AN EFFICIENT OPTIMIZATION PROCEDURE BASED ON CUCKOO SEARCH ALGORITHM FOR PRACTICAL DESIGN OF STEEL STRUCTURES

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ABSTRACT

Different kinds of meta-heuristic algorithms have been recently utilized to overcome the complex nature of optimum design of structures. In this paper, an integrated optimization procedure with the objective of minimizing the self-weight of real size structures is simply performed interfacing SAP2000 and MATLAB[®] softwares in the form of parallel computing. The meta-heuristic algorithm chosen here is Cuckoo Search (CS) recently developed as a type of population based algorithm inspired by the behavior of some Cuckoo species in combination with the Lévy flight behavior. The CS algorithm performs suitable selection of sections from the American Institute of Steel Construction (AISC) wide-flange (W) shapes list. Strength constraints of the AISC load and resistance factor design specification, geometric limitations and displacement constraints are imposed on frames. Effective time-saving procedure using simple parallel computing, as well as utilizing reliable analysis and design tool are also some new features of the present study. The results show that the proposed method is effective in optimizing practical structures.

1. INTRODUCTION

As the word *optimization* suggests, the most outstanding goal in such procedures is saving

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both the computational time and the materials to achieve an optimum solution. During the last decades, several optimization methods were proposed including mathematical and meta-heuristic algorithms. The latter methods which emerged as effective tools for global searching problems include some well-known approaches used for optimum design of steel frames. Genetic algorithms (GAs) inspired from Darwins natural selection theorem based on the idea of the survival of the fittest [1]; Ant Colony Optimization (ACO), a cooperative search technique mimicking the foraging behavior of the real-life ant colonies [2]; Particle Swarm Optimizer (PSO) motivated from the social behavior of bird flocking and fish schooling [3]; Harmony Search algorithm (HS) being conceptualized using the musical process of searching for a perfect state of harmony [4]; Big Bang-Big Crunch algorithm (BB-BC) relying on Big Bang and Big Crunch theory [5]; Charged System Search (CSS) method utilizing the governing laws of physics and mechanics [6]; Imperialist Competitive Algorithm (ICA) being a socio-politically motivated optimization algorithm [7]. Consequently, a population based algorithm entitled Cuckoo Search (CS), inspired by the behavior of some Cuckoo species in combination with Lévy flight behavior [8], is selected to optimize self-weight of three inclusive steel structures with the same structural system on two perpendicular directions. Structural models are analyzed and designed in accordance with AISC-LRFD specifications and displacement constraints.

Considering the fact that it has always been aspired to model the structures as practical and detailed as possible, one of the most prevalent analysis and design tools, the SAP2000, is employed here. The Open Application Programming Interface (OAPI) as one of its powerful features automates many of the processes required to build, analyze and design models and paves the path for two-way exchange of information with other third-party software as well. Moreover, to take full advantage of the enhancements offered by the new multi-core hardware era, a corresponding shift must take place in the software infrastructure, i.e., a shift to parallel computing in optimization [9]. This led us to choose the MATLAB$^®$ software utilizing its Parallel Computing Toolbox^{TM} in this research. The design optimization problem is first formulated, and then the details of the CS algorithm are developed. Finally, three worked examples containing one two-dimensional and two three-dimensional structures with the same topological properties as Hasançebi et al. [10], are presented to illustrate the features of the design method. The results show that using the parallel computing besides the reliable SAP2000 analyzer efficiently optimizes typical structural systems for practical purposes.

2. PARALLEL ALGORITHM FOR OPTIMIZATION OF STEEL STRUCTURES

2.1. Optimum design of steel frames problem

The main design effort involves sizing the individual beam, column, and bracing members after the topology and support conditions are established for a frame structure. Members are categorized into certain groups according to symmetry and fabrication conditions known as design variables. Optimum design of steel frames problem can be expressed as:

$$\text{Find} \qquad \{X\} = \left[x_1, \ x_2, \ \mathbf{K}, \ x_{ng} \right], \quad x_i \in D_i$$

$$\text{To minimize} \qquad W(\{X\}) = \sum_{i=1}^{ng} x_i \sum_{j=1}^{nm(i)} r_j . L_j \tag{1}$$

where $\{X\}$ is the set of design variables; ng is the number of groups; D_i is the cross-sectional areas available for the design variable x_i; $W(\{X\})$ presents weight of the structure; $nm(i)$ is the number of members for the ith group; ρ_j and L_j denote the material density and the length for the jth member, respectively.

