INTERNATIONAL JOURNAL OF OPTIMIZATION IN CIVIL ENGINEERING
Int. J. Optim. Civil Eng., 2014; 5(2):137-150

OPTIMAL WIND RESISTANT DESIGN OF TALL BUILDINGS UTILIZING MINE BLAST ALGORITHM

M. Shahrouzi*, †, A. Meshkat-Dini and A. Azizi
Engineering Department, Kharazmi University, Tehran, Iran

ABSTRACT

Practical design of tall frame-tube and diagrids are formulated as two discrete optimization problems searching for minimal weight under codified constraints under gravitational and wind loading due to Iranian codes of practice for steel structures (Part 6 & Part 10). Particular encoding of design vector is proposed to efficiently handle both problems leading to minimal search space. Two types of modeling are employed for the sizing problem; one by rigid floors without rotational degrees of freedom and the other with both translational and rotational degrees of freedom. The optimal layout of diagrids using rigid model is searched as the second problem. Then performance of Mine Blast Optimization as a recent meta-heuristic is evaluated in these problems treating a number of three-dimensional structural models via comparative study with the common Harmony Search and Particle Swarm Optimization. Considerable benefit in material cost minimization is obtained by these algorithms using tuned parameters. Consequently, effectiveness of HS is observed less than the other two while MBO has shown considerable convergence rate and particle swarm optimiztion is found more trustable in global search of the second problem.

Received: 10 October 2014; Accepted: 20 February 2015

KEY WORDS: Mine blast optimization; sizing; layout design; tall buildings.

1. INTRODUCTION

Over the last decades, various algorithms have been used to solve constrained engineering optimization problems. Some of these algorithms are based on numerical linear and nonlinear *Mathematical Programming* methods that require substantial gradient information and usually seek to improve the solution in the neighbourhood of a starting point. In case a problem has more than one local optimum the result of such MP methods may depend on

*Corresponding author: Faculty of Engineering, Kharazmi University, Tehran, Iran
†E-mail address: shahruzi@khu.ac.ir (M. Shahrouzi)

the selection of the initial point so that the solution does not necessarily coincide with the global optimum [1]. In the other hand, structural design of tall buildings is an engineering challenge and meanwhile a rewarding task due to considerable difference between several possible alternatives [2]. Besides, many real-world engineering optimization problems are more complex in nature and quite difficult to solve [3].

In contrary, meta-heuristic algorithms exhibit a common feature of over-passing local optima toward the global optimum using stochastic operators without need to gradient information [4]. Each of them, however, applies its special rules imitating some natural phenomena. These include the swarm behaviour such as in the *particle swarm optimization,* PSO [5], brain musical searching process for perfect state of harmony such as *Harmony Search*, HS [6], Big Bang - Big Crunch theory of universe physics [7] and the explosion in mine field in recently developed *Mine Blast Optimization,* MBO [8, 9].

Two efficient structural systems for tall three dimensional building models are treated hereinafter; namely *frame tube systems* and *diagrids*. The framed tube system is known as an economic solution for tall buildings over a wide range of heights [10]. In its basic form, the system consists of closely spaced perimeter columns tied at deep spandrel beams of each floor to form a tubular structure. Therefore, such a system acts like a cantilevered box beam under lateral loads. Alternatively, a new structural system is interested for tall buildings in recent decades called diagrids [11]. They include major diagonal members which carry lateral and vertical loads of connecting floor systems more efficiently because of their particular spatial forms. Moon studied a variety of geometrical changes on diagrid systems performance [12] while the present work utilizes a different module based approach.

This paper concerns minimal weight design of tall steel buildings against wind and gravitational loads. For the frame tubes, a pure sizing problem is formulated while both geometry of digarids and their sizing are altered in the second problem to minimize the corresponding material cost. Both search spaces are treated using discrete variables due to practical purposes. Consequently, performance of HS, PSO and MBO as recent meta-heuristics is evaluated and compared in either optimization problem. In this regard, three dimensional models of 10, 20 and 30 storey buildings are treated including those studied in literature. As a result, efficiency and suitability preference of each method in either case of structural systems is declared and reported.

2. PROBLEM FORMULATIONS AND THE PROPOSED ENCODING

The objective function, $f(x)$, in the optimizing problem in this paper is total weight of structural members. For such a constrained problem a penalty function is defined to calculate violation of the constraints which are to be satisfied as design requirements on (stress, drift, etc.) responses [13]. The following penalty function is employed here:

$$\text{Minimize } \hat{f}(\underline{X}) = W(\underline{X}) + \sum_{j} \varphi_j \mu_j .[\mathrm{g}_j(\underline{X})]^2 \tag{1}$$

$$W(\underline{X}) = \rho \sum_{i=1}^{NumMembers} A_i L_i \tag{2}$$

Where A_i and L_i denote cross sectional area and length of the i[th] member with the material density of ρ. $g_j(x)$ stands for the jth constraint and penalty constants are $\varphi_j > 0$. μ_j identifies whether the jth contraint is violated or not.

$$\mu_j = \begin{cases} 0 & if \;\; g_j(\underline{X}) \le 0 \\ 1 & if \;\; g_j(\underline{X}) > 0 \end{cases} \tag{3}$$

The problem stress and drift constraints are given by Iranian codes of practice for steel structures [14, 15].

