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A developed design optimization model for semi-rigid steel frames using teaching-learning-based optimization and genetic algorithms

Osman Shallan[a], Hassan M. Maaly[b] and Osman Hamdy*

Department of Structural Engineering, University of Zagazig, Zagazig, Egypt

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Abstract. This paper proposes a developed optimization model for steel frames with semi-rigid beam-to-column connections and fixed bases using teaching-learning-based optimization (TLBO) and genetic algorithm (GA) techniques. This method uses rotational deformations of frame members ends as an optimization variable to simultaneously obtain the optimum cross-sections and the most suitable beam-to-column connection type. The total cost of members plus connections cost of the frame are minimized. Frye and Morris (1975) polynomial model is used for modeling nonlinearity of semi-rigid connections, and the P-Δ effect and geometric nonlinearity are considered through a stepped analysis process. The stress and displacement constraints of AISC-LRFD (2016) specifications, along with size fitting constraints, are considered in the design procedure. The developed model is applied to three benchmark steel frames, and the results are compared with previous literature results. The comparisons show that developed model using both LTBO and GA achieves better results than previous approaches in the literature.

Keywords: teaching-learning-based optimization; genetic algorithm; steel frame optimization; semi-rigid connections; geometrically nonlinear; the P-Δ effect; rotational deformations variable

1. Introduction

In most design procedures, representations of a beam-to-column connection are simplified by assuming either a perfectly pinned or a fully rigid connection. However, beam-to-column connections are in fact semi-rigid, and their actual behavior is complex and nonlinear, as the connection possesses some rotational stiffness between these two extreme assumptions. Therefore, this simplified representation of connections cannot provide a real description of the connections or a realistic response of the frame.

In contrast to a fully rigid connection, representing a column-to-beam connection as semi-rigid decreases the stiffness of beam members. This decrease in stiffness leads to an increase in the drift of the frame under the same load. The increase in frame drift will, in turn, magnify the 2nd order effect (the P-Δ effect). Therefore, this effect, as well as geometric nonlinearity (i.e., the change in coordination) has to be considered through a stepped analysis.

AISC-LRFD describes two types of steel constructions: fully restrained (FR) and partially restrained (PR), where the PR type is assessed based on logical experimental and numerical studies. Because of the importance of realistic simulation of nonlinear behavior of semi-rigid beam-to-column connections, several searchers have conducted experimental and numerical studies on the modeling of various semi-rigid connections to deduce the nonlinear moment-rotation relationship for these connections, such as Frye and Morris (1975), Abdalla and Chen (1995), Chisala (1999), Kim *et al*. (2010) and Wu *et al*. (2012).

Optimization tools used in this study are a teaching-learning-based optimization algorithm (TLBO) and a genetic algorithm (GA). TLBO is one of the newest evolutionary optimization algorithms, which mimics teaching and learning process in a class (Rao *et al.* 2012). On the other hand, GA is one of the oldest evolutionary optimization algorithm, which imitates the evolution theory (Goldberg 1989).

This study aims to design a developed optimization model for steel frames that considers semi-rigid beam-to-column connections using the Frye and Morris (1975) connection models, and apply this developed model using TLBO and GA. In addition, the P-Δ effect and geometric nonlinearity are taken into account, and the resulting stress and displacement are checked based on AISC-LRFD (2016) constraints and size fitting constraints.

2. Optimization algorithms

There are different types of heuristic stochastic evolutionary optimization algorithms which are used in the literature studies. Where each algorithm mimics a certain evolutionary behavior in nature for the sake of reaching the optimum solution for a particular problem as shown in Table 1.

*Corresponding author, Ph.D. Student
E-mail: Osmanhmdy@gmail.com
[a]Professor and Head of Structural Department
E-mail: Osmanshalan@yahoo.com
[b]Associate Professor
E-mail: Dr.H.Maaly6@gmail.com

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Table 1 Optimization algorithms

Algorithm	Proposed by	Simulating
Genetic Algorithm (GA)	John Holland	Evolution theory of Darwin.
Particle Swarm (PSO)	Eberhart and Kennedy	The natural social behavior of bird flocks.
Ant Colony (ACO)	Marco Dorigo	The behavior of real ant colonies.
Big Bang-Big Crunch (BB-BC)	Osman and Eksin	Evolution of the universe.
Harmony Search (HS)	Geem *et al*.	Musical process.
Teaching-Learning-Based (TLBO)	Rao and Savsani	Teaching and learning process.

GA is one of the first evolutionary global optimization algorithms, it mimics the evolution theory of Darwin. It starts with a number of randomly suggested solutions called a population, these solutions are represented by a binary-string chromosome. After determining the fitness for each chromosome i.e. solution, the two reproduction operators, crossover and mutation, are carried out between the fittest solutions to produce the second generation. This reproductive process is repeated until reaching the last generation.

3. Teaching-learning-based optimization (TLBO)

Teaching-learning-based optimization algorithm (TLBO) is proposed by Rao and Savsani (2012) based on the effect of the influence of a teacher on the output of learners in a class. The algorithm consists of two main phases: (i) teacher phase and (ii) learner phase, as shown in the self-explanatory flowchart in Fig. 1. In this optimization algorithm, a group of learners is considered as population and different subjects offered to the learners are considered as design variables of the optimization problem, and fitness value of the optimization problem is determined based on learner's result. The algorithm parameters are only population size and number of generation and don't require any algorithm-specific control parameters.

Teacher phase, during this phase, a teacher tries to increase the mean result (i.e., fitness) of the class (i.e. population) in the subject (i.e., variable) taught by him or her depending on his or her capability as shown in the following equations.

$$Difference\_Mean_{j,k,i} = r_i\left(X_{j,kbest,i} - T_F M_{j,i}\right) \tag{1}$$

$$T_F = round\left[1 + rand(0,1)\{2-1\}\right] \tag{2}$$

$$X'_{j,k,i} = X_{j,k,i} + Difference\_Mean_{j,k,i} \tag{3}$$

where r_i is the random number in the range [0,1], T_f is teaching factor equal either 1 or 2 according to Eq. (2), $M_{j,i}$ is the mean result of the learners in subject number j and iteration number i, $X_{j,k,i}$ is the result (i.e., fitness) of learner number k in subject number j and iteration number i, $X'_{j,k,i}$ is updated value for $X_{j,k,i}$ and accepted only if gives better result, and $X_{j,kbest,i}$ is the best result among all learners.

