Periodica Polytechnica Civil Engineering

OnlineFirst (2018) paper 11654
https://doi.org/10.3311/PPci.11654
Creative Commons Attribution

RESEARCH ARTICLE

Layout Optimization of Planar Braced Frames Using Modified Dolphin Monitoring Operator

Ali Kaveh[1*], Seyed Rohollah Hoseini Vaez[2], Pedram Hosseini[2] and Elham Ezzati[2]

Received 28 October 2017; Revised 26 January 2018; Accepted 23 February 2018

Abstract
Determining the optimum placement of braces in steel frames has always been one of the most challenging issues in structural engineering. In this paper, the size and placement of the X-braces in planar frame structures is determined in a way that the total weight of the braced frames becomes minimum, while satisfying the design requirements and constraints. Variables of the optimization contain the cross sections for beams, columns, and X-braces as well as the placement of these braces in the frames. Attempt has also been made to consider all the constraints of an actual design problem. One of the other objectives of this study is to investigate the effect of including or excluding some of the constraints affecting the optimization of the planar frame design. For this purpose, the Colliding Bodies Optimization (CBO) and CBO-MDM algorithms have been utilized. Modified Dolphin Monitoring (MDM) operator is recently developed for improving the performance of the metaheuristic algorithms. Here, this operator is utilized to enhance the performance of the CBO algorithm to optimize the weight of the frames. For additional comparison of the results, the particle swarm optimization (PSO) algorithm and imperialist competitive algorithm (ICA) are used.

Keywords
layout optimization, planar braced frames, colliding bodies optimization, modified dolphin monitoring operator, metaheuristics

1 Centre of Excellence for Fundamental Studies in Structural Engineering, School of Civil Engineering, Iran University of Science and Technology, Narmak, Tehran-16, Iran
2 Department of Civil Engineering, Faculty of Engineering, University of Qom, Qom, Iran
* Corresponding author, email: alikaveh@iust.ac.ir

1 Introduction

Layout or topology optimization deals with the selection of the best configuration for structural systems and constitutes one of the newest and most rapidly expanding fields of structural design, although some of its basic concepts were established almost a century ago [1]. In other words, structural layout optimization is a technique which enables automatic identification of optimal arrangements of structural elements in frames [2].

In the field of structural engineering design, the main objectives include efforts to find design methods with optimum weight, cost of the construction, geometry, design and optimal topology along with satisfying the design constraints. For example, the optimal design of steel frames requires the selection of suitable steel sections for frame members from a set of standard steel sections. This choice should be made in such a way that not only the steel has the minimum weight, but also the strength constraints and serviceability of the structure are within the limits specified by the design specifications. In building frames, lateral loads are mainly supported by the lateral system. One of the commonly used structural systems for providing the lateral reinforcement of steel structures is the combination of a moment resisting frame with a braced frame forming a dual building frame system. Since determining the best location of bracings is not easy, one of the steps that can be taken to achieve this goal is using trial and error methods. This can be done by using metaheuristic optimization algorithms having an appropriate accuracy and speed.

Some metaheuristic algorithms for designing structures consist of Genetic algorithms which is based on the evolution of living organisms [3]; Ant colony optimization inspired by rules governing the behavior of the real ants to find the shortest path between a nest and food for the prediction of best solution [4]; Particle swarm optimization (PSO) that is a population based stochastic optimization technique inspired by nature and social behavior of bird flocking or fish schooling [5]; Imperialist competitive algorithm (ICA) that is inspired by the political model and competition between empires [6]; Harmony search (HS) algorithm that is based on process which takes place when a musician searches for a better state of harmony [7, 8]; Charged system search algorithm (CSS) that uses the electric laws of physics and the Newtonian laws of mechanics to guide charged particles to explore location of the optimum [9]; Dolphin Echolocation Optimization (DEO) which mimics strategies used by dolphins for their Locating and hunting process [10]; Colliding bodies optimization (CBO) and Enhanced colliding bodies optimization (ECBO) which are inspired by a collision between two objects in one dimension [11, 12]; Grey wolf optimizer (GWO) algorithm mimics the leadership hierarchy and hunting mechanism of grey wolves [13]; Vibrating particle system (VPS) and Enhanced vibrating particle system (EVPS) simulating the free vibration of single degree of freedom systems with viscous damping [14]; Ant lion optimizer (ALO) mathematically models the interaction of ants and ant lions [15], Grasshopper optimization algorithm (GOA) mathematically models and mimics the behavior of grasshopper swarms [16]. Detailed study of many recently developed metaheuristic algorithms can be found in the recently published book by Kaveh [17].

The above mentioned metaheuristic algorithms have been successfully applied in various fields of science and engineering such as electrical engineering [18], mechanical engineering [19], computer science [20], civil engineering [17] and chemical engineering [21]. Simultaneous topology and size optimization of braced steel frames has been performed by taking into account the constraints of strength and drift. Studies on the optimal location of braces in steel frames were carried out by Hagishita and Ohsaki [22] using optimal placement of braces for steel frames with semi-rigid joints. Graph theoretical implementation of memetic algorithms in structural optimization of frame bracing layouts was studied by Kaveh and Shahrouzi [23]. Layout optimization of dual building frame system was assessed by Kaveh and Farhoudi using DEO algorithm by Kaveh and Farhoudi [24], followed by adding Dolphin Monitoring to metaheuristic algorithms, Kaveh and Farhoudi [25]. Evolutionary topology optimization of structures with multiple displacement and frequency constraints was carried out by Zuo el al. [26]. Topology optimization for braced frame in the design of large structures was investigated by Stromberg et al. [27]. Reinforcement layout optimization of RC D-regions was assessed by Zhang et al. [28].

In this study, layout optimization of the dual steel frames is conducted under gravity and lateral load aiming at minimization of the steel frames weight based on the AISC specifications. The CBO algorithm and the CBO hybridized by modified dolphin monitoring operator (CBO-MDM) are used for the optimization. Adding the operator MDM to CBO algorithm reduces the sensitivity of the CBO algorithm to empirical parameters. The correct empirical choice of the parameters of the metaheuristic algorithms depends on the type of the algorithm and the type of problem and only personal experience can set decent values for these parameters. On the other hand, adding MDM to an algorithm controls the convergence speed of the algorithm and prevents it from being trapped in local optima. This method adjusts the standard deviation purposefully at each stage of the algorithm's execution. The results are also compared with those of the PSO and ICA algorithms.

The following items can be briefly expressed about layout optimization of a dual building frame system:

- Layout optimization in this study consists of the simultaneous finding of the optimal topology and cross-sections for a dual building frame system.
- There exists an infinite number of possible configurations (for placement of X-braces) and cross-sections for a dual building frame system. Thus, finding the optimal layout of these types of frames are so difficult.
- Layout optimization of a dual building frame system is of considerable practical importance since it leads to saving a greater amount of material.
- A dual building frame system has more redundancy in comparison to other types of frame systems. This issue can cause more complication and the use of metaheuristic algorithms for finding an optimal answer as a suitable tool can be recommended.

This paper consists of five sections. After introduction in the first section, in the second section, the CBO algorithm and MDM (modified dolphin monitoring) method are briefly presented. In the third section, formulation for the optimization problem is provided. In the fourth section, numerical examples are studied and discussed. The final section is devoted to the concluding remarks.

2 The CBO algorithm and MDM operator

In this section the main steps of the CBO algorithm [12] and MDM operator [29] are presented briefly.

2.1 CBO algorithm

1. The positions of all the CBs are generated randomly (in a permissible range) in the first iteration.
2. The mass value for each CB is calculated and the quality of each CB is determined by the magnitude of the objective function. According to the mass values of each CB, they are categorized in two stationary and moving body groups, where moving bodies move to stationary bodies. New position of each CB is determined by the collision laws.
3. Iteration number determines when the optimization process is completed. It should be noted that, in this algorithm, the Coefficient Of Restitution (COR) is calculated using the following equation:

$$COR = 1 - \frac{iteration}{Maximum\ iteration} \quad (1)$$

where *iteration* and *Maximum iteration* are the number of *ith* iteration and the number of all iterations, respectively.

2.2 Modified dolphin monitoring method

1. MP value in each iteration is computed using the following equation:

$$MP_i = 10 + 60[\frac{i-1}{Loop \ \ Number - 1}] \quad (2)$$

2. The population within the mentioned range for each variable is calculated in each iteration and it is called as the available population dispersion index.

