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Size/Layout Optimization of Truss Structures Using Shuffled Shepherd Optimization Method

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Abstract

The main purpose of this paper is to investigate the ability of the recently developed multi-community meta-heuristic optimization algorithm, shuffled shepherd optimization algorithm (SSOA), in layout optimization of truss structures. The SSOA is inspired by mimicking the behavior of shepherd in nature. In this algorithm, agents are first divided into communities which are called herd and then optimization process, inspired by the shepherd's behavior in nature, is operated on each community. The new position of agents is obtained using elitism technique. Then communities are merged for sharing the information. The results of SSOA in layout optimization show that SSOA is competitive with other considered meta-heuristic algorithms.

Keywords

meta-heuristic algorithms, shuffled shepherd optimization algorithm, size/layout optimization, truss structures

1 Introduction

Structural optimization is one of the most important field in engineers which has attracted a great deal of attention. Structural optimization can be divided into three categories: (1) size optimization that obtains optimal cross-sections for the structural members; (2) size/layout optimization which finds the optimal form for the structure and cross-sections of the structural members; (3) topology optimization that seeks optimal cross-sections and connectivity between structural members. In layout optimization both sizing and configuration optimization variables are involved and these optimize the material usage leading to economical design of truss structures.

Layout optimization has been investigated by different researchers using different methods. For example Wu and Chow [1] used GA for discrete variables for sections and continuous variables for nodal coordinates, Hasançebi and Erbatur [2] proposed an improved GA by combining the GA with annealing perturbation and adaptive design space reduction strategies, Kaveh and Khayatazad [3] developed the ray optimization, Kaveh and Laknejadi [4] presented a hybrid evolutionary graph based multi-objective algorithm, Kaveh and Zolghadr [5] suggested the democratic PSO, Kaveh et al. [6] presented hybrid PSO and SSO algorithm, Kaveh and Ilchi Ghazaan [7] utilized improved ray optimization, Kaveh and Mahjoubi [8] proposed an improved spiral optimization algorithm for layout optimization of truss structures with frequency constraints, Kazemzadeh Azad et al. [9] utilized big bang-big crunch for layout optimization of truss under dynamic excitation, and Kaveh et al. [10] suggested a modified dolphin monitoring operator for layout optimization of planar braced frames.

Meta-heuristic algorithms can be categorized considering different views [11, 12]. The meta-heuristic algorithms can be categorized based on having one or more communities. As an example, particle swarm optimization (PSO) [13], bat algorithm (BA) [14], cuckoo search algorithm (CS) [15] slap swarm algorithm (SSA) [16], adaptive dimensional search (ADS) [17] and improved ray optimization algorithm (IRO) [18] are single community algorithms, while Shuffled Complex Evolution (SCE) [19], Shuffled Frog-leaping Algorithm (SFLA) [20], improved particle swarm optimization (IPSO) [21], Shuffled artificial bee colony algorithm (Shuffled-ABC) [22] are multi-community optimization algorithms.

As newly developed type of multi-community meta-heuristic algorithm, the shuffled shepherd optimization algorithm (SSOA) is introduced for design of structural

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optimization problem by Kaveh and Zaerreza [23]. This algorithm can be considered as multi-community and multi-agent method, where each community is called a herd and agent is a sheep. Each sheep when selected is called shepherd and move to new position

This paper considers: (i) The SSOA is introduced for optimization of layout problems. (ii) A comprehensive study of layout optimization for truss structures is presented. Some examples are chosen from the literature to verify the effectiveness of the algorithm. These examples are as follows: a 15-member planar truss with 23 design variables, an 18-member planar truss with 12 design variables, A 25-member spatial truss with 13 design variables, 47-member planar truss with 44 design variables, and a large-scale 272-member transmission tower with 72 design variables. The results show that the SSOA is very competitive with other methods in finding best solution.

The present paper is organized as follows: In Section 2 the SSOA is briefly described. In Section 3 four layout optimization of truss structures and a large-scale transmission tower are optimized utilizing the SSOA, and finally conclusions are derived in Section 4.

2 Shuffled shepherd optimization algorithm

The main objective of this section is to extend the application of the recently developed meta-heuristic algorithm called SSOA [23]. In SSOA, each solution candidate X_i containing a number of variables (i.e. $X_i = \{X_{i,j}\}$) are considered as sheep. Each sheep is arranged by its objective function value, and then divided into herds. In each herd the sheep are selected in order, selected sheep are called shepherd and sheep with better objective function in a herd are called horses. Therefore, there are some horses and sheep for each shepherd. A shepherd tries to guide the sheep to the horse, the new position of the shepherd is achieved by moving to one of the sheep and horse. This is done for two purposes: (i) moving to worse agent causes exploration; (ii) and moving to a better member results in exploitation. New position of shepherd update when new objective function is not worse than old objective function, this leads to an elitism in the algorithm.

The SSOA procedure can briefly be outlined as follows:

1) The SSOA parameters α_0, β_0, β_{max}, $iter_{max}$, h, s are set.

Where $iter_{max}$ is a maximum iteration number, 'h' is the number of herds; and 's' is the number of sheep in each herd.

2) The initial position of the ith sheep is determined randomly in an m-dimensional search space by the following equation (Eq. (1)):

$$X_i^0 = X_{\min} + rand \circ (X_{\max} - X_{\min}) \quad i = 1, 2, ..., n , \tag{1}$$

where X_i^0 is the initial solution vector of the ith sheep, X_{max} and X_{min} are the bound of design variables, $rand$ is a random vector with each component being in the interval [0,1], and the number of components are equal to the number of variables, n is the number of sheep (n is equal to $h \times s$) and sign '$\circ$' denotes element-by-element multiplication.

3) The value of the objective function for each sheep is evaluated and sorted by their objective function in an ascending order. To build the herds, spread the sheep to the herd. The first h sheep are selected and put randomly in each herd (put one sheep in each herd). Then select the second h sheep and put them in a herd again. This process is continued until all sheep are assigned into herd.

4) Select each sheep on a herd form first to the last one. Selected sheep is shepherd, sheep in herd better than shepherd is called horses. Select randomly one of the horses and the sheep; step size for each shepherd is calculated by

$$Stepsize_i = \beta \times rand \circ (X_d - X_i) + \alpha \times rand \circ (X_j - X_i), \tag{2}$$

where X_i, X_d, X_j are solution vectors of the shepherd, selected horse and selected sheep in an m-dimensional search space, respectively; $rand$ is a random vector which each component is in interval [0,1] and we have the number of components based on the number of components of solution vectors; α and β calculate by Eq. (3) and Eq. (4), respectively.

$$\propto = \alpha_0 - \frac{\alpha_0}{iter_{\max}} \times iteration \tag{3}$$

$$\beta = \beta_0 + \frac{\beta_{\max} - \beta_0}{iter_{\max}} \times iteration \tag{4}$$

First sheep selected in herd does not have better than itself so the first term of the step size is zero; and for the last sheep selected in herd which does not have worse than itself, the second term of the step size is zero.