Table 2 Comparison between previous studies

Study	Frame	Base	Used Algorithm	Design code
Musa and Ayse (2016)	Space	Fixed	GA	AISC-LRFD
Musa Artar (2016)[a]	Plane	Fixed	TLBO	AISC-ASD
Musa and Ayse (2015)	Plane	Semi-rigid	GA	AISC-ASD
Musa and Ayse (2015)[b]	Plane	Fixed	GA	AISC-LRFD
Musa and Ayse (2015)[b]	Space	Fixed	GA	AISC-LRFD
Hadidi and Rafiee (2015)	Plane	Fixed	New HS	AISC-LRFD
Mohammad and Payam (2015)	Plane	Fixed	Fuzzy GA	AISC-ASD
Alqedra *et al.* (2015)	Plane	Fixed	ITHS	AISC-LRFD
Arafa *et al.* (2015)	Plane	Fixed	HS	AISC-LRFD
Hadidi and Rafiee (2014)	Plane	Fixed	Improved PSO	AISC-LRFD
Rafiee and Hadidi (2013)	Plane	Fixed	BB-BC	AISC-LRFD
Hayalioglu and Degertekin (2010)	Plane	Semi-rigid	HS	AISC- LRFD
Hayalioglu and Degertekin (2005)	Plane	Semi-rigid	GA	AISC-LRFD
Hayalioglu and Degertekin (2004)	Plane	Fixed	GA	AISC-ASD
Hayalioglu and Degertekin (2004)	Plane	Fixed	GA	Turkish code
Degertekin and Hayalioglu (2004)	Plane	Semi-rigid	GA	Turkish code

[a]Braced frame, [b]Composite beam, ITHS: Intelligent tuned harmony search

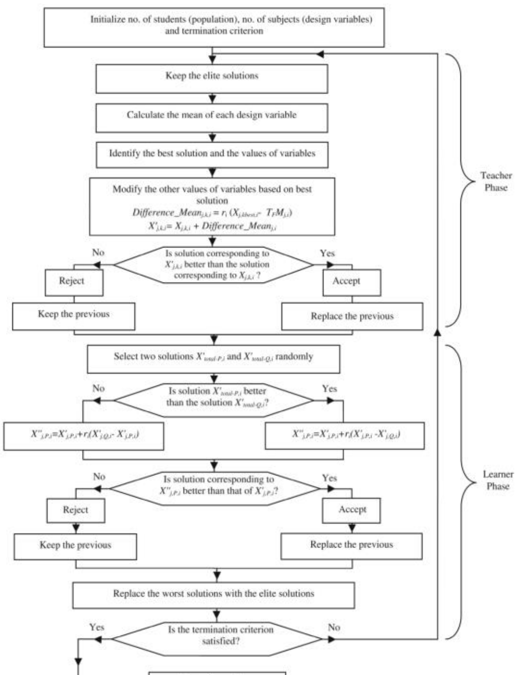

Fig. 1 Flowchart of TLBO algorithm (Rao *et al*. 2012)

Learner phase, in this phase, learners interact randomly with other learners for enhancing his or her knowledge randomly. For instances, select two learners P and Q such that $X'_{total-P,i} \neq X'_{total-Q,i}$

$$X''_{j,P,i} = X'_{j,P,i} + r_i\left(X'_{j,P,i} - X'_{j,Q,i}\right) \;\; if \;\; X'_{total-P,i} < X'_{total-Q,i} \tag{4}$$

Table 3 The curve-fitting constants

Connection type	Curve-fitting constants			Standardization parameter (**κ**)
	C_1	C_2	C_3	
1	4.28×10^{-3}	1.45×10^{-9}	1.51×10^{-16}	$\kappa = d_a^{-2.4} t_a^{-1.81} g^{0.15}$
2	3.66×10^{-4}	1.15×10^{-6}	4.57×10^{-8}	$\kappa = d_a^{-2.4} t_a^{-1.81} g^{0.15}$
3	2.23×10^{-5}	1.85×10^{-8}	3.19×10^{-12}	$\kappa = d^{-1.287} t^{-1.128} t_c^{-0.415} \ell_a^{-0.694} g^{1.35}$
4	8.46×10^{-4}	1.01×10^{-4}	1.24×10^{-8}	$\kappa = d^{-1.5} t^{-0.5} \ell_a^{-0.7} d_b^{-1.5}$
5	1.83×10^{-3}	1.04×10^{-4}	6.38×10^{-6}	$\kappa = d_g^{-2.4} t_p^{-0.4} d_b^{-1.5}$
6	1.79×10^{-3}	1.76×10^{-4}	2.04×10^{-4}	$\kappa = d_g^{-2.4} t_p^{-0.6}$
7	2.10×10^{-4}	6.20×10^{-6}	-7.60×10^{-9}	$\kappa = d^{-1.5} t^{-0.5} \ell_t^{-0.7} d_b^{-1.1}$
8	5.10×10^{-5}	6.20×10^{-10}	2.40×10^{-13}	$\kappa = d_p^{-2.3} t_p^{-1.6} t_w^{-0.5} g^{1.6}$

$$X''_{j,P,i} = X'_{j,P,i} + r_i\left(X'_{j,Q,i} - X'_{j,P,i}\right) \ \ if \quad X'_{total-Q,i} < X'_{total-P,i} \tag{5}$$

where $X''_{j,k,i}$ is updated value for $X'_{j,k,i}$ accepted only if gives better result.

4. Literature studies

Table 2 shows a comparison between the previous literature studies. Note that, all the literature studies performed a nonlinear analysis using the Frye and Morris (1975) model to simulate beam-to-column connections as it is shown in the next sections. For studies consider a semi-rigid base, Hensman and Nethercot (2001) model is used to simulate the semi-rigid base connection.

