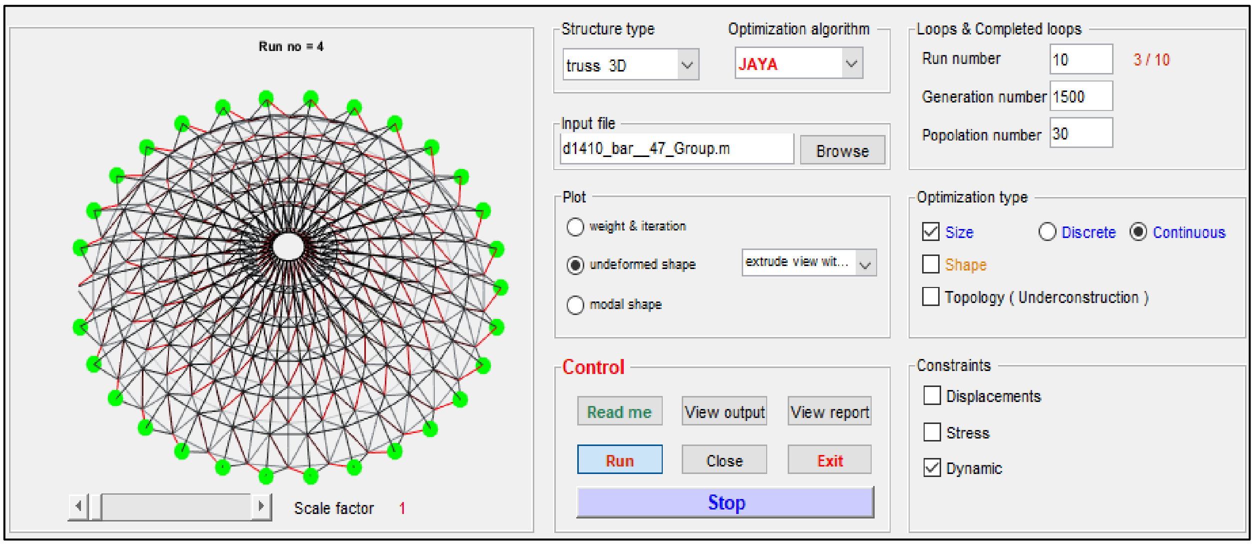


Fig. 3 The general viewing of the visually developed program

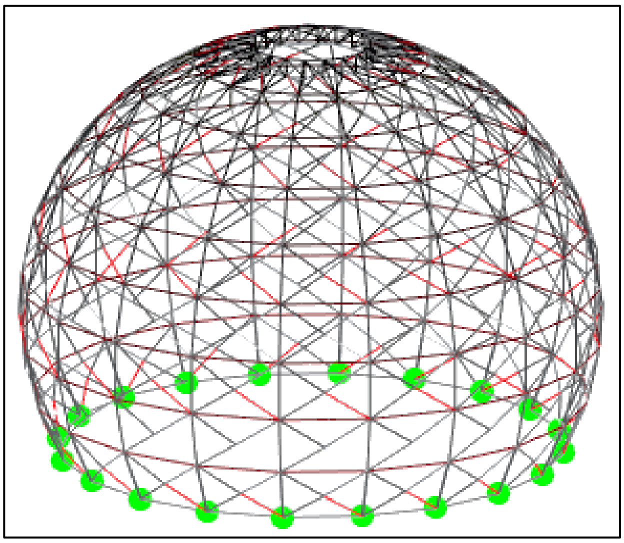


Fig. 4 1180 bar large-scale dome structure

Table 1 Constraints and material data for 1180 bar dome

Symbols	Definitions	value	unit
E	Modulus of elasticity	200	GPa
ρ	Material density	7850	kg/m^3
m	Non-structural mass	100 for all free nodes	kg
A	Cross-sectional area	$1\text{x}10^{-4} \le A \le 100\text{x}10^{-4}$	m^2
ω	Frequency constraints	$\omega_{1,2} \ge 7,\ \omega_{3,4,5} \ge 9$	Hz

generated initial population like the other population based optimization technique. When this algorithm updating the individuals which are the possible solution for the optimization problem uses the best and the worst individuals in the current population. As a main rule of this algorithm, Jaya tends to try to be close the best individual and avoids from the worst individual to find the best individual for the next population. In the Jaya algorithm, the main equation for the ith iteration is given in Eq. (21)

$$X^{new}_{j,k,i} = X_{j,k,i} + \left[r_{1,j,i}\left(X_{j,best,i} - \left| X_{j,k,i} \right| \right) \right] - \left[r_{2,j,i}\left(X_{j,worst,i} - \left| X_{j,k,i} \right| \right) \right] \tag{21}$$

