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Seismic optimal design of 3D steel frames using cuckoo search algorithm

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SUMMARY

The present article is concerned with optimization of real size 3D steel structures under seismic loading based on response spectral and equivalent static analyses. The effect of lateral seismic loading distribution on the achieved optimum designs is investigated. An integrated optimization procedure with the objective of minimizing the self-weight of frame is simply performed interfacing SAP2000 and MATLAB® software in the form of parallel computing. The meta-heuristic algorithm chosen here is the cuckoo search (CS) algorithm 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 the considered frames. Results show similar weights for optimum designs using spectral and equivalent static analyses; however, different material distribution and seismic behaviors are observed. Copyright © 2014 John Wiley & Sons, Ltd.

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KEY WORDS: optimum design; 3D steel frame; cuckoo search algorithm; meta-heuristic; response spectral; equivalent static

1. INTRODUCTION

A structural designer has a challenging work to achieve a safe and economical design of 3D steel frames. After assigning the sections from an available list to member groups, design checking for the safety and serviceability is conducted based on a set of accepted design rules such as those of the American Institute of Steel Construction (AISC) load and resistance factor design specification (AISC, 2001). Developments in computer hardware and software, advances in computer-based analysis and design tools, and advances in numerical optimization methods make it possible to formulate a design of 3D steel frames as an optimization problem and solve them by one of the optimization methods. Many of the optimization techniques have been developed during the last decades and at the pioneer are traditional mathematical-based methods that use the gradient information to search the optimal solutions with drawbacks such as complex derivatives, sensitivity to initial values, applicable in continuous search spaces, and the large amount of enumeration memory required (Lee and Geem, 2004). In recent years, in addition to heuristic optimization methods, stochastic optimization algorithms inspired by natural mechanisms have been developed for overcoming these disadvantages, making the optimization of complicated discrete engineering problems feasible.

In recent years, the investigation of various kinds of meta-heuristic algorithms for discrete optimization of steel frames has attracted much attention and many possible applications.

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Hasançebi *et al*. (2010) have conducted a comprehensive comparative study of various meta-heuristic algorithms on steel frames and have shown the evolutionary optimization as the most effective method. Following the past studies, Hasançebi *et al*. (2011) have optimized large 3D steel structures under lateral wind loads using parallel processing based on the evolutionary optimization. Kaveh *et al.* handled various types of stochastic methods for 2D and 3D steel frames under seismic and wind loads (Kaveh and Talatahari, 2010; Kaveh *et al*., 2012; Kaveh and Zakian, 2013). Many of the other techniques have been used for optimizing steel frames (Pezeshk *et al*., 2000; Camp *et al*., 2005; Degertekin, 2008; Saka, 2009). Very recently, a comprehensive review on steel skeletal frames design optimization based on mathematical and meta-heuristic algorithms has been carried out (Saka and Geem, 2013). In the optimization of steel frames, inclusive studies have been accomplished under static, wind, and seismic loading with static analysis approach, considering a limited number of load combinations. Optimum seismic design of steel structures based on other methods such as performance-based design and time history analysis has been conducted using meta-heuristic algorithms alongside cost-effective approximation techniques, such as artificial neural networks. The basic problem associated with the approximation techniques is the accuracy of the prediction, which may easily lead the solution algorithm to a local optima or infeasible solutions (Hasançebi *et al*., 2011).

The art of seismic analysis has been promoted along with the development of technology and reaches to various analysis techniques. Foremost, among these, has been the response spectral analysis method for dynamic analysis. This method can give more accurate results than the equivalent static approach. The contribution of this study is concerned with optimization of real size 3D steel structures under seismic loads based on response spectral and equivalent static analyses, to investigate the effect of lateral distribution of the seismic loads on the achieved optimum designs. 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 in this study and also took advantage of its open application programming interface feature. 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 (Luszczek, 2009). This led us to choose the MATLAB software, utilizing its Parallel Computing Toolbox in this research. In this paper, cuckoo search (CS) algorithm optimizes 3D steel frames under equivalent static and response spectral analyses. Yang (2008) has presented the CS as a population-based meta-heuristic algorithm inspired by the behavior of some cuckoo species in combination with Lévy flight behavior. Some recent research into the advances and applications of the CS for multi-criteria and constrained optimization, associated with practical engineering problems, can be found in previous studies (Durgun and Yildiz, 2012; Gandomi *et al*., 2013; Walton *et al*., 2013; Yıldız, 2013). This population-based algorithm like other ones can benefit the features of parallel computing against the computationally expensive actual structural analysis considering all load combinations recommended by provisions such as ASCE 7-05 (ASCE, 2005). The CS has been used successfully for optimum design of 2D and 3D frames under static loads and lateral dynamic loading based on wind loads and equivalent static approach (Kaveh and Bakhshpoori, 2012, 2013).

We will compare the optimization based on response spectral analysis with a typical equivalent static analysis and point out the differences of the achieved final optimum designs. This matter will be investigated and discussed using three 3D real size steel frames with specific features. Though the optimization procedure results in the same optimum designs from weight point of view, however, significantly different in material distribution and slightly well seismic response in all cases for response spectral analyses which can be preferred over the other.

The remaining sections of this paper are organized as follows. Section 2 states the integrated optimization process containing modeling of 3D steel frames, utilizing the CS algorithm, and summarizing the performed parallel computing system. Section 3 examines the search behavior of the parallel integrated optimization based on the CS algorithm. Section 4 applies the proposed parallel integrated optimization procedure to three examples. These examples consist of a five-story 325-member steel moment frame, an eight-story 504-member steel braced frame, and a nine-story 499-member irregular steel moment frame. Finally, the paper is concluded in Section 5.

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2. PARALLEL OPTIMIZATION OF STEEL FRAMES

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 (ng) according to symmetry and fabrication conditions known as design variables. The design groups are selected from steel sections of a given profile list. Optimum design of steel frames problem can be expressed as

$$\begin{aligned} &\text{Find} \qquad \{X\} = \left[x_1, x_2, \ \ldots, x_{ng}\right] \\ &\text{To minimize} \qquad W(\{X\}) = \sum_{i=1}^{ng} x_i \sum_{j=1}^{nm(i)} \rho_j \, . \, L_j \end{aligned} \tag{1}$$

where $\{X\}$ is the vector of integer values representing the sequence numbers of steel sections assigned to the ng member groups, $W(\{X\})$ presents the weight of the structure, $nm(i)$ is the number of members for the ith group, and 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-LRFD99 design code are considered within the scope of SAP2000. Each frame member should have sufficient strength to resist the internal forces. Therefore, the total stress ratio for the members is limited up to 1.0 (v_i^{sr} : the total stress ratio of the ith member ≤ 1). Drift criteria are considered for inter-story drift as some ratio (1/400) of the story height (v_i^{d} : the ith inter-story drift $\leq h_i/400$). Finally, the geometric constraints are considered for beam–column connections so that when a beam ($b1$) is connected to the flange of a column, the flange width of the beam (b_{b1}) is smaller than that of the column (b_c) (v_i^{g} : $b_{b1} \leq b_c$), and if a beam ($b2$) is connected to the web of a column, the flange width of the beam (b_{b2}) remains smaller than the clear distance between the flanges of the column (d_c) (v_i^{g} : $b_{b2} \leq d_c$) (Hasançebi *et al.*, 2011), as shown in Figure 1.