The MDM operator controls all location dispersion for each variable and iteration. For each variable, a region is defined as the center of mean and radius of 15% of the standard deviation. All locations (for each variable) are assessed and their percentage in the desired region is determined. Percent of locations in this region should be equal to the same value obtained by Eq. (2) in each iteration. If this percent is smaller or bigger than Eq. (2), the MDM method with two mechanisms results in equal repeated values (Eq. (2) and percent of location in the desired range) for both cases. For further clarity, the pseudo-code for making these two values equal is presented in the following [29]:

```
for j = 1:number of variables
  while available population dispersion index(j) ~= mandatory population dispersion(j)
     if available population dispersion index(j) > mandatory population dispersion(j)
        if rand < 0.5
variable of interest from population which are in the range = variable of interest
from available population which are out of the range;
        else
variable of interest from population which are in the range = values that are randomly
generated within the permitted range for jth variable;
        end
     elseif available population dispersion index(j) < mandatory population dispersion(j)
        if rand < 0.5
variable of interest from population which are out of the range = the best available
optimal variable to the stage;
        else
variable of interest from population which are out of the range = values that are in the
desired range;
        end
     end
  end
end
```

In this Pseudo-code, the *available population dispersion index* (j) and the *mandatory population dispersion* (j) are the percentages of the locations in the mentioned region and percentage of the locations that should be (from Eq. (2)) for each variable, respectively.

3 Statement of the problem

The present study is aimed at minimizing the steel frame weight with dual system (including OCBF with moderate X-braces) under the problem constraints and examining the best placement of X-braces in steel frames as well as examining the effects of considering or not considering some influential constraints in changing the place of the bracings. The variables of the problems include determining the presence or absence of the X-bracing in each bay as well as the type of beams, columns, and braces, if any. Sections for beams and columns are selected from W sections and braces are taken from HSS sections according to Table 1 and Table 2, respectively. In this study, the aim is to minimize the weight of the structures using Eq. (3). It should be noted that all equations are chosen from ASCE 7-10, AISE 360-05 and ANSI/AISE 341-05 specifications [30-32].

$$\begin{aligned} W &= \sum_{i=1}^{Nd} \rho_i A_i L_i \\ F &= W(1 + P \times penalty) \\ penalty &= \sum_{i=1}^{n} max\left[0, g_i\right] \end{aligned} \quad (3)$$

where W is the weight of the structure, ρ_i is the density of steel for each element, A is the cross sectional area, L is the length of each element of the structure, F is the objective function, P is the penalty coefficient, g is the constraints, *penalty* is the total violation of constraints and N_d is the number of elements.

The load combinations are considered as:

1.4 D

1.2 D + 1.6 L

$(1.2 + 0.2\ S_{ds})\ D + \rho Q_E + 0.5\ L$

$(0.9 - 0.9\ S_{ds})\ D + \rho Q_E$

$(1.2 + 0.2\ S_{ds})\ D + \Omega_0 Q_E + 0.5\ L$

$(0.9 - 0.9\ S_{ds})\ D + \Omega_0 Q_E$

where D and L are dead and live loads, respectively, S_{ds} is the design spectral response acceleration parameter at short periods, Q_E is the effect of horizontal seismic forces, and ρ is the redundancy factor and Ω_0 is the over-strength factor.

Constraints in this paper consist of two groups: mandatory constraints A and optional constraints B. All the frames examined in this article must comply with group A constraints. These constraints are governed by the AISC 360-05 and ASCE / SEI7-10 specifications and some additional constraints described below. In addition to the aforementioned constraints in group A, soft story and the tensile stress ratio are also controlled as optional constraints. It should be noted that rigid diaphragm assumption is considered in all the cases.

Table 1 List of the W-Sections

Section umber	Section	A (in²)	Section umber	Section	A (in²)	Section umber	Section	A (in²)
1	W6x8.5	2.51	32	W12x30	8.79	63	W12x53	15.6
2	W6x9	2.68	33	W10x30	8.84	64	W14x53	15.6
3	W8x10	2.96	34	W14x30	8.85	65	W10x54	15.8
4	W10x12	3.54	35	W8x31	9.12	66	W18x55	16.2
5	W6x12	3.55	36	W16x31	9.13	67	W21x55	16.2
6	W4x13	3.83	37	W10x33	9.71	68	W24x55	16.3
7	W8x13	3.84	38	W14x34	10	69	W21x57	16.7
8	W12x14	4.16	39	W8x35	10.3	70	W16x57	16.8
9	W10x15	4.41	40	W12x35	10.3	71	W12x58	17
10	W8x15	4.44	41	W18x35	10.3	72	W8x58	17.1
11	W6x15	4.45	42	W16x36	10.6	73	W10x60	17.6
12	W5x16	4.71	43	W14x38	11.2	74	W18x60	17.6
13	W12x16	4.71	44	W10x39	11.5	75	W14x61	17.9
14	W6x16	4.74	45	W8x40	11.7	76	W21x62	18.3
15	W10x17	4.99	46	W12x40	11.7	77	W24x62	18.3
16	W8x18	5.26	47	W16x40	11.8	78	W12x65	19.1
17	W5x19	5.56	48	W18x40	11.8	79	W18x65	19.1
18	W12x19	5.57	49	W14x43	12.6	80	W8x67	19.7
19	W10x19	5.62	50	W21x44	13	81	W10x68	20
20	W6x20	5.89	51	W12x45	13.1	82	W14x68	20
21	W8x21	6.16	52	W10x45	13.3	83	W16x67	20
22	W12x22	6.48	53	W16x45	13.3	84	W21x68	20
23	W10x22	6.49	54	W18x46	13.5	85	W24x68	20.1
24	W14x22	6.49	55	W8x48	14.1	86	W18x71	20.8
25	W8x24	7.08	56	W14x48	14.1	87	W12x72	21.1
26	W6x25	7.36	57	W21x48	14.1	88	W21x73	21.5
27	W10x26	7.61	58	W10x49	14.4	89	W14x74	21.8
28	W12x26	7.65	59	W12x50	14.6	90	W18x76	22.3
29	W14x26	7.69	60	W16x50	14.7	91	W24x76	22.4
30	W16x26	7.68	61	W18x50	14.7	92	W10x77	22.6
31	W8x28	8.24	62	W21x50	14.7	93	W16x77	22.9

3.1 Group "A" constraints

1. Stability

$$\theta_{max} < \frac{0.5}{\beta . C_d} \quad (4)$$

where θ_{max} is the maximum stability coefficient, β is the ratio of shear demand to shear capacity, and C_d is the deflection amplification factor.

Table 2 List of the HSS-sections

Section number	Section	A (in²)
94	HSS3X3X5/16	2.94
95	HSS3-1/2X2-1/2X5/16	2.94
96	HSS3-1/2X3-1/2X1/4	2.91
97	HSS3-1/2X2-1/2X1/4	2.44
98	HSS3X3X1/4	2.44
99	HSS3X2-1/2X1/4	2.21
100	HSS3X3X3/16	1.89
101	HSS3X2-1/2X3/16	1.71
102	HSS2-1/2X2-1/2X3/16	1.54

2. Drift

$$Drift \le 0.02 h_{sx} \quad (5)$$

where *Drift* is the maximum inter-story drift for each story and h_{sx} is the height of each story.

Considering the P-Δ effect (according to 12-7-8 of the ASCE 7-10 specification), Eq. (5) is replaced with Eq. (6).

$$Drift . \frac{C_d}{I} . \frac{1}{1-\theta} \le 0.02 h_{sx} \qquad \theta = \frac{P_x Drift}{V_x h_{sx} C_d} \quad (6)$$

where I is the importance factor and it is assumed to be 1.0, θ is the stability factor, P_x and V_x are the whole of the vertical design load above the level x and seismic shear forces between level x and level x-1.

3. Deflection

$$\Delta_L < \frac{l}{360}$$
$$\Delta_{L+D} < \frac{l}{240} \quad (7)$$

where Δ_L and Δ_{L+D} are the allowable deflections under the "live" and "live + dead" loads, respectively. Also, l is the desired span length.

4. Compactness

This constraint satisfies all the requirements of Table 1-8-1 of Seismic Provisions for Structural Steel Buildings according to ANSI/AISC 341-05 specifications.

