

## IMPROVED BAT ALGORITHM FOR OPTIMUM DESIGN OF LARGE-SCALE TRUSS STRUCTURES

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### ABSTRACT

Deterring the optimum design of large-scale structures is a difficult task. Great number of design variables, largeness of the search space and controlling great number of design constraints are major preventive factors in performing optimum design of large-scale truss structures in a reasonable time. Meta-heuristic algorithms are known as one of the useful tools to deal with these problems. This paper presents an improved bat algorithm for optimizing large-scale structures. The capability of the algorithm is examined by comparing the resulting design parameters and structural weight with those of other methods from literature.

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### 1. INTRODUCTION

In the field of optimization, finding optimum design of structures are known one of difficult and complex problems. Engineers can often perform suitable designs by some trial and error approaches for small structures. However for large-scale ones, great number of design variables, largeness of the search space, and controlling great number of design constraints are major preventive factors in performing optimum design in a reasonable time [1]. Therefore, using optimization algorithms to solve such difficult problems is inevitable. In general, the optimization methods are divided into two groups, known as mathematical

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methods and meta-heuristic ones. The first group often uses gradient values of functions (or its approximated values) and can find local optimum points with a small effort. However, in contrast to meta-heuristic algorithms, they cannot guarantee reaching the global point (or even near to it) for large-scale problems with non-convex and non-smooth search spaces.

The lack of dependency on gradient information, inherent capability to deal with both discrete and continuous design variables and automated global search features to produce near-optimum solutions (if not the global optimum) for complicated problems directed the researchers toward using meta-heuristic algorithms [2]. Therefore, meta-heuristic algorithms are known to be robust tools for dealing with today's large-scale engineering problems of increased complexity. These approaches are derivative-free methods and make use of the ideas inspired from the nature or social phenomenon, such as the biological evolutionary process (e.g., genetic algorithm (GA) [3], differential evolution (DE) [4] and biogeography-based optimization (BBO) [5]), physical phenomena (e.g. simulated annealing (SA) [6], charged system search (CSS) [7,8], Colliding Bodies Algorithm (CBO) [9]) or animal behavior (e.g., particle swarm optimization (PSO) [10], ant colony optimization (ACO) [11], artificial bee colony (ABC) [12], ant cuckoo search (CS) [13], firefly algorithm (FA) [14], krill herd (KH) [15] and bat algorithm (BA) [16]), etc. A detailed review of these algorithms as well as their applications in engineering optimization problems can be found in Yang et al. [17] and Kaveh [18].

In this paper, the BA is slightly improved and applied to optimal design of large-scale truss structures. Bat Algorithm (BA) has been developed based on the echolocation behavior of microbats. An extensive review of BA and its new variants can be found in the work of Yang and He [19]. They reviewed a wide range of diverse applications and case studies on this algorithm. However, because of the newness of BA compared to other techniques, few articles have been published concerning its application in structural optimization problems. Gandomi et al. [20] utilized BA to solve several constraint optimization problems. Optimum design of truss structures for minimizing the weight subject to stress, stability and displacement constraints according to American Institute of Steel Construction-Allowable Stress Design (AISC-ASD) specification is performed in [2]. Kaveh and Zakian [21] applied this algorithm to optimize some benchmark truss and frame structures. Also, BA is applied to discrete size optimization of steel frames by Hasançebi and Carbas [22].

The mechanism proposed in this paper is tested on two large-scale benchmark truss structures. Numerical results are compared to those of other methods available in literature. The performance study demonstrates the efficiency of the proposed method.

## 2. INTRODUCTION TO BAT ALGORITHM

In order to make the paper self-explanatory, the characteristics of BA is briefly explained in the following sub-sections.

### 2.1. Standard bat algorithm (BA)

BA is a multi-agent approach that simulates the behavior of microbats [23–24]. In echolocation, each pulse only lasts a few thousandths of a second (up to about 8–10 ms).

Nevertheless, it has a constant frequency which is usually in the range of 25–150 kHz corresponding to the wavelengths of 2–14 mm. In BA, the echolocation properties of microbats can be idealized as the following rules [16]:

1. All bats use echolocation to sense distance, and they also “know” the difference between food/prey and background barriers in some magical way;

2. Bats randomly fly with velocity  $v_i$  at position  $x_i$  with a fixed frequency  $f_{min}$ , varying wavelength  $k$  and loudness  $A_0$  to search for prey. They can automatically adjust the wavelength (or frequency) of their emitted pulses and adjust the rate of pulse emission  $r \in [0,1]$ , depending on the proximity of their target;

3. Although the loudness can vary in many ways, it is assumed that the loudness varies from a large (positive)  $A_0$  to a minimum constant value  $A_{min}$ .