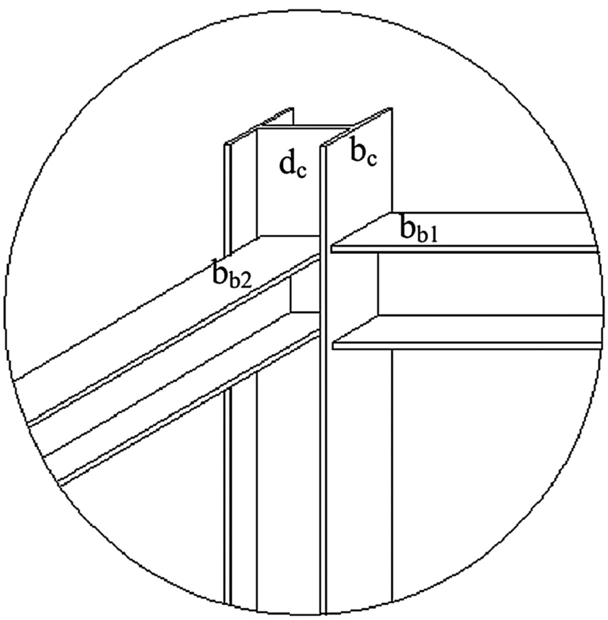

Figure 1. Geometric constraints of the beam–column connections.

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

$$f_{\text{cost}}(\{X\}) = (1+\varepsilon_1.\upsilon)^{\varepsilon_2} \times W(\{X\}), \quad \upsilon = \sum_{i=1}^{nm} \upsilon_i^{sr} + \sum_{i=1}^{nc} \upsilon_i^{g} + \sum_{i=1}^{2*ns} \upsilon_i^{d} \tag{2}$$

where υ is the constraint violation function; υ_i^{sr}, υ_i^{g}, and υ_i^{d} are the constraint violation for stress ratio, geometry, and inter-story drift, respectively. These constraints are checked *nm* times (the number of members of frame), (*nc*) times (the number of connections between distinct groups), and (*2*ns*) times in X and Y directions (twice the number of stories), respectively. ε_1 and ε_2 are penalty function exponents that 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 (Kaveh and Talatahari, 2010).

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 (Yang and Deb, 2010). 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 the host birds are able to combat with this parasite behavior of cuckoos and therefore 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 the frames (Yang and Deb, 2010). The pseudo-code of the optimum design algorithm is as follows (Kaveh and Bakhshpoori, 2013).

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), the 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

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

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 maximum allowable values for the jth variable, respectively; and $rand$ 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

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

where $nest_i^t$ is the ith nest current position, α is the step size parameter that is considered equal to 0.1, r is a random number from a standard normal distribution, $nest_{best}$ 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

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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's algorithm. In Mantegna's algorithm, the step length S can be calculated by (Yang, 2008)

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

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

$$u \sim N\left(0, \sigma_u^2\right), \quad v \sim N\left(0, \sigma_v^2\right) \tag{6}$$

$$\sigma_u = \left\{ \frac{\Gamma(1+\beta)\sin(\pi\beta/2)}{\Gamma[(1+\beta)/2]\,\beta\,2^{(\beta-1)/2}} \right\}^{1/\beta}, \quad \sigma_v = 1 \tag{7}$$

2.2.4. Alien eggs discovery

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

$$P_{ij} = \begin{cases} 1 & \textit{if rand} < pa \\ 0 & \textit{if rand} \geq pa \end{cases} \tag{8}$$

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

$$\begin{aligned} S &= rand.(nests(randperm1(n), :)\text{-}nests(randperm2(n), :)) \\ nest^{t+1} &= nest^{t} + S.{*}P \end{aligned} \tag{9}$$

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 a termination criterion of the algorithm.

2.3. Parallel computing system

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 (Luszczek, 2009), 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 is generated. The iteration continues until a stopping criterion is attained.

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3. SEARCH BEHAVIOR OF THE PARALLEL INTEGRATED OPTIMIZATION BASED ON THE CS

In this section, the search behavior of the proposed integrated optimization procedure based on the CS in solving the 3D real size steel frames is studied and will be analyzed in detail using experiments. In particular, answers to the following questions will be sought: (a) how CS works on 3D real size steel frames optimization and (b) how parameters of the CS are best set.

Hasançebi *et al*. (2010) have conducted a comprehensive comparative study of seven optimum structural design algorithms based on simulated annealing, evolution strategies, particle swarm optimizer, tabu search method, ant colony optimization, harmony search method, and simple genetic algorithm on optimum design of rigid steel frames. The effect of the parameters and search ability of the CS are investigated here using a 325-member braced space steel frame, which has been studied by Hasançebi *et al*. (2010). Figure 2 shows the 3D and plan views of this frame. The element grouping results in 12 column sections, six beam sections, and three brace sections for a total of 21 design variables. Group ordering is as follows: first group: outer xz columns, second group: outer yz columns, third group: corner columns, fourth group: braces, fifth group: inner columns, sixth group: outer beams, seventh group: inner beams for first story, and so forth for each of the two adjacent upper stories. The frame is subjected to gravity and earthquake loads. Gravity loads (G) are calculated as uniformly distributed load values for beam-type members considering a design dead load of 60.13 lb/ft^2 (2.88 kN/m^2), a design live load of 50 lb/ft^2 (2.39 kN/m^2), and a ground snow load of 25 lb/ft^2 (1.20 kN/m^2). Lateral forces, earthquake loads (E), are computed as to equivalent lateral force procedure, resulting in point loads applied at the center of gravity of each respective story. The gravity and lateral loads are combined under two loading conditions for the frame: (i) 1.0G + 1.0E (in X-direction) and (ii) 1.0G + 1.0E (in Y-direction). Detailed information can be found in the work of Hasançebi *et al*. (2010).