5. Strength

The following equations must be satisfied:

$$\begin{cases} \dfrac{P_u}{2\phi_c P_n} + \dfrac{M_u}{\phi_b M_n} - 1 \le 0, & for \dfrac{P_u}{\phi_c P_n} < 0.2 \\ \dfrac{P_u}{\phi_c P_n} + \dfrac{8M_u}{9\phi_b M_n} - 1 \le 0, & for \dfrac{P_u}{\phi_c P_n} \ge 0.2 \end{cases} \quad (8)$$

where P_u is the required strength (tension or compression), P_n is the nominal axial strength (tension or compression), $Ø_c$ is the resistance factor ($Ø_c$ = 0.9 for tension and $Ø_c$ = 0.85 for compression), M_u (containing M_{ux} and M_{uy}) is the required flexural strengths, M_n (containing M_{nx} and M_{ny}) is the nominal flexural strengths (for planar frames $M_{uy} = 0$ and $M_{ny} = 0$), and $Ø_b$ presents the flexural resistance reduction factor ($Ø_b$ = 0.90). The nominal tensile strength for yielding in the gross section is evaluated as follows:

The nominal tensile strength and compressive strength of a member are computed by Eq. (9) and Eq. (10), respectively:

$$P_n = A_g.F_y \quad (9)$$

$$P_n = A_g.F_{cr}$$
$$\begin{cases} \dfrac{kl}{r} \le 4.71\sqrt{\dfrac{F_y}{E}} & F_{cr} = (0.658^{\frac{F_y}{F_e}})F_y \\ \dfrac{kl}{r} > 4.71\sqrt{\dfrac{F_y}{E}} & F_{cr} = 0.877F_e \end{cases} \quad (10)$$
$$F_e = \frac{\pi^2 E}{(\frac{kl}{r})^2}$$

where A_g is the cross-sectional area of a member, and k is the effective length factor that is calculated by Eq. (11) and Eq. (12) for braced and unbraced frames, respectively.

$$k = \frac{3G_A G_B + 1.4(G_A + G_B) + 0.64}{3G_A G_B + 2(G_A + G_B) + 1.28} \quad (11)$$

$$k = \sqrt{\frac{1.6G_A G_B + 4.0(G_A + G_B) + 7.5}{G_A + G_B + 7.5}} \quad (12)$$

where, G_A and G_B are stiffness ratios of the columns and girders at two end joints of the considered column.

The values of M_{ux} and M_{uy} must be obtained by carrying out P–Δ analysis of the steel frame. This is an iterative process which is time consuming. In Chapter C of LRFD-AISC, an alternative procedure is suggested for the computation of M_{ux} and M_{uy} values. In this procedure, two first order elastic analyses are carried out.

$$P_r = P_{nt} + B_2 P_{lt}$$
$$M_r = B_1 M_{nt} + B_2 M_{lt} \quad (13)$$

where M_{nt} and M_{lt} moment values are calculated when the frame is analyzed under gravity and lateral loads, respectively. Also, B_1 and B_2 are the moment magnifier coefficient and the sway moment magnifier coefficient, respectively. These coefficients are calculated according to AISC. It should be noted that P_{nt} and P_{lt} are calculated like moment values.

6. Slenderness

The maximum value for this constraint is equal to 300 and 200 for tensile and compression members, respectively [33].

7. Constructional constraint

According to this constraint, the geometric constraint for two hypothetical beam-column connections of B_1 and B_2 are taken as:

$$\frac{b_{fb}}{b_{fc}} - 1 \le 0 \quad (14)$$

$$\frac{b'_{fb}}{d_c - 2t_f} - 1 \le 0 \quad (15)$$

In the above formulation, b_{fb}, b_{fc}, b'_{fb} are the flange width of B_1 beam, B_2 beam and column, respectively. d_c is the height of the column section and t_f is the column's flange thickness. Eq. (14) ensures that B_1 flange width is smaller than column's flange width. On the other hand, Eq. (15) causes the beam's flange width to be designed smaller than the free distance between the column flanges.

8. According to 5.6.1629 of the UBC specification, the following constraints should be considered:

8.1. The dual system can resist the entire load.

8.2. According to the definitions given in the specification for the dual system, the moment resisting frame must alone be able to resist at least 25% of the lateral load.

3.2 Group "B" constraints

1. Soft story

In accordance with 12.3.3.2 of the ASCE 7-10 specification, If the stiffness of a story is less than 70% of the above story or less than 80% of the average stiffness of the top 3 stories, it is considered as a soft story.

2. Tensile stress of first story columns

As the last constraint, tensile stress of the first-story columns is considered and its value can be a symbol of uplift and can also affect it. The presence of high tensile stress in the first story columns may cause problems such as placing part of the foundation in tensile and eventually overturning, or requiring the use of a pile. Therefore, by considering this constraint, attempts are made so that the columns of the first story receive less tension.

Group A constraints are considered in all the problems of this paper. As mentioned, one of the objectives of this study is to include the effect of considering or not considering the Group B constraints along with the provision of all Group A constraints.

4 Numerical examples

In this section, three planar steel frames containing three, six and nine stories with 5 spans are considered. For layout optimization of these frames, the CBO and CBO-MDM algorithms are used considering four different cases for three and six stories frames and only Case 4 of the nine story frame. For Case 1, A1-A8 and B1 and B2 constraints are considered. For Case 2, A1-A8 and B1 constraints are used. For Case 3, A1-A8 and B2 constraints are considered. For Case 4 only A1-A8 constraints are utilized.

It should be noted that in Case 4, the PSO and ICA algorithms are applied in addition to the CBO and CBO-MDM algorithms.

In these examples, the height of each story and the length of each span are considered as 3.0 m and 6.0 m, respectively. In all the design problems, the modulus of elasticity is (E) = 200 GPa, mass density (ρ) = 76.82 kN/m^3 and yield stress for beams, columns (F_y) = 344.7 MPa and (F_y) = 317.2 MPa for braces. The design dead and live loads are selected as 6.3 kN/m^2 and 1.96 kN/m^2, respectively. Earthquake loads are computed according to the ASCE 7-10 using R = 7, I = 1, S_s = 0.4 and S_l = 0.2 and seismic design category D.

In this study, a population of n = 60 is utilized for the CBO and CBO-MDM algorithms. Also, 1000 iterations and 30 independent runs are performed. The best, worst and average weights are provided in all the tables.

As mentioned before, sections for beams and columns are chosen from W sections and braces are taken from HSS sections according to Table 1 and Table 2.

4.1 The 3-story and 5-bay steel frame

Figure 1 shows the topology of the 3-story and 5-bay frame with all possible bracings. The element grouping is considered as one column section, one beam section and eleven brace sections. This frame is a dual building frame system.

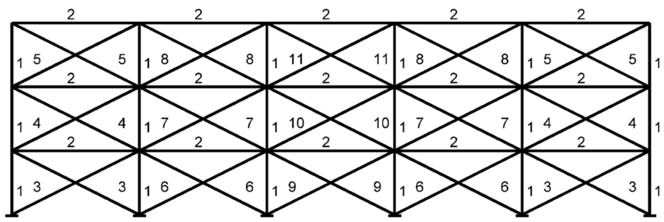


Fig. 1 Schematic and grouping of the 5-bay and 3-story frame with all braces

Table 3 shows a compression of the optimal layout design gained by CBO and CBO-MDM for 4 different cases, and optimal layout designs are obtained by the PSO and ICA algorithms for the Case 4. Figure 2(a) and Figure 2(b) indicate the best layout obtained by CBO and CBO-MDM for 4 cases, respectively, and Figure 2(c) shows the best layouts gained by the PSO and ICA for the Case 4. Figure 3 presents the

Table 3 Layout results for the 3-story and 5-bay steel frame

Element group	CBO-MDM Cases				CBO Cases				ICA	PSO
	1	2	3	4	1	2	3	4	Case 4	Case 4
1	50	31	47	31	60	31	50	31	31	37
2	28	28	28	28	28	28	28	28	28	28
3	-	-	-	-	100	-	-	-	100	-
4	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	100	-	100	-
6	-	-	-	-	-	96	-	96	-	96
7	100	-	-	-	-	-	-	-	100	-
8	-	-	-	-	-	-	-	-	-	-
9	100	96	96	96	-	-	98	-	100	96
10	-	96	98	96	100	96	100	96	-	96
11	102	100	102	100	102	100	-	100	-	96
Best Weight(kN)	73.70	61.30	70.28	61.3	78.2	63.2	74.3	63.2	64.29	65.8
Worst Weight(kN)	128.7	75.36	127.319	68.6	128	85.4	100.6	69.7	78.826	78.66
Average Weight(kN)	91.62	67.2	84.506	65.3	94.88	78.4	86.41	67.7	71.84	70.58