5. Modeling of a semi-rigid beam-to-column connection

The realistic behavior of a semi-rigid connection is similar to a rotational spring. Thus, many researchers have performed experimental and numerical studies on modeling such connections to obtain a sensible practical relationship between the moment applied to connection M and its relative spring rotation θ_r.

Some of those studies developed a linear model, whereas others obtained a nonlinear model, i.e., polynomial, exponential or even power models.

The Frye and Morris (1975) model is widely used in the literature studies and is adopted in this study because it is easy to apply and is an odd-power polynomial model, which is rationally good for simulation of nonlinear M-θ_r behavior of semi-rigid connection, as expressed in Eq. (6).

$$\theta_r = C_1(\kappa M)^1 + C_2(\kappa M)^3 + C_3(\kappa M)^5 \tag{6}$$

where C_1, C_2, and C_3 are curve-fitting constants, and κ is a standardization constant dependent on the connection type and geometry, as shown in Table 3 (Dhillon and O'Malley III 1999).

Fig. 2 shows the eight different beam-to-column connections used by The Frye and Morris (1975) model.

According to previous studies (Hadidi and Rafiee 2014), (Hadidi and Rafiee 2015), and others, to simplify the problem, some of the connection size parameters required in the Frye-Morris polynomial model (1975) of M-θ curve are considered fixed during the optimum design procedure, as shown in Table 4. Moreover, for connections 1, 2, and 8, d_a & d_p=web depth-10.16 cm. Also, for connections 5 and 6, d_g=beam depth+15.24 cm.

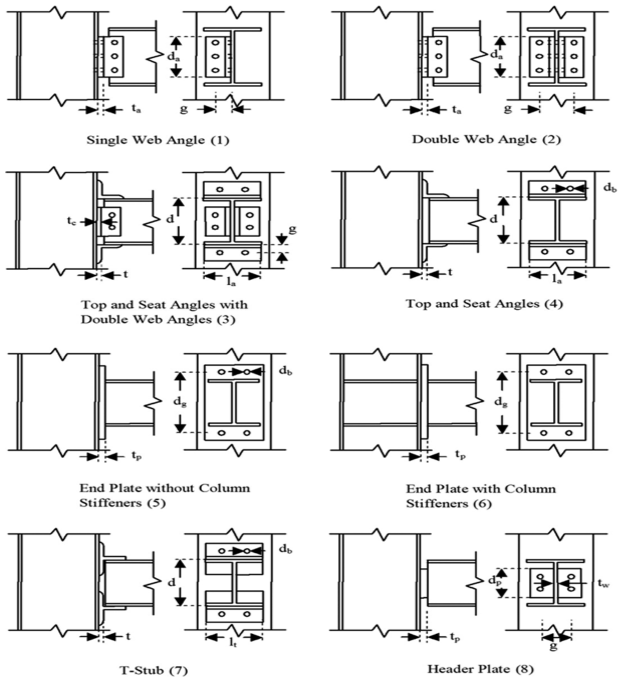

Fig. 2 Semi-rigid beam-to-column connection types (Hadidi and Rafiee 2015)

Table 4 The fixed connection size parameters and factor "S" used in Eq. (19)

Connection type	Fixed connection size parameters (cm)	Values in Eq. (19) (kN·mm/rad)
1	$t_a = 2.54, g = 11.43$	85×10^6
2	$t_a = 2.858, g = 25.4$	113×10^6
3	$t = 2.54, t_c = 2.54, g = 11.43$	282×10^6
4	$t = 2.54, d_b = 2.858$	226×10^6
5	$t_p = 2.54, d_b = 2.858$	339×10^6
6	$t_p = 2.54$	395×10^6
7	$t = 3.81, d_b = 2.858$	452×10^6
8	$t_p = 2.54, g = 25.4$	141×10^6

6. Nonlinear analysis process

In frame analysis, there are two types of members: a beam-column member and a beam member with semi-rigid connections. A beam-column member represents columns of the frame that are generally continuous with a fixed or flexible base and do not have any internal flexible connection to maintain the stability of the frame. However, it carries a large axial force, producing the P-Δ effect, which affects the stiffness of beam-column member number i $[\overline{K}]_i$, as shown in Eq. (7).

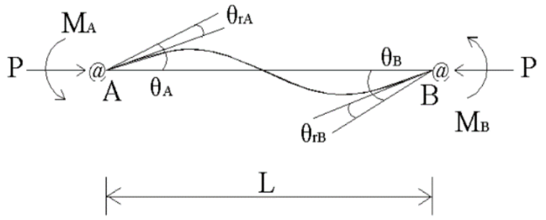

Fig. 3 Beam member with a rotational spring

$$\left[\overline{K}\right]_i = \left[K_E\right]_i + \left[K_P\right]_i \tag{7}$$

where $[K_E]_i$ is the conventional linear elastic stiffness and $[K_p]_i$ is the geometric stiffness (Dhillon and O'Malley III 1999).

By contrast, the stiffness of a beam member with semi-rigid connections carries a very small axial load but possesses a rotational spring stiffness because of its flexible end connections, as shown in Eq. (8) and Fig. 3 (Dhillon and O'Malley III 1999).

$$[K]_i = \begin{bmatrix} \frac{EA}{L} & & & & & \\ 0 & \frac{(S_{ii}+2S_{ij}+S_{jj})EI}{L^3} & & & & \\ 0 & \frac{(S_{ii}+S_{ij})EI}{L^2} & \frac{(S_{ii})EI}{L} & & & \\ \frac{-EA}{L} & 0 & 0 & \frac{EA}{L} & & \\ 0 & \frac{-(S_{ii}+2S_{ij}+S_{jj})EI}{L^3} & \frac{-(S_{ii}+S_{ij})EI}{L^2} & 0 & \frac{(S_{ii}+2S_{ij}+S_{jj})EI}{L^3} & \\ 0 & \frac{(S_{ij}+S_{jj})EI}{L^2} & \frac{(S_{ij})EI}{L} & 0 & \frac{-(S_{ij}+S_{jj})EI}{L^2} & \frac{(S_{jj})EI}{L} \end{bmatrix} \tag{8}$$