Based on Yang's simulations (Yang and Deb, 2009), considering algorithm essential parameters (population size or number of host nests (n) and probability pa) such as $n = 15$–25 and $pa = 0.15$–0.3 is efficient for most optimization problems. In order to adjust probability pa for the 3D real size steel frame optimization problem, we solve this example alternatively with a constant n equal to 7 and various amounts of pa within the [0, 1] interval with 28,000 as the maximum number of the analyses. Figure 3 shows the obtained best convergence histories of the CS performance for three independent runs in each case. As it is clear, the amounts from 0.2 to 0.3 are efficient for the algorithm, and the $pa = 0.3$ gives the best result. In order to adjust the population size, we design this frame with constant pa equal to 0.3 and various n values within the interval [5, 25] with 40,000 as the maximum number of analyses for five independent times. Based on Table 1, our simulations

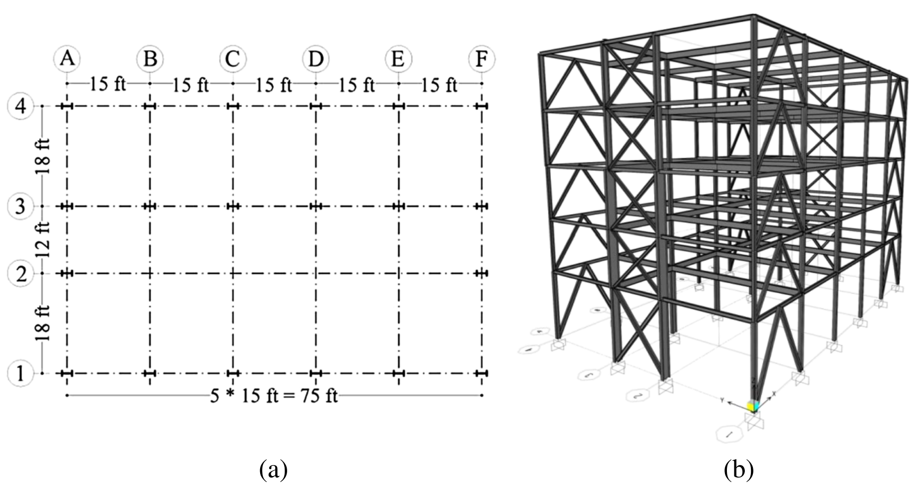

Figure 2. A 325-member braced space frame. (a) Plan view (x–y plane); (b) 3D view.

DOI: 10.1002/tal

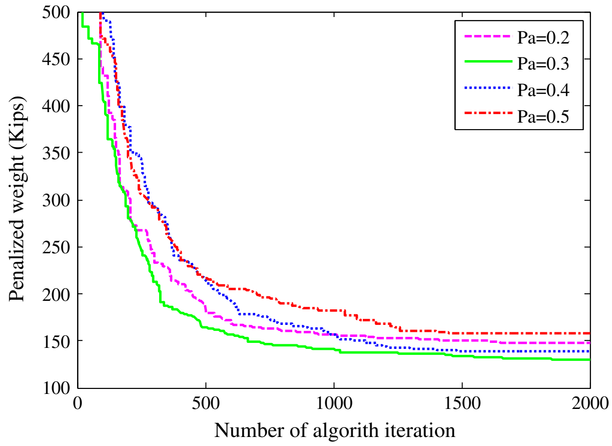

Figure 3. The convergence history for the best run with constant number of nests and different values of *pa*.

Table 1. Cuckoo search performance for 325-member braced frame with various amounts of *n*.

CS parameters $pa = 0.3$	Best run		Five runs (average ± SD)	
	Min weight (kips)	Min *Noa*	Weight (kips)	*Noa*
$n = 5$	138.853	18,542	143.692 ± 4.651	28,547 ± 8683
$n = 7$	131.694	26,340	138.456 ± 2.363	28,485 ± 1752
$n = 10$	131.983	29,432	137.721 ± 3.665	32,874 ± 4427
$n = 15$	129.592	32,563	135.417 ± 3.172	35,653 ± 5860
$n = 20$	132.463	35,773	136.034 ± 4.234	37,874 ± 2807
$n = 25$	132.127	38,762	134.183 ± 2.342	39,649 ± 1235

Noa, number of analysis; SD, standard deviation; Min, minimum; CS, cuckoo search.

show that the values between 7 and 15 yield to effective performance of the CS from accuracy and convergence rate point of view. It should be noted that the larger values of *n* result in better outcome from reliability point of view; however, the computational time increases. All together, it seems that choosing $n = 7$ can provide efficient performance of CS considering both accuracy and computational time. Thus, we used these values ($pa = 0.3$ and $n = 7$) for the numerical examples in the subsequent section. To answer the first question, how the CS works on 3D real size steel frames optimization, Table 2 presents the best result of five independent runs based on the CS beside the first three best algorithms (evolutionary algorithms (ESs), simulated annealing (SA), and tabu search method (TSO)) of the Hasançebi study. As it is clear, the CS performs effectively in optimizing this type of engineering optimization problems. The difference between the optimum yielded design by CS and the ones of the first two algorithms is negligible.

4. 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 the 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. Considering the effect of the initial solution on the final results and the stochastic nature of the meta-heuristic algorithms, each case is independently

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Table 2. The optimum designs of 325-member braced space steel frame obtained with non-deterministic search techniques.

Member group	Method			
	ESs	SA	TSO	Present study
1	W8 × 40	W18 × 40	W12 × 35	W8 × 31
2	W8 × 24	W8 × 24	W8 × 24	W8 × 24
3	W21 × 62	W18 × 60	W12 × 53	W8 × 31
4	W6 × 15	W6 × 15	W6 × 20	W6 × 20
5	W18 × 50	W16 × 45	W18 × 50	W14 × 53
6	W12 × 14	W12 × 14	W10 × 17	W8 × 18
7	W18 × 40	W18 × 40	W18 × 40	W16 × 40
8	W8 × 18	W8 × 24	W8 × 21	W8 × 21
9	W8 × 18	W14 × 22	W6 × 15	W24 × 55
10	W12 × 50	W12 × 50	W14 × 53	W6 × 20
11	W6 × 15	W6 × 15	W6 × 15	W6 × 15
12	W21 × 44	W21 × 44	W18 × 46	W8 × 31
13	W12 × 14	W12 × 14	W12 × 16	W12 × 16
14	W18 × 40	W18 × 40	W18 × 40	W16 × 40
15	W8 × 13	W8 × 13	W8 × 15	W8 × 31
16	W12 × 14	W12 × 14	W12 × 14	W12 × 14
17	W14 × 34	W14 × 34	W16 × 36	W10 × 26
18	W6 × 15	W6 × 15	W5 × 16	W6 × 15
19	W14 × 34	W14 × 34	W14 × 34	W8 × 31
20	W12 × 14	W12 × 14	W12 × 14	W8 × 18
21	W18 × 40	W18 × 40	W18 × 40	W16 × 40
Weight, lb(kg)	128,637.77 (58,349.11)	128,788.82 (58,417.63)	131,782.50 (59,775.54)	131,694.43 (59,735.59)

ESs: evolutionary algorithms, SA: simulated annealing, and TSO: tabu search optimization.

solved for three times with random initial designs, and the result of the best run is reported. The maximum numbers of structural analyses as 28,000 and 35,000 are considered as termination criteria for the first example and the next two ones, respectively. The parameters of the discrete CS algorithm are set to the following recommended values based on the previous section: $n = 7$ and $pa = 0.3$.