The first and second problem formulations are then distinguished by encoding of design vector X. For the 1st (Sizing) problem it is defined as $\underline{X} = < y_1, ..., y_m >$ where each of its components can be associated an integer index related to the corresponding section in the available list of structural profiles [16].

In the 2nd problem, the design vector $\underline{X} = < y_1, ..., y_m, z_1, ..., z_n >$ includes not only sizing indices $y_1, ..., y_m$ but also geometrical variables: $z_1, ..., z_n$. Every such z_k denotes the number of frame stories corresponding to the k^{th} diagrid module where k is numbered from the lowest module to the highest one. For example a sample vector of $< z_k > = < 3, 4, 2, 1, 1, 1, 4, 1, 1, 2 >$ can be decoded to the diagrid of Figure 1. By such an encoding, the angle of each diagonal macro brace is treated as a discrete geometrical variable.

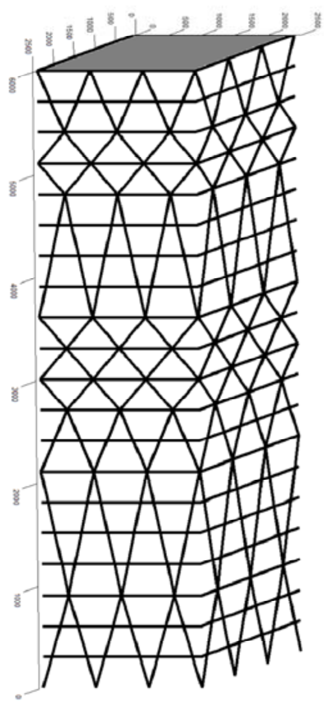


Figure 1. Sample decoded diagrid model

3. UTILIZED OPTIMIZATION ALGORITHM

This paper uses standard versions of HS and PSO [17-19], however, MBO is more recently developed and so is explained here. The idea of the MBO algorithm is based on observation of a mine bomb explosion, in which the thrown pieces of shrapnel collide with other mine bombs near the explosion area resulting in their explosion [8]. Hence, the goal is to find the mines, particularly the one with the most explosive effect located at optimal point X^*which can cause the most casualties (minor max cost $f(x)$ per X^*). When a mine bomb is exploded, it spreads many pieces of shrapnel and the casualties ($f(x)$) caused by each piece of shrapnel are calculated. Each shrapnel piece has definite directions and distances to collide with other mine bombs.

The prescribed algorithm start with one or more initial points called first shot points represented by X_0^f. The super script f refers to the number of first shot points. Due to experience of the method author, large number of first shot points did not offer significant improvement in the optimization process for all problems and so one first shot point is utilized in the present work.

To start with feasible first shot point, define new first shot point as below:

$$X_0^{new} = LB + rand \times (UB - LB) \tag{4}$$

WhereX_0^{new}, LB and UB are the new generated first shot point using algorithm, lower and upper bounds of the problem, respectively. $rand$ is a uniformly distributed random number.

Suppose that X is the current location of a mine bomb given as:

$$X = \{X_m\}, \quad m = 1,2,3, \cdots, N_d \tag{5}$$

In which N_d is the search space dimension equal to the number of independent variables.

Consider that N_s shrapnel pieces are produced by the mine bomb explosion causing another mine to explode at X_{n+1} location:

$$X_{n+1}^f = X_{e(n+1)}^f + exp\left(-\sqrt{\frac{M_{n+1}^f}{D_{n+1}^f}}\right) X_n^f, \quad n = 0,1,2,3, \ldots \tag{6}$$

Where$X_{e(n+1)}^f$, D_{n+1}^f and M_{n+1}^f are the location of exploding mine bomb collided by shrapnel, the distance and the direction (slope) of the thrown shrapnel pieces in each iteration, respectively.

The location of exploding mine bomb $X_{e(n+1)}^f$ is defined as:

$$X_{e(n+1)}^f = d_n^f \times rand \times \cos(\theta) \tag{7}$$

Where θ is the angle of the shrapnel pieces which is a constant value and is calculated using$\theta = 360/N_s$. The exponential term in Eq. (5) is used to improve the obtained blast point by influencing the information from previous solutions (X_n^f).