$$S_{ii} = \frac{1}{K_R}\left(4 + \frac{12EI}{LK_B}\right) \tag{9}$$

$$S_{jj} = \frac{1}{K_R}\left(4 + \frac{12EI}{LK_A}\right) \tag{10}$$

$$S_{ij} = \frac{2}{K_R} \tag{11}$$

$$K_R = \left(1 + \frac{4EI}{LK_A}\right)\left(1 + \frac{4EI}{LK_B}\right) - \left(\frac{EI}{L}\right)^2\left(\frac{4}{K_A K_B}\right) \tag{12}$$

$$K_A = \frac{M_A}{\theta_{rA}} \;\; \& \;\; K_B = \frac{M_B}{\theta_{rB}} \tag{13}$$

where K_A & K_B are the corresponding rotational spring stiffness of the beam member with semi-rigid connections at the A & B ends, Θ_{rA} & Θ_{rB} are the relative spring rotations for the semi-rigid connections at the A & B ends due to their flexibility, M_A & M_B are the applied moments at the A & B ends, and Θ_A & Θ_B are the rotational deformation of the A & B ends, as shown in Fig. 3.

Because of the connection flexibility, fixed end moments M_{FA} & M_{FB} have to be modified as driven by Dhillon and O'Malley III (1999).

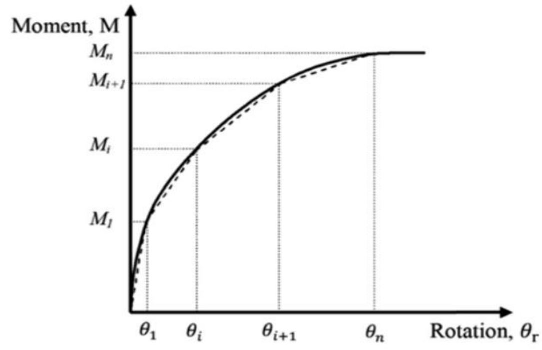

Fig. 4 Secant stiffness through the M-Θ_r curve

To achieve nonlinear analysis while considering the P-Δ effect and connection flexibility, an incremental load approach in conjunction with a secant stiffness approach is applied (Dhillon and O'Malley III 1999), (Chajes and Churchill 1987) where the connection secant stiffness SE is expressed as

$$SE = \frac{\Delta M}{\Delta \theta_r} \tag{14}$$

where ΔM is the change in end moment during a load increment and $\Delta\theta_r$ is the change in relative spring rotation during a load increment, as shown in Fig. 4.

The stiffness matrix of the whole frame structure [S] is formed by assembling and superimposing local stiffness matrices of frame members, i.e., either beam-column members or beam members with semi-rigid connections.

Substituting a load increment $\{\Delta F\}$ into the equilibrium equation Eq. (15) results in an incremental displacement $\{\Delta D\}$ and updates the geometric coordination of the frame structure to consider geometric nonlinearity through the analysis process.

$$\{\Delta F\} = [S]\{\Delta D\} \tag{15}$$

The nonlinear analysis procedure is presented in the following steps (Dhillon and O'Malley III 1999), (Sedat and Degertekin 2004), (Hadidi and Rafiee 2015)

1- Divide the applied load into a number of small load increments.

2- Linear analysis of the first load increment is performed to obtain the initial response of the frame and use it as an initial estimation for nonlinear analysis.

3- Construct the stiffness matrix of the whole frame [S] by assembling and superimposing local stiffness matrices for all members $[\overline{K}]_i$ & $[K]_i$.

4- Solve the equilibrium equation Eq. (15) to obtain incremental displacements $\{\Delta D\}$ and to determine incremental end forces.

5- Obtain the secant stiffness of semi-rigid connections using Eq. (14).

6- Use the latest connection secant stiffness and member end forces to update a member's stiffness matrices $[\overline{K}]_i$ & $[K]_i$ where the latest incremental displacements are used to update the geometric coordination of the whole frame.

7- Repeat steps 3 to 6 until convergence is obtained.

8- Calculate the accumulated displacement and forces at convergence.

9- Continue the analysis using the new load increment until stopping at the final load increment.

7. Design constraints

Design constraint check is one of the most important processes during structural optimization that because it assures that the resulting frame is safe and usable.

The optimum design solution in the current study has the following constraint, similar to previous studies (Dhillon and O'Malley III 1999), (Hadidi and Rafiee 2015) and others.

1- AISC-LRFD Strength constrain using interaction equation of bending moment and axial force as expressed in the following equations.

$$\text{For} \quad \frac{P_u}{\phi P_n} \geq 0.2 \qquad \left(\frac{P_u}{\phi P_n}\right) + \frac{8}{9}\left(\frac{M_{ux}}{\phi_b M_{nx}}\right) \leq 1 \tag{16}$$

$$\text{For} \quad \frac{P_u}{\phi P_n} < 0.2 \qquad \frac{1}{2}\left(\frac{P_u}{\phi P_n}\right) + \left(\frac{M_{ux}}{\phi_b M_{nx}}\right) \leq 1 \tag{17}$$

where P_u and P_n are the required and nominal strength of a member, respectively, either compression or tension, and $\emptyset$ is a reduction factor equal to 0.9 in the case of tension or compression. Additionally, M_{ux} and M_{nx} are the required and nominal flexural strength of a member about its major axis, respectively, where the bending reduction factor $\emptyset_b$ equals 0.9.

Semi-rigidity of beam member ends are considered in calculated the restraint factor G (Dhillon and O'Malley III 1999)

2- Roof drift and inter-story drift constraints are also considered, where the allowable roof drift is equal to 0.0052×total frame height. Moreover, the allowable inter-story drift is determined as story height/300.

3- The third type of constraint is size adaptation, which consists of two constructional considerations. The first one ensures that the flange width of the beam is not larger than column flange width at all connections. The second one considers the fact that the column of each floor cannot be larger in depth than the column below.