The design should be carried out in such a way that the frame satisfies the strength, displacements and geometric requirements. Stress checks based on the AISC-LRDF99 design code are considered within the scope of SAP2000. Drift criteria is considered for overall drift and inter-storey drift as some ratio (1/400) of the building and storey height, respectively. Geometric constraints are considered for beam column connections so that when a beam is connected to the flange of a column, the flange width of the beam is smaller than that of the column, and if a beam is connected to the web of a column, the flange width of the beam remains smaller than the clear distance between the flanges of the column [10].

In order to handle the constraints, a penalty approach is utilized. In this method, the aim of the optimization is redefined by introducing the cost function as:

$$f_{\cos t}\left(\{X\} \right) = \left(1 + e_1 . u \right)^{e_2} \times W\left(\{X\} \right), \quad u = \sum_{i=1}^{nm} u_i^{sr} + \sum_{i=1}^{nc} u_i^{g} + \sum_{i=1}^{ns} u_i^{id} + u^{td} \tag{2}$$

where υ is the constraint violation function; υ_i^{sr}, υ_i^{g}, υ_i^{d} and υ^{td} are constraint violation for stress ratio, geometry, inter-storey drift and total drift, respectively. ε_1 and ε_2 are penalty function exponents which are selected considering the exploration and the exploitation rate of the search space. Here, ε_1 is set to unity; ε_2 is selected in a way that it decreases the penalties and reduces the cross-sectional areas. Thus, in the first steps of the search process, ε_2 is set to 1 and ultimately increased to 3 , Ref. [7].

2.2. Cuckoo search optimization algorithm

Cuckoo Search is a meta-heuristic algorithm inspired by some species of a bird family called Cuckoo because of their special lifestyle and aggressive reproduction strategy [8]. These species lay their eggs in the nests of other host birds with amazing abilities like selecting the recently spawned nests and removing existing eggs that increase hatching probability of their eggs. The host takes care of the eggs presuming that the eggs are its own. However, some of host birds are able to combat with this parasites behavior of Cuckoos, and throw out the discovered alien eggs or build their new nests in new locations. The cuckoo breeding analogy is used for developing new design optimization algorithm. A generation is represented by a set of host nests. Each nest carries an egg (solution). The quality of the solutions is improved by generating a new solution from an existing solution and modifying certain characteristics. The number of solutions remains fixed in each generation. In this study the later version of the CS algorithm is used for optimum design of frames [11]. The pseudo-code of the optimum design

algorithm is as it follows [12]:

2.2.1. Initialize the cuckoo search algorithm parameters

The CS parameters are set in the first step. These parameters consist of the number of nests (n), the step size parameter (α), discovering probability (pa) and the maximum number of frame analyses as the stopping criterion.

2.2.2. Generate initial nests or eggs of host birds

The initial locations of the nests are determined by the set of values randomly assigned to each decision variable as:

$$nest_{i,j}^{(0)} = ROUND\left(x_{j,\min} + rand.(x_{j,\max} - x_{j,\min})\right) \tag{3}$$

where $nest_{i,j}^{(0)}$ determines the initial value of the jth variable for the ith nest; $x_{j,min}$ and $x_{j,max}$ are the minimum and the maximum allowable values for the jth variable; $rand$ is a random number in the interval [0, 1]. The rounding function is accomplished due to the discrete nature of the problem.

2.2.3 Generate new cuckoos by lévy flights

In this step, all the nests except for the best one are replaced based on quality by new Cuckoo eggs produced with Lévy flights from their positions as

$$nest_i^{(t+1)} = nest_i^{(t)} + a.\, S.(nest_i^{(t)} - nest_{best}^{(t)}).r \tag{4}$$

where $nest_i^t$ is the ith nest current position, α is the step size parameter; r is a random number from a standard normal distribution and $nest_{best}$ is the position of the best nest so far; and S is a random walk based on the Lévy flights. The Lévy flight essentially provides a random walk while the random step length is drawn from a Lévy distribution. In fact, Lévy flights have been observed among foraging patterns of albatrosses, fruit flies and spider monkeys. One of the most efficient and yet straightforward ways of applying Lévy flights is to use the so-called Mantegna algorithm. In Mantegna's algorithm, the step length S can be calculated by [13]:

$$S = \frac{u}{|v|^{1/b}} \tag{5}$$

where β is a parameter between [1, 2] interval and considered to be 1.5; u and v are drawn from normal distribution as:

$$u \sim N(0,\, s_u^2), \quad v \sim N(0, s_v^2) \tag{6}$$

$$s_u = \left\{ \frac{\Gamma(1+b)\ \sin(pb/2)}{\Gamma\left[(1+b)/2\right]\ b\ 2^{(b-1)/2}} \right\}^{1/b}, \qquad s_v = 1 \tag{7}$$

2.2.4. Alien eggs discovery

The alien eggs discovery is preformed for each component of each solution in terms of probability matrix such as:

$$P_{ij} = \begin{cases} 1 & if \ rand < pa \\ 0 & if \ rand \geq pa \end{cases} \qquad (8)$$

where *rand* is a random number in [0, 1] interval and *pa* is the discovering probability. Existing eggs are replaced considering quality by the newly generated ones from their current positions through random walks with step size such as:

$$S = rand .\left(nests\left(randperm1(n),:\right) - nests\left(randperm2(n),:\right)\right)$$
$$nest^{t+1} = nest^{t} + S.*P \qquad (9)$$

where *randperm1* and *randperm2* are random permutation functions used for different rows permutation applied on nests matrix and *P* is the probability matrix.

2.2.5. Termination criterion

The generating new Cuckoos and discovering alien eggs steps are alternatively performed until a termination criterion is satisfied. The maximum number of frame analyses is considered as termination criterion of the algorithm.

2.3. Parallel computing system

A visit to the neighborhood PC retail store provides ample proof that we are in the multi-core era. This created demand for software infrastructure to utilize mechanisms such as parallel computing to exploit such architectures. In this respect, the MathWorks introduced Parallel Computing Toolbox software and MATLAB® Distributed Computing Server [14]. Regarding that our individual designs proposed by population based meta-heuristic algorithms are evaluated independently, electing one of MATLABs most basic programming paradigms, the parallel for-loops [14], makes it easy for user to handle in such optimization problem.

Since the parallel computing technique enables us to perform several actions at the same time, it is needed to adjust the analysis and design assumptions for a prime model of structure in the SAP2000 environment. Once the optimization algorithm invokes the model, a set of section groups are assigned to the predefined groups of members. A certain feasible number of proposed solutions get invoked for analysis and evaluating the penalized fitness value following the PARFOR conditional command, and consequently a next set of population are generated. The iteration continues until a stopping criterion is attained.

3. NUMERICAL EXAMPLES

Before initiating optimization process, it is necessary to set the search space. The steel

members (columns, beams and braces), used for the design of steel frames consist of 297 W-shaped sections starting from W6×9 to W36×848. These sections with their properties are used to prepare a design pool. The sequence numbers assigned to this pool that sorted with respect to area of sections are considered as design variables. In other words the design variables represent a selection from a set of integer numbers between 1 and the number of sections.

Constant analysis and design assumptions considered for the prime model of each example are as follows: material property for all sections is considered as A36 default steel material with weight per unit volume of $\rho=0.2836$ lb/in^3, modulus of elasticity of $E=29000$ ksi and a yield stress of $f_y=36$ ksi; All nodes of each storey are constrained to each other in the form of TranslationX and TranslationY; Frame elements are modeled as line elements connected at points without specifying two end offsets; The steel design code is selected as AISC-LRFD99. The framing type is considered as Ordinary Concentrically Braced Frames (OCBF) and Ordinary Moment Frames (OMF) for first two and last frames, respectively.

Considering the effect of the initial solution on the final results and the stochastic nature of the meta-heuristic algorithms, each case is independently solved for five times with random initial designs. Afterwards the best run is chosen for performance evaluation of CS. The maximum numbers of structure analyses equaling to 28,000 is considered as termination criteria for all cases. The parameters of the CS algorithm are considered as $n=7$, $\alpha=0.1$ and $pa=0.3$ [12].