5) The temple solution vector for each sheep calculate by the following equation (Eq. (5)):

$$X_i^{temple} = X_i^{old} + stepsize_i . \tag{5}$$

If temple objective function is not worse than old objective function, then the position of the sheep is changed, so we have $X_i^{new} = X_i^{temple}$, otherwise the position of the shepherd is not changed and we have $X_i^{new} = X_i^{old}$. After position of the all sheep is updated merged the herds for sharing information.

6) The optimization is repeated from step 3 until a termination criterion, specified as the maximum number of iterations, is satisfied

The pseudo-code of the SSOA is presented in Algorithm 1

3 Numerical examples

The ability of the SSOA is tested using five layout optimization problems. Four of these problems include discrete sizing variables and continuous configuration variables, and in the last example sizing and configuration variables are continuous. Parameter settings of the SSOA and the number of iteration limits on numeric examples are listed in Table 1.

3.1 The 15-bar planar truss structure

The first layout optimization problem is the 15-bar planar truss subjected to traversal load of 10 kip as shown in Fig. 1. The optimization problem includes 15 discrete sizing variables for the cross-section areas and 8 continuous layout variables for nodal coordinates. All members are subjected to stress limitation of ± 25 ksi. Optimization variables and input data of the truss are given in Table 2.

Algorithm 1 Pseudo-code of the SSOA algorithm

```
Procedure SSOA
  Initialize algorithm parameters
  Initial position by Eq. (1)
  The value of objective function of sheep is evaluated
  While iteration < maximum iteration
    Sort sheep by objective function
    Build herds
    For each herd
      For each sheep
        The horse and sheep are chosen
        The step size calculated by Eq. (2)
        Temple solution vector calculated by Eq. (5)
        The value of objective function of temple solution is evaluated
          If temple objective function isn't worse than old objective function
            Solution vector is updated
          End if
      End for
    End for
  merged the herds
  End while
End procedure
```

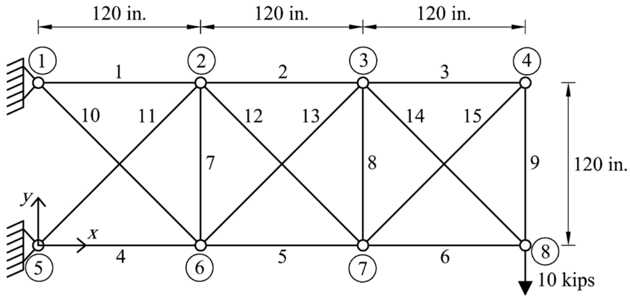

Fig. 1 Schematic of the 15-bar planar truss

Table 3 shows that the SSOA finds the optimal solution with the least number of analyses compared to the other algorithm. Average and standard deviation of the SSOA for 30 independent runs are 78.3675 (lb) and 3.0373 (lb), respectively. Best solution for this problem is 72.5152 that has been found by Kazemzadeh Azad and Jayant Kulkarni [24] but average of 50 independent runs is 79.49 that is more than that of the SSOA. Fig. 2 shows the best

Table 2 Simulation data for the 15-bar planar truss

Sizing variables	Layout variables
A_i, $i = 1, 2, \ldots, 15$	$x_2 = x_6$; $x_3 = x_7$; y_2; y_3; y_4; y_6; y_7; y_8
Possible sizing variables	
$A_i \in S$ = {0.111,0.141,0.174,0.220,0.270,0.287,0.347,0.440,0.539,0.954, 1.081,1.174, 1.333,1.488,1.764,2.142,2.697,2.800,3.131,3.565,3.813, 4.805,5.952,6.572,7.192,8.525, 9.300,10.850,13.330,14.290,17.170, 19.180}(in^2)	
Layout variables bounds	
$100\ in. \le x_2 \le 140\ in.$; $220\ in. \le x_3 \le 260\ in.$; $100\ in. \le y_2 \le 140\ in.$; $100\ in. \le y_3 \le 140\ in.$; $50\ in. \le y_4 \le 90\ in.$; $-20\ in. \le y_6 \le 20\ in.$; $-20\ in. \le y_7 \le 20\ in.$; $20\ in. \le y_8 \le 60\ in.$;	
Young modulus E = 10^4 (ksi)	
Material density ρ = 0.1 (lb/in^3)	

Table 1 Parameters setting and maximum iteration number for the SSOA

Problem	$\propto_0$	β_0	β_{max}	Number of herds	Size of herds	Maximum iteration number
15-bar planar truss	1.5	2	3	4	4	490
18-bar planar truss	0.6	2.3	2.5	4	4	599
25-bar spatial truss	0.5	2.4	2.6	4	4	300
47-bar planer truss	0.5	2	2.3	4	5	1.100
272-bar transmission tower	0.5	2.0	2.4	3	10	1.700

Table 3 Optimum result for the 15-bar planar truss

Design variables	Tang et al. [25]	Rahami et al. [26]	Kazemzadeh Azad et al. [24]	Miguel et al. [27]	Ho-Huu et al. [28]		Present work
				FA	R-ICDE	D-ICDE	SSOA
A_1	1.081	1.081	0.954	0.954	1.081	1.081	0.954
A_2	0.539	0.539	0.539	0.539	0.539	0.539	0.539
A_3	0.287	0.287	0.111	0.220	0.270	0.141	0.111
A_4	0.954	0.954	0.954	0.954	0.954	0.95	0.954
A_5	0.954	0.539	0.539	0.539	0.954	0.539	0.539
A_6	0.220	0.141	0.347	0.22	0.22	0.287	0.347
A_7	0.111	0.111	0.111	0.111	0.111	0.111	0.111
A_8	0.111	0.111	0.111	0.111	0.111	0.111	0.111
A_9	0.287	0.539	0.111	0.287	0287	0.141	0.174
A_{10}	0.220	0.440	0.44	0.440	0.22	0.347	0.44
A_{11}	0.440	0.539	0.44	0.440	0.44	0.44	0.44
A_{12}	0.440	0.270	0.174	0.220	0.44	0.27	0.174
A_{13}	0.111	0.220	0.174	0.220	0.174	0.27	0.174
A_{14}	0.220	0.141	0.347	0.270	0.174	0.287	0.347
A_{15}	0.347	0.287	0.111	0.220	0.347	0.174	0.111
x_2	133.612	101.5775	105.7835	114.967	117.4983	100.0309	111.2513
x_3	234.752	227.9112	258.5965	247.040	242.9729	238.7010	248.7576
y_2	100.449	134.7986	133.6284	125.919	112.3731	132.8471	132.8862
y_3	104.738	128.2206	105.0023	111.067	101.2684	125.3669	109.3964
y_4	73.762	54.8630	54.4546	58.298	54.6397	60.3072	55.1655
y_6	-10.067	-16.4484	-19.929	-17.564	-12.3953	-10.6651	-19.5015
y_7	-1.339	-13.3007	3.6223	-5.821	-14.3909	-12.2457	10.1465
y_8	50.402	54.8572	54.4474	31.465	54.6396	59.9931	52.1898
Weight (lb)	79.820	76.6854	72.5152	75.55	80.5688	74.6818	72.8615
No. of analyses	8,000	8,000	10,000	8,000	7,980	7,980	7,856