8. Penalty and fitness function

In accordance with previous studies (Hadidi and Rafiee 2015), (Hadidi and Rafiee 2014) and others, the total cost of the steel frame considering members and semi-rigid connection costs as defined by Xu and Grierson (Xu and Grierson 1993).

$$Total\_Cost = \sum_{i=1}^{NM} \gamma_s A_i L_i + \sum_{i=1}^{NB} \sum_{j=1}^{2} \left(\beta_{ij} R_{ij} + \beta_{ij}^0\right) \tag{18}$$

where γ_s is the steel density, A_i is the cross-sectional area, L_i is the member length, R_{ij} is the rotational stiffness of the connection, β_{ij} is the cost coefficient, and β_{ij}^0 is the cost of a pinned connection with zero rotational stiffness. Moreover, j represents two ends of a semi-rigid connection, and NM and NB represent the total number of members and beams in the frame, respectively. The value of β_{ij} is calculated for both semi-rigid beam ends as follows

$$\beta_{ij} = \frac{0.225 \gamma_s A_i L_i}{S_i} \tag{19}$$

where S_i is an estimated value for rotational stiffness of a connection depending on the connection type, as shown in Table 4. The costs of a pinned connection $\beta_{i1}^0 \, and \, \beta_{i2}^0$ are accepted to be equal to (Hadidi and Rafiee 2015), (Hayalioglu and Degertekin 2004)

$$\beta_{ij}^0 = 0.125 \gamma_s A_i L_i \tag{20}$$

Penalty function ensures dismissing the solutions violate the constraints by giving them a bad fitness value as expressed in the following equation.

$$Fitness = Total\_\cos t + C \times 10^8 \tag{21}$$

where C is the penalty constant equals zero for the solutions don't violate any of the constraints otherwise, it equals one.

9. Developed model

To combine a frame structure, previous optimization models use a random cross-sections variable by optimization technique, along with semi-rigid column-to-beam connection types as either a variable such as cross-sections or predetermined. Next, the stepped nonlinear analysis is performed and followed by design check for the resulting stresses and displacements according to the design constraints.

By contrast, the current study proposes a developed model using rotational deformations as a variable, as demonstrated in the following method steps:

1- The developed model starts by analyzing the frame using any proper cross-sections with a fully rigid beam-to-column connection to obtain the nodes deformations and members' moments M_A and M_B at the A and B ends.

Proper cross-sections mean that column cross-sections of higher floors are smaller than those of lower floors and that beam cross-sections are smaller than those of the columns on the same floor.

2- The developed model uses rotational deformations as a variable with the same corresponding rotation signal obtained in the previous step, where the spring relative rotation of the suggested semi-rigid beam-to-column connection is evaluated to be (5-20)% of the rotational deformation value.

3- Based on the moment obtained in the first step, the rotational deformations variable and the allowable inter-story drift, the suggested optimum cross-section inertia I is obtained using Eq. (24) to get the lightest corresponding cross-section among the available cross sections library.

$$M_A - M_{FA} = \frac{EI_1}{L}\left[4(\theta_A - \theta_{rA}) + 2(\theta_B - \theta_{rB})\right] - \frac{6\Delta}{L^2} \quad (22)$$

$$M_B - M_{FB} = \frac{EI_2}{L}\left[4(\theta_B - \theta_{rB}) + 2(\theta_A - \theta_{rA})\right] - \frac{6\Delta}{L^2} \quad (23)$$

$$I = Max(I_1, I_2) \quad (24)$$

where θ_A & θ_B are the suggested rotational deformations at the A & B ends, θ_{rA} & θ_{rB} are the relative spring beam-to-column connections rotations at the A & B ends, M_{FA} & M_{FB} are the fixed end moments at the A & B ends, Δ is equal the allowable inter-story drift for columns and zero for beams, and L is the member length.

Note: θ_{rA} equals $0.2\times\theta_A$ for beams and zero for columns, amd θ_{rA} equals $0.2\times\theta_B$ for beams and zero for columns. So, Eq. (24) could be expressed for column inertia I_c, and beams inertia I_b as following

$$I_c = Max\left(\frac{M_A - M_{FA} + \frac{6\Delta}{L^2}}{\frac{E}{L}\left[4\theta_A + 2\theta_B\right]}, \frac{M_B - M_{FB} + \frac{6\Delta}{L^2}}{\frac{E}{L}\left[4\theta_B + 2\theta_A\right]}\right) \quad (25)$$

$$I_b = Max\left(\frac{M_A - M_{FA}}{\frac{E}{L}\left[3.2\theta_A + 1.6\theta_B\right]}, \frac{M_B - M_{FB}}{\frac{E}{L}\left[3.2\theta_B + 1.6\theta_A\right]}\right) \quad (26)$$

4- Through the use of the suggested cross-section, the connection relative rotation is calculated for all of the eight flexible connection types available $\theta_{r1}, \theta_{r2}, \dots\dots, \theta_{r8}$ for both beam ends using Eq. (6) considering M_A & M_B obtained from the pre-analysis process in step 1. Then, a comparison of the relative rotations of the suggested semi-rigid connections, which are obtained in the third step θ_{rA} & θ_{rB}, is performed to obtain the nearest one and assign it as the optimum suggested flexible connection.

5- Through the use of the suggested optimum cross-section and the suggested optimum semi-rigid connection, the whole frame is combined and the stepped nonlinear analysis process is carried out before the final verification of the design constraints.

After many ranges were evaluated, the range of (0 to $250)\times10^{-5}$ was found to provide a proper range for the rotational deformation variable. This relatively small range indicates less computational effort compared with the traditional method, i.e., using both the cross-sections and connection types as variables. Additionally, the developed model simultaneously optimizes both the member cross-sections and the beam-column semi-rigid connection type. Also, it obtains better design optimization results than previous works, as will be shown in the following numerical studies.

10. Numerical examples

Nonlinear analysis is performed, and design constraints are checked as explained previously for three benchmark problems. The used algorithms properties, steel properties, and computer properties are as follows.