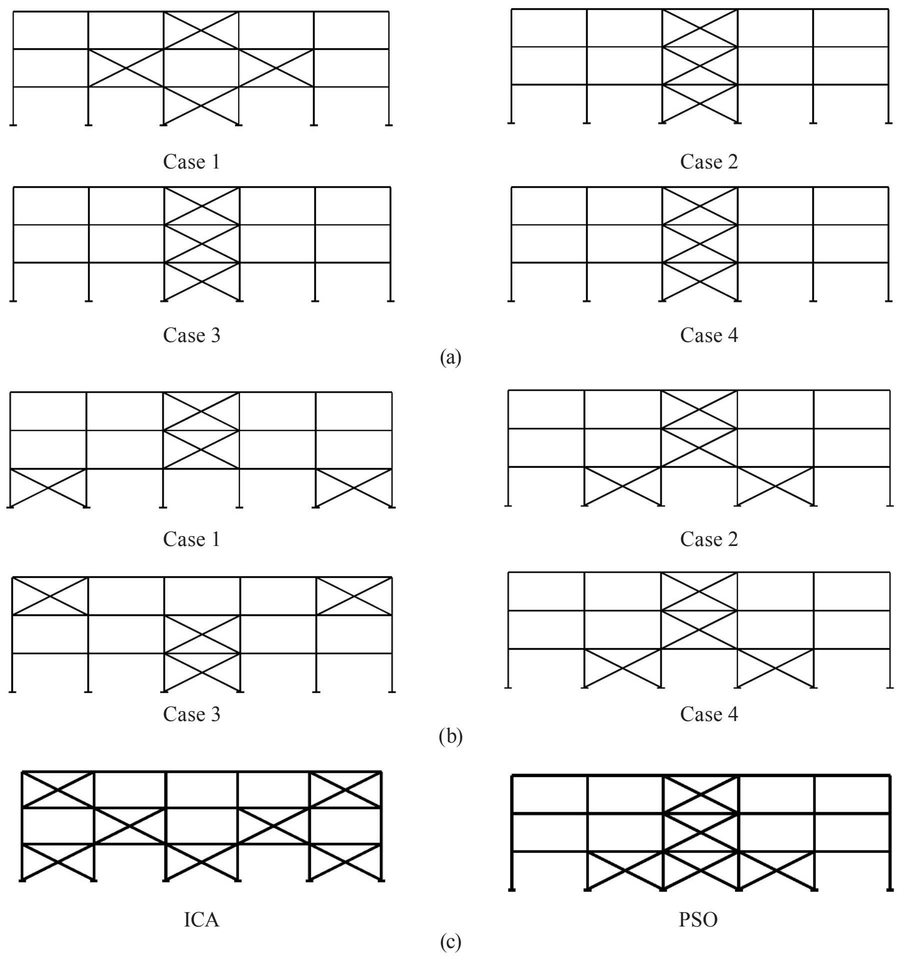


Fig. 2 Best layout obtained for 4 cases for the 5-bay and 3-story frame (a) By CBO algorithm (b) By CBO-MDM algorithm (c) By PSO and ICA algorithms

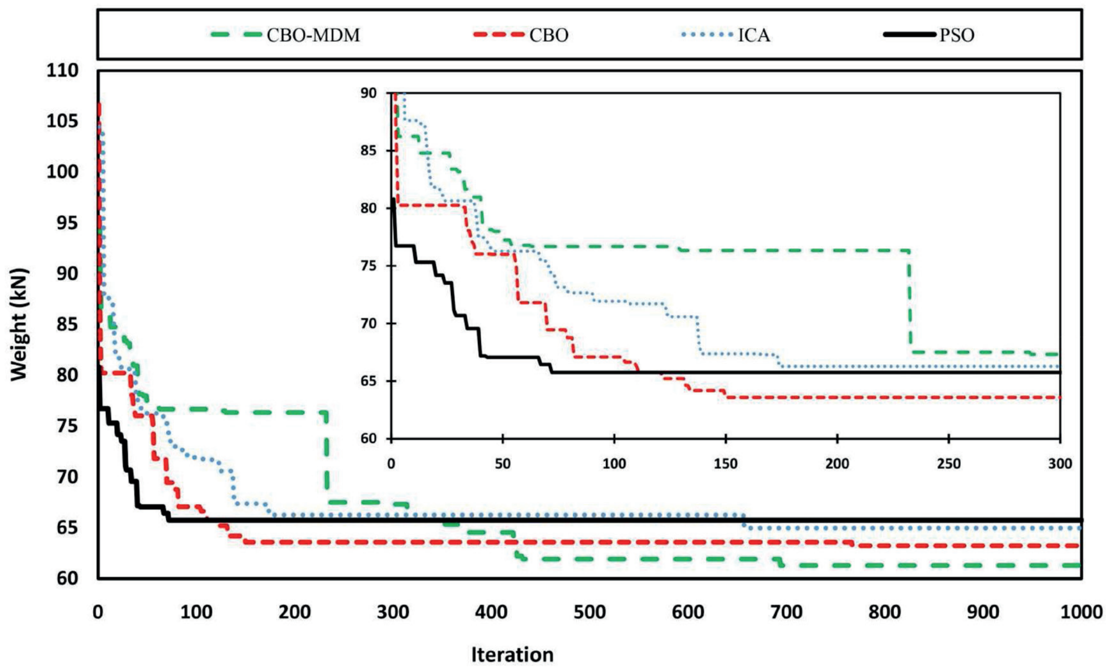


Fig. 3 Convergence histories of the CBO, CBO-MDM, PSO and ICA for the best layout optimization of the Case 4 of the 5-bay and 3-story frame

convergence histories of the CBO, CBO-MDM, PSO and ICA for the best layout optimization of the Case 4. Figure 4 illustrates the convergence histories of the CBO and CBO-MDM for the best layout optimization of the Case 4 (with schematics of layout obtained at some stages of the optimization process).

Finally, Figure 5 present the stress ratios and their story drift for optimal layout optimization (Case 4) of CBO-MDM and CBO algorithms, respectively.

4.2 The 6-story and 5-bay steel frame

Figure 6 shows the topology of the 6-story and 5-bay frame with all possible braces. The element grouping results in two column sections, two beam sections, and eighteen bracing sections. This frame is a dual building frame system. Table 4 shows a compression of the optimal layout design obtained by CBO, CBO-MDM and CBO-DM for 4 different cases and optimal layout design obtained by PSO and ICA algorithms for Case 4.

This table shows the performances of both operators (DM and MDM) in the CBO algorithm. It can be seen that the MDM operator acts better than the DM operator. The MDM operator considers a range, while DM operator considers only the mode parameter) instead of the mentioned range). Thus, DM operator has less control on the dispersion of locations (especially in the first half of iterations) in comparison to the MDM operator.

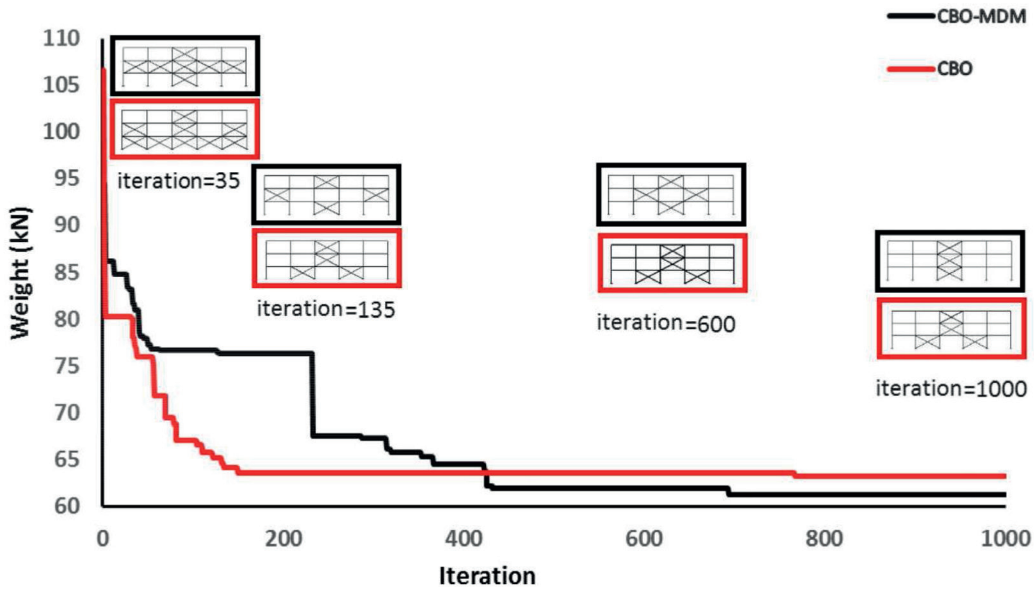
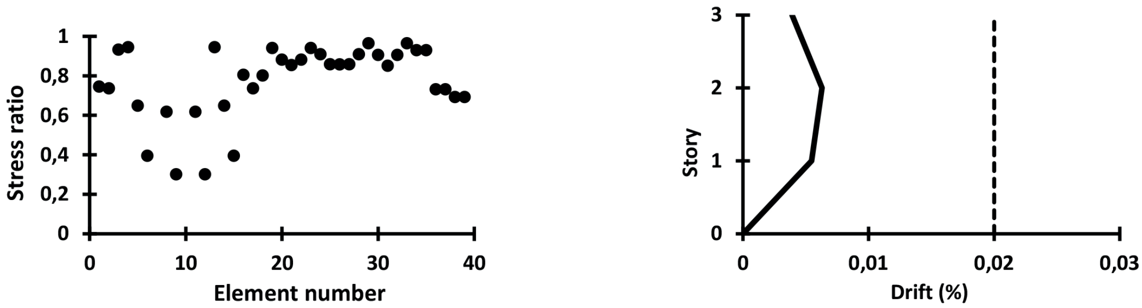
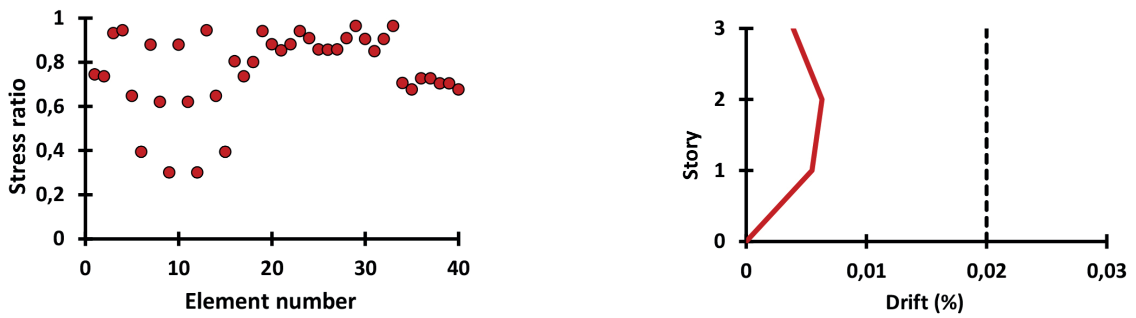