The basic steps of BA can be summarized as the pseudo-code shown in Fig. 1, [20].

For each bat ( $i$ ), its position  $x_i$  and velocity  $v_i$  in a  $d$ -dimensional search space should be defined.  $x_i$  and  $v_i$  should also be subsequently updated during the iterations. The new solutions  $x_i^t$  and velocities  $v_i^t$  at time step  $t$  can be calculated by:

$$f_i = f_{min} + (f_{max} - f_{min})\beta \tag{1}$$

$$v_i^t = v_i^{t-1} + (x_i^{t-1} - x^*)f_i \tag{2}$$

$$x_i^t = x_i^{t-1} + v_i^{t-1} \tag{3}$$

where  $\beta$  in the range of  $[0,1]$  is a random vector drawn from a uniform distribution. Here,  $x^*$  is the current global best location (solution), which is located after comparing all the solutions among all the  $n$  bats. As the product  $\lambda_i f_i$  is the velocity increment, either  $f_i$  (or  $\lambda_i$ ) can be used to adjust the velocity change while fixing the other factor  $\lambda_i$  (or  $f_i$ ), depending on the type of the problem of interest. For implementation,  $f_{min} = 0$  and  $f_{max} = 100$  are used, depending on the domain size of the problem of interest. Initially, each bat is randomly assigned a frequency that is drawn uniformly from  $[f_{min}, f_{max}]$ .

For the local search part, once a solution is selected among the current best solutions, a new solution for each bat is generated locally using a local random walk, as

$$x_{new} = x_{old} + \varepsilon A^t \tag{4}$$

where the random number  $\varepsilon$  is drawn from  $[-1,1]$ , while  $A^t = \langle A_i^t \rangle$  is the average loudness of all the bats at this time step. The update of the velocities and positions of bats have some similarities to the procedure in the standard particle swarm optimization as  $f_i$  essentially controls the pace and range of the movement of the swarming particles. To a degree, BA can be considered as a balanced combination of the standard particle swarm optimization and the intensive local search controlled by the loudness and pulse rate. Once a bat found its prey, the loudness usually decreases and the rate of pulse emission increases. In this case, the loudness can be chosen as any value of convenience. For simplicity,  $A_0 = 1$  and  $A_{min} = 0$  can be used. Assuming  $A_{min} = 0$  means that a bat has just found the prey and temporarily stop emitting any sound, we have:

$$A_i^{t+1} = \alpha A_i^t \quad (5)$$

$$r_i^{t+1} = r_i^0 (1 - e^{-\gamma t}) \quad (6)$$

where  $\alpha$  and  $\gamma$  are constants. In the simplest case,  $\alpha = \gamma$  can be used. For the simulations in this study,  $\alpha = \gamma = 0.9$ , Ref. [6].

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Objective function  $f(x)$ ,  $x = (x_1, \dots, x_d)^T$ 
Initialize the bat population  $x_i$  ( $i = 1, 2, \dots, n$ ) and  $v_i$ 
Define pulse frequency  $f_i$  at  $x_i$ 
Initialize pulse rates  $r_i$  and the loudness  $A_i$ 
while ( $t < \text{Max number of iterations}$ )
    Generate new solutions by adjusting frequency,
    and updating velocities and locations/solutions
    if ( $\text{rand} > r_i$ )
        Select a solution among the best solutions
        Generate a local solution around the selected best solution
    end if
    Generate a new solution by flying randomly
    if ( $\text{rand} < A_i \ \& \ f(x_i) < f(x^*)$ )
        Accept the new solutions
        Increase  $r_i$  and reduce  $A_i$ 
    end if
    Rank the bats and find the current best  $x^*$ 
end while
Postprocess results and visualization

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Figure 1. Pseudo-code of the bat algorithm (BA)

## 2.2. Improved BA

Exploration ability of the bat algorithm is acceptable, however its convergence speed needs to be improved for large-scale problems in order to reduce the required number of iterations. Here, the average loudness of bats,  $A^t$  is defined dynamically as [21]:

$$A_i^{t+1} = A_i^{\max} e^{c \cdot t}, \quad c = \frac{\ln(A_i^{\max} - A_i^{\min})}{t_{\max}} \quad (7)$$

where  $A_i^{\max}$  and  $A_i^{\min}$  are the minimum and maximum values for  $A_i$ , respectively.  $t_{\max}$  stands for maximum number of iterations. Proper tuning of this parameter reduces the number of the iterations