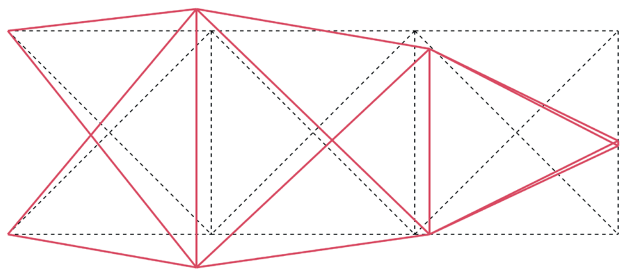

Fig. 2 Comparison of optimized layout for the 15-bar planar truss

shape of the 15-bar planar truss find by the present work. Fig. 3 shows the convergence histories of the best result and the mean performance of 30 independent runs for the 15-bar planar truss.

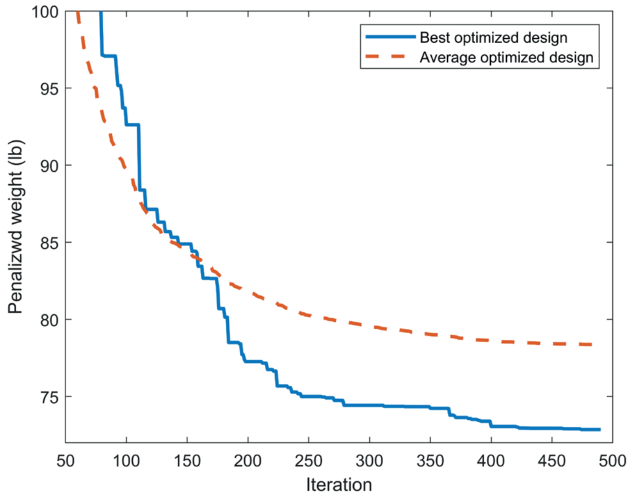

Fig. 3 Convergence histories of the optimization for the 15-bar planar truss

3.2 The 18-bar planar truss structure

For the 18-bar planar truss structure shown in Fig. 4, material density is 0.1 lb/in^3 and the modulus of elasticity is 10,000 ksi. The members are subjected to the stress limit of ± 25 ksi and Euler buckling stresses for compression member (the buckling strength of the ith element is set to $4EA/L^2$). Members are classified into four groups as follows: $A_1 = A_4 = A_8 = A_{12} = A_{16}$; $A_2 = A_6 = A_{10} = A_{14} = A_{18}$; $A_3 = A_7 = A_{11} = A_{15}$; $A_5 = A_9 = A_{13} = A_{17}$. Hence there are four sizing variables for cross section areas which are chosen from following discrete set:

$S = \{2.00, 2.25, 2.50, \ldots, 21.25, 21.50, 21.75\}$ (in^2)
and eight layout variables with the following bounds:
$775\ in. \leq x\_3 \leq 1225\ in.$
$525\ in. \leq x\_5 \leq 975\ in.$
$275\ in. \leq x\_7 \leq 725\ in.$
$25\ in. \leq x\_9 \leq 475\ in.$
$-225\ in. \leq y_3, y_5, y_7, y_9 \leq 245\ in.$

Table 4 presents the optimum designs obtained by the other methods and SSOA. It can be seen that SSOA has found a smaller weight compared to those of Hasançebi and Erbatur [29], Kaveh and Kalatjari [30], Rahami et al. [26] and Ho-Huu et al. [28] but with higher number of analyses than them and found higher weight than Kazemzadeh Azad et al. [24] but with smaller number of analyses, and the average and standard deviation of SSOA for 40 independent runs are 4768.5 (lb) and 474.10 (lb), respectively. Optimum layout found by SSOA is shown in Fig. 5. The convergence curves for the best result and the mean performance of 40 independent runs for the 18-bar planar truss are shown in Fig. 6.

3.3 The 25-bar spatial truss

The third layout optimization problem is the 25-bar spatial truss as shown in Fig. 7. The optimization problem includes 13 design variables containing 8 discrete sizing variables for the cross-section areas and 5 continuous layout variables for nodal coordinate. All members are subjected to stress limitation of ± 40 ksi and all nodal displacement in all directions is limited to ±0.3 in. Optimization variables and input data of this truss are provided in Table 5.