Fig. 4 Convergence histories of the CBO and CBO-MDM for the best layout optimization of the Case 4 of the 5-bay and 3-story frame.



stress ratios story drift

(a) For optimal layout optimization of CBO-MDM algorithm (Case 4)



stress ratios story drift

(b) For optimal layout optimization of CBO algorithm (Case 4)

Fig. 5 Stress ratios and the story drift of the 5-bay and 3-story frame.

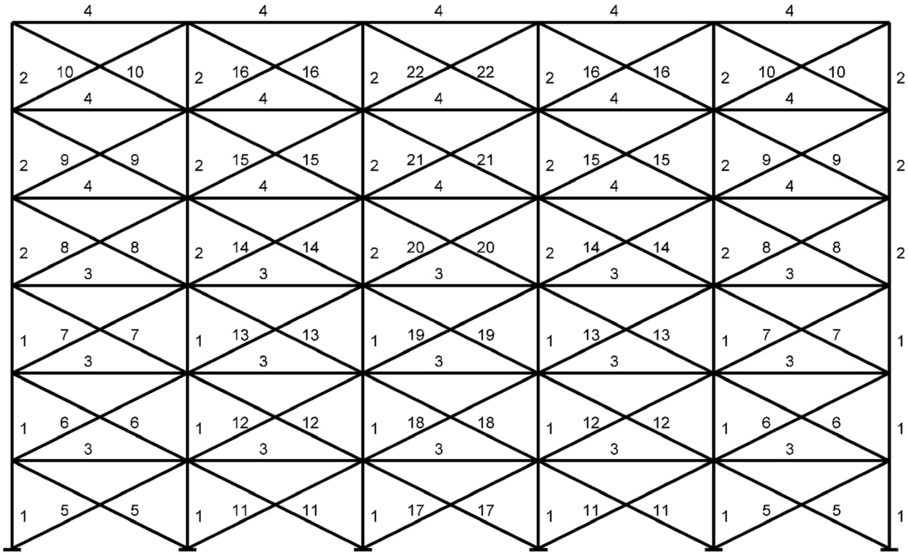


Fig. 6 Schematic and grouping of the 5-bay and 3-story frame with all braces

Table 4 The layout results for the 5-bay and 6-story frame.

Element group	CBO-MDM Cases				CBO Cases				CBO-DM Cases				ICA	PSO
	1	2	3	4	1	2	3	4	1	2	3	4	4	4
1	91	58	80	51	91	58	83	59	88	58	83	51	56	76
2	91	37	80	37	91	37	83	37	88	37	83	37	37	40
3	28	28	28	28	28	28	28	28	28	28	28	28	34	34
4	28	28	28	28	28	28	28	28	28	28	28	28	28	28
5	-	96	-	96	-	96	96	96	96	-	-	-	96	96
6	-	-	100	-	96	-	96	-	96	-	96	-	-	-
7	-	-	96	-	-	-	96	-	96	-	96	-	-	-
8	96	-	96	-	-	-	96	-	96	-	96	-	-	-
9	96	-	-	-	-	-	-	-	96	-	-	-	-	-
10	-	-	-	-	96	-	-	-	100	-	-	-	96	-
11	-	-	96	-	96	-	-	-	-	96	96	96	-	-
12	-	96	96	96	-	96	-	96	-	96	100	96	96	96
13	-	-	-	-	98	96	-	-	-	96	-	96	-	-
14	-	-	-	-	-	96	-	-	-	96	-	-	96	-
15	-	-	-	-	98	96	96	-	-	100	-	-	-	-
16	-	-	-	-	-	-	-	-	-	101	-	-	-	-
17	96	-	-	-	-	-	-	-	-	-	-	96	-	-
18	96	96	-	-	-	-	-	-	-	-	-	100	-	-
19	96	96	-	96	98	-	-	96	-	-	-	100	96	96
20	-	96	-	96	98	-	-	96	-	-	-	96	-	96
21	-	96	96	96	-	-	-	96	-	-	100	96	96	96
22	102	96	-	96	-	100	100	100	-	-	101	101	-	100
BW	202.7	150.1	193.6	144.7	209.4	153.3	194.2	148.1	205.1	153	194	150.3	156.6	164.9
WW	251	180	200	160	274	184	253	182	254	211	232	183	196	184
AW	227	165	197	150	245	170	233	168	235	175	207	179	172	175

BW: Best Weight (kN); WW: Worst Weight (kN); AW: Average Weight (kN)

