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Examination of three meta-heuristic algorithms for optimal design of planar steel frames

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Abstract. In this study, the three different meta-heuristics namely the Grey Wolf Optimizer (GWO), Stochastic Fractal Search (SFS), and Adaptive Differential Evolution with Optional External Archive (JADE) algorithms are examined. This study considers optimization of the planer frame to minimize its weight subjected to the strength and displacement constraints as per the American Institute of Steel and Construction - Load and Resistance Factor Design (AISC-LRFD). The GWO algorithm is associated with grey wolves' activities in the social hierarchy. The SFS algorithm works on the natural phenomenon of growth. JADE on the other hand is a powerful self-adaptive version of a differential evolution algorithm. A one-bay ten-story planar steel frame problem is examined in the present work to investigate the design ability of the proposed algorithms. The frame design is produced by optimizing the W-shaped cross sections of beam and column members as per AISC-LRFD standard steel sections. The results of the algorithms are compared. In addition, these results are also mapped with other state-of-art algorithms.

Keywords: grey wolf optimizer; stochastic fractal search; steel frame optimization; JADE; AISC-LRF

1. Introduction

Designing a structure in an optimum way, by reducing the cost of structural raw materials is a challenging task for designers under present day conditions. To fulfill these criteria, it is preferable to reduce the structural raw material cost by reducing the size (weight) of the structural beams and column members while considering certain design constraints, (Kaveh *et al*. 2010). The strength and displacement constraints are usually selected according to the American Institute of Steel and Construction - Load and Resistance Factor Design (AISC-LRFD) (AISC 2010) specifications to ensure practicability.

Over the last three decades, many meta-heuristic techniques have been proven useful in the optimization field by several researchers. For example, established and recently developed optimizers include: Ant Colony Optimization (Camp *et al*. 2005), Adaptive Harmony Search (Carbas *et al*. 2009, Hasançebi *et al*. 2009), Big Bang-Big Crunch (Hasançebi and Azad 2012,

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Hasançebi and Azad 2013, Kaveh and Abbasgholiha 2011), Bat Inspired Algorithm (Hasançebi and Carbas 2014), Charged System Search (Kaveh and Talatahari 2012), Enhanced Harmony Search (EHS) (Maheri and Narimani 2014), Grey Wolf Optimizer (GWO) (Mirjalili *et al*. 2014), Design Driven Harmony Search (Murren and Khandelwal 2014), Genetic Algorithm (GA) (Pezeshk *et al*. 2000, Safari *et al*. 2013, Safari *et al*. 2011), Cuckoo Search Algorithm (Saka and Dogan 2012), Stochastic Fractal Search (SFS) (Salimi 2015), Teaching-Learning Based Optimization (TLBO) (Vedat 2012), and Adaptive Differential Evolution with Optional External Archive (JADE) (Zhang and Sanderson 2009). Hall *et al*. (1989) presented the combined first order and second order design procedure in the account for nonlinear load-displacement (P-Δ) effects to design the minimum weight frame.(You may want to use this last reference and the beginning of the paragraph)

The GWO algorithm represents the leadership skills and the hunting activity of grey wolves in a social atmosphere. The social hierarchy of grey wolves consists of four levels from top to bottom, i.e., Alpha (α), Beta (β), Delta (δ) and Omega (ω) respectively (Mirjalili *et al*. 2014). The grey wolf hunting activities' three stages are: (i) To track, chase, and approach the prey (ii) To pursue, encircle, and harass the prey until it becomes stable (iii) Attack in the direction of the prey.

The Fractal Search (FS) algorithm, which is a basic algorithm of the SFS, is a dynamic algorithm which contains the number of search agents that are modified. Hence, the FS algorithm demands more effort (Salimi 2015). However the SFS algorithm uses two main processes as follows: (i) the diffusing process and (ii) the updating process. In the diffusing process, each particle of the SFS diffuses near its current position. In the updating process, the algorithm mimics how search agents (particles) in the group update their position based on the position of other search agents in the group (Salimi 2015).