3.1. A 224-member planar frame

The first example is the 24-storey 3-bay 2-dimensional X-type braced steel frame. Figure 1 shows the configuration, the service loading conditions and the numbering of member groups. The elements grouping results in 16 column sections, 8 beam sections and 8 brace sections for a total of 32 design variables. The frame is subjected to six loading combinations extracted from the AISC-LRFD99 design code disregarding the ones with negative wind loads. The CS algorithm performed for five times of which the most optimum design weighted 503.87 kips. The sectional designations of the best optimum solution for member groups are presented in Table 1. Results summary for members total stress ratios and the inter-storey drifts are listed in Table 2. The convergence history for the best result is shown in Figure 2, and for clarity the upper bound of y axis limited to 5000 kips. To recognize the role of each load combination, its contribution for determining the maximum stress ratio and inter-storey drifts is computed having expressed in Table 3. It can be interpreted that the strength constraints govern the design of the frame under gravity loading, and the displacement constraints become active for the wind loads. By the way, the maximum value of sway at the top storey is 0.35ft resulted from 0.9Dead+1.6Windx load combination which is smaller than 0.73ft as total drift constraint.
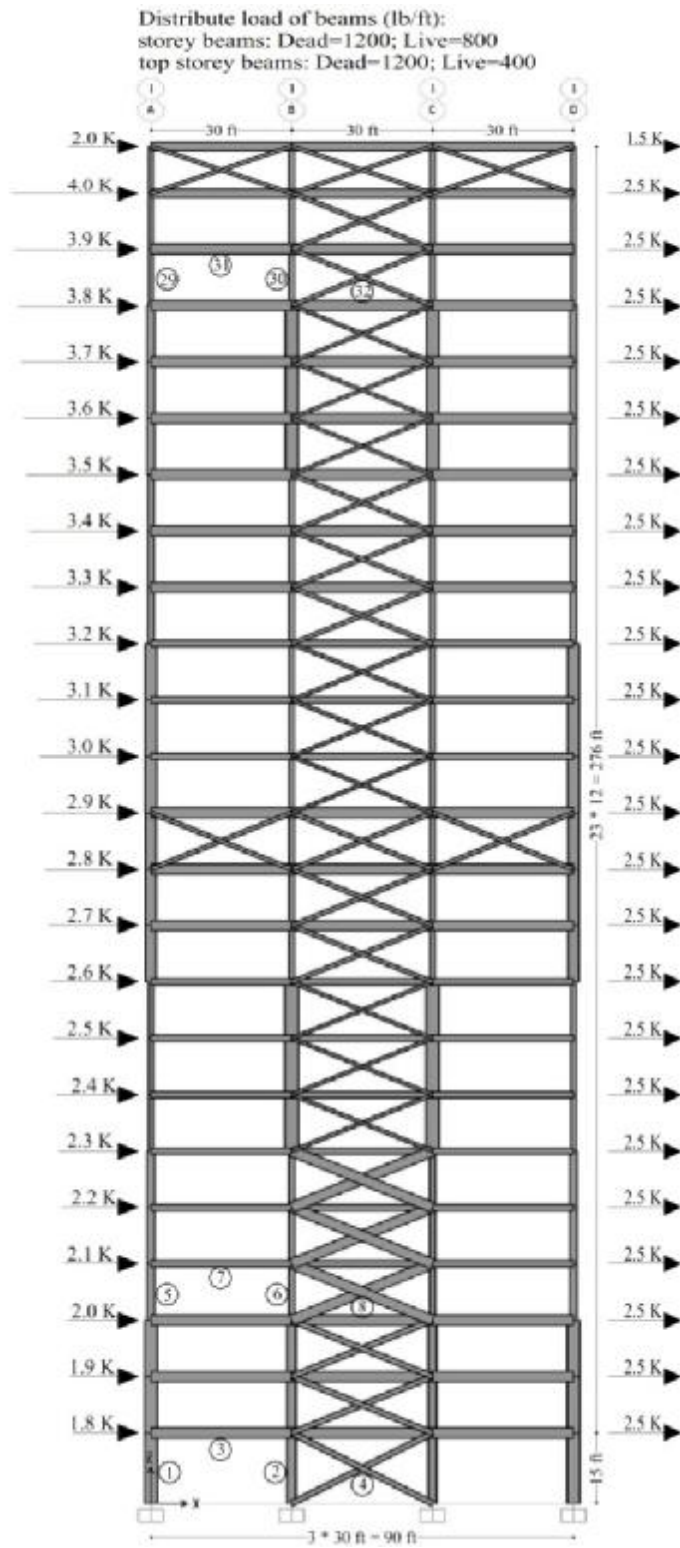
Distribute load of beams (lb/ft):
storey beams: Dead=1200; Live=800
top storey beams: Dead=1200; Live=400