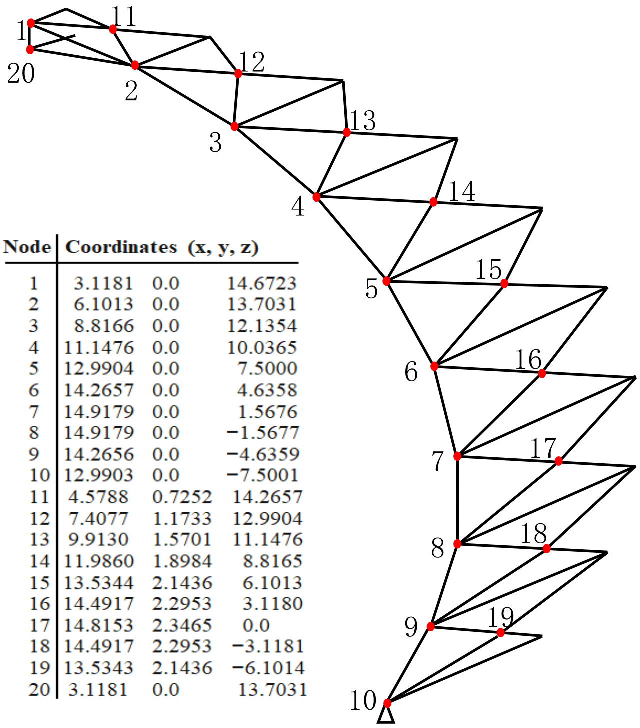
Where, “r” is the random number and “X” represents any individual in the current population. By using this equation, if the new created individual (*Xnew*) is better than its previous state, the new individual is accepted for the next iteration. To determine the quality of individuals the objective function of the problem is used. In this equation, the square brackets with positive sign is used to be close to the best individual and the he square brackets with negative sign is used to avoid from the worst individual. As seen from the Eq.(21), the Jaya algorithm has a simple form to carried out the optimization problem. The algorithm doesn’t use many optimization parameters. In the other words, the Jaya algorithm is basically a parameter-less optimization algorithm and does not require any algorithm-specific parameter. Because of this advantage, Jaya algorithm has a very easy implement in the optimization process. Detailed knowledge about this algorithm can be found in Rao (2016).

5. Numerical examples

In this study, two different large-scale dome structures are examined with the frequency constraints. One of them is the 1180 bar dome structure and the other one is the 1410 bar dome structure. In the optimization process, the population size and the number of iteration is taken as 30 and 1500, respectively.

As mentioned in the introduction section, the general viewing of the visually developed program is given in Fig. 3. by using this program 10 independent runs is carried out for each examples. The computer properties are: Intel (R) Core(TM) i3-5005U CPU @ 2.00GHz and 4 GB of Ram.

For two examples the materials properties, lower and the upper bounds of the cross-sectional areas of the design variables which are the bar elements of the dome structures and the frequency constraint are the same and they are given in the Table 1.



Node	Coordinates (x, y, z)		
1	3.1181	0.0	14.6723
2	6.1013	0.0	13.7031
3	8.8166	0.0	12.1354
4	11.1476	0.0	10.0365
5	12.9904	0.0	7.5000
6	14.2657	0.0	4.6358
7	14.9179	0.0	1.5676
8	14.9179	0.0	−1.5677
9	14.2656	0.0	−4.6359
10	12.9903	0.0	−7.5001
11	4.5788	0.7252	14.2657
12	7.4077	1.1733	12.9904
13	9.9130	1.5701	11.1476
14	11.9860	1.8984	8.8165
15	13.5344	2.1436	6.1013
16	14.4917	2.2953	3.1180
17	14.8153	2.3465	0.0
18	14.4917	2.2953	−3.1181
19	13.5343	2.1436	−6.1014
20	3.1181	0.0	13.7031