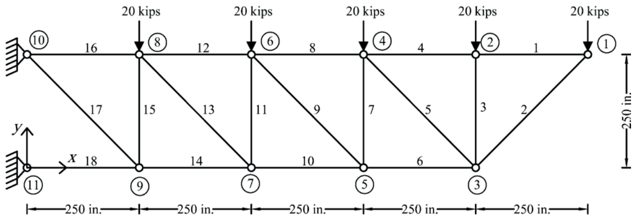

Fig. 4 Schematic of the 18-bar planar truss

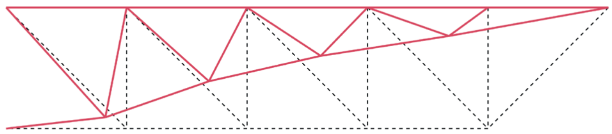

Fig. 5 Comparison of optimized layout for the 18-bar planar truss

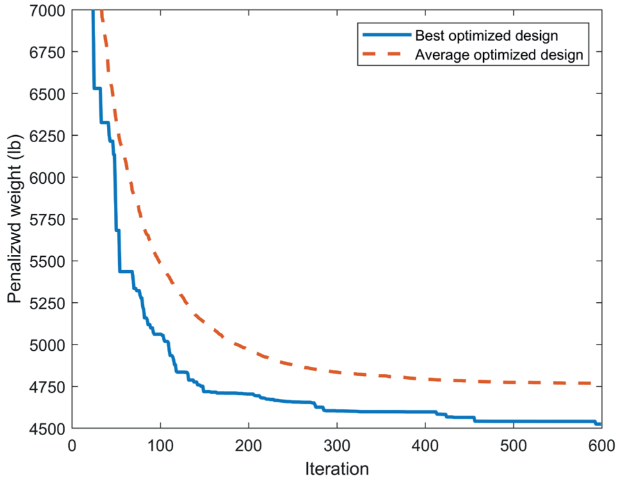

Fig. 6 Convergence histories of the optimization for the 18-bar planar truss

Table 4 Optimum result for the 18-bar planar truss

Design variables	Hasançebi and Erbatur [29]	Kaveh and Kalatjari [30]	Rahami et al. [26]	Kazemzadeh Azad et al. [24]	Ho-Huu et al. [28]		Present work
					R-ICDE	D-ICDE	SSOA
A_1	12.5	12.25	12.75	12.75	12.25	13	12
A_2	18.25	18	18.50	18.25	18	17.5	18
A_3	5.50	5.25	4.75	5	5.5	6.5	5
A_5	3.75	4.25	3.25	3.25	4.5	3	4.5
x_3	933	913	917.4775	916.0812	909.52	914.06	918.8398
y_3	188	186.8	193.7899	191.4300	184.02	183.06	191.2096
x_5	658	650	654.3243	650.0573	646.71	640.53	652.8561
y_5	148	150.5	159.9436	153.4968	147.73	133.74	150.1858
x_7	422	418.8	424.4821	419.4508	416.45	406.12	420.8011
y_7	100	97.40	108.5779	105.5322	96.46	92.63	97.6796
x_9	205	204.8	208.4691	205.6591	204.03	196.69	205.7989
y_9	32	26.70	37.6349	36.4848	25.32	37.06	23.2213
Weight (lb)	4574.28	4547.9	4530.68	4520.2	4591.42	4554.29	4524.94
No. of analyses	N/A	N/A	8,000	10,000	8,025	8,025	9,600

Table 5 Simulation data for the 25-bar spatial truss

Sizing variables			
A1; A2=A3=A4=A5; A6=A7=A8=A9; A10=A11; A12=A13;			
A14=A15=A16=A17; A18=A19=A20=A21; A22=A23=A24=A25			
Layout variables			
$x_4 = x_5 = -x_3 = -x_6; x_8 = x_9 = -x_7 = -x_{10};$			
$y_3 = y_4 = -y_5 = -y_6; y_7 = y_8 = -y_9 = -y_{10};$			
$z_3 = z_4 = z_5 = z_6$			
Possible sizing variables			
$A_i \in S = \{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6,$			
$1.7, 1.8, 1.9, 2.0, 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.8, 3.0, 3.2, 3.4\} \left(in^2\right)$			
Layout variables bounds			
$20\ in. \le x_4 \le 60\ in.;$			
$40\ in. \le x_8 \le 80\ in.;$			
$40\ in. \le y_4 \le 80\ in.;$			
$100\ in. \le y_8 \le 140\ in.;$			
$90\ in. \le z_4 \le 130\ in.;$			
Loads			
nodes	F_x (kips)	F_y (kips)	F_z (kips)
1	1.0	-10	-10
2	0.0	-10	-10
3	0.5	0.0	0.0
6	0.6	0.0	0.0
Young modulus $E = 10^4$ (ksi)			
Material density $\rho = 0.1$ (lb/in^3)			

Table 6 shows that SSOA has found the best solution with the least number of analyses among the other algorithms. Average weight and standard deviation for 30 independent runs are 122.4073 lb and 6.3443 lb, respectively. Optimum layout found by SSOA is shown in Fig. 8.

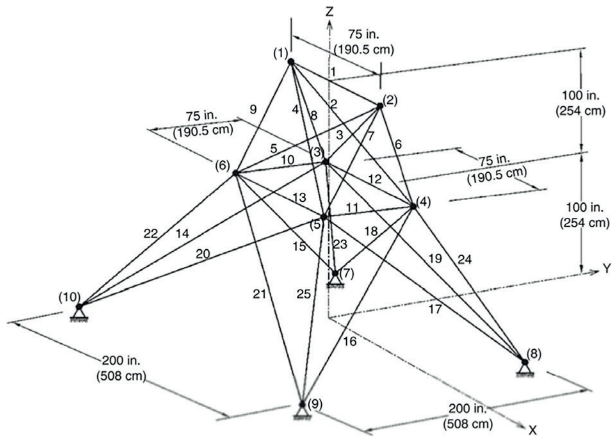

Fig. 7 Schematic of the 25-bar spatial truss

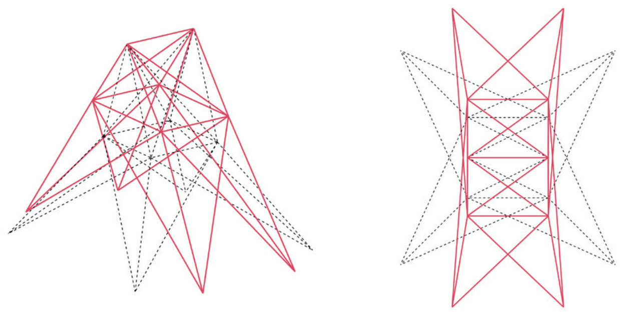

Fig. 8 Comparison of optimized layout for the 25-bar spatial truss

Table 6 Optimum result for the 25-bar spatial truss

Design variables	Wu and Chow [1]	Kaveh and Kalatjari [30]	Tang et al. [25]	Rahami et al. [26]	Ho-Huu et al. [28]		Present work
					R-ICDE	D-ICDE	SSOA
A1	0.1	0.1	0.1	0.1	0.2	0.1	0.1
A2	0.2	0.1	0.1	0.1	0.2	0.1	0.1
A6	1.1	1.1	1.1	1.1	0.9	0.9	1.0
A10	0.2	0.1	0.1	0.1	0.2	0.1	0.1
A12	0.3	0.1	0.1	0.1	0.2	0.1	0.1
A14	0.1	0.1	0.2	0.1	0.2	0.1	0.1
A18	0.2	0.1	0.2	0.2	0.2	0.1	0.1
A22	0.9	1.0	0.7	0.8	1.0	1.0	0.9
x4	41.07	36.23	35.47	33.0487	36.380	36.83	37.6762
y4	53.47	58.56	60.37	53.5663	57.080	58.53	54.4273
z4	124.6	115.59	129.07	129.9092	126.62	122.67	129.9991
x8	50.80	46.46	45.06	43.7826	48.200	49.21	51.9006
y8	131.48	127.95	137.06	136.8381	139.90	136.74	139.5535
Weight (lb)	136.20	124.0	124.943	120.115	145.275	118.76	117.2591
No. of analyses	N/A	N/A	6,000	10,000	6,000	6,000	4,816

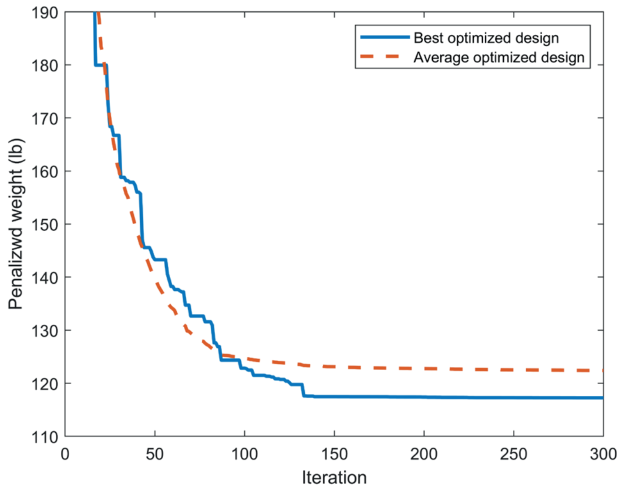

Fig. 9 Convergence histories of the optimization for the 25-bar spatial truss

Convergence curves for the best result and the mean performance of 30 independent runs for the 25-bar spatial truss are shown in Fig. 9.