Three different examples are studied in this investigation. These examples consist of two regular space frames, i.e. a 325-member ordinary steel moment frame (OMRF) and a 504-member ordinary steel braced frame (OCBF), and an irregular 499-member steel moment frame, containing 15, 32, and 26 member groups, respectively. The first two examples are analyzed and designed under both static and spectral loadings. The last example is optimized under the spectral loading with the participation of 9 and 18 vibration modes.

In all SAP2000 modeling, analysis, and design procedures, the fundamental assumptions are made to idealize the results as follows: The height of each story is 3.2 m (10.5 ft), each frame member is modeled as a line element with an offset of 0.5 at each end joint, and all nodes are constrained to each other at each floor level in order to act as a horizontal diaphragm. Material property for all sections is considered as A36 default steel material with weight per unit volume of $\rho = 7849$ t/m^3 (0.2836 lb/in.^{3}), modulus of elasticity of $E = 199{,}948$ Mpa (29,000 ksi), and a yield stress of $f_y = 248.2$ MPa (36 ksi). All the story floors carry a uniformly distributed design dead load of D.L. = 292.9 kg/m^2 (60 lb/ft^2) and a design live load of L.L. = 195.3 kg/m^2 (40 lb/ft^2). The roof slab carries a design live load of L.L. = 97.6 kg/m^2 (20 lb/ft^2).

The main objective of this study is to investigate the effect of lateral load distribution and analysis method on optimum design. Hence, equivalent static and modal response spectral analyses are applied to compute and distribute the lateral seismic loads within the SAP2000. The procedure is outlined in sections 12.8 and 12.9 of ASCE 7–05. The following assumptions are made to compare the results of static and spectral load cases: the response modification factor, $R = 3.25$ (for OCBF) and 3.5 (for OMRF); system over strength factor, $\Omega_0 = 2$; deflection amplification, $C_d = 3$; importance factor, $I = 1.0$; 0.2-s spectral acceleration, $S_s = 0.4$; 1-s spectral acceleration, $S_1 = 0.2$; and site class = D. The

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definition of the spectral function that is used in this study is based on section 1613 of IBC (2009) code provisions utilized automatically via SAP2000. Figure 4 shows the design response spectral as acceleration versus period.

Table 3 tabulated the load combinations considered in the design of the frames according to the design code specification (ASCE 7-05).

4.1. *Example 1: a five-story 325-member steel moment frame*

A five-story moment-resisting frame building is simulated as the first design example. Figure 5 shows the 3D view and plan view (xy) of the structure. All 325 members are categorized into 15 design groups considering the symmetry and practical point of views as first group: corner columns, second group: outer columns, third group: inner columns, fourth group: outer beams, fifth group: inner beams for the first story, and so forth for each of the two adjacent upper stories.

The sectional designations of the best optimum solution for member groups are presented in Table 4. It is visible that CS yields the same weight optimum design equal to 43.4 t (95.8 kips) in both examples but is significantly different in material distribution. According to this table, the difference of material distribution is more apparent in the columns.

Figure 6 shows the stress ratio of members for the achieved optimum design based on both static and spectral analyses. There is no significant difference between the two analyses, but for both examples, the CS results in a more economic design for columns than beams, which can be due to the well grouping system considered for columns. Detailed results for the stress ratio of members (beams, columns, and all members) containing largest and smallest observed values, arithmetic average, and standard

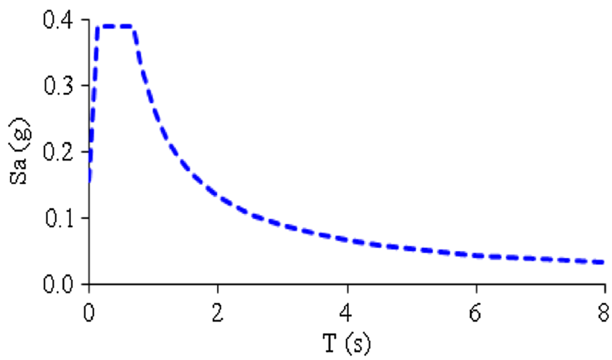

Figure 4. Design response spectrum.

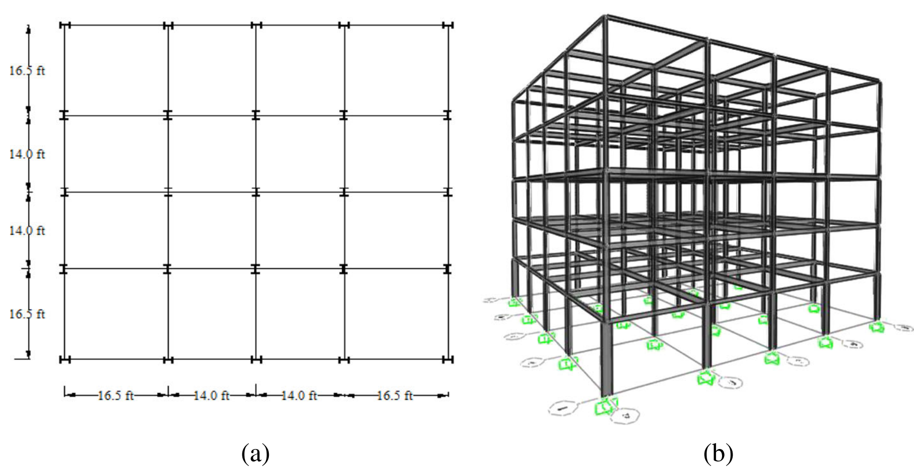

Figure 5. (a) Plan view and (b) 3D view of the five-story 325-member steel moment frame.

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Table 3. Load combinations based on ASCE 7-05.