The distance D_{n+1}^f and the direction of shrapnel pieces M_{n+1}^f are defined as:

$$D_{n+1}^f = \left[\sum_{i=1}^{m}(X_{it} - X_{i(t-1)})^2\right]^{1/2} \qquad t = \mu, \dots, N_{LastIter} \tag{8}$$

$$M_{n+1}^f = \frac{F_t - F_{t-1}}{D_{n+1}^f} \qquad t = \mu, \dots, N_{LastIter} \tag{9}$$

Where F is the function value for the X. To calculate the initial distance for each shrapnel pieces $d_0 = (UB - LB)$ in each dimension is used. The algorithms iterates up to the pre-assigned $N_{LastIter}$. In order to explore the design space at smaller and larger distances, the exploration factor (μ) is introduced. This constant is used in the early iterations of the algorithm and is compared with an iteration number (k). If it is higher than k, then the exploration process begins.

The distance of thrown shrapnel pieces in exploration phase changes as below:

$$X_{e(n+1)}^f = d_n^f \times (|randn|)^2 \times \cos(\theta) \tag{10}$$

A larger value for the exploration factor (μ) makes it possible to explore more remote regions, thus the value of μ determines the intensity of the exploration. To increase the global search capability of the algorithm, distance of the shrapnel pieces are reduced gradually to allow the mine bombs search the probable global minimum location.

The reduction in d_n^f is given as:

$$d_n^f = \frac{d_{n-1}^f}{\exp(k/\alpha)}, \quad n = 1,2,3, \dots \tag{11}$$

Where α and k are the reduction constants and the iteration number index. The choice of α as a user-defined parameter depends on the complexity of the problem. The role of α is to reduce the distance of each shrapnel piece adaptively according to Eq. (11).

4. WIND LOADING CRITERIA

Regarding considerable influencing factors related to wind loads, there are appropriate codified provisions which have been recommended by building codes. Increasing wind force in height and similar frequency content in tall buildings and major frequency band of wind excitation show importance of the research. According to Iranian national building code, part 6 [14], for buildings with height to effective width ratio of 4 or more or height above 60 meters and also structures with main frequency in range 0.25Hz-1Hz, wind loading must be applied dynamically. Dynamic state parameters contain some feature of structure and wind stream such as turbulence intensity, height, natural vibration frequency and damping ratio of the structural system.

Wind pressure or suction on each outer surface of structure is:

$$p = I_w.q.C_e.C_g.C_p \tag{12}$$

Where $\mathrm{I_w}$, q and $\mathrm{C_p}$ are importance factor, basic wind pressure for target region and outsider pressure factor, respectively. $\mathrm{C_g}$ addresses gust effect factor and $\mathrm{C_e}$ stands for exposure factor. In the wind resistance related codes, there are advises to test some different cases of wind loading and take the most critical case as design loading base. Fig.2 demonstrates such states of loading due to Iranian code of practice.

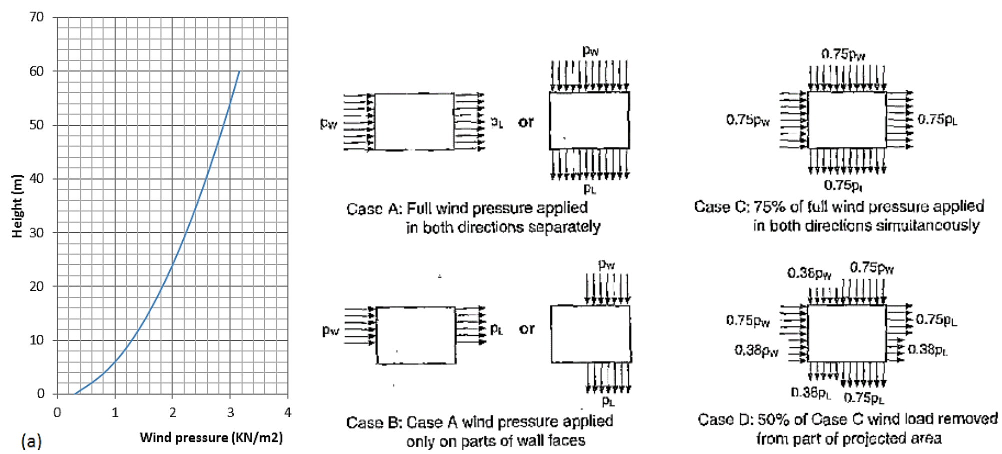


Figure 2. (a) General display of wind pressure against height at study region for 20-storey structure; (b) Different wind load cases in Iranian building code [14,15]

5. NUMERICAL EXAMPLES

Performance of the employed algorithms is evaluated using two sets of examples; sizing of frame tube systems and simultaneous optimization of size and geometry in diagrid models.