Also in the improved BA, a microbat is allowed to update its echolocation parameters each time when it produces a solution that surpasses its individual best, not the global best necessarily, [2]. Also, the Eq. (6) is modified as follows for adaptation of pulse rate parameter, [2]:

$$r_i^{t+1} = 1 - (1 - r_i^0) \gamma^{t+1} \leq r_{\max} \quad (8)$$

Eq. (6) facilitates a more gradual change of pulse rate parameter from its initial (minimum) value of  $r_i^0$  towards  $r_{\max}$ , whereas in Eq. (8) the pulse rate immediately approaches  $r_{\max}$  in a few iterations and remains stationary at this value thereafter, Ref. [2]. A graphical comparison of the Eq. (6) and Eq. (8) is presented in Fig. 2.

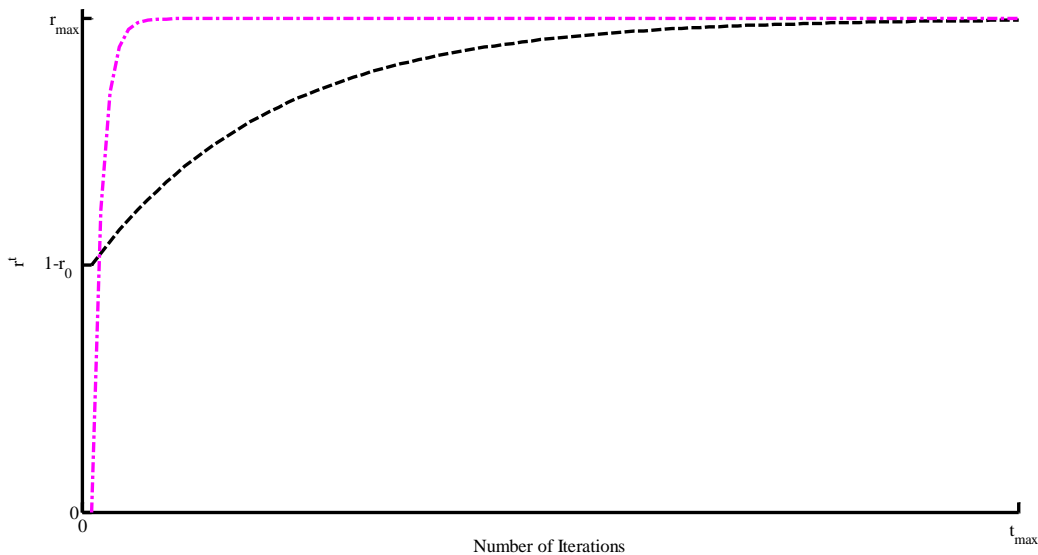


Figure 2. Comparison of pulse rate adaptation strategies

### 3. STRUCTURAL OPTIMIZATION PROBLEMS

#### 3.1 Statement of the optimization design problem

The general formulation of the weight minimization problem for a truss structure is as follows:

$$\begin{aligned} &\text{minimize} && W(x) = \sum_{i=1}^n \rho_i \cdot x_i \cdot L_i \\ &\text{subject to :} && \delta_{\min} \leq \delta_i \leq \delta_{\max} && i = 1, 2, \dots, m \\ &&& \sigma_{\min} \leq \sigma_i \leq \sigma_{\max} && i = 1, 2, \dots, n \\ &&& \sigma_i^b \leq \sigma_i \leq 0 && i = 1, 2, \dots, nc \\ &&& x_{\min} \leq x_i \leq x_{\max} && i = 1, 2, \dots, ng \end{aligned} \quad (9)$$

where  $W(x)$  is the weight of the structure;  $n$  is the number of members making up the structure;  $m$  represents the number of nodes;  $nc$  denotes the number of compression elements;  $ng$  is the number of groups (number of design variables);  $\rho_i$  is the material density of member  $i$ ;  $L_i$  denotes the length of member  $i$ ;  $x_i$  represents the cross-sectional

area of member  $i$  chosen from the set of areas between  $x_{\min}$  and  $x_{\max}$ ;  $min$  is the lower bound and  $max$  is the upper bound;  $\sigma_i$  and  $\delta_i$  are the stress and nodal deflection respectively;  $\sigma_i^b$  denotes allowable buckling stress in member  $i$  when it is in compression.