Load combination	Equivalent static		Response spectral	
	Steel design	Scale factor	Steel design	Scale factor
UDSTL1	Strength	1.4 D	Strength	1.4 D
UDSTL2	Strength	1.2 D + 1.6 L	Strength	1.2 D + 1.6 L
UDSTL3	Strength	1.2 D + 1.0 L + 1.0 E_x	Strength	1.2 D + 1.0 L + 1.0 RS_x
UDSTL4	Strength	1.2 D + 1.0 L − 1.0 E_x	Strength	1.2 D + 1.0 L + 1.0 RS_y
UDSTL5	Strength	1.2 D + 1.0 L + 1.0 E_y	Strength	0.9 D + 1.0 RS_x
UDSTL6	Strength	1.2 D + 1.0 L − 1.0 E_y	Strength	0.9 D + 1.0 RS_y
UDSTL7	Strength	0.9 D + 1.0 E_x	Deflection	1.0 D
UDSTL8	Strength	0.9 D − 1.0 E_x	Deflection	1.0 D + 1.0 L
UDSTL9	Strength	0.9 D + 1.0 E_y		
UDSTL10	Strength	0.9 D − 1.0 E_y		
UDSTL11	Deflection	1.0 D		
UDSTL12	Deflection	1.0 D + 1.0 L		

D is the dead load, L represents the live load, and E_x, E_y, RS_x, and RS_y are the earthquake loads.

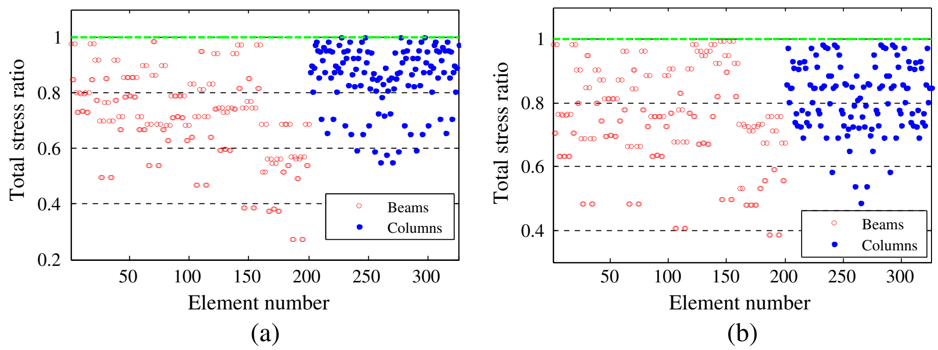

Figure 6. Comparison of the allowable and existing stress ratio of members for the 325-member moment frame. (a) Equivalent static analysis; (b) spectral analysis.

deviation are reported in Table 5. Figure 7 shows the seismic performance of the frame in the Y-direction in the form of inter-story drift and lateral displacement of stories. All the inter-story drifts are smaller than the maximum allowable value equal to 0.26. As it is depicted, the optimized frame has better performance when the lateral dynamic loads are considered based on spectral analyses. Based on these figures, displacement constraints are not active here, and the strength constraints govern the design of the frame that can be interpreted because of the short height of the frame in spite of the moment-resisting system of the frame. To recognize the role of each load combination, its contribution for determining the maximum stress ratio is computed and expressed in Table 6. It is worth to mention that considering the combination of gravity loading (1.2 Dead Load + 1.6 Live Load) is necessary.

4.2. Example 2: an eight-story 504-member steel braced frame

The eight-story steel braced frame is modeled as the second design example. The frame is braced with inverted V-type braces along the X-direction and with X-type bracing system along the Y-direction. The 3D view and plan view of the structure containing the orientation of the columns and bracing bays are shown in Figure 8. The frame consists of 504 members that are grouped into 32 design groups: first group: braced bays columns along *x*-axis, second group: braced bays columns along *y*-axis, third group: rest of the columns, fourth group: outer beams of the inverted V-type braced bays (xz plane), fifth group: rest of the outer beams, sixth group: inner beams, seventh group: inverted V-type braces, eighth group: X-type braces, and so forth for each of the two adjacent stories.

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Table 4. Sectional designations and weight of the best optimum design obtained by the cuckoo search for the 325-member moment frame.

			Ready sections	
Story	Group no.	Group type	Equivalent static	Spectral response
1st	1	Column	W18 × 40	W5 × 19
	2	Column	W16 × 36	W12 × 26
	3	Column	W8 × 40	W18 × 60
	4	Beam	W8 × 13	W8 × 13
	5	Beam	W14 × 22	W14 × 22
2nd–3rd	6	Column	W10 × 22	W8 × 21
	7	Column	W8 × 28	W10 × 33
	8	Column	W12 × 45	W12 × 40
	9	Beam	W10 × 17	W10 × 15
	10	Beam	W14 × 22	W14 × 22
4th–5th	11	Column	W6 × 15	W5 × 16
	12	Column	W8 × 18	W8 × 28
	13	Column	W12 × 26	W10 × 26
	14	Beam	W6 × 12	W8 × 13
	15	Beam	W14 × 22	W10 × 19
Minimum weight, tons (kips)			43.496 (95.892)	43.476 (95.848)

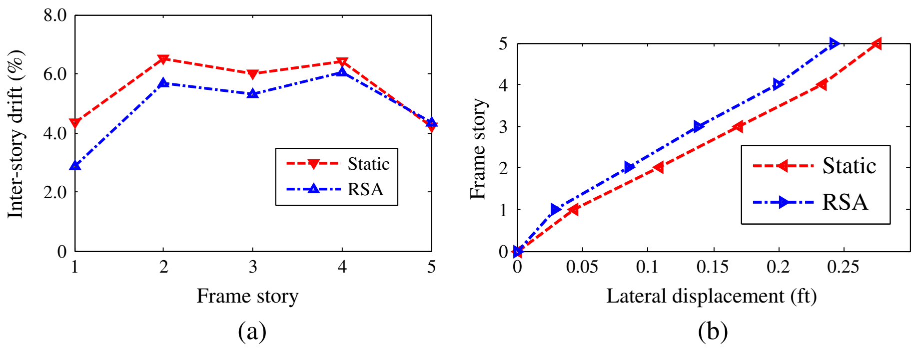

Figure 7. Seismic performance of the 325-member moment frame for both equivalent static (Static) and response spectra analysis (RSA). (a) Inter-story drift; (b) lateral displacement.

The minimum weight for the optimum feasible design obtained by CS algorithm and related sectional designations are summarized in Table 7 under two different lateral seismic loadings. The optimum design based on the equivalent static analysis is 1 t (2 kips) lighter than the design based on the spectral analysis in which the difference is near to 1%. But like the first example, the difference between material distributions for the two analysis types is significant here, too. The convergence history of the best result for both cases is shown in Figure 9, and for clarity, the upper bound of y-axis limited to 2000 kips. Step-like movements in the diagram of CS performance in both cases exhibit how it escapes from local minimum points in order to find a better optimum design. As it is clear, CS shows better performance in the aspect of convergence speed in the case of equivalent static analysis.