3.4 47-bar planer truss

The 47-bar planer truss shown in Fig. 10 is optimized by different researchers for three load cases as shown in Table 7. The optimization problem includes 44 design variables containing 27 discrete sizing variables for the cross-section areas and 17 continuous layout variables for nodal coordinate. All members are subjected to stress limitation in tension and compression of 20 ksi and 15 ksi, respectively. Euler buckling stresses for compression members (the buckling strength of the *i*th element) is set to $3.96EA/L^2$, and there is no limitation for nodes displacement. Optimization variables and input data of truss are given in Table 7.

Comparison of the optimal design by this work with optimum designs obtained by Salajegheh and Vanderplaats [31], Hasançebi and Erbatur [2, 29] and Panagant and Bureerat [32] is provided in Table 8. It can be seen that SSOA found the lightest weight (1869.876 lb) in less number of analyses (20,020), with average and standard deviation being 1929.91 lb and 29.55 lb, respictivly. Optimum layout found by SSOA is shown in Fig 11. Fig. 12 shows the convergence curves for the best result and the mean performance of 30 independent runs for the 47-bar planar truss.

3.5 The 272-bar transmission tower

Last layout optimization problem is the optimization of 272-bar transmission tower shown in Fig. 13. The 272-bar transmission tower first time presented by Kaveh and

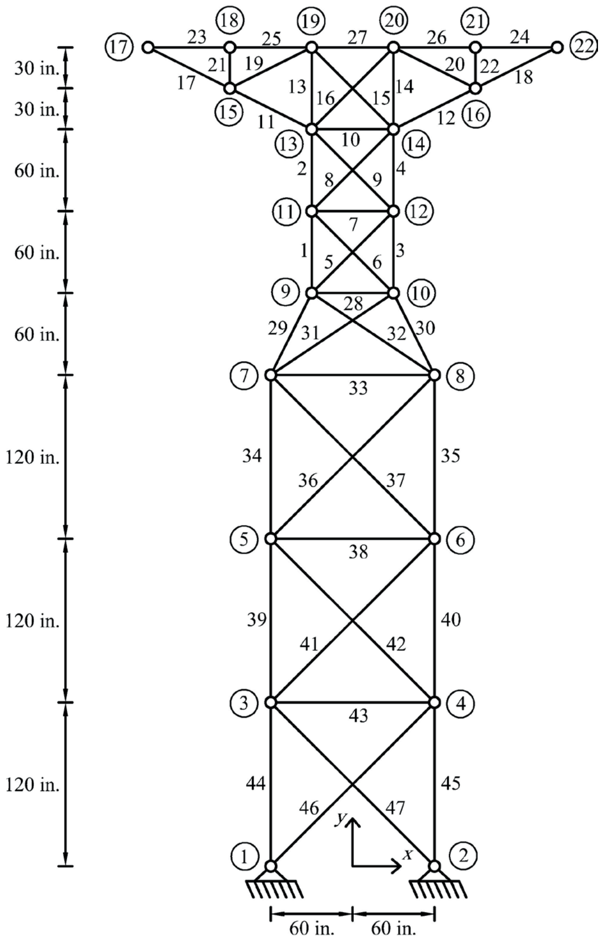

Fig. 10 Schematic of the 47-bar planar truss

Table 7 Simulation data for the 47-bar planar truss

Sizing variables			
$A_3 = A_1$; $A_4 = A_2$; $A_5 = A_6$; A_7; $A_8 = A_9$; A_{10}; $A_{12} = A_{11}$; $A_{14} = A_{13}$; $A_{15} = A_{16}$; $A_{18} = A_{17}$; $A_{20} = A_{19}$; $A_{22} = A_{21}$; $A_{24} = A_{23}$; $A_{26} = A_{25}$; A_{27}; A_{28}; $A_{30} = A_{29}$; $A_{31} = A_{32}$; A_{33}; $A_{35} = A_{34}$; $A_{36} = A_{37}$; A_{38}; $A_{40} = A_{39}$; $A_{41} = A_{42}$; A_{43}; $A_{45} = A_{44}$; $A_{46} = A_{47}$			
Layout variables			
$x_2 = -x_1; x_4 = -x_3; y_4 = y_3; x_6 = -x_5; y_6 = y_5; x_8 = -x_7; y_8 = y_7;$ $x_{10} = -x_9; y_{10} = y_9; x_{12} = -x_{11}; y_{12} = y_{11}; x_{14} = -x_{13}; y_{14} = y_{13};$ $x_{20} = -x_{19}; y_{20} = y_{19}; x_{21} = -x_{18}; y_{21} = y_{18}$			
Possible sizing variables			
$A_i \in S = \{0.1, 0.2, 0.3, 0.4, \ldots, 4.8, 4.9, 5.0\}(in^2)$			
Loads			
case	Nodes	F_x (kips)	F_y (kips)
1	17	6.0	-14.0
	22	6.0	-14.0
2	17	6.0	-14.0
3	22	6.0	-14.0
Young modulus $E = 3 \times 10^4$ (ksi)			
Material density $\rho = 0.3$ (lb/in^3)			