Design variable configurations		
Group number	**Stage 2 18 element**	**Stage 1 8 element**
1	1 6 11	1 6 11 15 19
2	15 19	23 27 31 35
3	23 27	4 10 14 18 22
4	31 35	26 30 34 38 40
5	4 10	2 7 41 42 8 12 43 44 13 16 45 46
6	14 18 22	17 20 47 48 21 24 49 50 25 28 51 52
7	26 30	29 32 53 54 33 36 55 56 37 39 57 58
8	34 38 40	3 5 9 59
9	2 7 41 42	
10	8 12 43 44	
11	13 16 45 46	
12	17 20 47 48	
13	21 24 49 50	
14	25 28 51 52	
15	29 32 53 54	
16	33 36 55 56	
17	37 39 57 58	
18	3 5 9 59	

Note: for stage 3, configurations of 59 elements a given in the first column of the Table 2.

Fig. 5 Details for the sub-structure of the 1180 bar large-scale dome structure

5.1 1180-bar large-scale dome structure

As a first example, the 1180-bar large-scale dome structure is given in the Fig.4. This example was previously examined by Kaveh and Ghazaan (2016) by using Enhanced colliding bodies optimization (ECBO). This dome structure has 1180 bar elements and 400 nodes. To create the full geometry of this structure the sub-structure module is given in the Fig. 5. This structure is design for three stages. There are 8, 18 and 59 elements for the stage 1, 2, and 3, respectively. The nodal connections for the elements are given in the first column of the Table 2.

To compare the results with the literature, the optimal results obtained in this study and the results given by the Kaveh and Ghazaan (2016) are shown in Table 2. As seen from this table, not only the weight of the dome structure but also the average weight of the structure and the standard deviation on average weight are better than the result given in literature. In the other words, the Jaya algorithm gives a good performance according to the literature.

In this table, $\overline{x}$ is the average optimized weight and σ is the standard deviation on average weight.

The natural frequencies obtained from the best results are given in the Table 3. As seen from this table, the frequencies calculated for the optimal results are not violating the frequencies constraints. For the best results, the convergence histories are given in the Figure 6.

In the case of 8 groups, the best results, average results and the standard deviation on average weight are 43541.4799 kg, 43546.9646 kg and 3.0932 kg, respectively. The cross-sectional are for the optimal results are: [8.4623; 36.4302; 10.2406; 21.4232; 8.1631; 11.5888; 29.90582; 3.5867] cm^2 and the obtained natural frequencies are: [7.0000; 7.0000; 9.0011; 9.0011; 9.1921] Hz.

In the case of 18 groups, the best results, average results and the standard deviation on average weight are 39603.4177 kg, 39612.5565 kg and 6.2852 kg, respectively. The cross-sectional are for the optimal results are: [7.0012; 10.6389; 21.9795; 44.7401; 12.4743; 7.9064; 13.6473; 23.6179; 8.7483; 6.2008; 6.5201; 8.4447; 10.7739; 13.6831; 18.6224; 25.8895; 35.9319; 3.2359] cm^2 and the obtained natural frequencies are: [7.0001; 7.0001; 9.0006; 9.0006; 9.0848] Hz.

5.2 1410-bar large-scale dome structure

As a second example, the 1410-bar large-scale dome structure is given in the Fig.7. This example was previously examined by Kaveh and Ghazaan (2016) by using Enhanced colliding bodies optimization (ECBO). This dome structure has 1410 bar elements and 390 nodes. To create the full geometry of this structure the sub-structure module is given in the Fig. 8. This structure is design for three stages. There are 10, 20 and 47 elements for the stage 1, 2, and 3, respectively. The nodal connections for the elements are given in the first column of the Table 4.