Figure 1. A 224-member planar frame

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Table 1. Sectional designations and weight of the best optimum design obtained by the CS

Group no.	224-member frame	325-member frame	568-member frame
1	W27×178	W8×31	W14×90
2	W40×324	W18×71	W30×108
3	W12×65	W8×31	W24×68
4	W10×100	W8×24	W21×62
5	W33×130	W14×53	W14×22
6	W33×263	W8×18	W14×211
7	W24×94	W16×40	W40×221
8	W18×86	W8×31	W12×106
9	W27×161	W24×55	W27×114
10	W27×178	W6×20	W14×22
11	W12×58	W6×20	W24×94
12	W14×82	W8×31	W21×132
13	W36×150	W8×18	W40×192
14	W44×198	W16×40	W18×55
15	W18×76	W8×31	W24×103
16	W18×86	W12×30	W18×119
17	W21×147	W10×26	W33×118
18	W36×260	W6×15	W27×161
19	W14×61	W8×31	W21×50
20	W27×84	W8×18	W10×33
21	W12×120	W16×40	W10×77
22	W16×100	-	W16×100
23	W8×58	-	W33×152
24	W30×90	-	W10×22
25	W10×100	-	W10×15
26	W12×96	-	-
27	W14×43	-	-
28	W16×77	-	-
29	W24×131	-	-
30	W30×116	-	-
31	W12×65	-	-
32	W30×99	-	-
Best weight (kips)	503.870	138.0	636.722

Table 2. Summary results of total stress ratio and inter-storey drifts

Frame		Min	Max	Mean	SD
224-member	Total stress ratio	0.0146	0.9832	0.5818	0.2861
	Inter-storey drift X	0.0026	0.0193	0.0150	0.0043
325-member	Total stress ratio	0.0273	0.9562	0.4663	0.2759
	Inter-storey drift X	0.0080	0.0154	0.0125	0.0029
	Inter-storey drift Y	0.0165	0.0300	0.0247	0.0059
568-member	Total stress ratio	0.0744	0.8849	0.4363	0.1799
	Inter-storey drift X	0.0169	0.0299	0.0250	0.0039
	Inter-storey drift Y	0.0176	0.0300	0.0267	0.0039

Note: Max= largest observation; Min=smallest observation; Mean=arithmetic average; SD= standard deviation
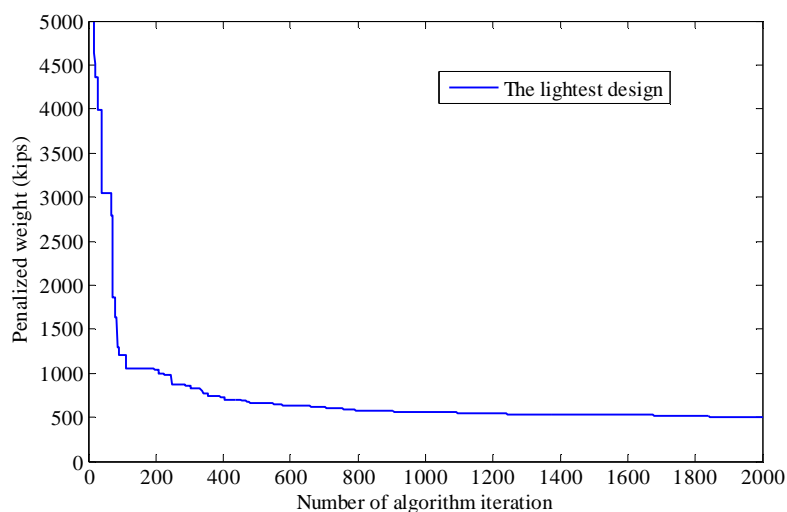

