Biogeography-Based Optimization Algorithm for Designing of Planar Steel Frames

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Abstract: The optimization can be defined as a solution of problem under specific conditions to achieve a specific purpose. Optimization strategies commonly used for solving of various problems and have gained great importance in recent years especially in engineering. Evolving optimization methods over the years has many varieties such as shape optimization, topology optimization, size optimization etc. The latest trend of optimization methods is metaheuristics which are more useful with easy applicable to complex problems regarding to traditional optimization methods. So that metaheuristics have supplanted the traditional methods particularly in engineering by the time. In this study, a planar steel frame which is designed according to the requirements comprised by AISC-LRFD (American Institute of Steel Construction-Load and Resistance Factor Design) has been optimized by aid of biogeography-based optimization (BBO) algorithm.

Keywords: Planar Steel Frames, Optimum Design, Stochastic Search Techniques, Biogeography-Based Optimization, Metaheuristics..

1. Introduction

Many of design problem in engineering are too complex and multifaceted due to nonlinear characteristics Stochastic optimization methods are compatible for dealing with nonlinear and complex design problems especially in civil engineering. Since stochastic optimization methods do not need any gradient information, these methods can be much more applicable in civil engineering problems.

In the literature, there are immense efficient studies on various metaheuristic optimization methods inspired by natural phenomena in structural engineering field. For instance, charged system search algorithm has been used in design optimization of skeletal structures [1], simulated annealing, evolution strategies, particle swarm optimizer, tabu search method, ant colony optimization, harmony search and simple genetic algorithm have been used in design of real size pin jointed structures [2], swarm intelligence based algorithms, harmony search method and charged system search have been practiced shape and topology optimization design of skeletal structures [3], firefly algorithm has been used to obtain the optimum design of retaining walls [4], harmony search algorithm has utilised optimum design of concrete cantilever retaining walls [5], genetic algorithm has applied multi-storey composite steel frames [6]. Among these, biogeography-based optimization (BBO) algorithm has outstanding popularity due to its capacity of rapidly converging to near-global optimum [7]. Biogeography is the study of the geographical distribution of biological organisms [8]. It is related to immigration, emigration and population of species etc. Robert MacArthur and Edward Wilson [9] have investigated on

mathematical models of biogeography interest. They have focused on the distribution of species among at neighbouring islands. Then, inspired by the science of biogeography Dan Simon presented a new computational intelligence algorithm, so-called biogeography-based optimization (BBO) algorithm [10].

There are some studies in different areas include the application of BBO; such as constrained optimization problems [11], best compromise solution of economic emission dispatch [12], optimal job scheduling in cloud computing [13], soft-sensor models [14], AC transmission system devices [15]. In structural engineering, BBO is also promisingly utilized in obtaining the optimum design of cost optimization of reinforced concrete cantilever retaining walls under seismic loading [16], optimization of spatial steel frames [17], optimal carbon dioxide emissions of the RC retaining wall design [18].

In this paper, optimum design of planar steel frames according to AISC-LRFD (American Institute of Steel Construction-Load and Resistance Factor Design) [19] is investigated by using BBO algorithm. Main purpose of this study is to find minimum design weight of a planar steel frame by selecting suitable steel sections taking into account of code requirements according to AISC-LRFD. Code specifications necessitate the consideration of a combined strength constraint with lateral torsional buckling for beam-column members. Furthermore displacement constraints as well as inter-storey drift restrictions of multi storey frames are also included in the design formulation. Further constraints related with the constructability of a steel frame are also considered.

2. Optimum Design Formulation to AISC-LRFD

The discrete optimum design problem of steel frames where the minimum weight is considered as the objective can be explained as follows:

Find a vector of integer values I (Equation 1) representing the sequence numbers of steel sections assigned to Nd member

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groups

$$\mathbf{I}^T = [I_1, I_2, ..., I_{N_d}] \qquad (1)$$

to minimize the weight (W) of the frame

$$W = \sum_{i=1}^{N_d} \rho_i A_i \sum_{j=1}^{N_t} L_j \qquad (2)$$

where Ai and ρi are the length and unit weight of the steel section adopted for member group i, respectively, Nt is the total number of members in group i, and Li is the length of the member j which belongs to group i.