Table 2 Optimal results for 1180-bar dome with 59 groups

Element number (nodes)	Areas (cm^2)			
	Kaveh and Ghazaan (2016)		This study	
	ECBO	Cascade	Iter: 1500	Iter: 2000
1(1–2)	7.6678	8.011	7.4902	7.2951
2(1–11)	11.1437	8.7028	10.288	10.0202
3(1–20)	1.852	3.1616	2.8154	2.2254
4(1–21)	14.5563	13.682	14.3818	14.4745
5(1–40)	4.9499	3.2865	3.2997	3.1635
6(2–3)	6.8095	6.0397	7.0717	6.1055
7(2–11)	6.6803	8.437	7.1267	7.4452
8(2–12)	6.7889	6.4122	6.5986	6.1321
9(2–20)	1.063	2.6346	2.081	2.0210
10 (2–22)	9.1602	11.744	11.1052	11.6685
11 (3–4)	6.9891	7.9272	7.0249	6.7546
12 (3–12)	6.9881	5.4548	5.4783	5.6377
13 (3–13)	6.9555	6.7221	7.2631	7.0624
14 (3–23)	7.5443	8.1544	6.766	7.0211
15 (4–5)	9.5431	9.756	9.2738	9.1227
16 (4–13)	6.9123	6.5905	7.9777	5.6027
17 (4–14)	8.9891	7.0392	8.1812	7.5350
18 (4–24)	6.8926	6.9219	6.8833	7.4734
19 (5–6)	12.6128	11.6919	11.8537	12.9880
20 (5–14)	8.1983	9.889	8.0856	7.3120
21 (5–15)	11.8358	9.3316	10.075	10.0703
22 (5–25)	9.7321	9.1093	8.2918	9.4058
23 (6–7)	19.165	18.1212	15.9571	17.2086
24 (6–15)	10.4682	10.6725	9.8801	10.6750
25 (6–16)	14.1178	13.534	11.6648	12.5926
26 (6–26)	11.14567	12.0248	11.0499	11.6369
27 (7–8)	23.4125	23.1245	24.2095	21.4858
28 (7–16)	15.5167	15.263	13.3378	13.5946
29 (7–17)	16.6613	18.3075	17.6358	17.4000
30 (7–27)	15.9631	15.2361	16.7628	14.5421
31 (8–9)	37.0532	40.0749	32.4883	35.4919
32 (8–17)	22.2937	18.4775	20.6652	18.6342
33 (8–18)	22.7409	26.0689	23.9697	25.3160
34 (8–28)	23.5624	21.2213	20.1878	22.2539
35 (9–10)	47.7652	46.3724	51.6804	51.4201
36 (9–18)	22.5066	23.6689	27.3289	24.9577
37 (9–19)	34.6418	35.0703	32.4601	34.5291
38 (9–29)	31.6492	27.9369	31.51	32.2597
39 (10–19)	32.7268	34.2912	36.697	35.6710
40 (10–30)	1.05206	1.0726	1.0005	1.0445
41 (11–21)	11.3681	8.5106	9.0174	9.6966
42 (11–22)	6.5512	6.8664	6.4358	7.0081
43 (12–22)	6.3619	5.8229	5.4054	6.5742
44 (12–23)	5.9296	5.3986	6.1835	5.6216
45 (13–23)	7.8739	8.0669	6.8674	7.1827
46 (13–24)	6.2794	6.9797	6.7361	6.1849
47 (14–24)	7.6206	7.2735	8.6935	7.7539
48 (14–25)	7.2937	9.1827	8.591	7.6625
49 (15–25)	10.5783	10.6227	9.2928	9.8545
50 (15–26)	10.1173	11.574	9.0195	10.4573
51 (16–26)	15.1088	15.5194	13.941	15.2639
52 (16–27)	12.8251	14.1342	15.3832	13.1448
53 (17–27)	17.4375	17.1612	16.901	16.1681
54 (17–28)	20.1153	19.0798	19.4671	18.1630
55 (18–28)	24.2121	23.4414	26.7748	23.4467
56 (18–29)	23.3175	26.5726	25.5598	27.4008
57 (19–29)	34.6196	33.4104	33.2553	34.1134
58 (19–30)	35.297	37.1198	37.4924	35.3212
59 (20–40)	8.8569	4.7593	5.0902	4.1362
Weight (kg)	37984.39	37770.71	37575.29	37439.44
$\bar{x}$ (kg)	38042.15	37885.15	37596.35	37453.56
σ (kg)	101.43	133.84	11.4975	5.9071