Figure 2. The best design history of the 224-member braced 2D steel frame

Table 3. Contribution of the load combinations corresponding to the maximum stress ratios of the members and inter-storey drifts

Load combinations		Total stress ratio	Inter-storey drift
UDSTL1	1.4Dead	0	0
UDSTL2	1.2Dead+1.6 Live	0.723	0.083
UDSTL3	1.2 Dead+1.0Live+1.6Windx	0.246	0.542
UDSTL4	0.9 Dead+1.6Windx	0.031	0.375
UDSTL5	1.0Dead	0	0
UDSTL6	1.0Dead+1.0Live	0	0

3.2. A 325-member braced space frame

Second example is a 5-storey concentric braced space frame. Figure 3 shows the 3D and plan views of the frame. The frame is braced with chevron bracing system along the x-direction and with X-type bracing system along the y-direction. The element grouping results in 12 column sections, 6 beam sections and 3 brace sections for a total of 21 design variables. Groups ordering are as following; 1st group: outer xz columns, 2nd group: outer yz columns, 3rd group: corner columns, 4th group: braces, 5th group: inner columns, 6th group: outer beams, and 7th group: inner beams for first storey and so forth for each two adjacent upper stories. The frame is subjected to gravity and earthquake loads. The gravity loads include dead load equal to 60 lb/ft^2 for all stories, and live load as 40 lb/ft^2 and 20 lb/ft^2 for floor and roof stories, respectively. Equivalent linear Dead loads are approximately calculated as 300 lb/ft for outer beams and 600 lb/ft for inner beams for all stories. Live load values are considered two-third of their Dead load for floor levels and one-third for roof level beams. Typically, in accordance with most current building codes such as ASCE7-05 [15], the design is carried out by transforming the dynamic loads to equivalent static loads applied horizontally on the structure. Accordingly, the lateral forces corresponding to storey levels are 11, 19, 27, 38 and 32 kips from bottom to top and the same for two perpendicular directions applied at the center of the gravity of each respective storey. The load combinations outlined based on AISC-LRFD99, results in 10 combinations for our purpose in this structure. The sectional designations for the most optimum solution weighted 138.0 kips by CS are expressed in Table 1. Results summary for members total stress ratios and the inter-storey drifts are listed in Table 2. The convergence history for the best result is shown in Figure 4, and for clarity the upper bound of y axis limited to 560 kips.

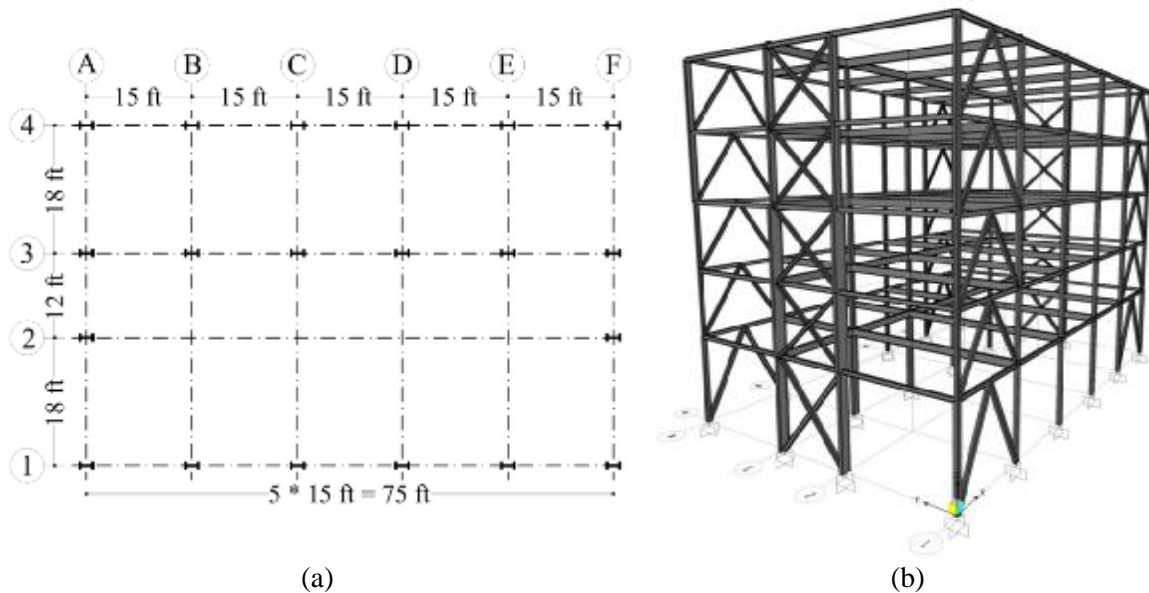(a)   (b)