The members subjected to

$$\frac{(\delta_j - \delta_{j-1})}{h_j} \le \delta_{ju} \qquad j = 1, ..., ns \qquad (3)$$

$$\delta_i \le \delta_{iu} \qquad i = 1, ..., nd \qquad (4)$$

$$V_u \le \phi V_n \qquad (5)$$

$$\left(\frac{P_u}{\phi_c P_n}\right) + \left(\frac{8}{9}\frac{M_{ux}}{\phi_b M_{nx}}\right) \le 1.0 \quad for \quad \frac{P_u}{\phi_c P_n} \ge 0.2 \qquad (6)$$

$$\left(\frac{P_u}{2\phi_c P_n}\right) + \left(\frac{M_{ux}}{\phi_b M_{nx}}\right) \le 1.0 \quad for \quad \frac{P_u}{\phi_c P_n} \le 0.2$$

$$3. \ B_{jb} \le B_{jc} \qquad j = 1, ..., nj \qquad (7)$$

$$D_s \le D_{s-1} \qquad s = 1, ..., nu \qquad (8)$$

$$m_s \le m_{s-1} \qquad (9)$$

Equation (3) represents the inter-storey drift of the multi-storey frame. δj and δj−1 are lateral deflections of two adjacent storey levels and hj is the storey height. ns is the total number of storeys in the frame.

Equation (4) defines the displacement restrictions that may be required to include other than drift constraints such as mid-span deflections of beams. nd is the total number of restricted displacements in the frame. δju is the allowable lateral displacement. The horizontal deflection of columns is limited due to unfactored imposed load and wind loads to height of column/300 in each storey of a building with more than one storey. δiu is the upper bound on the deflection of beams which is given as (span/300) if they carry plaster or other brittle finish.

Equation (5) represents the shear capacity check for beam-columns. φ is resistance factor in shear, Vu required shear strength, Vn is nominal shear strength.

Equation (6) defines the local capacity check for beam-columns. Mnx is nominal flexural strength, Mux is applied moment, Pn is nominal axial strength, Pu is applied axial load, Øc is resistance factor for columns if the axial force is in compression, Øb is resistance factor in bending. It is apparent that computation of compressive strength ØcPn of a compression member requires its effective length.

Equation (7) is included in the design problem to ensure that the flange width of the beam section at each beam-column connection at joint j should be less than or equal to the flange width of column section. nj represents the total number of joints in the frame.

Equations (8) and (9) are required to be included to make sure that the depth and the mass per meter of column section at storey

s at each beam-column connection are less than or equal to width and mass of the column section at the lower storey s −1. nu is the total number of these constraints.

4. Biogeoprapy Based Optimization (BBO) Algorithm

The BBO algorithm is one of the recent additions to the metaheuristic algorithms, introduced by Dan Simon in 2008 [8]. The BBO algorithm was developed by simulating the theory of island biogeography, which describes the extinction and migration of a species between islands. In the BBO algorithm, the island term is defined as an isolated area for species. The two main indices, called the habitat suitability index (HSI) and suitability index variables (SIVs), control the extinction and migrations. The HSI describes the suitability of the habitats for life. Habitats with a high HSI provide good living standards for the species, which are related to value of the objective function. These habitats have a low immigration rate and high emigration rate since they are already nearly saturated. Fig. 1 shows the relationship between species count, immigration rate and emigration rate [8]. In the figure, I and E represent the maximum immigration and emigration rates, respectively, λ and μ are the immigration and the emigration rates, respectively, S0 is the equilibrium number of species and Smax is the maximum species
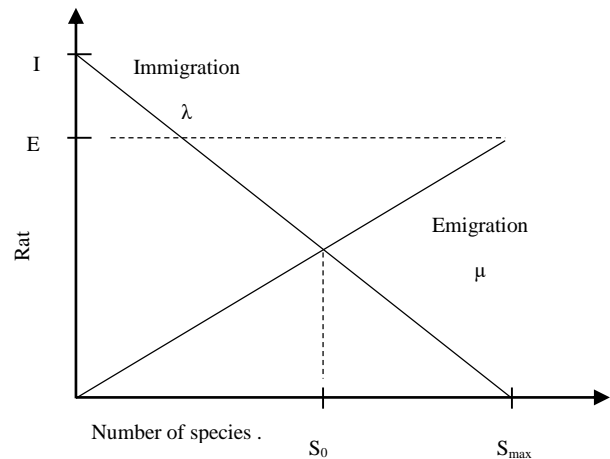
Figure. 1 Species model of a single habitat where λ is immigration rate and μ is emigration rate

The BBO algorithm consists of two main parts: migration and mutation. In the migration part, the new solution is generated by modifying the independent design variable of the old solution. The probability of the modification is related to the immigration rate of the solution. If an independent variable is to be modified, then the value of the independent design variable is determined using the roulette wheel selection method, which is related to the emigration probability. The emigration probability is calculated as follows [16]:

$$P(x_j) = \frac{\mu_j}{\sum_{i=1}^{N} \mu_i} \qquad j = 1, ..., ps \qquad (10)$$

where ps is the population size.