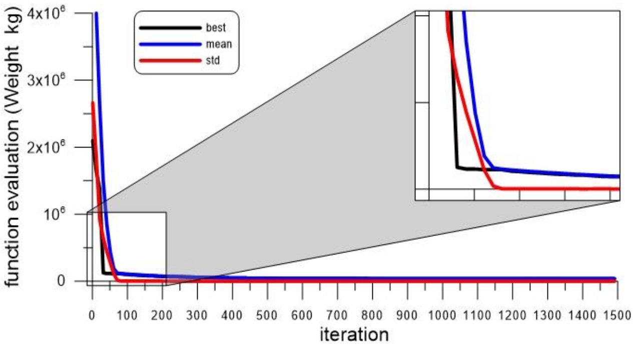


Fig. 6 The convergence history of the weight, mean and standard deviation on weight for the 1180 bar dome structure

Table 3 Natural frequencies (Hz) for the optimal results of the 1180-bar dome

Frequency number	Kaveh and Ghazaan (2016)		This study	
	ECBO (non-cascade)	Cascade opt.	Iter = 1500	Iter = 2000
1	7.000	7.000	7.0001	7.0001
2	7.001	7.001	7.0001	7.0001
3	9.000	9.002	9.0016	9.0002
4	9.000	9.002	9.0016	9.0002
5	9.064	9.062	9.0095	9.0259

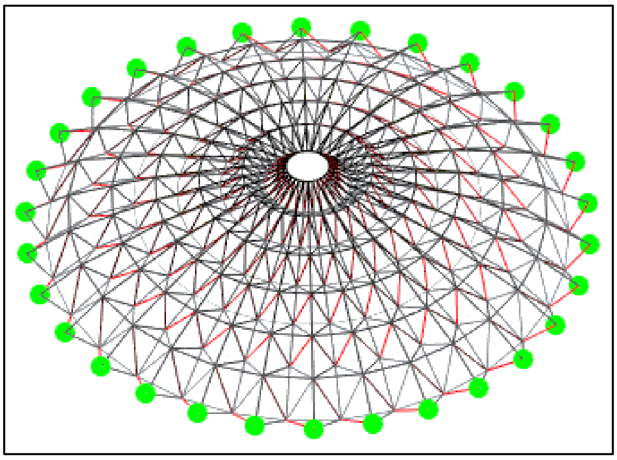


Fig. 7 1410 bar large-scale dome structure

At the end of the optimization process, the obtained best results for the1410 bar dome structures are compared in the Table 4. The best solution, mean solution and the standard deviation on average weight of the structure obtained by using Jaya algorithm are better than the results given in literature. Also, the natural frequencies obtained from the best results are given in the Table 5. As seen from this table, the frequencies calculated for the optimal results are not violating the frequencies constraints. For the best results, the convergence histories are given in the Figure 9.

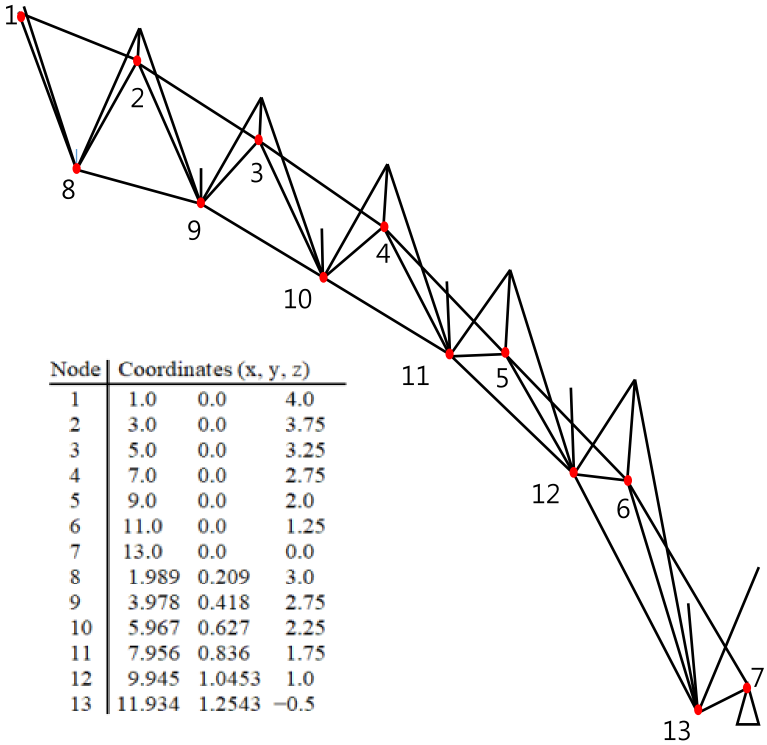
In the case of 10 groups, the best results, average results and the standard deviation on average weight are 11803.5266 kg, 11807.0802 kg and 2.0477 kg, respectively. The cross-sectional are for the optimal results are: [13.2487; 11.4097; 2.7786; 5.8285; 5.1139; 1.8319; 3.1119; 4.2923; 5.0813; 6.7814] cm^2 and the obtained natural frequencies are: [7.0009; 7.0009; 9.0001; 9.0012; 9.0012] Hz.