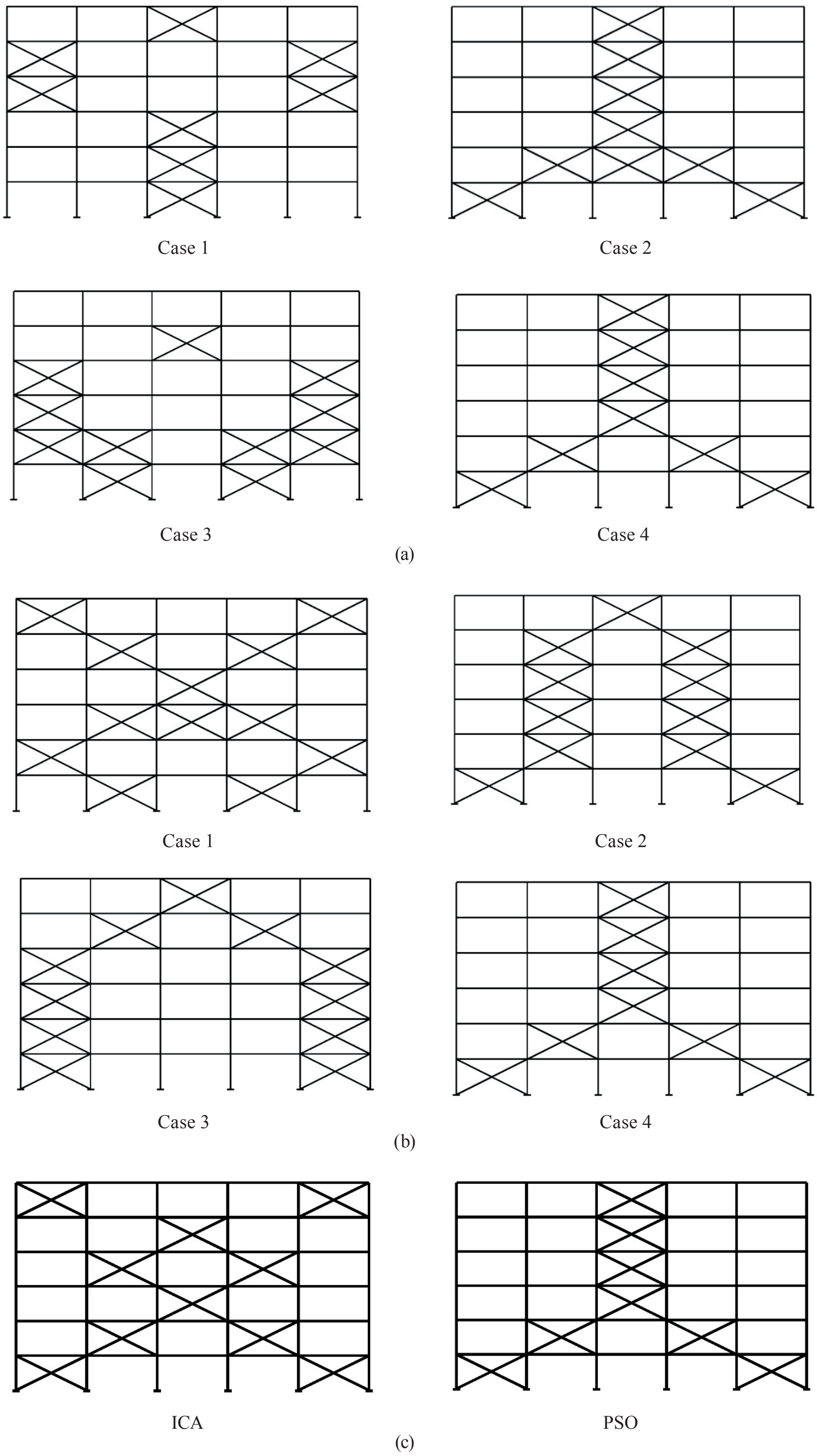


Fig. 7 Best layout obtained for 4 cases for the 5-bay and 6-story frame (a) By CBO algorithm (b) By CBO-MDM algorithm (c) By PSO and ICA algorithms.

Figure 7(a) and Figure 7(b) illustrate the schematics of the best layout obtained by CBO and CBO-MDM for 4 cases, respectively. In addition, Figure 7(c) shows the best layout gained by the PSO and ICA for the Case 4. Figure 8 presents convergence histories of the CBO, CBO-MDM, PSO and ICA for the best layout optimization of the Case 4. Figure 9 shows the convergence histories of the CBO and CBO-MDM for the best layout optimization of this structure for the Case 4 (with schematic of layouts obtained at some stages of the optimization process).

Figure 10 present the existing stress ratios and their story drifts for Case 4 optimal layout optimization of the CBO-MDM and CBO algorithms.

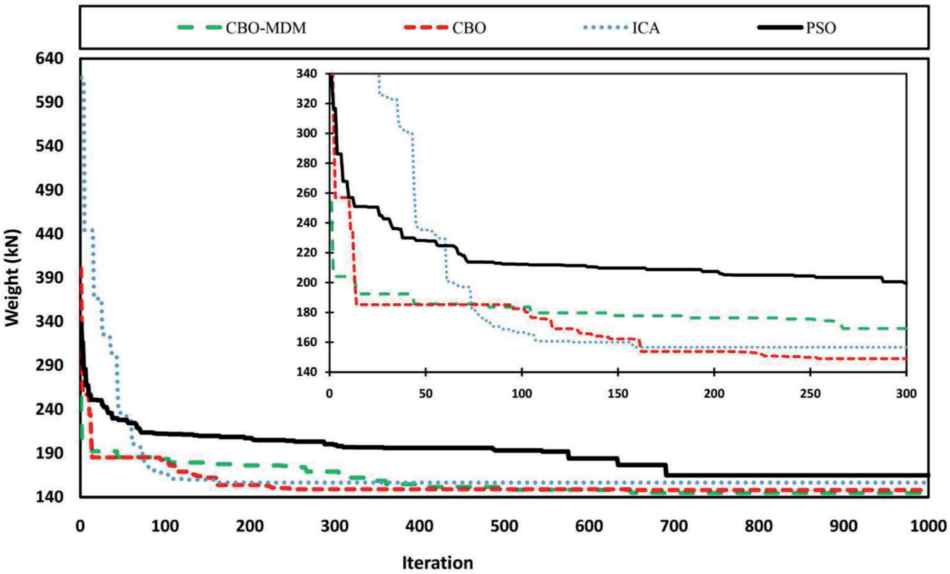


Fig. 8 Convergence histories of the CBO, CBO-MDM, PSO and ICA for the best layout optimization of the Case 4 of the 5-bay and 6-story frame

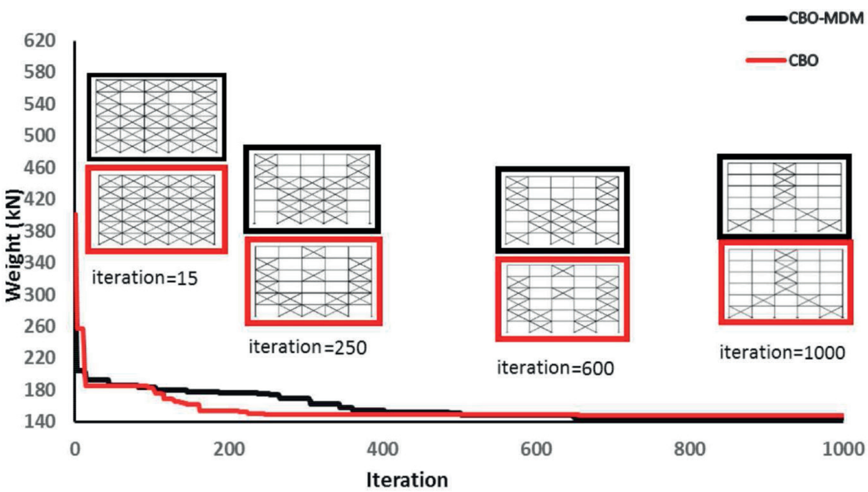
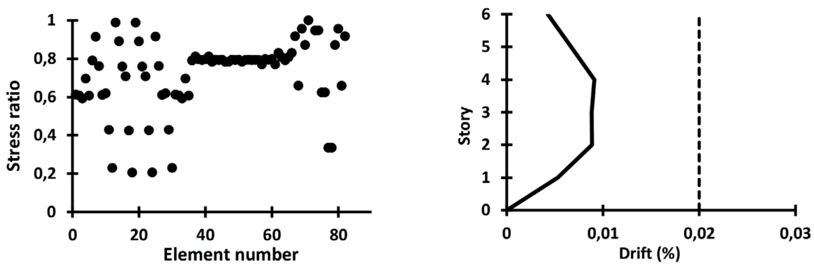
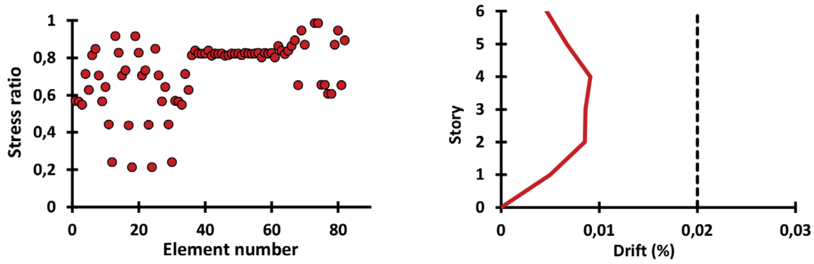


Fig. 9 Convergence histories of the CBO and CBO-MDM for the best layout optimization of the (Case 4) of the 5-bay and 6-story frame



stress ratios story drift

(a) For optimal layout optimization of CBO-MDM algorithm (Case 4)



stress ratios story drift

(b) For optimal layout optimization of CBO algorithm (Case 4)

Fig. 10 Stress ratios and the story drift of the 5-bay and 6-story frame

4.3 The 9-story and 5-bay steel frame

Figure 11(a) shows the topology of the 9-story and 5-bay frame with all possible bracings. The element grouping is considered as three column sections, three beam sections and twenty seven bracing sections. This structure is a dual building frame system.

Table 5 shows a compression of the optimal layout designs obtained by the CBO, CBO-MDM, PSO and ICA for the Case 4. Figure 11(b) illustrates the best layout obtained by the CBO, CBO-MDM, PSO and ICA for the Case 4, respectively. Figure 12 presents the convergence histories of the CBO, CBO-MDM, PSO and ICA for the best layout optimization of the Case 4.