### 3.2 Constraint handling

The penalty function is utilized to handle the constraints. After analyzing a structure, the deflection of each node and the stress in each member are obtained. These values are compared with allowable limits to calculate the penalty functions as:

$$\begin{cases} \sigma_i^{\min} < \sigma_i < \sigma_i^{\max} & \Rightarrow \Phi_{\sigma}^{(i)} = 0 \\ \sigma_i^{\min} > \sigma_i \text{ or } \sigma_i^{\max} < \sigma_i & \Rightarrow \Phi_{\sigma}^{(i)} = \frac{\sigma_i - \sigma_i^{\min/\max}}{\sigma_i^{\min/\max}} \end{cases} \quad i = 1, 2, \dots, n \quad (10)$$

$$\begin{cases} \sigma_b < \sigma_i < 0 & \Rightarrow \Phi_{\sigma b}^{(i)} = 0 \\ \sigma_k < 0 \wedge \sigma_i < \sigma_b & \Rightarrow \Phi_{\sigma b}^{(i)} = \frac{\sigma_i - \sigma_b}{\sigma_b} \end{cases} \quad i = 1, 2, \dots, nc \quad (11)$$

$$\begin{cases} \delta_i^{\min} < \delta_i < \delta_i^{\max} & \Rightarrow \Phi_{\delta}^{(i)} = 0 \\ \delta_i^{\min} > \delta_i \text{ or } \delta_i^{\max} < \delta_i & \Rightarrow \Phi_{\delta}^{(i)} = \frac{\delta_i - \delta_i^{\min/\max}}{\delta_i^{\min/\max}} \end{cases} \quad i = 1, 2, \dots, m \quad (12)$$

In optimizing structures, objective is to find the minimum amount of merit function. Merit function is defined as

$$Mer^k = \varepsilon_1 \cdot W^k + \varepsilon_2 \cdot (\Phi_{\sigma}^k + \Phi_{\delta}^k + \Phi_{\sigma b}^k)^{\varepsilon_3} \quad (13)$$

Here,  $Mer^k$  is the merit function for ant  $k$ ;  $\varepsilon_1$ ,  $\varepsilon_2$  and  $\varepsilon_3$  are the coefficients of merit function.  $\Phi_{\sigma}^k$ ,  $\Phi_{\delta}^k$  and  $\Phi_{\sigma b}^k$  are the summation of stress penalties, summation of nodal deflection penalties and summation of buckling stress penalties for ant  $k$ , respectively.

For multiple loadings, after analyzing the structure and determining the penalty functions for each component of the load, the total penalty function is calculated through addition of penalty functions of stress, buckling stress for each member, and deflection for each node, as:

$$Mer^k = \varepsilon_1 \cdot W^k + \varepsilon_2 \cdot \sum_{i=1}^{np} (\Phi_{\sigma(i)}^k + \Phi_{\delta(i)}^k + \Phi_{\sigma b(i)}^k)^{\varepsilon_3} \quad (14)$$

where  $np$  is the number of multiple loadings. In this paper, for a better control on other parameters,  $\varepsilon_1$  is set to 1 and the coefficient  $\varepsilon_2$  is taken as the weight of the structure and the coefficient  $\varepsilon_3$  is set in a way that the penalties decrease. In the first iterations of the search process,  $\varepsilon_3$  is set to 1.5 but gradually it is increased to 3, Ref. [1].

#### 4. NUMERICAL EXAMPLES

In this section, two large-scale truss optimization examples are optimized utilizing the presented method. Then the final results are compared to the solutions of other methods to demonstrate the efficiency of this approach. The proposed algorithm is coded in Matlab and structures are analyzed using the direct stiffness method.

##### 4.1 A 244-bar transformation tower

The first example is a 244-bar transmission tower shown in Fig. 3. Members of the transmission tower are initially collected into 26 groups as given by Saka [25] but in this study all members of the transmission tower are linked into 32 groups to enlarge the problem [26]. The value of the modulus of elasticity is taken as 30,450 ksi (210,000 MPa) and the material density is 0.1 lb/in<sup>3</sup> (2767.990 kg/m<sup>3</sup>). The allowable value of 20.30 ksi (140 MPa) is employed for tensile stresses and the formulation of buckling obeying AISC-ASD (1989) [27] code is considered for compressive stresses. The displacement limitations of  $\pm 1.77$  in (4.5 cm) are imposed on nodes 1 and 2, and limitations of  $\pm 1.18$  in (3.0 cm) on nodes 17, 24 and 25 in x-direction. These nodes are subjected to the displacement limits of  $\pm 0.59$  in (1.5 cm) in y-direction. The load cases considered are shown in Table 1. The minimum cross-sectional area of all members is 0.775 in<sup>2</sup> (5.0 cm<sup>2</sup>) and the maximum cross-sectional area is 20.0 in<sup>2</sup> (129.03 cm<sup>2</sup>).