JADE is one of the most powerful self-adaptive versions of differential evolution DE (Zhang and Sanderson 2009). The algorithm is free from optimization parameter settings. Its search strategy is based on DE operators' incorporation with the use of an external archive. The values of optimization parameters such as a scaling factor are varied during an optimization process by means of self-adaptation.

This paper presents an optimum design of the planar steel frame structure, employing three different meta-heuristics, namely the GWO, JADE, and SFS, which are inspired by evolutionary concepts. The GWO, JADE, and SFS algorithms have shown good results for various optimization problems such as tension/compression spring, welded beam, pressure vessel design, and benchmark functions in past literature (Mirjalili *et al*. 2014, Salimi 2015, Zhang and Sanderson 2009). Hence, they are implemented in this study.

The rest of the paper is arranged as follows: section 2 formulates the optimum plane frame design problem, section 3 presents optimization of planer steel frame design problem and section 4 concludes the work.

2. Problem formulation

The objective of the design problem is to minimize the weight (Eq. (2)) of the frame structure to be subjected to the strength and displacement constraints, (Eqs. (3)-(5)) specified by AISC-LRFD (AISC 2010) specifications. To achieve this objective, the planer steel frame design process demands selection of steel cross sections as the design variables (Eq. (1)) for its column and beam members from a standard structure design manual. According to the AISC-LRFD (AISC 2010) constraints, the frame design problem is formulated as follows (Maheri and Narimani 2014, Pezeshk *et al*. 2000, Saka and Dogan 2012, Vedat 2012, Adodu *et al*. 2016, Alberdi and Khandelwal 2015)

$$Find, X = [A_1, A_2, A_3, \ldots\ldots, A_{nd}] \tag{1}$$

To minimize the weight 'f' of the frame structure, which is expressed as

$$f(X) = \sum_{i=1}^{nd} A_i \sum_{j=1}^{mt} \rho_i L_i \tag{2}$$

Subjected to, $C_k^{\sigma} \leq 0$, *where* $k=1,\ldots,na$

$C_r^{\delta} \leq 0$, *where* $r=1,\ldots,ns$

$1 \leq A_i \leq mk$, *where* $i=1,\ldots,nd$

where 'X' represents the design variables; 'nd' and 'mt' are the total numbers of design groups and the total number of members in group 'i' of frame structure respectively. 'ρ_j' and 'L_j' are mass density and length of member 'j' respectively. 'A_i' is the cross sectional area (W-shaped) of member group 'i' of the frame structure, which is chosen from standard structure design manual, AISC-LRFD (AISC 2010). The inequalities parameter, i.e., $C_k^{\sigma} \leq 0$ and $C_r^{\delta} \leq 0$, represents the strength and displacement constraints specified by the AISC-LRFD specification respectively. 'na' and 'ns' represent the number of beams and columns and the number of stories respectively. 'mk' shows the total number of W-shaped cross sectional area, which is considered for structure design in group 'i'.

The strength constraints, $C_k^{\sigma} \leq 0$, for frame members subjected to axial force and bending are expressed as per AISC-LRFD specifications as follows

$$C_k^{\sigma} = \frac{P_u}{\emptyset \times p_n} + \frac{8}{9}\left(\frac{M_{ux}}{\emptyset_b \times M_{nx}} + \frac{M_{uy}}{\emptyset_b \times M_{ny}}\right) - 1 \qquad , if\ \frac{P_u}{\emptyset \times p_n} \geq 0.2 \tag{3}$$

$$C_k^{\sigma} = \frac{P_u}{2 \times \emptyset \times p_n} + \left(\frac{M_{ux}}{\emptyset_b \times M_{nx}} + \frac{M_{uy}}{\emptyset_b \times M_{ny}}\right) - 1 \qquad , if\ \frac{P_u}{\emptyset \times p_n} < 0 \tag{4}$$