Figure 10 shows the stress ratio of members for the achieved best optimum design based on both static and spectral analyses. There is no significant difference between the two analyses, but for both cases, beams are designed more economically than other types of members. Detailed results for the stress ratio of members (beams, columns, braces, and all members) containing largest and smallest observed values, arithmetic average, and standard deviation are also reported in Table 4. Figure 11

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Table 5. Summary results of stress ratios for frame members (all, columns, beams, and braces).

Frame			Min	Max	Mean	SD
MRF_325	Static	All	0.274	0.999	0.761	0.163
		Beams	0.274	0.986	0.702	0.161
		Columns	0.549	0.999	0.857	0.115
	Spectra	All	0.386	0.994	0.769	0.145
		Beams	0.386	0.994	0.738	0.157
		Columns	0.485	0.985	0.820	0.106
CBF_504	Static	All	0.025	0.995	0.670	0.242
		Beams	0.363	0.994	0.723	0.161
		Columns	0.025	0.983	0.591	0.268
		Braces	0.264	0.995	0.666	0.183
	Spectra	All	0.018	0.994	0.643	0.230
		Beams	0.362	0.994	0.731	0.161
		Columns	0.018	0.922	0.561	0.284
		Braces	0.067	0.904	0.552	0.196
Irregular_499	9 modes	All	0.258	1.000	0.664	0.160
		Beams	0.335	1.000	0.659	0.165
		Columns	0.258	0.962	0.671	0.151
	18 modes	All	0.177	0.995	0.698	0.147
		Beams	0.177	0.995	0.686	0.165
		Columns	0.310	0.984	0.717	0.110

Max, largest observation; Min, smallest observation; Mean, arithmetic average; SD, standard deviation.

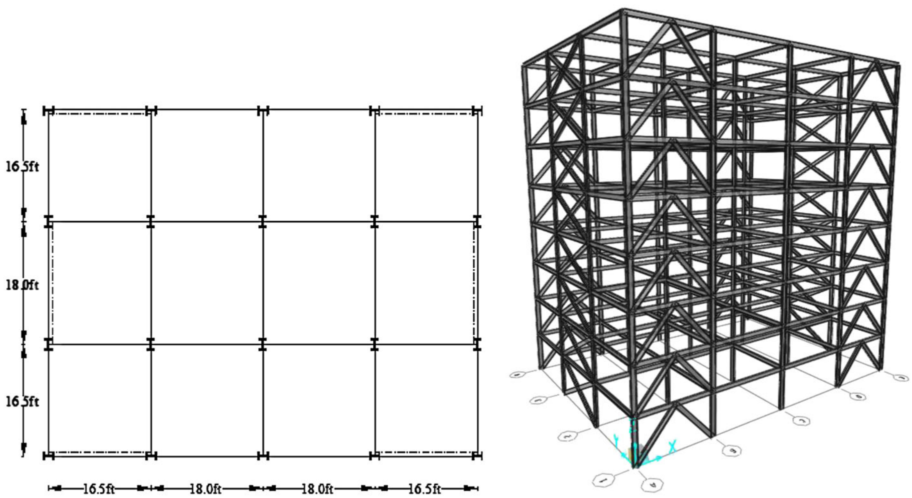

Figure 8. 3D view and plan view of the eight-story 504-member steel braced frame.

shows the seismic performance of the frame in the Y-direction in the form of inter-story drift and lateral displacement of stories. All the inter-story drifts are smaller than the maximum allowable value equal to 0.26. As it can be observed, the frame has better performance when the lateral dynamic loads are considered based on spectral analyses. Displacement constraints are not active here due to bracing system of the frame, and the strength constraints govern the optimum design. To recognize the role of each load combination, its contribution for determining the maximum stress ratio is computed as shown in Table 5. Based on this table, considering the combination of gravity loads and the combination of dead and lateral loads is vital.

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Table 6. Contribution of the load combinations corresponding to the maximum stress ratios of the members.

Load combination	MRF 325		CBF		Irregular	
	Equivalent	Spectra	Equivalent	Spectra	9 modes	18 modes
UDSTL1	0	0	0	0	0	0
UDSTL2	0.061	0.209	0.627	0.619	0.092	0.084
UDSTL3	0.208	0.403	0.105	0.222	0.421	0.437
UDSTL4	0.211	0.388	0.101	0.127	0.487	0.479
UDSTL5	0.260	0	0.0635	0.032	0	0
UDSTL6	0.260	0	0.0635	0	0	0
UDSTL7	0	0	0.02	0	0	0
UDSTL8	0	0	0.02	0	0	0
UDSTL9	0	□	0	□	□	□
UDSTL10	0	□	0	□	□	□
UDSTL11	0	□	0	□	□	□
UDSTL12	0	□	0	□	□	□

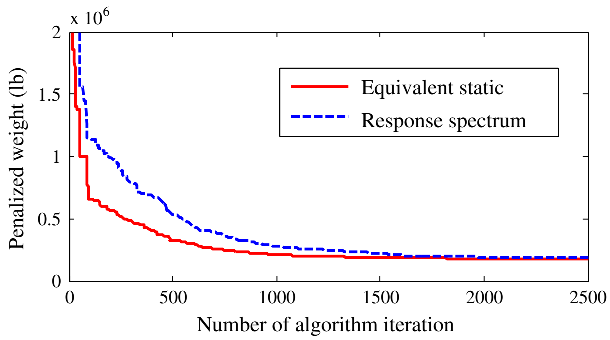

Figure 9. The best design history of the 504-member braced space steel frame.

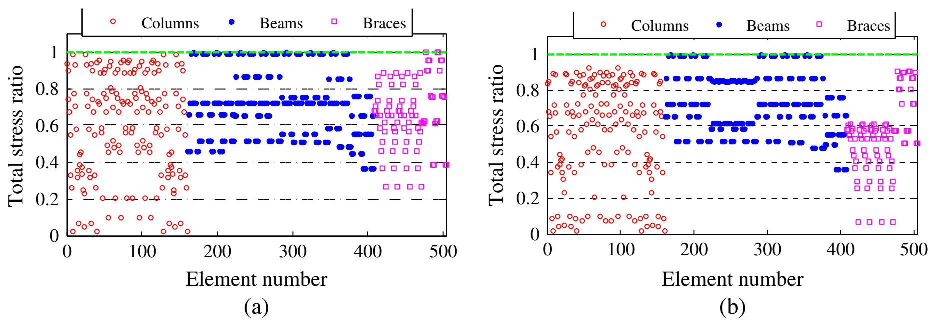

Figure 10. Comparison of the allowable and existing stress ratio of members for the 325-member moment frame. (a) Equivalent static analysis; (b) spectral analysis.