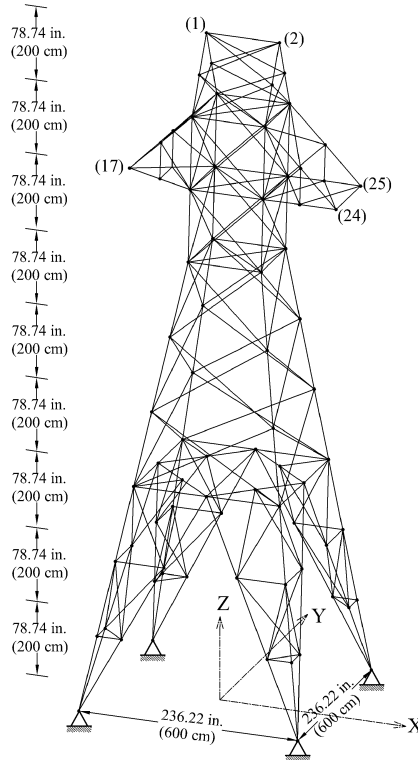


Figure 3. A 244-bar transformation tower

Table 1: Loading conditions for the 244-bar transformation tower

Node	Case 1			Case 2		
	$P_X$ kips (kN)	$P_Y$ kips (kN)	$P_Z$	$P_X$	$P_Y$ kips (kN)	$P_Z$
1	-2.448 (10)	-6.744 (30)	0.0	0.0	-80.899 (360)	0.0
2	2.448 (10)	-6.744 (30)	0.0	0.0	-80.899 (360)	0.0
17	8.568 (35)	-20.224 (90)	0.0	0.0	-40.449 (180)	0.0
24	42.82 (175)	-10.112 (45)	0.0	0.0	-20.224 (90)	0.0
25	42.82 (175)	-10.112 (45)	0.0	0.0	-20.224 (90)	0.0

The maximum number of analyses is 15,000 for the BA. The BA achieves the best solution 2,374.05 kg while the different imperialist competitive algorithm (i.e. CICA, OICA and ICA algorithms [28]) achieves 2,478.95 kg, 2,517.29 kg and 2,562.09 kg, respectively. The HPSACO and PSOPC algorithms [26] achieved 2,415.02 kg and 2,652.56kg, respectively. Clearly, BA algorithm can find the best results comparing the other methods. Although, the differences between the results of HPSACO and BA are small, however it is worth to note that HPSACO utilizes the PSO with two auxiliary tools (ACO and HS) and if one adds these tools to this new algorithm, obviously the resultant method will be improved. Fig. 4 shows the convergence history for the minimum weight of 244-bar transformation tower solved by the BA-based method.