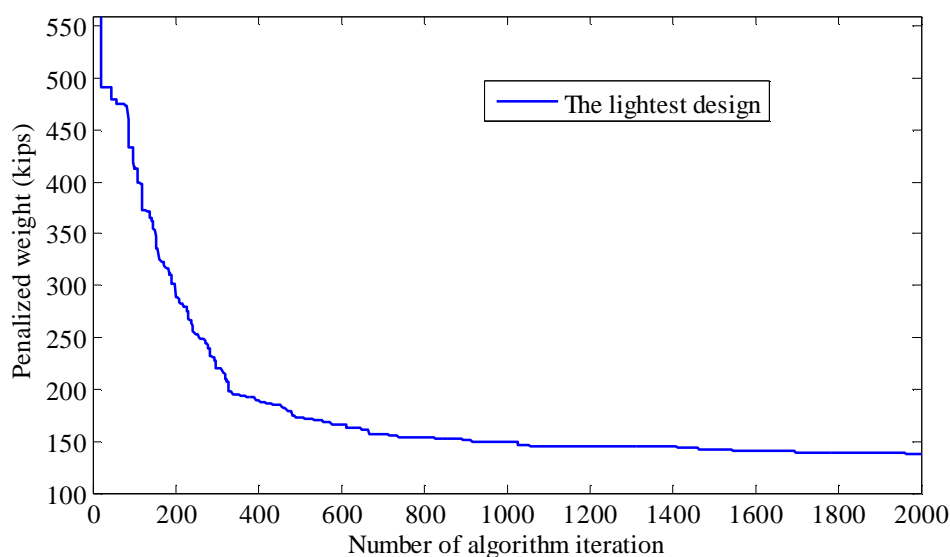Figure 3. A 325-member braced space frame. (a) plan view (x-y plane), (b) 3D view

Figure 4. The best design history of the 325-member braced space steel frame

3.3. A 568-member moment space frame

Figure 5 represents a 10-storey moment resisting steel space frame as third example in this study. The element grouping results in 15 column sections and 10 beam sections for a total of 25 design variables. Groups ordering are as following; 1st group: corner columns, 2nd group: side columns, 3rd group: inner columns, 4th group: side beams, 5th group: inner beams, for first three stories and so forth for each two adjacent upper stories and last storey. The frame is subjected to gravity, wind and earthquake loads. The gravity loads include dead load equal to 60 lb/ft^2 for all stories, and live load as 40 lb/ft^2 and 20 lb/ft^2 for floor and roof stories, respectively. Equivalent linear Dead loads are approximately calculated as 300 lb/ft for outer and inner beams for all stories. Live load values are considered two-third of their Dead load for floor levels and one-third for roof level beams. Equivalent static loads as transformed earthquake loads applied horizontally at the center of the gravity of each storey and wind loads applied as distributed loads on outer beams [10] and the same for X and Y directions, are presented in Table 4. The sectional designations for the most optimum solution weighted 636.722 kips by CS are expressed in Table 1. Results summary for members total stress ratios and the inter-storey drifts are listed in Table 2. To recognize the role of each load combination, its contribution for determining the maximum stress ratio and inter-storey drifts is computed having expressed in Table 5. The maximum value of sway at the top storey is 0.25ft and 0.27ft in the X and Y directions, respectively which are smaller than 0.3ft as total drift constraint.