General algorithms' control parameters are chosen via a number of trials as given in Tables 1 to 3.

Table 1: Control parameters for HS

Population Size	$N_{LastIter}$	HMCR	PAR
11	250	0.9	0.8~0.3

Table 2: Control parameters for PSO

Population Size	$N_{LastIter}$	$C_{Inertial}$	$C_{Cognitive}$	C_{Social}
11	250	0.9~0.1	2.1	1.9

Table 3: General control parameters for MBO

Population Size	$N_{LastIter}$	α	μ	$N_{First\ shot\ points}$
11	250	40000	50	1

5.1 Sizing of frame tube systems

The first set of structural models, consist of three steel frames in 10, 20 and 30-storey forms for pure sizing optimization. The plan and a side frame of 20-storey model are shown in Fig.3. It is assumed that interior beam-column joints in the structure are hinged. Lateral load resistant system contains only perimeter frames and linear allowable stress design methodology is applied.

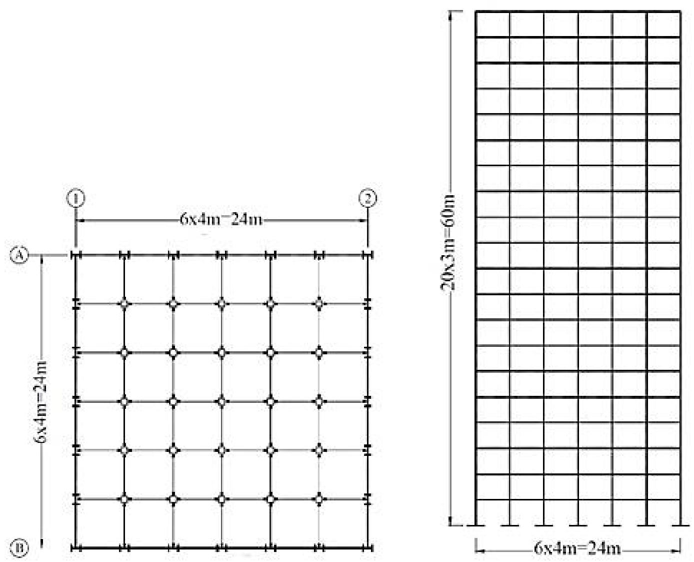


Figure 3. Structural models: General plan and elevation of 20-storey building [20]

Uniform dead and live loads at floors are considered 500 $\mathrm{kgf/m^2}$ and 200 $\mathrm{kgf/m^2}$, respectively. Design considerations and load cases have been selected according to Iranian national building code, part 10 [15]. Thus, different load cases with wind load phrase are selected.

The results of a side frame as main lateral force resistance system of the treated tube structures are reported, hereinafter. In Fig.4a comparison of convergence rate and performance in finding better solutions for three prescribed algorithms are presented. In this test MBO has revealed good convergence rate and considerably better results than HS and PSO. Although effective parameters in particle swarm algorithm and harmony search algorithm were tuned many times, still MBO can achieve better results than the other algorithms.

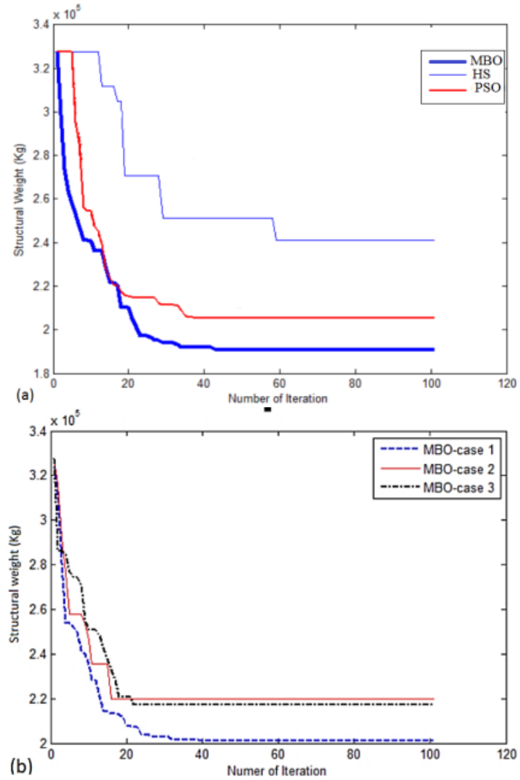


Figure 4. Comparison of results; (a) MBO, PSO and HS algorithms of 20-storey model; (b) MBO results with different effective parameters for 20-storey model

When meta-heuristic methods are evaluated, one of the most aspects of specific method is its effective parameters study. Fig.4b demonstrates the effect of tuning these parameters for MBO method. According to this figure, results either in convergence rate or quality of final optima are different in the three cases. Table 4 gives corresponding effective parameters in each case; where R stands for a reduction distance marker. If variation of function values in the current iteration is more than R, distance of shrapnel in next iteration is reduced in order to concentrate on the optimal points. Assuming the maximum iteration number $N_{LastIter}$, μ in Table 4 denotes the percentage of the iterations that algorithm are in the exploration phase.