Mutation is used to increase the number of species in the islands. If mutation occurs, the new solution is generated using a random

search, as described in Equation (11). The mutation probability of each design is described in Equation (12).

$$x_i = x_{li} + rand(0,1)(x_{ui} - x_{li}) \quad i = 1,..., ps \quad (11)$$

$$m(s) = m_{max}\left(\frac{1 - P_s}{P_{max}}\right) \quad (12)$$

where xli and xui are upper and lower bounds of the ith design variable (xi), rand(0,1) is a random number between 0 and 1, mmax is the maximum mutation probability defined by the user, Ps is the number of species in the habitat, and Pmax is the maximum number of species.

Each design is analyzed under the external loading and the design constraints given in Equations (3)–(9) are checked. If a candidate design does not satisfy the design constraints, its objective function value is penalized in accordance with constraint violations using Equation (13):

$$f_{cost,p} = f_{cost}(1 + C)^\varepsilon \quad (13)$$

where fcost is the objective function value given by Equation (2), fcost,p is the penalized objective function value, C is the summation of constraint violations calculated using the constraint functions stated by Equations (3)–(9), and ε is the penalty coefficient, which is taken as 2.0 in this study. In general form, constraint violations are calculated as:

$$C_i = \begin{cases} 0 & g_i(x) \le 0 \\ g_i(x) & g_i(x) > 0 \end{cases} \quad i = 1,..., NC \quad (14)$$

where gi(x) is the ith constraint function, x is the vector of design variables, and NC is the number of constraint functions in the optimum design problem.

4. Design Example

In present study, optimization of a six-storey, two-bay planar steel frame shown in Fig. 2 is considered as design example. The frame consists of 30 members that are collected in 8 groups as shown in the figure. The allowable inter-storey drift is 1.17cm while the lateral displacement of the top storey is limited to 7.17cm.

Furthermore, the wide-flange (W) profile list of ready sections is used to size the structural members. The material properties of steel are taken as follows: modulus of elasticity (E) = 208 GPa (30,167.84 ksi) and yield stress (Fy) = 250 MPa (36.26 ksi), and unit weight of the steel (ρ) = 7.85 ton/m3.

The investigated example includes minimum weight design of a planar steel frame structure. The optimum design to this frame with the BBO is sought by implementing the algorithm over a predefined number of iterations such as 20,000. In order to evaluate the accuracy of the final solution obtained with the BBO, the optimum solution is compared to those previously reported in the literature by some other robust metaheuristic algorithms, and the results are evaluated. The frame is formerly designed by three different optimum design algorithms that are based on three different metaheuristic algorithms such that cuckoo search algorithm, particle swarm optimizer and big bang-big crunch algorithm as reported in Ref. [20]

Due to the stochastic nature of the BBO, design problem is independently solved several times and the best result collected is

used for comparison. The population size is set to 75, and the number of elites that specify how many of the best solutions to keep from one generation to the next is set to 2.0 for the design example. The mutation probability per solution per independent variable is selected as 0.01, as well. These parameter values are assigned as constant that are arbitrarily chosen within their recommended ranges by Simon [7, 8] based on the observed efficiency of the technique in different problem fields. It is obvious that best values of these parameters depend on the size of search space.
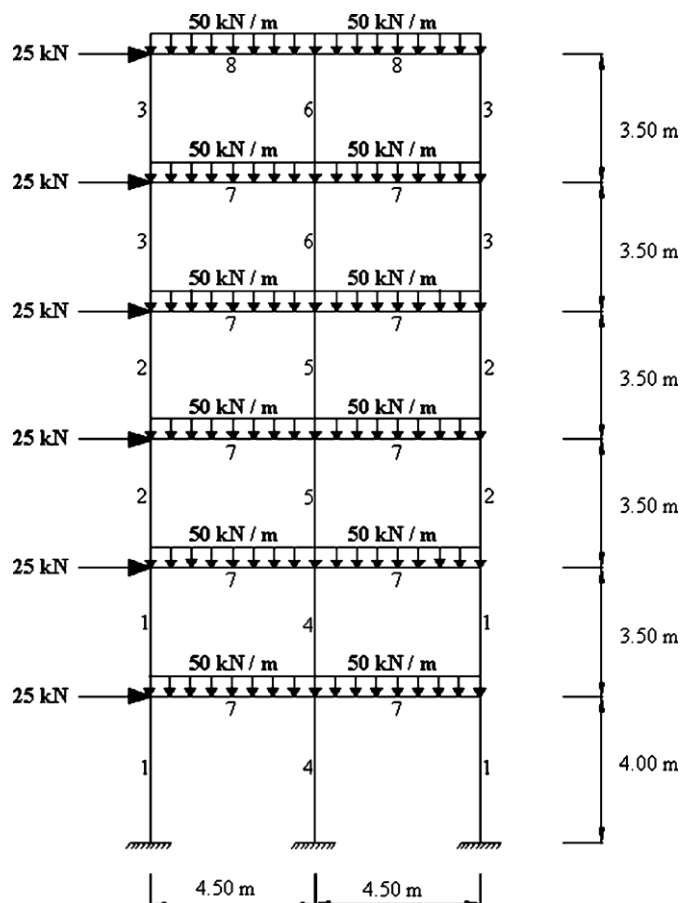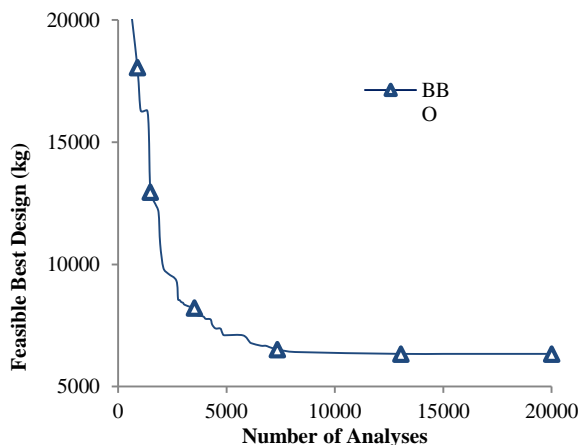