Table 4 Optimal results for 1410-bar dome with 47 groups

Element number (nodes)	Areas (cm^2)		
	Kaveh and Ghazaan 2016		This study
	ECBO	Cascade opt.	
1(1–2)	7.7765	7.9969	6.6653
2(1–8)	6.2173	6.1723	5.0789
3(1–14)	23.9162	35.5011	33.339
4(2–3)	11.2399	10.251	9.5379
5(2–8)	2.5775	5.3727	5.4172
6(2–9)	1.8559	1.3488	1.7628
7(2–15)	16.9202	11.4427	14.0602
8(3–4)	13.7947	9.7157	9.0404
9(3–9)	5.4502	1.3005	1.9963
10 (3–10)	2.9751	2.5046	2.5228
11 (3–16)	13.7811	10.7849	8.7362
12 (4–5)	9.387	10.1954	10.4295
13 (4–10)	2.3499	2.23	2.3369
14 (4–11)	4.9125	5.1186	4.4866
15 (4–17)	11.8755	14.0053	16.7746
16 (5–6)	8.8668	8.9713	9.6907
17 (5–11)	3.6304	4.0756	3.2888
18 (5–12)	6.2651	5.9211	6.7055
19 (5–18)	15.103	10.6915	11.7489
20 (6–7)	13.1091	10.622	12.8298
21 (6–12)	5.294	4.5064	5.5121
22 (6–13)	5.9929	8.4086	7.7936
23 (6–19)	1	5.8405	1.0357
24 (7–13)	4.9879	5.0342	4.9353
25 (8–9)	3.178	3.8932	2.9911
26 (8–14)	5.9226	6.1647	4.5208
27 (8–15)	2.4607	6.899	5.3977
28 (8–21)	7.571	11.6387	11.3557
29 (9–10)	4.8616	3.8343	3.8486
30 (9–15)	1.5956	1.4772	1.9605
31 (9–16)	4.9084	1.3075	1.6180
32 (9–22)	11.6118	4.4876	3.6639
33 (10–11)	5.2554	6.0196	5.1480
34 (10–16)	2.8687	2.6729	2.5736
35 (10–17)	2.3286	1.6342	3.2355
36 (10–23)	1.6159	1.841	4.1646
37 (11–12)	6.9795	6.8841	6.4193
38 (11–17)	5.3159	4.1393	4.6251
39 (11–18)	2.9915	3.3264	3.4082
40 (11–24)	1.0018	1	1.0165
41 (12–13)	4.1091	6.9376	6.3471
42 (12–18)	6.013	4.4568	6.6384
43 (12–19)	5.8695	4.6758	4.1479
44 (12–25)	1	1.0084	1.1126
45 (13–19)	7.7041	7.5103	6.8687
46 (13–20)	3.76	5.2449	4.6976
47 (13–26)	1.0006	1.055	1.2576
Weight (kg)	10,739.19	10,504.20	10,316.36
$\overline{X}$ (kg)	10,812.20	10,590.67	10,349.06
σ (kg)	64.91	52.51	12.41

$\overline{X}$:Average optimized weight (kg)

σ :Standard deviation on average weight (kg)