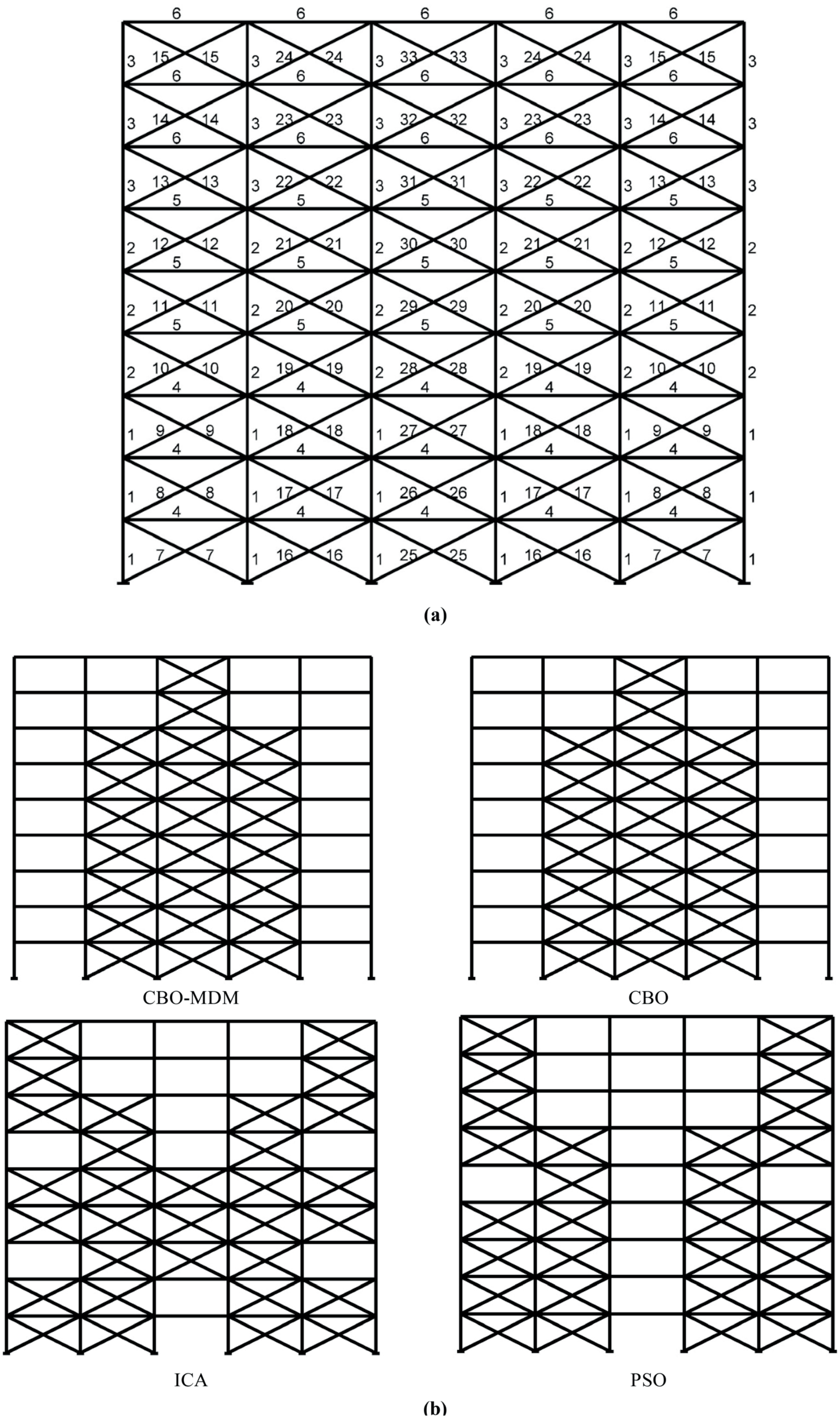


Fig. 11 (a) Schematic and grouping of the 5-bay and 9-story frame with all bracings, (b) Best layouts obtained by the CBO-MDM, CBO, PSO and ICA algorithms for Case 4 of the 5-bay and 9-story frame

Table 5 Layout results for the 5-bay and 9-story frame

Element group	CBO-MDM Case 4	CBO Case 4	ICA Case 4	PSO Case 4
1	87	87	80	93
2	63	63	56	93
3	37	37	44	63
4	34	34	28	28
5	28	28	28	28
6	28	28	28	28
7	-	-	96	96
8	-	-	96	96
9	-	-	-	96
10	-	-	96	96
11	-	-	96	-
12	-	-	-	96
13	-	-	96	96
14	-	-	96	96
15	-	-	96	96
16	96	96	96	96
17	96	96	96	96
18	96	96	96	96
19	96	96	96	96
20	96	96	96	96
21	96	96	96	96
22	96	96	96	-
23	-	-	-	-
24	-	-	-	-
25	96	96	-	-
26	96	96	-	-
27	96	96	96	-
28	96	96	96	-
29	96	96	96	-
30	96	96	-	-
31	96	96	-	-
32	96	96	-	-
33	96	96	-	-
BW	276.432	276.432	283.588	319.27
WW	335.533	348.95	370	401.16
AW	320.731	322.42	347.51	361.9

BW: Best Weight (kN); WW: Worst Weight (kN); AW: Average Weight (kN)

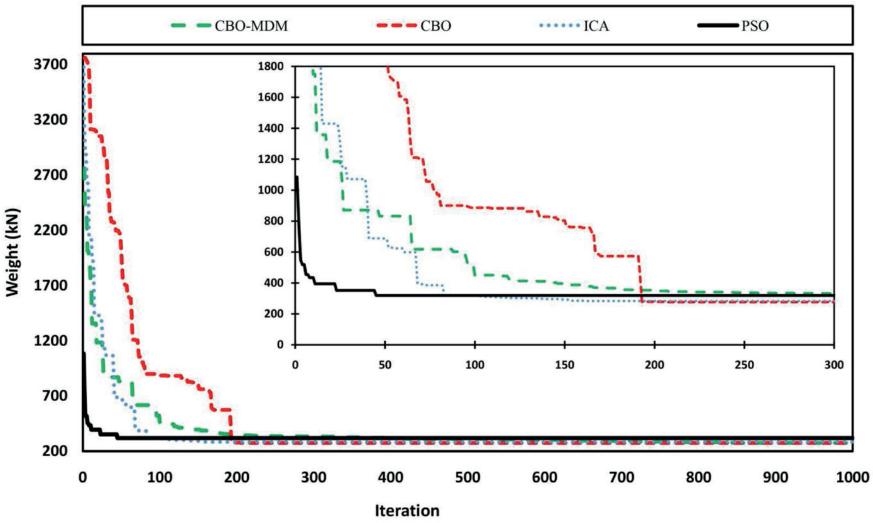


Fig. 12 Convergence histories of the CBO, CBO-MDM, PSO and ICA for the best layout optimization of the Case 4 of the 5-bay and 9-story frame

5 Discussion and conclusions

5.1 Discussion

In this study four various cases are investigated as:

- Case 1 containing A1-A8 and B1 and B2 constraints.
- Case 2 containing A1-A8 and B1 constraints.
- Case 3 containing A1-A8 and B2 constraints.
- Case 4 containing only A1-A8 constraints.

Changing in the arrangement of the braces, results in changing the stress ratios of all elements, the story drifts, the weight of the structure and tensile stress of the first-story columns. In this study, layout optimization of three problems are investigated. From figures and tables, the following results can be obtained:

- Tables show that the lightest weight does not necessarily correspond to the least number of braces. Since smaller number of braces can increase the stress ratios (in beams and columns) and consequently increase the cross-sections of the frame structure and eventually increase the weight of the structure.
- The results show that if only Group A constraints are implemented (such as Case 4), bracings will be more distributed in central bays. In this case, stress ratios are close to allowable capacity. In fact, stress ratios are determinative
- The lightest weight is obtained for Case 4 because fewer constraints are implemented for this case.
- When all of the constraints (Case 1) are taken into account, the braces will be distributed more in the side bays. One of the most effective factors, in this case, is controlling the tensile stress of the first story columns (B2 constraint). This constraint results in reduction of the tensile stresses of the first story columns. Therefore, heavier cross-sections should be selected for columns. Additional explanation about this constraint is presented in section 3.2.
- When all of the constraints (Case 1) are taken into account, the weight of the structure will eventually increase and the stress ratios have a great difference with the allowable capacity of each element. In fact, in Case 1 other constraints (especially B2 constraint) except stress constraints are determinative.
- Tables and figures show the performance of the MDM operator. This operator enhances the performance of the CBO algorithm because it controls the population dispersion.

5.2 Conclusions

In this research, design optimization of three different steel frames with gravity and seismic loadings are performed according to well established specifications. Additionally, attempt has been made to make the selected constraints as consistent as possible with the design of a real structure. The study also aimed at assessing the effect of considering or not considering two groups of constraints (4 different modes) and their effect on the layout configuration of the structures and selecting the type of elements to reduce the weight of the structure.