where 'P_u' and 'P_n' are the required and nominal axial strength (compression or tension) respectively. 'M_{ux}' and 'M_{uy}' are the required flexural strengths about the major and minor axes respectively. 'M_{nx}' and 'M_{ny}' are the nominal flexural strengths about the major and minor axis respectively (for 2-D frames, 'M_{ny}'=0). 'ϕ' is the resistance factor shown as 'ϕ_c' for compression members (equal to 0.85) and 'ϕ_t' for tension members (equal to 0.90) respectively. 'ϕ_b' is the flexural resistance factor, with a value of 0.90 (AISC 2010).

The displacement constraints, $C_r^{\delta} \leq 0$, represent the inter-story drift for a multi-story frame structure, which are expressed as follows (Togan 2012)

$$C_r^{\delta} = \frac{\delta}{\delta_{ru}} - 1 \quad Where, \delta = \delta_r - \delta_{r-1} \tag{5}$$

where, δ_r and δ_{r-1} are lateral deflection of two adjacent story levels. δ_{ru} is the allowable lateral displacement (equal to h_r/300, where h_r is the height of the story).

The penalty function used in this study is known as the Kaveh-Zolghadr technique, which is formulated as follows (Pholdee and Bureerat 2014)

$$f(X) = (1 + \varepsilon_1 \times \upsilon)^{\varepsilon_2} \tag{6}$$

where, 'f' represents the value of penalized function; ε_1 and ε_2 are taken as 2.

$$v = \sum_{i=1}^{na} s_i + \sum_{i=1}^{ns} w_i, \text{ where } s_i = \left|1 - \frac{C_{ki}^{\sigma}}{C_{ki,all}^{\sigma}}\right| \; and \; w_i = \left|1 - \frac{C_{ri}^{\delta}}{C_{ri,all}^{\delta}}\right| \quad (7)$$

where, C_k^{σ} and C_r^{δ} represent the strength and displacement constraint violations respectively. '*na*' and '*ns*' represent the number of beams and columns and the number of stories respectively. At a design solution '*X*', if the *i*th constraint is not violated, the value of s_i and w_i will be taken as equal to zero; otherwise, s_i and w_i will be taken as per Eq. (7) (Pholdee and Bureerat 2014).

3. Design problem

In the present study, there are two test problems of planar frames. The first problem is a design of a two-bay, three-story frame as shown in Fig. 1. There are two design variables assigned for the cross-sections of the beams and the columns respectively. The frame is made of a material with modulus of elasticity of 29,000 ksi, a yield stress of 36 ksi and a density of 0.284 lb/in^3. More details are given in Maheri and Narimani (2014). For the second test problem, the one-bay, ten-story planer steel frame (Fig. 2) is optimized. This frame consists of 30 members (10-beams and 20-columns) and they are categorized into 9 design groups. Frame geometry and loading conditions of one-bay, ten-story steel frame is presented in Fig. 1. This frame is considered by the many researchers using various algorithms, namely the EHS (Maheri and Narimani 2014), GA (Pezeshk *et al.* 2000) and TLBO (Togan 2012). The material properties, such as the modulus of elasticity (E) and yield stress (Fy) are considered as 29000 ksi and 36 ksi, respectively. All 268-*W* shaped sections for beam members and 66-*W* shaped sections (*W*14 and *W*12 sections only) for column members as per AISC-LRFD (AISC 2010) are considered to design the frame (Togan 2012). For each column, the out-of-plane effective length factor (K_y) is considered as 1.0, while for each beam member it is specified as one-sixth of the span length (Togan 2012).