Figure 2 Six storey- two bay planar steel frame

The section designations attained for each member group by BBO algorithm and by the others posted in the literature are tabulated in Table 1. Besides, minimum frame weight located by the BBO algorithm is compared with the available results reported in the literature based on a cuckoo search optimization (CSO), a particle swarm optimizer (PSO), and a big bang-big crunch (BB-BC) algorithm [20]. Also, maximum constraint values for each algorithm are illustrated in this table. According to these results, the BBO algorithm locates an optimum design weight of 62.090kN, (6331.44kg) which is lighter than the design weights obtained by the other techniques. The optimum design produced by BBO is 9.17, 15.94, and 16.51% lighter than those attained by CSO, PSO, and BB-BC, respectively.

Table 1. Optimum Designs for Six-Storey; Two-Bay Planar Steel Frame

#	Member Type	BBO	CSO [20]	PSO [20]	BB-BC [20]
1	Column	W460X74	W460X82	W530X74	W460X106
2	Column	W410X53	W410X53	W310X52	W410X60
3	Column	W250X38.5	W310X38.7	W200X41.7	W250X49.1
4	Column	W610X113	W610X82	W460X89	W360X64
5	Column	W360X64	W530X66	W460X89	W360X64
6	Column	W310X38.7	W150X29.8	W360X72	W200X41.7
7	Beam	W410X46.1	W460X60	W460X60	W460X60
8	Beam	W360X32.9	W460X52	W460X68	W460X60
Max. inter storey drift (cm)		1.16	0.77	0. 78	0.78
Max. strength ratio		0.99	0.94	0.99	0.98
Max. top storey drift (cm)		5.321	4.421	4.533	4.654
Minimum weight. kg (kN)		6331.44 (62.090)	6970.60 (68.358)	7532.11 (73.865)	7583.56 (74.369)
No. of structural analysis		13040	18000	6890	9250

It is noticed that in optimal design attained by BBO algorithm inter-storey as well as to ultimate strength constraints values are very close to their upper bounds while the top storey drift constraint is 5.321cm which is relatively less than its upper bound 7.17cm. This clearly indicates that strength ratio and inter-storey drift constraints dominate in the design. It is apparent from Table 1 that while biogeography-based optimization algorithm required more structural analysis than particle swarm and big bang-big crunch algorithms, it required less structural analysis than cuckoo search algorithm to reach the optimum design. It should be worthwhile to mention that the biogeography-based optimization algorithm used in this study is the standard one not the improved version.

Figure 3. Design history of BBO for six-storey, two-bay planar steel frame

The design history of BBO algorithm is illustrated in Fig. 3. It is apparent from the figure that BBO algorithm shows rapid convergence rate. Therefore, it can be concluded that BBO algorithm has relatively demonstrated best performance in yielding the optimum design of six-storey, two-bay planar steel frame, so far.

5. Conclusion

The optimum design algorithm developed in this study is based on biogeography-based optimization (BBO) technique which selects the optimum W-section designations from W-sections table for the beams and columns of a planar steel frame such that design constraints described in AISC-LRFD are satisfied and the frame has the minimum weight. In view of the results obtained it is concluded that the BBO method is an efficient and robust technique that can successfully be used in optimum design of planar steel frames and determines lighter optimum solutions

compare to cuckoo search, particle swarm and big bang-big crunch methods. In the optimum design of six-storey, two-bay planar steel frame, the optimum design weight obtained by the BBO approach is 9.17, 15.94, and 16.51% lighter than the one attained by the other three metaheuristic techniques. Furthermore, the BBO technique basically has only three parameter to be specified by a user which are the population size, the number of elites, and the mutation probability. This provides robustness to the algorithm compared to many other metaheuristic techniques that require pre-determination of more parameters.

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