Table 8 Optimum result for the 47-bar planar truss

Design variables	Salajegheh and Vanderplaats [29]	Hasançebi and Erbatur [2]	Hasançebi and Erbatur [25]	Panagant and Bureerat [30]	Present work SSOA
A_3	2.61	2.5	2.5	2.7	2.8
A_4	2.56	2.2	2.5	2.6	2.5
A_5	0.69	0.7	0.8	0.7	0.7
A_7	0.47	0.1	0.1	0.1	0.1
A_8	0.80	1.3	0.7	0.8	1.0
A_{10}	1.13	1.3	1.3	1.2	1.1
A_{12}	1.71	1.8	1.8	1.7	1.8
A_{14}	0.77	0.5	0.7	0.8	0.7
A_{15}	1.09	0.8	0.9	0.9	0.8
A_{18}	1.34	1.2	1.2	1.3	1.5
A_{20}	0.36	0.4	0.4	0.3	0.4
A_{22}	0.97	1.2	1.3	1.0	1.0
A_{24}	1.00	0.9	0.9	1.0	1.1
A_{26}	1.03	1.0	0.9	1.0	1.0
A_{27}	0.88	3.6	0.7	0.9	5.0
A_{28}	0.55	0.1	0.1	0.1	0.1
A_{30}	2.59	2.4	2.5	2.6	2.7
A_{31}	0.84	1.1	1.0	0.9	0.9
A_{33}	0.25	0.1	0.1	0.1	0.1
A_{35}	2.86	2.7	2.9	2.8	3.0
A_{36}	0.92	0.8	0.8	1.1	0.8
A_{38}	0.67	0.1	0.1	0.1	0.1
A_{40}	3.06	2.8	3.0	3.0	3.2
A_{41}	1.04	1.3	1.2	1.1	1.1
A_{43}	0.10	0.2	0.1	0.1	0.1
A_{45}	3.13	3.0	3.2	3.1	3.3
A_{46}	1.12	1.2	1.1	1.1	1.1
x_2	107.76	114	104	109.61	100.5396
x_4	89.15	97	87	93.078	81.0279
y_4	137.98	125	128	126.65	137.2003
x_6	66.75	76	70	70.752	63.8334
y_6	254.47	261	259	246.32	254.1838
x_8	57.38	69	62	56.172	56.1445
y_8	342.16	316	326	356.26	327.9040
x_{10}	49.85	56	53	48.498	48.2708
y_{10}	417.17	414	412	436.37	407.5132
x_{12}	44.66	50	47	42.37	42.4458
y_{12}	475.35	463	486	490.66	468.8267
x_{14}	41.09	54	45	41.61	45.8692
y_{14}	513.15	524	504	521.04	515.2907
x_{20}	17.90	1.0	2.0	1.4026	0.0010
y_{20}	597.92	587	584	597.36	586.9443
x_{21}	93.54	99	89	95.312	80.7351
y_{21}	623.94	631	637	625.99	621.5769
Weight (lb)	1900	1925.79	1871.7	1871.7	1869.876
No. of analyses		100,000	N/A	187,488	22,020

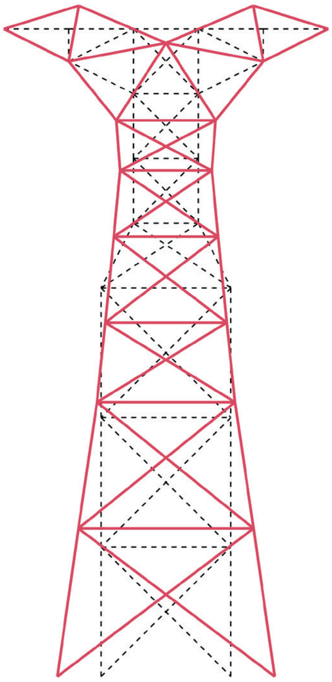

Fig. 11 Comparison of optimized layout for the 47-bar planar truss

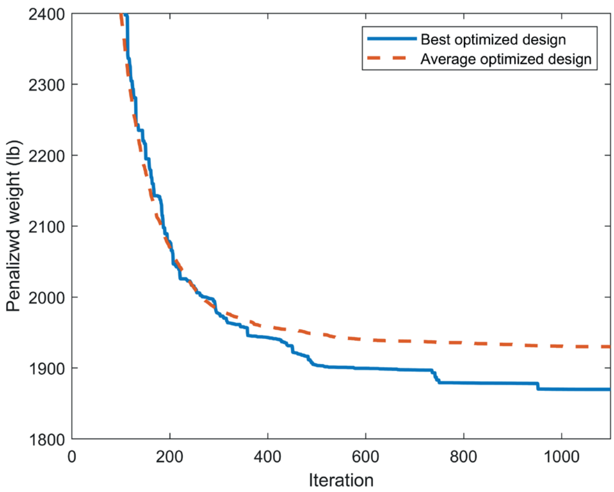

Fig. 12 Convergence histories of the optimization for the 47-bar planar truss

Massoudi [33] for size optimization with one single load case and Kaveh and Zaerreza [23] added 11 load cases to the basic load case as indicated in Table 9.

In this paper layout variables are added to this problem and all nodes are considered to be free to move in all direction. Nodes 1, 2, 11, 20, 29 are fixed and 62, 63, 64, 65 are fixed in the z-direction. Nodal coordinate, grouping members and end nodes of the members are available in [33]. The optimization problem includes 72 design variables containing 28 continuous sizing variables for the cross-section areas and 44 continuous layout variables for nodal coordinate. The modulus of elasticity is 2×10^8 kN/m^2 and

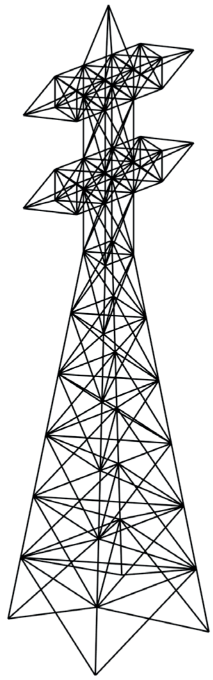

Fig. 13 Schematic of the 272-bar transmission tower

all members are subjected to stress limitation of ±275000 kN/m^2, Euler buckling stresses for compression members (the buckling strength of the ith element is set to $4EA/L^2$) and displacement of nodes 1, 2, 11, 20, 29 are limited to 20 mm in Z-direction and to 100 mm in X- direction and Y- direction. Optimization variables of truss are given in Table 10.

Optimum volume found by SSOA is presented in Table 11. Optimum volume obtained by Kaveh and Zaerreza [23] without configuration variables has been 1168200.624, that is 36.93 percent more that value obtained by the present work. This indicates that optimization processes of this structure need configuration variables. Maximum stresses ratio is 0.89 which has happened in load Case 1 in element 263, and average volume and standard deviation for 30 independent runs are 764061.589 cm^3 and 15485.12 cm^3, respictively. Displacements for nodes 1, 2, 11, 20, 29 are shown in Fig. 14. Optimum layout found by SSOA is shown in Fig. 15. The convergence curves for the best result and the mean performance of 30 independent runs for the 272-bar transmission tower are illustrated in Fig. 16.

4 Conclusions

In this paper, the capability of the new meta-heuristic algorithm so-called Shuffled Shepherd Optimization algorithm in layout optimization of structure is investigated. SSOA is a multi-community algorithm that mimics the shepherd behavior in nature.