4.3. Example 3: nine-story 499-member irregular steel moment frame

The nine-story frame building is selected as the last example case. The 3D and plan views are shown in Figure 12. Four hundred ninety-nine members of the structure are collected in 23 groups containing 11 and 12 groups for column and beam members, respectively. Orientation of the columns and element groups numbering are shown in Figure 12(b, c) in which each column group is shown with numbered enclosed dashed lines. The beam groups are also distinguished with different colors.

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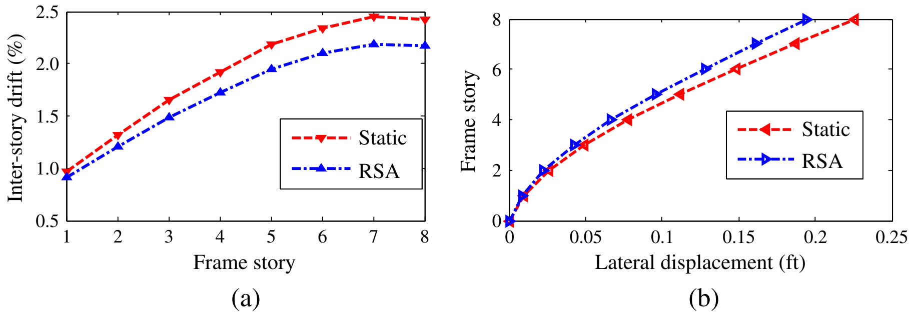

Figure 11. Seismic performance of the 504-member braced frame for both equivalent static (Static) and response spectra analysis (RSA). (a) Inter-story drift; (b) lateral displacement.

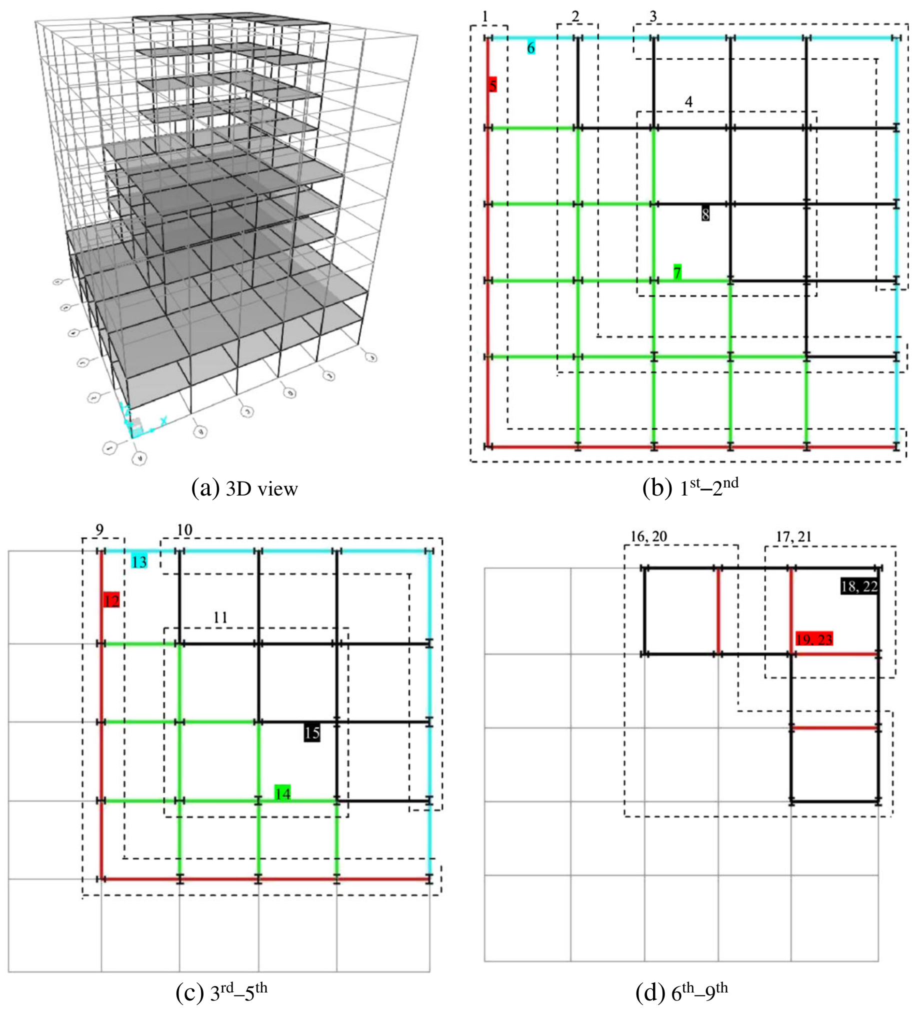

Figure 12. 3D view, plan views, and grouping sets of the nine-story 499-member steel frame.

It is apparent that in an irregular structure, higher modes of vibration participate as well as primary vibration modes. In order to investigate the effect of higher modes of vibration on the optimum design, the structures are analyzed and designed with 9 and 18 modes with approximately 90% and 97% of mass participations, respectively. The minimum weight for the optimum feasible design obtained by CS algorithm and related sectional designations are summarized in Table 8 with the participation of

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9 and 18 vibration modes. The optimum designs are weighted the same, but there is 1 kips difference. Material distributions are approximately the same, and highest difference is observed in the top four stories (Table 8).

Figure 13 shows the stress ratio of members for the achieved optimum designs with the participation of 9 and 18 modes. There is no significant difference between the two cases, and unlike the two previous regular examples, there is no difference between beams and columns in this irregular frame. Detailed results for the stress ratio of members (beams, columns, and all members) containing largest and smallest observed values, arithmetic average, and standard deviation are reported in Table 4. The mean value for the stress ratio of all members is nearly 0.7 in the two cases with a standard deviation equal to 0.15. Figure 14 shows the seismic performance of the frame in the Y-direction in the form of inter-story drifts. This figure shows lower drifts in the nine-mode participation case. All the inter-story drifts are smaller than the maximum allowable value equal to 0.26. Based on these figures, both safety and serviceability constraints are active here. To recognize the role of each load combination, its contribution for determining the maximum stress ratio is computed as shown in Table 5. Based on this table, considering the combination of gravity loads is necessary.

Table 7. Sectional designations and weight of the best optimum design obtained by the cuckoo search for the eight-story 504-member braced frame.