In this study, the population size and the number of loops are set as 10 and 20 respectively for the two-bay, three-story problem, while they are set as 20 and 200 for the one-bay, ten-story problem. As a result, the number of function evaluations for the first test problem is 200 while it is set as 4000 evaluations for the second problem. In addition, statistical results are measured by performing 30 independent runs and best results are presented for the GWO, JADE, and SFS algorithms. Table 1 compares the results from the best runs of the implemented algorithms and those obtained from the literature. It was found that all the algorithms used in this paper can search for the same feasible optimum solution (16686.57 lbs), which is better than those found in the literature. Table 2 compares the results of the various algorithms with the best designs (AISC *W*-Shapes and Weight) obtained in the literature. It can be seen that the GWO, JADE, and SFS algorithms recommended the optimum cross sections, presented in the last three columns of Table 2, and the best design in terms of optimum weight without violating the stated constraints. The GWO, JADE, and SFS algorithms achieved the optimum weight are as 55246.18 lbs., 51231.77 lbs., and 50868.31 lbs. considering stated cross sections presented in Table 1 respectively.

Table 3 presents the statistical results of the GWO, JADE, and SFS algorithms. In the table, we shall use the mean values to measure the convergence rate of the algorithm, whereas the standard deviation determines their search consistency. According to the results, the best method in terms of both convergence rate and consistency is JADE, while SFS is the second best for the first design case. The t-test to compare the mean values obtained from SFS with the other are carried out and it is shown that JADE is insignificantly better than SFS at the confidence level of 0.05, while both

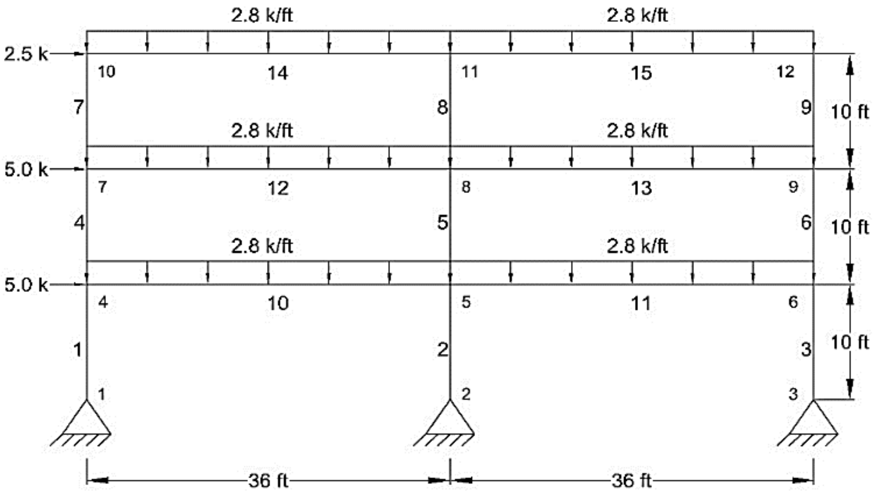

Fig. 1 Two-bay, three-story planer frame

Table 1 Optimum results obtained for the two-bay, three-story frame design problem

	AISC *W*-shapes					
	Pezeshk *et al.* (2000)	Togan (2012)	Maheri and Narimani (2014)	This study		
Element group	GA	TLBO	EHS	GWO	SFS	JADE
1 (beams)	W24×62	W24×62	W21×55	W21×57	W21×57	W21×57
2 (columns)	W10×60	W10×49	W10×68	W10×49	W10×49	W10×49
Weight (lb)	18,792	17,789	18000	16686.57	16686.57	16686.57
No. of Analyses	1,800	-	220	W21*57	200	200