Table 4: General control parameters for MBO

Case	*Shrapnels number*	$N_{LastIter}$	$R(kg)$	μ	d_0
1	11	100	300	20	$(UB-LB)/2$
2	11	100	700	50	$(UB-LB)/4$
3	11	100	1000	10	$(UB-LB)/8$

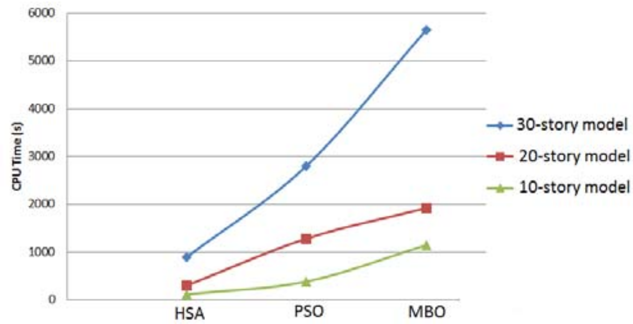


Figure 5. CPU-time comparison in sizing of 10-storey, 20-storey and 30-storey models

In order to study time-complexity of the treated algorithms, their corresponding elapsed times are compared in Fig.5 for any of the 10, 20 and 30 storey examples. Regarding previous Figure, it is concluded that MBO requires more computational effort to derive its superior quality results with respect to PSO in the same number of iterations. Similar conclusion is extracted for PSO with respect to HS with a further consideration that HS requires one fitness evaluation in its every iteration after initiation, in spite of the other two algorithms.

As another issue, the effect of structural modelling on the results is investigated. In a three dimensional model, if the floors are taken rigid the amount of material required to resist the wind differs with the flexible floor model with rotational and transitional degrees of freedom at the corresponding connections. Consequent deformations and stresses in the structure will also be affected because rigid floors activate axial behaviour of flange plane frames in frame tube structure.

Fig.6 shows results of some MBO runs with flexible floor modelling vs. a rigid floor model. As can be realized, less structural material is required in the optimal design of rigid floor model compared with those of the flexible floor models. It is, of course, required to compensate lower lateral stiffness of the hinged connected models in comparison to higher stresses in rigid connections of the other model.

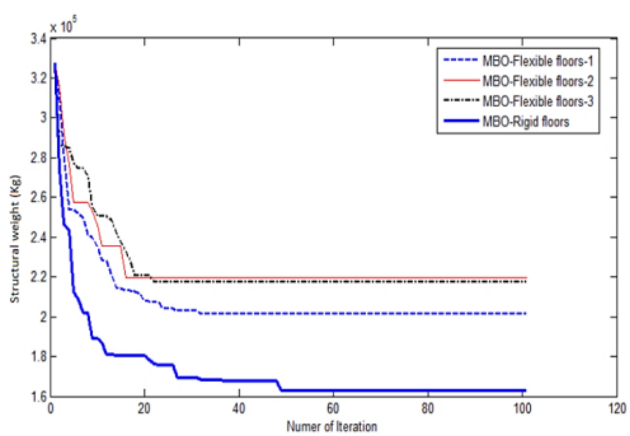


Figure 6. Floors flexibility and rigidity states

As an important criterion for structural design of tall buildings, overriding the drift constraint by the optimization is also concerned in the present work. Consider the maximum allowable drift by the applied code be (H/500) where "H" is the height of structure. Fig.7 shows that such a constraint is activated in the 20 storey and 30 storey examples, however, in the 10-storey model, stress ratios has reached their codified limits. Thus, stress of structural members is determinative in some models, while the drift constraint is critical in the others. It can also be noted that although the MBO has resulted in lighter structural designs, HS or PSO have caused more values of maximal storey drifts.

5.2 Optimal Geometry and Sizing Design of diagrids

As the second issue both sizing and geometrical design of a 20-story diagrid model is studied here. General model characteristics including dead/live/wind loads and section list are taken similar to the literature [20]. There are 10 symmetric groups for sizing of beams, columns and diagonal members in this example while 16 sections are assignable to each group.