Table 5 Member sections and story connections (TLBO)

Mem. grouping no.	Sections	Story no.	Conn. type
1	W24X68	1	7
2	W24X55	2	6
3	W18X35	3	6
4	W24X68	4	6
5	W24X55	5	6
6	W18X35	6	6
7	W18X35	7	7
		8	5
		9	7

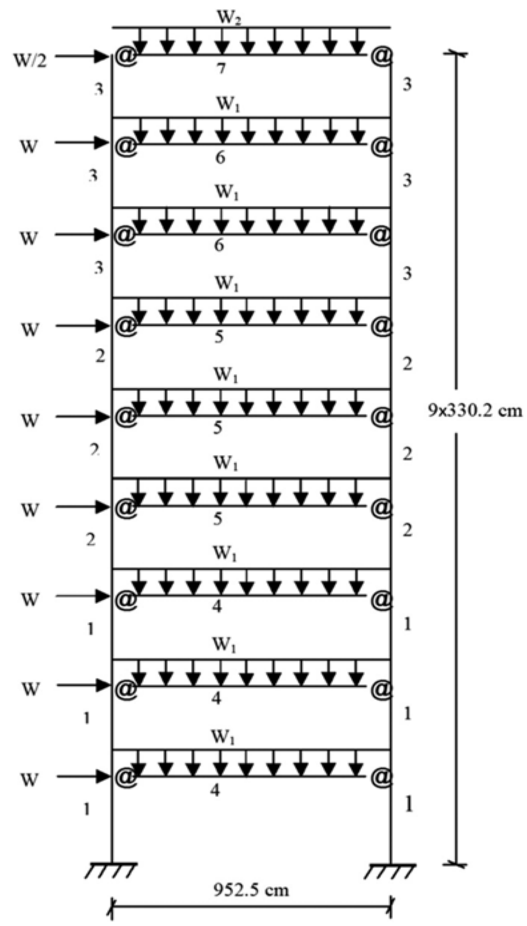

Fig. 5 Single bay with a nine-story frame (Hadidi and Rafiee 2015)

<u>Algorithms properties</u>

The algorithms used in the following numerical examples are a binary-string genetic algorithm with a cross-over of 0.9 and a mutation of 0.05 as reproduction parameters, along with a teaching-learning optimization algorithm. Both of the algorithms have a population size of 100, and 50 maximum generations. The algorithm variable is the rotational deformations in range of $(0\text{-}250)\times10^{-5}$ with an increment of 1×10^{-5} as illustrated before.

Table 6 Member sections and story connections (GA)

Mem. grouping no.	Sections	Story no.	Conn. type
1	W24X68	1	7
2	W24X55	2	6
3	W18X35	3	6
4	W24X68	4	6
5	W24X55	5	6
6	W18X35	6	6
7	W16X31	7	7
		8	5
		9	5

Table 7 Comparisons between the current study and previous works

Study	Algorithm	Connection type	T.s (mm)	W (kg)	T.C (kg)
Rafiee *et al.* (2013)	BB-BC	1	56	38,718	40,520
		2	55	32,617	36,235
		3	**66**	**14,809**	**16,881**
		4	76	23,956	25,786
		5	54	30,804	33,488
		6	65	33,481	35,799
		7	44	43,450	53,601
		8	71	44,527	46,146
Hadidi and Rafiee (2014)	HS-PSO	1	79	18,693	21,486
		2	73	13,182	17,886
		3	70	13,468	15,464
		4	71	14,288	16,499
		5	70	12,901	15,773
		6	69	12,136	14,970
		7	**69**	**11,590**	**14,787**
		8	73	19,722	21,757
Hadidi and Rafiee (2015)	BB-BC	Various	71	14,512	17,201
	HS	Various	75	13,960	16,495
	HS-BB-BC	Various	**77**	**12,218**	**14,610**
This study	TLBO	Various	78	11,420	14,462
	GA	Various	**79**	**11,363**	**14,410**

HS-PSO: Harmony search-based particle swarm. T.s: Roof drift, W: Frame weight, T.C: Total frame cost

<u>Steel properties</u>

The steel used is A36, where $\mathrm{E} = 200$ Gpa, yield stress $\mathrm{f_y} = 250$ Mpa, shear modulus $\mathrm{G} = 77.2$ Gpa and unit weight of material $\gamma_s = 7.85\ \mathrm{t/m^2}$, according to AISC-LRFD (2016).

<u>Computer properties</u>

The computer used in solution has a processor of core i5-2430M@2.4 GHz, 4 GB installed memory (RAM), with the 64-bit operating system.

10.1 Single bay with a nine-story frame

Fig. 5 shows the geometry of the single bay with a nine-story frame, along with the member grouping and design loads. The W, W1, and W2 loads are equal to 17.8 kN, 27.14 kN/m, and 24.51 kN/m, respectively. The time consumed for this example is 46 minutes.

The member sections and story connections for the optimum solutions using TLBO and GA are presented in Tables 5 and 6, respectively, whereas Table 7 shows a comparison between the total frame cost of the optimum frame in this study with those in previous studies, along with frame weight and roof drift. As shown from the comparison, the developed model using both TLBO and GA obtains better results than all the literature studies.

Table 8 concentrates on the comparison between the current study result and the best literature result Hadidi and Rafiee (2015). The comparison shows that the developed model produces a result using GA better than using TLBO, where it provides the optimum frame of 14,462 kg and 14,410 kg cost using TLBO and GA, respectively, denotes a 1.01% and 1.37% reduction in cost compared with the best literature result (Hadidi and Rafiee 2015). In addition, the comparison demonstrates that the developed model produces a 6.53% and 7.00% reduction in weight using TLBO and GA, respectively, leading to a reduction in the frame loads. Also, the developed model produces a higher story drift than the best literature result and most of the literature results as shown in Table 7 using both TLBO and GA, that means, the proposed frames have less total stiffness compared with the literature results due to the reduction in weight and selecting the most proper connections.