Table 9 Loading condition for the 272-bar transmission tower

Case	Force direction	Nodes					
		1	2	11	20	29	Other free nodes
	F_x (kN)	20	20	20	20	20	5
1	F_y (kN)	20	20	20	20	20	5
	F_z (kN)	-40	-40	-40	-40	-40	0
	F_x (kN)	0	20	20	20	20	5
2	F_y (kN)	0	20	20	20	20	5
	F_z (kN)	0	-40	-40	-40	-40	0
	F_x (kN)	20	0	20	20	20	5
3	F_y (kN)	20	0	20	20	20	5
	F_z (kN)	-40	0	-40	-40	-40	0
	F_x (kN)	20	20	20	0	20	5
4	F_y (kN)	20	20	20	0	20	5
	F_z (kN)	-40	-40	-40	0	-40	0
	F_x (kN)	20	0	0	0	0	5
5	F_y (kN)	20	0	0	0	0	5
	F_z (kN)	-40	0	0	0	0	0
	F_x (kN)	0	20	0	0	0	5
6	F_y (kN)	0	20	0	0	0	5
	F_z (kN)	0	-40	0	0	0	0
	F_x (kN)	0	0	0	20	0	5
7	F_y (kN)	0	0	0	20	0	5
	F_z (kN)	0	0	0	-40	0	0
	F_x (kN)	0	0	20	20	20	5
8	F_y (kN)	0	0	20	20	20	5
	F_z (kN)	0	0	-40	-40	-40	0
	F_x (kN)	0	20	20	0	20	5
9	F_y (kN)	0	20	20	0	20	5
	F_z (kN)	0	-40	-40	0	-40	0
	F_x (kN)	0	0	20	0	20	5
10	F_y (kN)	0	0	20	0	20	5
	F_z (kN)	0	0	-40	0	-40	0
	F_x (kN)	0	0	0	20	20	5
11	F_y (kN)	0	0	0	20	20	5
	F_z (kN)	0	0	0	-40	-40	0
	F_x (kN)	0	0	20	20	0	5
12	F_y (kN)	0	0	20	20	0	5
	F_z (kN)	0	0	-40	-40	0	0

In order to demonstrate the ability of the SSOA in layout optimization problems, four classic layout optimization problems (consisting of the optimization of 15-bar planar truss,18-bar planar truss, 25-bar spatial truss and 47-bar planar truss) and one large scale problem (optimization of 272-bar transmission tower) are performed by the SSOA. For the 15-bar planer truss, the solution found by SSOA is only 0.3463 lb more than the best solution found by other method but with smaller number of analyses among the others. In the 18-bar planar truss best solution is found by SSOA which is only 0.1 percent more than other method. In the 25-bar spatial truss and in 47-bar planar truss SSOA has found best solution with less number of analyses among the others and the result of 272-bar spatial truss shows that this problem needs configuration variables for improving the optimal solution. In SSOA both worst and

Table 10 Simulation data for the 272-bar transmission tower

Sizing variables
Group1, Group2, Group3, …, Group28
Layout variables
$x_{10}=x_9=-x_4=-x_3; y_{10}=y_4=-y_3=-y_9; z_{10}=z_9=z_4=z_3;$
$x_8=x_7=-x_5=-x_6; y_8=y_6=-y_5=-y_7; z_8=z_7=z_6=z_5;$
$x_{19}=x_{18}=-x_{12}=-x_{13}; y_{19}=y_{13}=-y_{12}=-y_{18}; z_{19}=z_{18}=z_{13}=z_{12};$
$x_{17}=x_{16}=-x_{14}=-x_{15}; y_{17}=y_{15}=-y_{14}=-y_{16}; z_{17}=z_{16}=z_{15}=z_{14};$
$x_{28}=x_{27}=-x_{21}=-x_{22}; y_{28}=y_{22}=-y_{21}=-y_{27}; z_{28}=z_{27}=z_{22}=z_{21};$
$x_{26}=x_{25}=-x_{23}=-x_{24}; y_{26}=y_{24}=-y_{23}=-y_{25}; z_{26}=z_{25}=z_{24}=z_{23};$
$x_{37}=x_{36}=-x_{30}=-x_{31}; y_{37}=y_{31}=-y_{30}=-y_{36}; z_{37}=z_{36}=z_{31}=z_{30};$
$x_{35}=x_{34}=-x_{32}=-x_{33}; y_{35}=y_{33}=-y_{32}=-y_{34}; z_{35}=z_{34}=z_{33}=z_{32};$
$x_{41}=x_{40}=-x_{38}=-x_{39}; y_{41}=y_{39}=-y_{38}=-y_{40}; z_{41}=z_{40}=z_{39}=z_{38};$
$x_{45}=x_{44}=-x_{42}=-x_{43}; y_{45}=y_{43}=-y_{42}=-y_{44}; z_{45}=z_{44}=z_{43}=z_{42};$
$x_{49}=x_{48}=-x_{46}=-x_{47}; y_{49}=y_{47}=-y_{46}=-y_{48}; z_{49}=z_{48}=z_{47}=z_{46};$
$x_{53}=x_{52}=-x_{50}=-x_{51}; y_{53}=y_{51}=-y_{50}=-y_{52}; z_{53}=z_{52}=z_{51}=z_{50};$
$x_{57}=x_{56}=-x_{54}=-x_{55}; y_{57}=y_{55}=-y_{54}=-y_{56}; z_{57}=z_{56}=z_{55}=z_{54};$
$x_{61}=x_{60}=-x_{58}=-x_{59}; y_{61}=y_{59}=-y_{58}=-y_{60}; z_{61}=z_{60}=z_{58}=z_{59};$
$x_{65}=x_{64}=-x_{62}=-x_{63}; y_{65}=y_{63}=-y_{62}=-y_{64}$
Layout variables bounds
$1\le x_{10},x_{19},x_{28},x_{37}\le 2.25$
$0.1\le x_8,x_{17},x_{26},x_{35}\le 0.9$
$0.1\le x_{45},x_{41}\le 1.5$
$0.1\le x_{49},x_{53}\le 2$
$0.1\le x_{57},x_{61}\le 2.5$
$0.1\le x_{65}\le 3$
$0.1\le y_{10},y_8,y_{19},y_{17},y_{28},y_{26},y_{37},y_{35},y_{41}\le 1$
$0.1\le y_{45},y_{49},y_{53},y_{57},y_{61},y_{65}\le 1$
$17.3\le z_{10},z_8\le 19$
$15.5\le z_{19},z_{17}\le 16.6$
$14.9\le z_{28},z_{26}\le 15.4$
$13.8\le z_{37},z_{35}\le 14.811\le z_{41}\le 13.7$
$9.6\le z_{45}\le 10.9$
$7.5\le z_{49}\le 9.5$
$5.6\le z_{53}\le 7.4$
$3.6\le z_{57}\le 5.5$
$1\le z_{61}\le 3.5$
Possible sizing variables
1000 mm^2 ≤ Group1, Group2, ..., Group28 ≤ 16.000 mm^2
Young modulus E = 2 × 108 (KN/m^2)