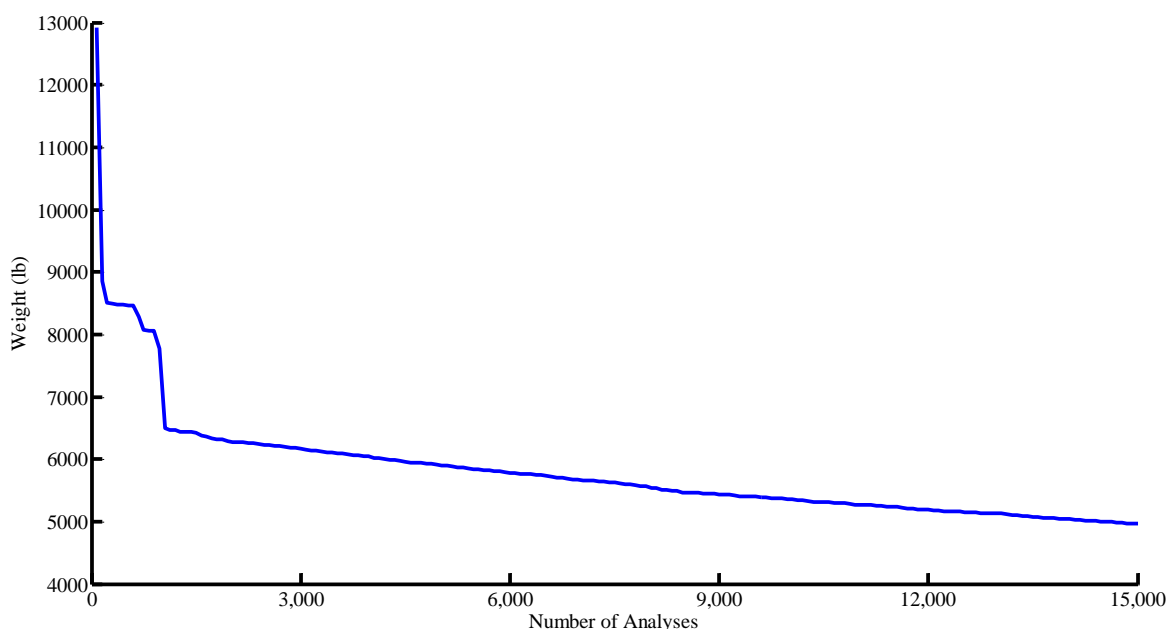


Figure 4. Convergence history of BA for the 244-bar transformation tower

#### 4.2 A 942-bar spatial truss

A 26-story-tower space truss containing 942 elements and 244 nodes is considered as the



second large-scale example. Fifty-nine design variables are used to represent the cross-sectional areas of 59 element groups in this structure, employing the symmetry of the structure. Fig. 5 shows the geometry and the 59 element groups. The material density is  $0.1 \text{ lb/in}^3$  ( $2767.990 \text{ kg/m}^3$ ) and the modulus of elasticity is  $10,000 \text{ ksi}$  ( $68,950 \text{ MPa}$ ). The members are subjected to the stress limits of  $\pm 25 \text{ ksi}$  ( $172.375 \text{ MPa}$ ) and the four nodes of the top level in the x, y, and z directions are subjected to the displacement limits of  $\pm 15.0 \text{ in}$  ( $38.10 \text{ cm}$ ) (about  $1/250$  of the total height of the tower). The allowable cross-sectional areas in this example are selected from  $0.1$  to  $20.0 \text{ in}^2$  (from  $0.6452 \text{ cm}^2$  to  $129.032 \text{ cm}^2$ ). The loading on the structure consists of:

- 1) The vertical load at each node in the first section is equal to  $-3 \text{ kips}$  ( $-13.344 \text{ kN}$ );
- 2) The vertical load at each node in the second section is equal to  $-6 \text{ kips}$  ( $-26.688 \text{ kN}$ );
- 3) The vertical load at each node in the third section is equal to  $-9 \text{ kips}$  ( $-40.032 \text{ kN}$ );
- 4) The horizontal load at each node on the right side in the x direction is equal to  $-1 \text{ kips}$  ( $-4.448 \text{ kN}$ );
- 5) The horizontal load at each node on the left side in the x direction is equal to  $1.5 \text{ kips}$  ( $6.672 \text{ kN}$ );
- 6) The horizontal load at each node on the front side in the y direction is equal to  $-1 \text{ kips}$  ( $-4.448 \text{ kN}$ );
- 7) The horizontal load at each node on the back side in the x direction is equal to  $1 \text{ kips}$  ( $4.448 \text{ kN}$ ).

This example has been optimized using 5 meta-heuristic algorithms, previously. The CSS method [8] achieved a good solution after 15,000 analyses and found an optimum weight of  $47,371 \text{ lb}$  ( $210,716 \text{ N}$ ). The best weights for the GA, PSO, BB-BC and HBB-BC were  $56,343 \text{ lb}$  ( $250,626 \text{ N}$ ),  $60,385 \text{ lb}$  ( $268,606 \text{ N}$ ),  $53,201 \text{ lb}$  ( $236,650 \text{ N}$ ) and  $52,401 \text{ lb}$  ( $233,091 \text{ N}$ ), respectively [1]. The new algorithm can find the best result among others as shown in Table 2. The best result of this algorithm is equal to  $46,015 \text{ lb}$  ( $204,684 \text{ N}$ ). The new algorithm has better performance in terms of standard deviation and the average weight. It converges to a solution after 15,000 analyses of structures in average. Table 3 provides the statistic information for this example and the convergence history is shown in Fig. 6.