Table 8 Comparisons between the current study result and the best literature result

Study	Algorithm	Results				Increment %		Reduction %	
		T.s (mm)	C.C (kg)	W (kg)	T.C (kg)	T.s (mm)	C.C (kg)	W (kg)	T.C (kg)
Hadidi and Rafiee (2015)	HS-BB-BC	77	2,392	12,218	14,610	—	—	—	—
This study	TLBO	78	3,042	11,420	14,462	1.30%	27.17%	6.53%	1.01%
	GA	79	3,047	11,363	14,410	2.60%	27.38%	7.00%	1.37%

HS-BB-BC: Harmony search-based big bang-big crunch, C.C: Connection cost (C.C=T.C-W)

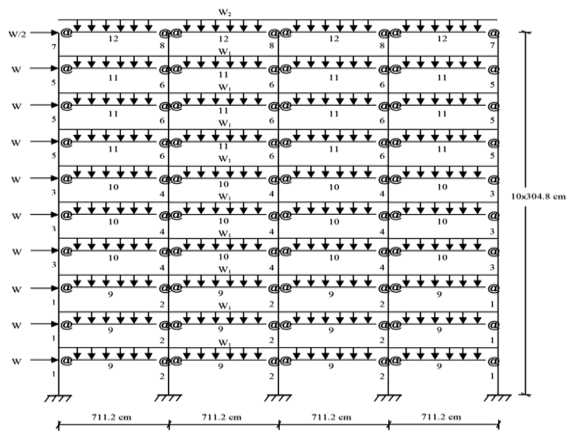

Fig. 6 Four bays with a ten-story frame (Hadidi and Rafiee 2015)

Table 9 Member sections and story connections (TLBO)

Mem. grouping no.	Sections	Story no.	Conn. type
1	W30X90	1	7
2	W30X116	2	7
3	W21X44	3	6
4	W27X84	4	4
5	W18X40	5	4
6	W18X40	6	6
7	W18X35	7	7
8	W16X31	8	7
9	W21X44	9	5
10	W21X44	10	5
11	W18X40		
12	W16X31		

Table 10 Member sections and story connections (GA)

Mem. grouping no.	Sections	Story no.	Conn. type
1	W27X84	1	6
2	W33X118	2	6
3	W24X76	3	6
4	W24X76	4	8
5	W24X55	5	6
6	W21X44	6	4
7	W18X40	7	3
8	W16X31	8	7
9	W21X44	9	5
10	W24X55	10	5
11	W18X35		
12	W16X31		

10.2 Four bays with a ten-story frame

The second example is four bays with a ten-story frame. Fig. 6 shows the geometry of the frame, the member grouping and the design loads. The values of W, W1, and W2 are 44.49 kN, 47.46 kN/m, and 42.91 kN/m, respectively. Table 9 and 10 show the member sections and story connections for the optimum solutions using TLBO and GA, respectively. The time consumed for this example is two hours and 27 minutes.

Table 11 shows a comparison between the total frame cost of the optimum frame in this study with those from previous studies, besides the frame weight and roof drift. The comparison shows that the developed model using both TLBO and GA achieves better results than all the literature studies.

Table 12 gives attention to the comparison between the current study result and the best literature result Hadidi and Rafiee (2015). The comparison clearly shows that the developed model provides the optimum frame of a 41,827 kg and 41,676 kg cost using TLBO and GA, respectively, shows a 5.67% and 6.01% cost reduction compared with the best literature result (Hadidi and Rafiee 2015). In addition, the comparison reveals that the developed model produced a 9.47% and 8.73% reduction in weight using TLBO and GA, respectively, which in turn reduces the frame loads. Besides, the developed model produces a higher story drift than the best literature result and most of the literature results as shown in Table 11 using both TLBO and GA, that means, the proposed frames have less total stiffness compared with all the literature result due to the reduction in weight and selecting the most suitable connections.

Table 11 Comparisons between the current study and previous works

Study	Algorithm	Connection type	T.s (mm)	W (kg)	T.C (kg)
Rafiee *et al.* (2013)	BB-BC	1	67	128,418	140,744
		2	25	195,578	237,050
		3	35	100,254	106,868
		4	**58**	**87,432**	**93,255**
		5	37	111,865	123,743
		6	40	103,357	113,055
		7	26	150,274	204,773
		8	56	126,120	136,881
Hadidi and Rafiee (2014)	HS-PSO	1	76	52,196	58,939
		2	62	43,746	55,118
		3	**58**	**40,040**	**46,328**
		4	68	41,853	47,788
		5	63	38,532	46,407
		6	48	37,950	46,469
		7	49	38,737	47,328
		8	75	47,018	53,489
Hadidi and Rafiee (2015)	BB-BC	Various	41	114,133	120,891
	HS	Various	55	50,772	60,691
	HS-BB-BC	Various	**68**	**38,115**	**44,343**
This study	TLBO	Various	68	34,507	41,827
	GA	Various	**75**	**34,786**	**41,676**

Table 12 Comparisons between the current study result and the best literature result

Study	Algorithm	Result				Increment %		Reduction %	
		T.s (mm)	C.C (kg)	W (kg)	T.C (kg)	T.s (mm)	C.C (kg)	W (kg)	T.C (kg)
Hadidi and Rafiee (2015)	HS-BB-BC	68	6,228	38,115	44,343	—	—	—	—
This study	TLBO	68	7,320	34,507	41,827	0.00%	17.53%	9.47%	5.67%
	GA	75	6,890	34,786	41,676	10.29%	10.63%	8.73%	6.01%

10.3 Three bays with a twenty-four-story frame

The 168-member frame is the third design example in this study, and its geometry, along with the member grouping and design loads, is shown in Fig. 7. The W, W1, W2, W3, and W4 loads have values of 25.628 kN, 4.378 kN/m, 6.362 kN/m, 6.917 kN/m, and 5.954 kN/m,

Table 13 Comparison between the current study and previous works

Study	Algorithm	Connection type	T.s (mm)	W (kg)	T.C (kg)
Rafiee *et al.* (2013)	BB-BC	1	204	381,754	502,197
		2	245	139,161	202,737
		3	170	236,249	267,414
		4	184	211,149	249,806
		5	**237**	**140,536**	**171,868**
		6	231	150,362	176,864
		7	240	359,372	385,074
		8	190	297,834	383,738
Hadidi and Rafiee (2014)	HS-PSO	1	200	384,890	505,366
		2	245	135,368	189,791
		3	194	172,004	205,473
		4	208	175,521	210,296
		5	238	133,930	162,582
		6	217	137,054	165,828
		7	**221**	**125,589**	**156,161**
		8	203	261,722	341,798
Hadidi and Rafiee (2015)	BB-BC	Various	212	238,721	260,152
	HS	Various	174	209,040	289,580
	HS-BB-BC	Various	**255**	**132,313**	**151,481**
This study	TLBO	Various	263	105,550	131,322
	GA	Various	**268**	**102,778**	**128,226**