Table 11 Optimum design cross-section for the 272-bar transmission tower

Design variables	Present work	Design variables	Present work
Group 1	1000.2	z_{19}	16.1015
Group 2	1000.0	x_{17}	0.7327
Group 3	1000.2	y_{17}	0.4548
Group 4	1000.0	z_{17}	15.5185
Group 5	3412.4	x_{28}	1.2562
Group 6	1000.4	y_{28}	0.1003
Group 7	3786.5	z_{28}	15.1170
Group 8	1003.0	x_{26}	0.7572
Group 9	1008.1	y_{26}	0.4915
Group 10	1003.2	z_{26}	15.1625
Group 11	4498.3	x_{37}	1.1038
Group 12	1001.0	y_{37}	0.1902
Group 13	1000.1	z_{37}	14.3021
Group 14	1000.4	x_{35}	0.8821
Group 15	4615.9	y_{35}	0.6002
Group 16	1000.3	z_{35}	13.9793
Group 17	1000.0	x_{41}	0.9384
Group 18	1005.6	y_{41}	0.7835
Group 19	4826.0	z_{41}	12.3261
Group 20	1000.4	x_{45}	1.0161
Group 21	1001.7	y_{45}	0.9049
Group 22	1001.4	z_{45}	10.7022
Group 23	5092.8	x_{49}	1.1052
Group 24	1000.8	y_{49}	0.9440
Group 25	1008.1	z_{49}	8.9221
Group 26	1007.6	x_{53}	1.2439
Group 27	5072.8	y_{53}	1.0765
Group 28	1000.8	z_{53}	7.1762
x_{10}	1.0311	x_{57}	1.5098
y_{10}	0.1003	y_{57}	1.2954
z_{10}	17.3610	z_{57}	4.9926
x_8	0.2283	x_{61}	1.9012
y_8	0.4300	y_{61}	1.6430
y_8	17.30005	z_{61}	2.4470
x_{19}	1.0000	x_{65}	2.3101
y_{19}	0.2649	y_{65}	1.9996
Volume(cm^3)			736814.944
No. of analyses			51,030

better agents have role in optimization process and results of the present study show that considering the worst agents in the optimization process can improve the performance of the algorithm and leads to better design.

Compliance with ethical standards

Conflict of interest: No potential conflict of interest was reported by the authors.

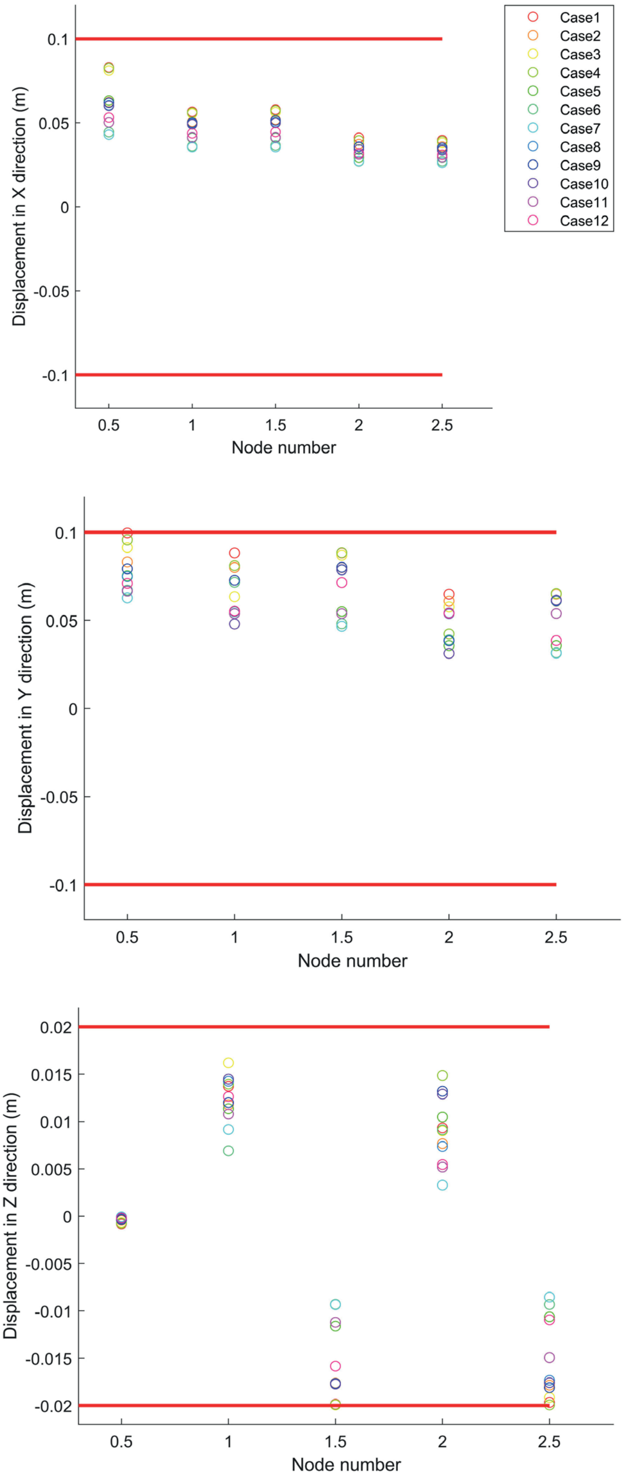

Fig. 14 Compression of allowable and existing displacements for the 272-bar transmission tower

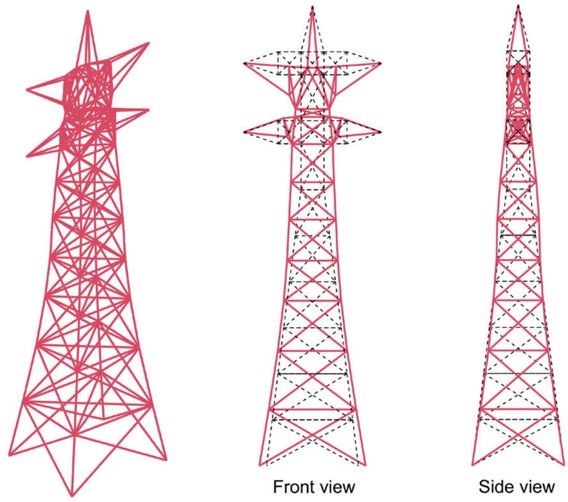

Fig. 15 Comparison of optimized layout for the 272-bar transmission tower

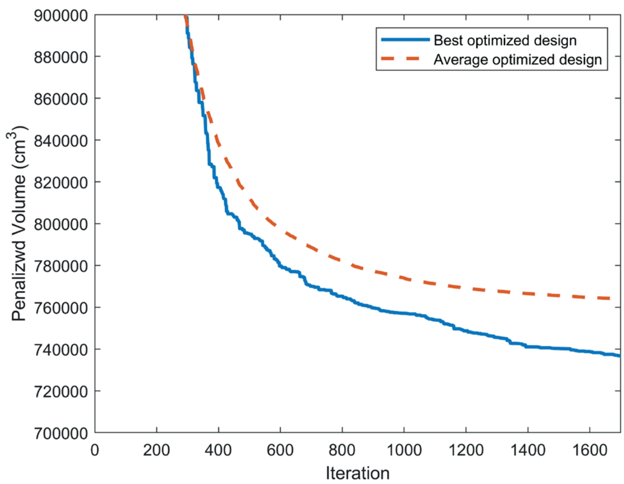

Fig. 16 Convergence histories of the optimization for the 272-bar transmission tower

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