Table 2 Optimum results obtained for the one-bay, ten-story frame design problem

	AISC *W*-shapes					
	Pezeshk *et al.* (2000)	Togan (2012)	Maheri and Narimani (2014)	This study		
Element group	GA	TLBO	EHS	GWO	SFS	JADE
1 (column 1-4)	W14x233	W14x233	W14x159	W14x211	W14x176	W30x99
2 (column 5-8)	W14x176	W14x176	W14x730	W14x68	W14x68	W24x84
3 (column 9-12)	W14x159	W14x145	W14x61	W12x72	W14x68	W27x84
4 (column 13-16)	W14x99	W14x99	W12x87	W14x82	W14x68	W30x90
5 (column 17-20)	W12x79	W12x65	W14x283	W14x68	W14x68	W40x466
6 (Beam 21-23)	W33x118	W30x108	W24x68	W30x108	W33x118	W36x650
7 (Beam 24-26)	W30x90	W30x90	W14x99	W24x94	W24x84	W36x650
8 (Beam 27-29)	W27x84	W27x84	W21x111	W30x99	W24x84	W36x650
9 (Beam-30)	W24x55	W21x44	W33x201	W24x94	W24x84	W36x650
Weight (lb)	65136	61813	59514	55246.18	50868.31	51231.77
No. of Analyses	3000	-	1412	4000	4000	4000

Table 3 Statistical results of the GWO, JADE and SFS algorithms

Methods	Minimum (lb)	Maximum (lb)	Mean (lb)	Standard Deviation	T-Test (p-value)
			two-bay, three-story frame design problem		
GWO	16686.57	22352.89	18507.15	1831.22	0.00601
JADE	16686.57	19112.37	17253.82	582.18	0.13692
SFS	16686.57	18879.59	17494.76	653.18	-
			one-bay, ten-story frame design problem		
GWO	55246.18	94018.16	66235.75	9451.19	4.67×10^{-12}
JADE	51231.77	55879.18	53146.62	1217.60	4.14×10^{-11}
SFS	50868.31	52507.97	51264.31	370.29	-

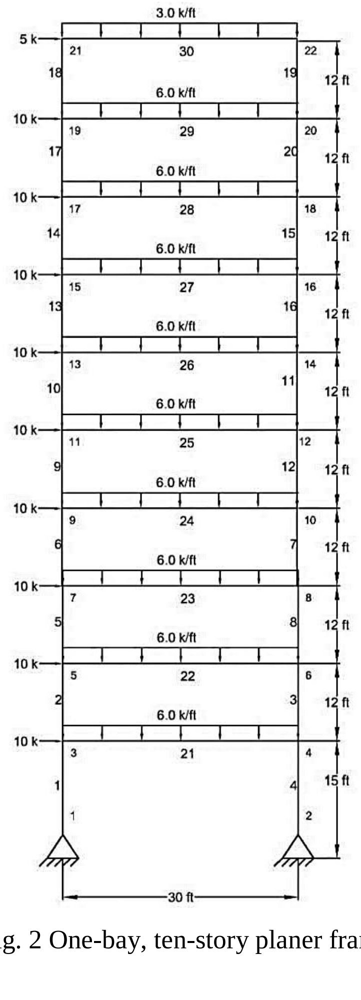

Fig. 2 One-bay, ten-story planer frame

are significantly better than GWO. For the second test problem, which has more design variables, the best method based on the mean values is SFS while the second best is JADE. The statistical test shows that SFS is significantly better than both JADE and GWO. From the results in Tables 1-2, it can be seen that the results in this study are superior to those reported in the literature (notice that this study uses a higher number of analysis for the second test problem), therefore, we report it as the new baseline for planar steel frame optimization.

5. Conclusions

The present work used the GWO, SFS, and JADE algorithms to optimize the two-bay, three-story and one-bay, ten-story planer steel frame structures according to AISC-LRFD specifications. The obtained results are compared to results of the GA, TLBO, and EHS. The GWO, JADE, and SFS algorithms achieved best optimum weight of 16686.57 lbs. for the first design problem and 55246.18 lbs., 51231.77 lbs., and 50868.31 lbs. respectively for the second design problem. The results show that the GWO, JADE, and SFS algorithms offered lesser weight design compared to the GA, TLBO and EHS. Among the three implemented meta-heuristics, the best method is SFS while the second best is JADE. The results in this paper can be used as the new baseline for research in this field.

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