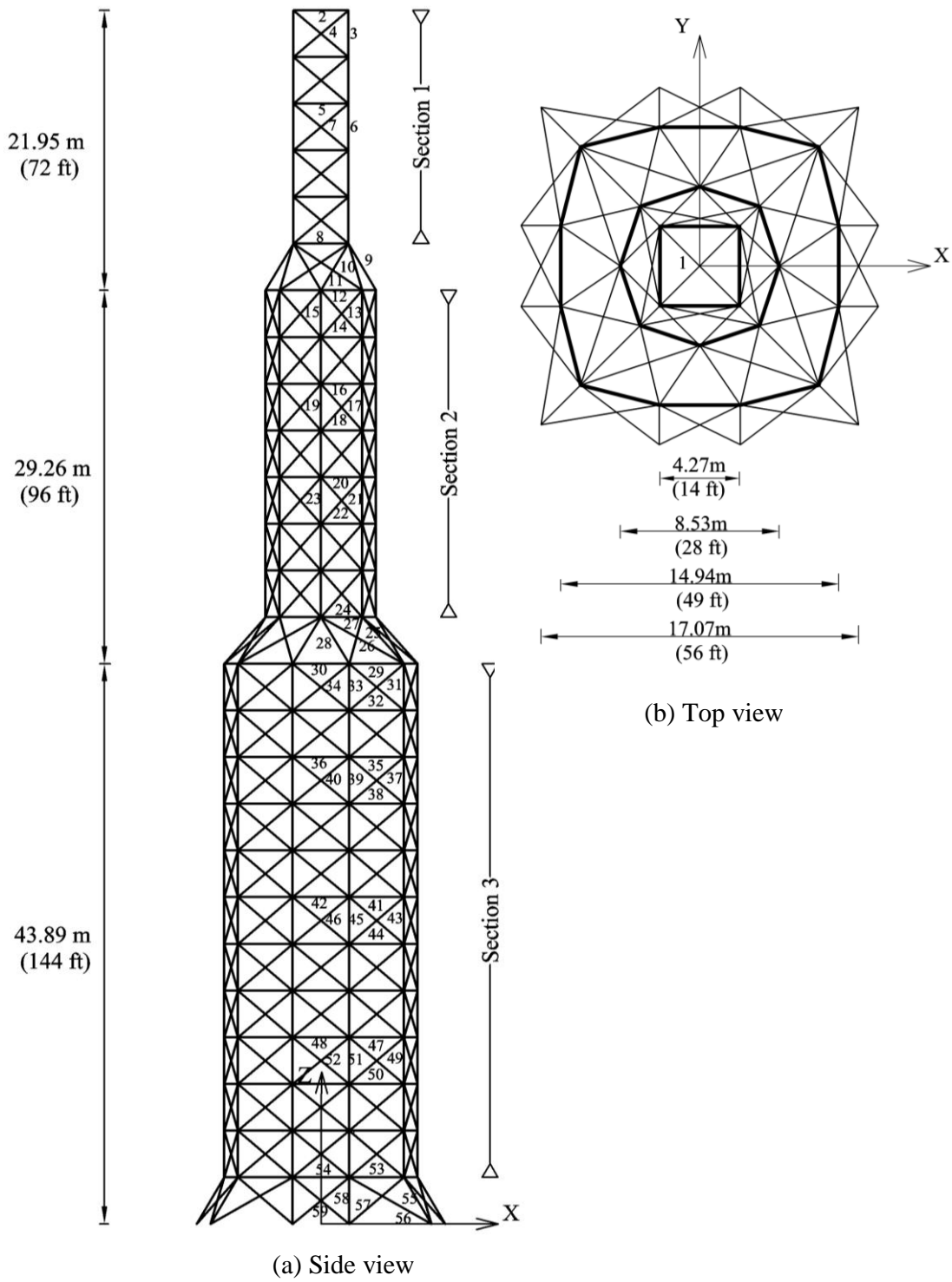


Figure 5. A 942-bar spatial truss

Table 2: The results of the optimum design of the BA algorithm for the second example

Optimal cross-sectional areas (cm <sup>2</sup> )								
Members		Area	Members		Area	Members		Area
1	$A_1$	1.037	21	$A_{21}$	2.575	41	$A_{41}$	0.516
2	$A_2$	2.078	22	$A_{22}$	0.360	42	$A_{42}$	0.698
3	$A_3$	1.472	23	$A_{23}$	3.195	43	$A_{43}$	20.445
4	$A_4$	0.511	24	$A_{24}$	5.087	44	$A_{44}$	0.5346
5	$A_5$	0.681	25	$A_{25}$	18.907	45	$A_{45}$	1.577
6	$A_6$	16.556	26	$A_{26}$	0.523	46	$A_{46}$	0.483
7	$A_7$	0.362	27	$A_{27}$	2.570	47	$A_{47}$	0.521
8	$A_8$	3.086	28	$A_{28}$	18.787	48	$A_{48}$	1.164
9	$A_9$	2.208	29	$A_{29}$	4.869	49	$A_{49}$	19.870
10	$A_{10}$	3.833	30	$A_{30}$	4.864	50	$A_{50}$	0.852
11	$A_{11}$	0.803	31	$A_{31}$	13.328	51	$A_{51}$	3.796
12	$A_{12}$	1.047	32	$A_{32}$	0.870	52	$A_{52}$	0.406
13	$A_{13}$	2.730	33	$A_{33}$	0.901	53	$A_{53}$	11.861
14	$A_{14}$	0.535	34	$A_{34}$	1.290	54	$A_{54}$	17.975
15	$A_{15}$	20.282	35	$A_{35}$	0.135	55	$A_{55}$	18.179
16	$A_{16}$	1.329	36	$A_{36}$	0.202	56	$A_{56}$	3.225
17	$A_{17}$	2.022	37	$A_{37}$	18.407	57	$A_{57}$	2.636
18	$A_{18}$	0.538	38	$A_{38}$	0.652	58	$A_{58}$	5.326
19	$A_{19}$	18.070	39	$A_{39}$	1.425	59	$A_{59}$	0.258
20	$A_{20}$	0.324	40	$A_{40}$	0.357			
<i>Weight</i>		204684 N						