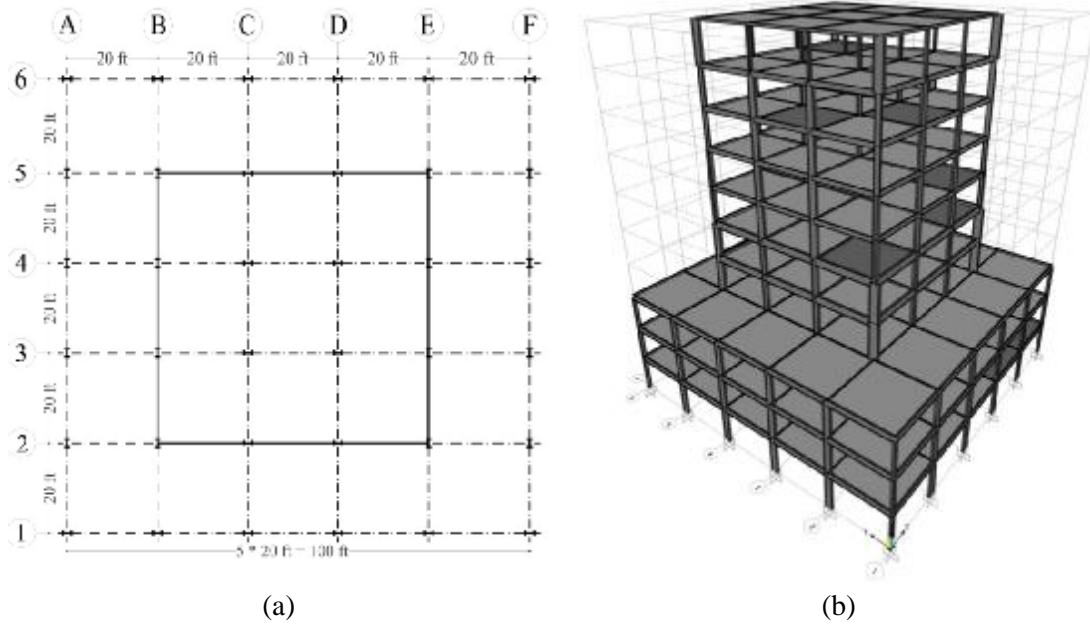(a)   (b)

Figure 5. A 568-member moment space frame. (a) plan view (x-y plan), (b) 3D view

Table 4. Wind and earthquake loading on the 568-member moment space frame

Floor No.	Wind loads		Earthquake loads (kips)
	Windward (lb/ft)	Leeward (lb/ft)	
1	112.51	127.38	16
2	128.68	127.38	32
3	144.68	127.38	48
4	156.86	127.38	23
5	167.19	127.38	29
6	176.13	127.38	35
7	184.06	127.38	40
8	191.21	127.38	46
9	197.76	127.38	52
10	101.90	63.90	54

Table 5. Contribution of the load combinations corresponding to the maximum stress ratios of the members and inter-storey drifts

Load combination	Total stress ratio	Inter-storey driftX	Inter-storey driftY
1.4Dead	0	0	0
1.2Dead+1.6Live	0.119718	0	0
1.2Dead+1.0Live+1.6WindX	0.019366	0	0
1.2Dead+1.0Live+1.6WindY	0.035211	0	0
0.9Dead+1.6WindX	0	0	0
0.9Dead+1.6WindY	0	0	0
1.2Daed+1.0Live+1.0EX	0.18662	1.0	0
1.2Daed+1.0Live-1.0EX	0.190141	0	0
1.2Daed+1.0Live+1.0EY	0.221831	0	1.0
1.2Daed+1.0Live-1.0EX	0.227113	0	0
0.9Daed+1.0EX	0	0	0
0.9Daed-1.0EX	0	0	0
0.9Daed+1.0EY	0	0	0
0.9Daed-1.0EY	0	0	0

4. CONCLUDING REMARKS

A new integrated optimization procedure proposed involving the SAP2000 by its OAPI functions is validated on three inclusive steel structures. The Cuckoo Search algorithm is of recently published meta-heuristic optimization algorithms utilized in this study.

Based on this study it can be concluded that the CS yields acceptable convergence performance from the early iterations.

An easy-to-handle Parallel Computing technique is an effective time-saving procedure applied here using MATLAB$^{®}$ software and a typical multi-core hardware. Coupling with the SAP2000, made the optimization process visual, easier, and more inclusive by considering various load combinations and their contribution in structural behavior. Undeniably, SAP2000 program enables user to work with any other type of structures, international codes, load types and their combinations, as well as linear, nonlinear, static and dynamic analysis of structures.

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