Node	Coordinates (x, y, z)		
1	1.0	0.0	4.0
2	3.0	0.0	3.75
3	5.0	0.0	3.25
4	7.0	0.0	2.75
5	9.0	0.0	2.0
6	11.0	0.0	1.25
7	13.0	0.0	0.0
8	1.989	0.209	3.0
9	3.978	0.418	2.75
10	5.967	0.627	2.25
11	7.956	0.836	1.75
12	9.945	1.0453	1.0
13	11.934	1.2543	−0.5

Design variable configurations

Group number	Stage 2 20 element	Stage 1 10 element
1	3 7 11	3 7 11 15 19 23
2	15 19 23	1 4 8 12 16 20
3	1 4 8	28 32 36 40 44 47
4	12 16 20	25 29 33 37 41
5	28 32	2 26 5 27
6	36 40 44 47	6 30 9 31
7	25 29	10 34 13 35
8	33 37 41	14 38 17 39
9	2 26	18 42 21 43
10	5 27	22 45 24 46
11	6 30	
12	9 31	
13	10 34	
14	13 35	
15	14 38	
16	17 39	
17	18 42	
18	21 43	
19	22 45	
20	24 46	

Note: for the stage 3, configurations of 47 elements are given in the first column of the Table 4.

Fig. 8 Details of the sub-structure of the 1410 bar large-scale dome structure

Table 5 Natural frequencies (Hz) for the optimal results of the 1410-bar dome

Frequency number	Kaveh and Ghazaan (2016) ECBO	Kaveh and Ghazaan (2016) Cascade opt.	This study
1	7.008	7.002	7.0053
2	7.008	7.003	7.0053
3	9.001	9.001	9.0014
4	9.012	9.001	9.0024
5	9.012	9.003	9.0024

In the case of 20 groups, the best results, average results and the standard deviation on average weight are 10734.2657 kg, 10743.9653 kg and 5.1722 kg, respectively. The cross-sectional are for the optimal results are: [18.5378; 8.6871; 8.3837; 11.2676; 7.2715; 1.0000; 3.4296; 6.7405; 4.5356; 4.3436; 1.5834; 2.9358; 4.1282; 3.2551; 5.2209; 3.6068; 5.7540; 4.7796; 7.5651; 4.8300] cm^2 and the obtained natural frequencies are: [7.0006; 7.0006; 9.0006; 9.0084; 9.0084] Hz.

As seen from the Fig.6 and Fig.9, the best solution, mean solution and the standard deviation convergence quickly. For each example, the proposed algorithm was able to find better solutions with faster convergence. Even though this property, it is seem that the population of these algorithms lose diversity and get drop the local optimum. To overcome the local optimum some operator such as mutation and crossover can be added to develop the efficiency for the Jaya algorithm. So, the optimal results maybe near to the global optimum solution.

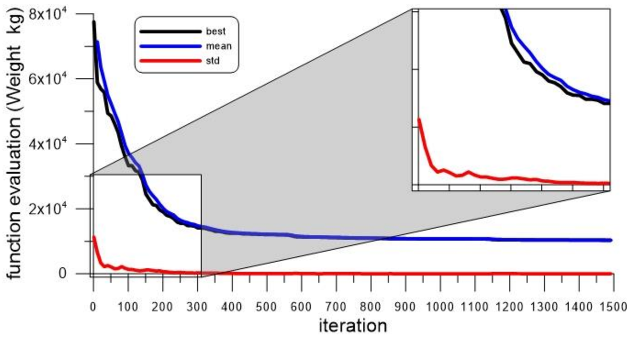


Fig. 9 The convergence history of the weight, mean and standard deviation on weight for the 1410 bar dome structure

6. Conclusion

The main purpose of this study is to make the optimal design of the large-scale dome structure using a metaheuristic algorithm named Jaya. For this aim 2 large-scale domes structure are examined with different grouping. To carry out the optimization process a visual computer codes are developed. This program can take into account the different metaheuristic algorithm and different type of structure such as 2D and 3D truss. The results of this study shows that the proposed algorithm has the best solution by compared the result given in the literature. For the first and the second numerical examples, the obtained weights of the structures are the 37439.44 kg and 10316.36 kg, respectively. It can be concluded that the proposed algorithm can be used in the design of the large-scale structures.

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