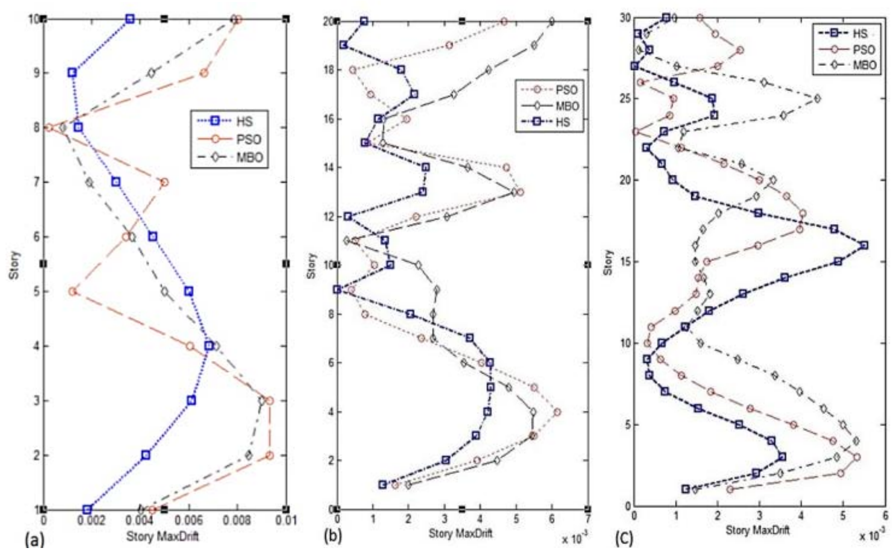


Figure 7. The maximum drift of stories; (a) 10-storey model; (b) 20-storey model; (c) 30-storey models

Results of 12 independent runs declared that MBO is not so stable in achieving global optimum as in the previous problem; however, its convergence rate is usually better than PSO. Nevertheless, HS takes less computational effort to achieve its optima in charge of more structural weight and either standard deviation of the results (Table 5). Fig. 8 demonstrates trend of changes in side-frame design of the diagrid as HS search progresses. Table 5 also summarizes statistical results of testing the three methods showing superiority of PSO in such a weight minimization problem.

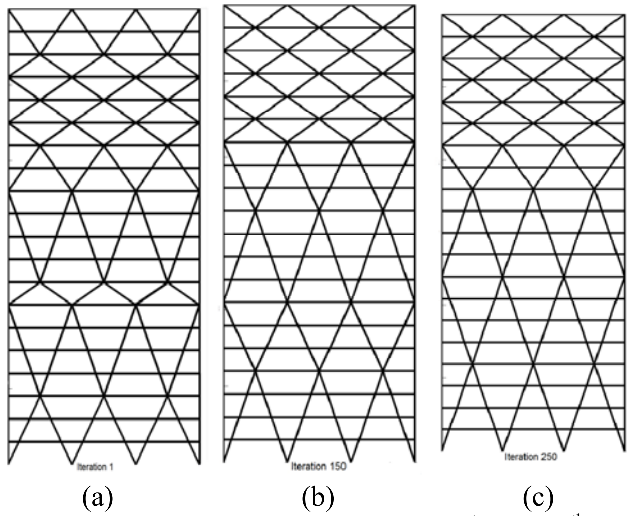


Figure 8. The diagrid side-frame design by HS in the (a) 1st; (b) 150th and (c) last iteration

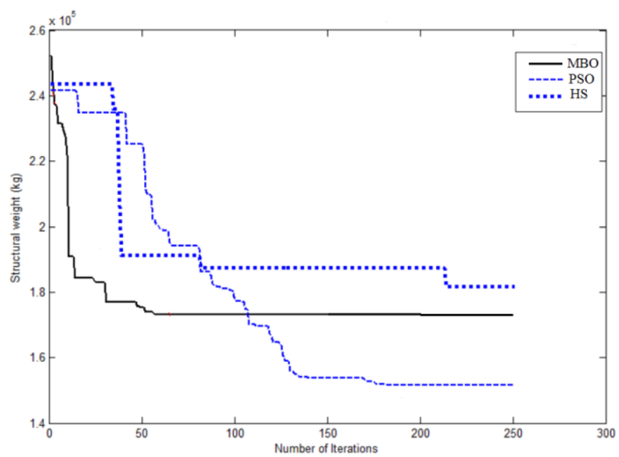


Figure 9. Convergence curves by HS, PSO and MBO for the 20-Storey diagrid optimization