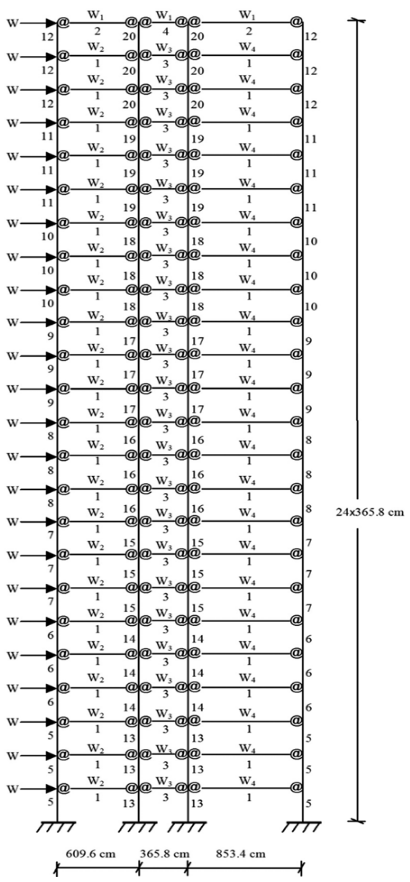

Fig. 7 Three bays with a twenty-four-story frame (Hadidi and Rafiee 2015)

Table 14 Member sections and story connections (TLBO)

Mem. grouping no.	Sections	Story no.	Conn. type
1	W24X84	1,2	7
2	W12X14	3,4	7
3	W30X90	5,6	7
4	W8X10	7,8	7
5	W33X118	9,10	7
6	W33X118	11,12	7
7	W30X90	13,14	7
8	W24X84	15,16	6
9	W24X84	17,18	3
10	W24X84	19,20	4
11	W24X84	21,22	8
12	W24X84	23,24	1
13	W30X116		
14	W30X116		
15	W30X108		
16	W30X90		
17	W24X84		
18	W24X84		
19	W24X84		
20	W24X84		

Table 15 Member sections and story connections (GA)

Mem. grouping no.	Sections	Story no.	Conn. type
1	W24X84	1,2	7
2	W10X12	3,4	7
3	W30X90	5,6	7
4	W10X12	7,8	7
5	W30X108	9,10	7
6	W30X99	11,12	7
7	W30X99	13,14	6
8	W30X99	15,16	6
9	W30X90	17,18	3
10	W30X90	19,20	4
11	W30X90	21,22	8
12	W30X90	23,24	1
13	W33X118		
14	W33X118		
15	W33X118		
16	W33X118		
17	W30X90		
18	W30X90		
19	W30X90		
20	W24X84		

respectively. The time consumed for this example is four hours and 38 minutes.

Table 13 presents a comparison between the total frame cost of the optimum frame in this study with those from

Table 16 Comparisons between the current study result and the best literature result

Study	Algorithm	Result				Increment %		Reduction %	
		T.s (mm)	C.C (kg)	W (kg)	T.C (kg)	T.s (mm)	C.C (kg)	W (kg)	T.C (kg)
Hadidi and Rafiee (2015)	HS-BB-BC	255	19,168	132,313	151,481	—	—	—	—
This study	TLBO	263	25,772	105,550	131,322	3.14%	34.45%	20.23%	13.31%
	GA	268	25,448	102,778	128,226	5.10%	32.76%	22.32%	15.35%

previous studies, along with the frame weight and roof drift. As shown from the comparison, the developed model using both TLBO and GA obtains better results than all the literature studies.

Member sections and story connections for the optimum solutions using TLBO and GA are shown in Tables 14 and 15, respectively.

Table 16 focuses on the comparison between the current study result and the best literature result Hadidi and Rafiee (2015). The comparison shows that the developed model obtains outcome using GA better than using TLBO, where it presents the optimum frame of cost of 131,322 kg and 128,226 kg using TLBO and GA, respectively, signifies a 13.31% and 15.35% reduction in cost compared with the best literature result (Hadidi and Rafiee 2015). Additionally, the comparison reveals that the developed model produces a 20.23% and 22.32% reduction in weight using TLBO and GA, respectively, leading to a reduction in the frame loads. On the other hand, the developed model obtains a story drift higher than all the literature results, as shown in Table 15 using both GA and TLBO, that means, the proposed frames have less total stiffness compared with all the literature result due to the reduction in weight and selecting the most appropriate connections.

11. Conclusions

Previous studies have used the cross-sections as a variable, either with a constant flexible connection type or with a variable flexible connection type. These approaches result in a proposed frame with randomly selected cross-sections and semi-rigid beam-to-column connections.

• This study developed an optimization model to reduce and shrink the randomness in selecting the proposed cross-sections and connection types and to optimize both of them simultaneously.

• The proposed cross-sections and connection types obtained in the current study are calculated based on logical equations, which depend on a small range of the random rotational rotations variable and on the moments originating from the logical pre-analysis process and inter-story drift constraint.

• In contrast to the traditional method, the computational effort does not depend on the number of available cross-sections. Thus, the developed model provides the ability to select member cross-sections from a huge number of available cross-sections without any increase in time or computational effort.

• The developed model also simultaneously optimizes the cross-section and the semi-rigid beam-to-column connection type using only the rotational deformations as a variable instead of adding more variables or increasing the computational effort. Furthermore, using a lower population size and generation number compared with previous works leads to the method requiring less computational effort and consuming less time.

• The developed model was applied to three benchmark problems using both TLBO and GA, and the results were compared to those from previous studies found in the literature. The comparisons show that the developed model resulted in a lower weight and cost than the previous works.

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