Table 3: Performance comparison for the second example

	GA	PSO	BB-BC	HBB-BC	CSS	BA
<i>Best weight (lb)</i>	56343 (250,626 N)	60385 (268606 N)	53201 (236650 N)	52401 (233091 N)	47371 (210716 N)	46015 (204,684 N)
<i>Average weight (lb)</i>	63223 (281230 N)	75242 (334693 N)	55206 (245568 N)	53532 (238122 N)	48603 (216197 N)	47856 (212874 N)
<i>Std Dev (lb)</i>	6640.6 (29,539 N)	9906.6 (44,067N)	2621.3 (11660 N)	1420.5 (6318 N)	950.4 (4,227 N)	712.36 (3,168 N)
<i>No. of analyses</i>	50,000	50,000	50,000	30,000	15,000	15,000

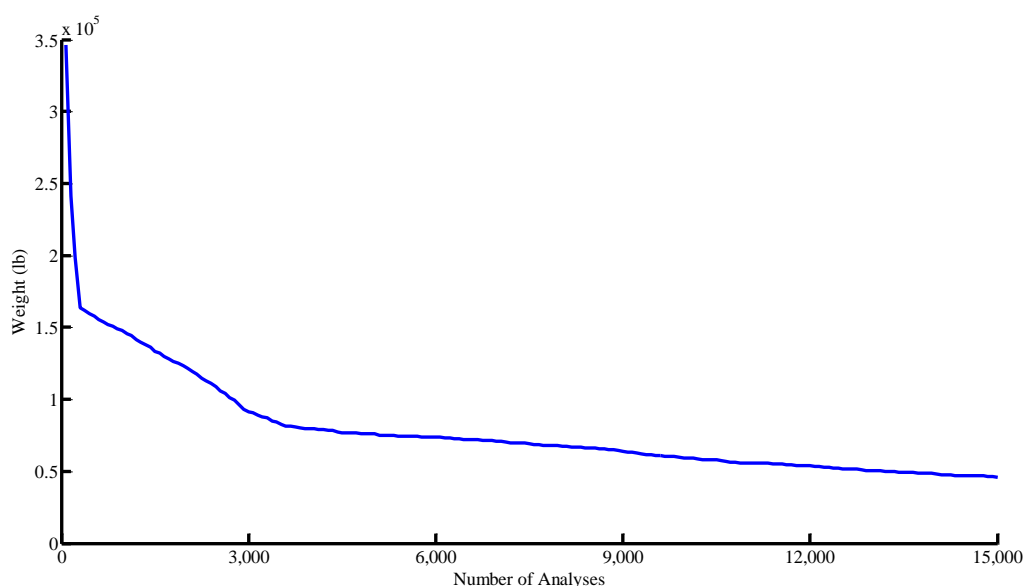


Fig. 6 Convergence history of BA for the 942-bar spatial truss

## 5. CONCLUDING REMARKS

Determining the optimum design of large-scale structures is known as one of difficult optimization problems. In this paper, the bat algorithm is improved and applied to solve these problems. Exploration ability of the bat algorithm is acceptable; however, its convergence speed needs to be improved for large-scale problems. In this paper, three improvements are suggested to solve this problem and improve the BA-based algorithm. The first improvement corresponds to the average loudness of bats which is defined dynamically. The second one belongs to updating echolocation parameters in which a microbat is allowed to update its echolocation parameters each time when it produces a solution. Finally, the pulse rate parameter is redefined to facilitate a more gradual change of it. These mechanisms reduce the required number of analyses. The robustness of the new algorithm is tested by optimum design of two large-scale trusses. The results illustrate the efficiency of the proposed algorithm.

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