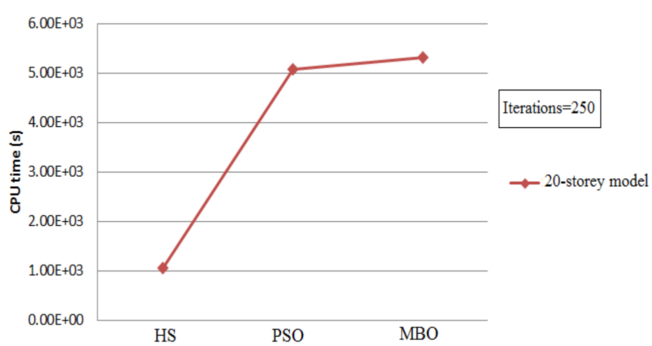
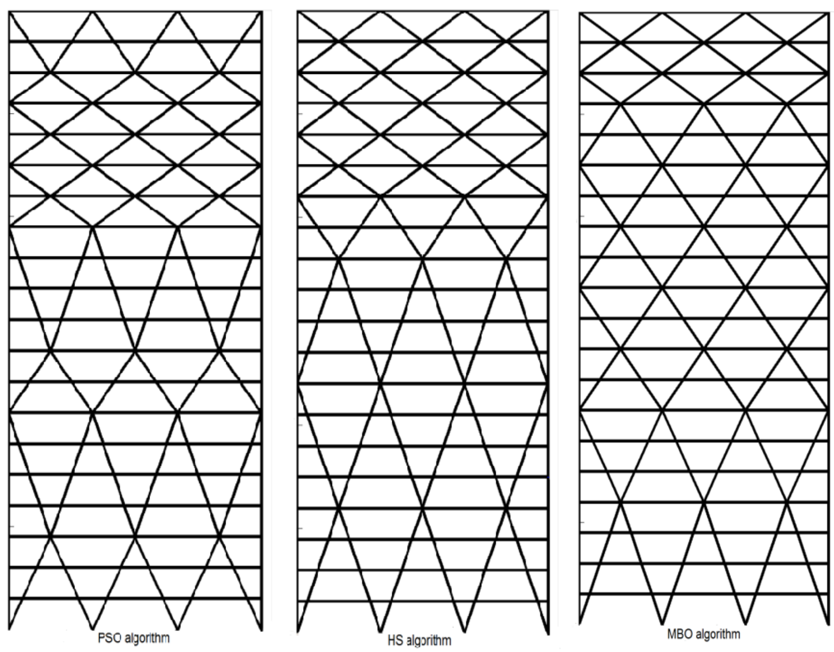


Figure 10. Required elapsed time by HS, PSO and MBO for the 20-Storey diagrid optimization

Fig. 9 not only confirms this result but also shows higher capability of PSO in avoiding premature convergence in global search with respect to the other treated algorithms. However, it requires more computational effort for such a task than HS as demonstrated in Fig.10. It is worth mentioning that the highest CPU-time in this test belongs to MBO.

Table 5: Results comparison for the geometry and size optimization of 20-Storey example

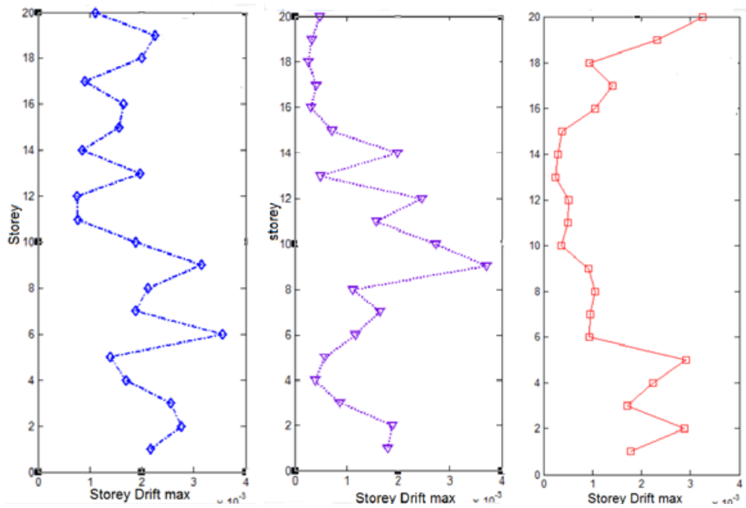
Method	Min. W (10^3 kg)	Max. W (10^3 kg)	Average W (10^3 kg)	Standard deviation
PSO	154	170	162	5.7
MBO	172	209	182	6.8
HS	182	215	194	12.4



(a) (b) (c)

Figure 11.Optimal design layout of the 20-Storey diagrid by (a) PSO; (b) HS; (c) MBO

Fig.11 shows final layouts for the 20-storey diagrid by each of the optimization algorithms. As can be realized, the MBO design seems providing more regular modules with gradual variation of diagonals angle with respect to the others. Consequently, Fig.12 shows that it has led the critical drift location to distribute toward the top level while such a location is near the base for PSO and HS designs.