			Ready sections	
Story	Group no.	Group type	Equivalent static	Spectral response
1st–2nd	1	Column	W18 × 40	W10 × 39
	2	Column	W16 × 36	W8 × 67
	3	Column	W8 × 40	W8 × 48
	4	Beam	W8 × 13	W6 × 9
	5	Beam	W14 × 22	W6 × 20
	6	Beam	W10 × 22	W10 × 26
	7	Brace	W14 × 22	W5 × 19
	8	Brace	W6 × 15	W8 × 31
3rd–4th	9	Column	W8 × 28	W8 × 28
	10	Column	W12 × 45	W14 × 48
	11	Column	W10 × 17	W10 × 39
	12	Beam	W14 × 22	W6 × 9
	13	Beam	W6 × 15	W14 × 22
	14	Beam	W8 × 18	W12 × 26
	15	Brace	W8 × 18	W6 × 15
	16	Brace	W12 × 26	W8 × 28
5th–6th	17	Column	W12 × 26	W8 × 24
	18	Column	W6 × 12	W12 × 30
	19	Column	W14 × 22	W8 × 28
	20	Beam	W18 × 40	W6 × 9
	21	Beam	W16 × 36	W6 × 20
	22	Beam	W8 × 40	W10 × 26
	23	Brace	W6 × 12	W8 × 18
	24	Brace	W14 × 22	W8 × 24
7th–8th	25	Column	W8 × 13	W12 × 26
	26	Column	W14 × 22	W8 × 24
	27	Column	W10 × 22	W8 × 24
	28	Beam	W8 × 28	W8 × 10
	29	Beam	W12 × 45	W6 × 20
	30	Beam	W10 × 17	W10 × 26
	31	Brace	W18 × 40	W6 × 15
	32	Brace	W16 × 36	W10 × 22
Minimum weight, tons (kips)			81.939 (180.645)	83.007 (182.100)

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Table 8. Optimum designs obtained by the cuckoo search for the irregular steel moment frame.

Story	Group no.	Group type	Ready sections 9 modes	Ready sections 18 modes
1st–2nd	1	Column	W8 × 35	W10 × 26
	2	Column	W8 × 31	W8 × 31
	3	Column	W10 × 39	W10 × 45
	4	Column	W10 × 54	W14 × 68
	5	Beam	W6 × 12	W6 × 12
	6	Beam	W12 × 16	W8 × 15
	7	Beam	W8 × 18	W8 × 18
	8	Beam	W14 × 22	W12 × 22
3rd–5th	9	Column	W10 × 22	W10 × 22
	10	Column	W10 × 39	W14 × 53
	11	Column	W12 × 53	W10 × 49
	12	Beam	W10 × 15	W10 × 17
	13	Beam	W12 × 16	W10 × 17
	14	Beam	W8 × 15	W8 × 15
	15	Beam	W14 × 22	W14 × 22
5th–6th	16	Column	W12 × 45	W8 × 35
	17	Column	W14 × 43	W24 × 68
	18	Beam	W10 × 17	W8 × 15
	19	Beam	W6 × 25	W14 × 26
7th–8th	20	Column	W14 × 30	W8 × 31
	21	Column	W16 × 89	W8 × 31
	22	Beam	W12 × 16	W8 × 13
	23	Beam	W12 × 22	W6 × 25
Minimum weight, tons (kips)			74.628 (164.527)	74.051 (163.254)

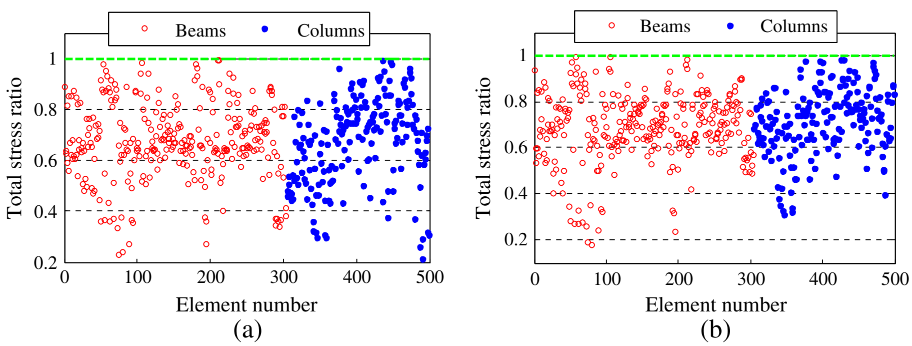

Figure 13. Comparison of the allowable and existing stress ratio of members for the 325-member moment frame. (a) Equivalent static analysis; (b) spectral analysis.

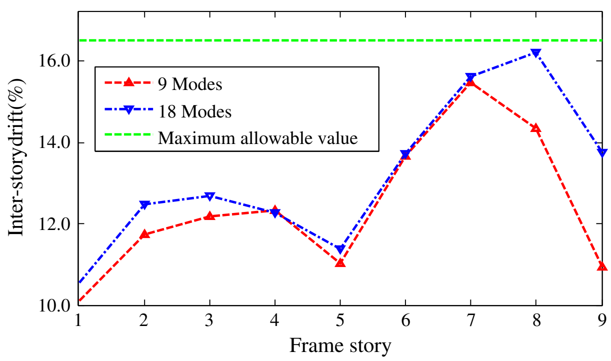

Figure 14. Comparison of the allowable and existing inter-story drift for the 499-member moment frame.

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5. CONCLUDING REMARKS

An integrated optimization procedure is used in the form of parallel computing based on the CS algorithm for minimizing the self-weight of frames within the discrete search space under geometric limitations, safety, and serviceability constraints based on building provisions. The optimization based on response spectral analysis and the typical equivalent static analysis is investigated and discussed using three 3D real size steel frames with specific features. These examples consist of a five-story 325-member steel moment frame, an eight-story 504-member steel braced frame, and a nine-story 499-member irregular steel moment frame.

Based on this study, it can be indicated that CS yields acceptable convergence performance from the early iterations and the convergence rate is relatively higher in the case of equivalent static analysis. In the first two examples, CS yields the same weight for optimum designs but is significantly different in material distribution and well seismic response for response spectral analyses, which is of great practical interest and can be preferred over the other. It has been shown that the stress ratio of members for the achieved optimum designs is affected by the number of design variables considered for frames. In the third example, the number of participating modes has been investigated on the achieved optimum designs in the form of an irregular frame, and the results show that there is no significant difference of material distribution and optimum weight. In order to recognize the role of each load combination, its contribution for determining the maximum stress ratio is computed in all case studies. Based on the results obtained, considering the combination of the gravity loading and the combination of dead and lateral loads is inevitable.

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