In this study, the CBO, CBO-MDM, CBO-DM, PSO and ICA algorithms are used to perform the design optimization. The CBO method is inspired from the collision of two fixed and moving particles. The algorithm has previously been successfully applied to many other optimization problems. The MDM operator has recently been proposed. This operator can be incorporated to all the metaheuristic algorithms to make them less dependent on tuning the empirical parameters. In fact, this operator makes the search space better reviewed, and the algorithms get less trapped in local optima. All the obtained results of this research confirm that incorporating the MDM operator on the CBO algorithm improves the results. Also, all the results of the Case 4 show that the CBO and CBO-MDM have obtained better layouts in comparison to the other two algorithms. Also, according to Table 4, MDM operator has obtained better answer in comparison to the DM operator.

Finally, it is recommended that the layout optimization of steel frames should also be considered under the effect of wind loads and the placement of the bracings should be compared with those of the present study. The layout optimization of other types of braces instead of X-braces is also recommended

References

[1] Rozvany, G., Bendsoe, M., Kirsch, U. "Layout optimization of structures". *Applied Mechanics Reviews*, 48 (2), pp. 41–119. 1995. https://doi.org/10.1115/1.3005097

[2] Park, P., Gilbert, M., Tyas, A., Popovic-Larsen, O. "Potential use of structural layout optimization at the conceptual design stage". *International Journal of Architectural Computing*, 10(1), pp. 13–32. 2012. https://doi.org/10.1260/1478-0771.10.1.13

[3] Goldberg, D. E., Holland, J. H. "Genetic algorithms and machine learning". *Machine Learning*, 3(2), pp. 95–99. 1988. https://doi.org/10.1023/A:1022602019183

[4] Dorigo, M., Birattari, M., Stutzle, T. "Ant colony optimization". *IEEE Computational Intelligence Magazine*, 1(4), pp. 28–39. 2006. https://doi.org/10.1109/MCI.2006.329691

[5] Kennedy, J., Eberhart, R. "Particle swarm optimization". Neural Networks, 1995 Proceedings, IEEE International Conference on: IEEE; 1995. p. 1942–1948. https://doi.org/10.1109/ICNN.1995.488968

[6] Atashpaz-Gargari, E., Lucas, C. "Imperialist competitive algorithm: an algorithm for optimization inspired by imperialistic competition". Evolutionary computation, 2007 CEC 2007 IEEE Congress on: IEEE; 2007. p. 4661–4667. https://doi.org/10.1109/CEC.2007.4425083

[7] Geem, Z. W. "*Music-inspired harmony search algorithm: theory and applications*". Springer, 2009. https://doi.org/10.1007/978-3-642-00185-7

[8] Geem, Z. W., Kim, J. H., Loganathan, G. V. "A new heuristic optimization algorithm: harmony search". *Simulation*, 76(2), pp. 60–68. 2001. https://doi.org/10.1177/003754970107600201

[9] Kaveh, A., Talatahari, S. "A novel heuristic optimization method: charged system search". *Acta Mechanica*, 213(3), pp. 267–289. 2010. https://doi.org/10.1007/s00707-009-0270-4

[10] Kaveh, A., Farhoudi, N. "A new optimization method: dolphin echolocation". *Advances in Engineering Software*, 59: pp. 53–70. 2013. https://doi.org/10.1016/j.advengsoft.2013.03.004

[11] Kaveh, A., Ilchi Ghazaan, M. "Enhanced colliding bodies optimization for design problems with continuous and discrete variables". *Advances in Engineering Software*, 77, pp. 66–75. 2014. https://doi.org/10.1016/j.advengsoft.2014.08.003

[12] Kaveh, A., Mahdavi, V. R. "Colliding bodies optimization: a novel metaheuristic method". *Computers & Structures*, 139: pp. 18–27. 2014. https://doi.org/10.1016/j.compstruc.2014.04.005

[13] Mirjalili, S., Mirjalili, S. M., Lewis, A. "Grey wolf optimizer". *Advances in Engineering Software*, 69, pp. 46–61. 2014. https://doi.org/10.1016/j.advengsoft.2013.12.007

[14] Kaveh, A., Ilchi Ghazaan, M. "A new meta-heuristic algorithm: vibrating particles system". *Scientia Iranica Transaction A, Civil Engineering*, 24(2), pp. 551–566. 2017. https://doi.org/10.24200/sci.2017.2417

[15] Mirjalili, S. "The ant lion optimizer". *Advances in Engineering Software*, 83, pp. 80–98. 2015. https://doi.org/10.1016/j.advengsoft.2015.01.010

[16] Saremi, S., Mirjalili, S., Lewis, A. "Grasshopper optimisation algorithm: Theory and application". *Advances in Engineering Software*, 105, pp. 30–47. 2017. https://doi.org/10.1016/j.advengsoft.2017.01.004

[17] Kaveh, A. "*Advances in Metaheuristic Algorithms for Optimal Design of Structures*". 2nd edition. Springer International Publishing. Switzerland, 2017. https://doi.org/10.1007/978-3-319-46173-1

[18] Ansari, J., Jamei, M., Kazemi, A. "Integration of the wind power plants through a novel, multi-objective control scheme under the normal and emergency conditions". *International Transactions on Electrical Energy Systems*, 26(8), pp. 1752–1782. 2016. https://doi.org/10.1002/etep.2176

[19] Guedria, N. B. "Improved accelerated PSO algorithm for mechanical engineering optimization problems". *Applied Soft Computing*, 40, pp. 455–67. 2016. https://doi.org/10.1016/j.asoc.2015.10.048

[20] Mandal, T., Acharyya, S. "Optimal task scheduling in cloud computing environment: Meta heuristic approaches". Electrical Information and Communication Technology (EICT), 2015 2nd International Conference on: IEEE; 2015. p. 24–28. https://doi.org/10.1109/EICT.2015.7391916

[21] Pavão, L., Pozo, C., Costa, C., Ravagnani, M., Jiménez, L. "A metaheuristic approach for financial risks management in heat exchanger networks". *Computer Aided Chemical Engineering*, 40, pp. 955–960. 2017. https://doi.org/10.1016/B978-0-444-63965-3.50161-6

[22] Hagishita, T., Ohsaki, M. "Optimal placement of braces for steel frames with semi-rigid joints by scatter search". *Computers & Structures*, 86(21–22), pp. 1983–193. 2008. https://doi.org/10.1016/j.compstruc.2008.05.002

[23] Kaveh, A., Shahrouzi, M. "Graph theoretical implementation of memetic algorithms in structural optimization of frame bracing layouts". *Engineering Computations*, 25(1), pp. 55–85. 2008. https://doi.org/10.1108/02644400810841422

[24] Kaveh, A., Farhoudi, N. "Layout optimization of braced frames using differential evolution algorithm and dolphin echolocation optimization". *Periodica Polytechnica Civil Engineering*, 59(3), pp. 441–449. 2015. https://doi.org/10.3311/PPci.8155

[25] Kaveh, A., Farhoudi, N. "Dolphin monitoring for enhancing metaheuristic algorithms: Layout optimization of braced frames". *Computers & Structures*, 165, pp. 1–9. 2016. https://doi.org/10.1016/j.compstruc.2015.11.012

[26] Zuo, Z. H., Xie, Y. M., Huang, X. "Evolutionary topology optimization of structures with multiple displacement and frequency constraints". *Advances in Structural Engineering*, 15(2), pp. 359–372. 2012. https://doi.org/10.1260/1369-4332.15.2.359

[27] Stromberg, L. L., Beghini, A., Baker, W. F., Paulino, G. H. "Topology optimization for braced frames: combining continuum and beam/column elements". *Engineering Structures*, 37, pp. 106–124. 2012. https://doi.org/10.1016/j.engstruct.2011.12.034

[28] Zhang, H., Liu, X., Yi, W. "Reinforcement Layout Optimisation of RC D-regions". *Advances in Structural Engineering*, 17(7), pp. 979–992. 2014. https://doi.org/10.1260/1369-4332.17.7.979

[29] Kaveh, A., Hoseini Vaez, S. R., Hosseini, P. "Modified Dolphin Monitoring Operator for Weight Optimization of Frame Structures". *Periodica Polytechnica Civil Engineering*, 61(67), pp. 770–779. 2017. https://doi.org/10.3311/PPci.9691

[30] ANSI/AISC 360-05. Specification for Structural Steel Buildings. American Institute of Steel Construction. 2005.

[31] ANSI/AISC 341-05. Seismic Provisions for Structural Steel Buildings. American Institute of Steel Construction. 2005.

[32] Minimum Design Loads for Buildings and Other Structures. American Institute of Steel Construction. 2010.

[33] Salmon, C. G., Johnson, J. E. "*Steel structures: design and behavior: emphasizing load and resistance factor design*". Prentice Hall, 1996.