(a) (b) (c)

Figure 12.The maximum drift of diagrid stories in the optimal of (a) PSO; (b) HS; (c) MBO

7. CONCLUSION

Sizing optimization of frame tube structures subjected to codified gravitational and wind load combinations have been studied here utilizing proper discrete space problem formulation. Integer coding of design variables make it possible to accurately choose between structural sections available from practical lists. As a recent optimization tool, MBO performance was evaluated and compared in this problem compared with two well-known algorithms; i.e., HS and PSO. After suitable parameter tuning, they are applied to a set of medium- to high-rise steel buildings using three dimensional analyses. Such a parameter tuning reveals the best results of MBO using the lowest reduction marker, moderate exploration factor and the highest initial bandwidth among 3 treated cases.

In the light of the current study on sizing of three steel building examples, it is observed that more structural material is required to withstand sway under wind loading in flexible floors than in rigid floor modeling. Additionally, drift constraint was activated for higher buildings while stress limits were critical for the lower rise ones. It is also found that MBO designs can better satisfy such code regulations in tube structures even with lower amount of structural material than the other two algorithms, however, in charge of more computational effort.

As the next issue, both geometry and sizing of a diagrid example were optimized by the meta-heuristic algorithms. Observing trend of layout variation during the search declared that in the optimal designs size of diagonal modules decreases as getting close to the roof level in order to compensate high displacement increase there. It may be interpreted addressing flexural/cantilever action of such high rise building systems.

In such a discrete problem, PSO has shown better quality of final result than the other employed algorithms due to its capability in global search. MBO design has been superior to the others in transmitting maximal drift location to the less critical top floors by its redistribution of stiffness among the diagrid height. However, it required greater computational time than PSO and HS to accomplish such a task even using one starting shot point.

REFERENCES

1. Arora JS. Introduction to optimum design, Elsevier, US, 2004.
2. Tranath BS. *Structural analysis and design of tall buildings*, McGraw-Hill Inc, New York, 1988.
3. Ali MM, Moon K. Structural Developments in Tall Buildings: Current Trends and Future Prospects, *Architectural Science Review* 2007; **50**(3): 205-23.
4. Kaveh A. *Advances in Metaheuristic Algorithms for Optimal Design of Structures,* Springer International Publishing, Switzerland, 2014.
5. Kennedy J, Eberhart R. *Swarm Intelligence*, Academic Press, London, 2001.
6. Lee KS, Geem ZW. A new meta-heuristic algorithm for continuous engineering optimization: harmony search theory and practice, *Computer methods in applied mechanics and engineering* 2005; **194**(36): 3902-33.
7. Erol KO, Eksin I. A new optimization method: Big Bang–Big Crunch, *Advances in Engineering Software* 2006; **37**(2): 106-11.
8. Sadollah A, Bahreininejad A, Eskandar H, Hamdi M. Mine blast algorithm for optimization of truss structures with discrete variables, *Computers & Structures* 2012; **102**: 49-63.
9. Sadollah A, Bahreininejad A, and Eskandar H, Hamdi M. Mine blast algorithm: A new population based algorithm for solving constrained engineering optimization problems, *Applied Soft Computing* 2013; **13**(5): 2592-2612.
10. Kwan AKH. Simple method for approximate analysis of framed tube structures, *Journal of Structural Engineering* 1994; **120**(4): 1221-39.
11. Moon K, Connor JJ, Fernandez JE. Diagrid Structural Systems for Tall Buildings: Characteristics and Methodology for Preliminary Design, *The Structural Design of Tall and Special Buildings* 2007; **16**(2): 205-30.
12. Moon K. Optimal grid geometry of diagrid structures for tall buildings, *Architectural Science Review* 2008; **51**(3): 239-51.
13. Fourie PC, Groenwold AA. The particle swarm optimization algorithm in size and shape optimization, *Structural and Multidisciplinary Optimization*, 2002; **23**(4): 259-67.
14. Applied loads on buildings- Part 6, *Iranian national building code*, Tehran, Iran, 2013.
15. Steel design manual- Part 10, *Iranian national building code*, Tehran, Iran, 2013.
16. Kaveh A, Shahrouzi M. Direct index coding for discrete sizing optimization of structures by genetic algorithms, *International Journal of Civil Engineering* 2005; **3**(3-4), 166-81.
17. Mahdavi M, Fesanghary M, Damangir E.An improved harmony search algorithm for solving optimization problems, *Applied Mathematics and Computation* 2007, **188**(2): 1567-79.
18. Eberhart RC, Kennedy J. A new optimizer using particle swarm theory, In *Proceedings of the Sixth International Symposium on Micro Machine and Human Science* 1995; **1**: 39-43.
19. Perez RE, Behdinan K. Particle swarm approach for structural design optimization, *Computers & Structures* 2007, **85**(19): 1579-1588.
20. Movahed H, Meshkat-Dini A, Tehranizadeh M. Seimic evaluation of steel special moment resisting frames affected by pulse type ground motions, *Asian Journal of Civil Engineering* 2014; **15**(4): 575-85.