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Using Fuzzy Genetic Algorithm for the Weight Optimization of Steel Frames with Semi-rigid Connections

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Abstract

In this paper, combination of genetic algorithm (GA) and fuzzy logic is used for weight optimization of steel frames with rigid or semi-rigid connections. In the genetic algorithm, uniform crossover operator is employed and also, binary coding is used to achieve better convergence. Behavior of steel frames depends highly on beam to column connections. Here, beam to column connections are assumed to be semi-rigid or rigid. Linear analysis and design has been used for steel frame structures. Matlab program has been utilized for the process of optimization in combination with OpenSees software for frame analysis. Beams and columns sections are selected from a standard set of steel sections such as American Institute of Steel Construction (AISC) wide-flange (W) shapes. Displacement and stress constraints are imposed on the frame. Frye and Morris polynomial model is used for semi-rigid connection. Also, the proposed algorithm considers a fitness function using appropriate balancing factors which leads to a faster convergence. Three different design examples with various types of connections are presented to demonstrate the efficiency and robustness of the proposed approach. The results show that the fuzzy genetic algorithm results in lighter structures consuming less computation time compared to simple genetic algorithm.

Keywords: weight optimization, semi-rigid connection, genetic algorithm, fuzzy logic

1. Introduction

Lateral forces on the structures due to earthquake excitation are highly dependent on the weight of structure. Decreasing weight of steel frames by performing optimization procces will result in less quake loads and consequently reduces earthquake damages.

Response of an structure is related to the behavior of connections. In the most of steel frame designs, beam to column connections are assumed either fully rigid or hinged. But experimental studies have shown that beam to column connections have semi-rigid behaviors (Jian-Yi, 1999). The flexibility of connections depends on geometric parameter. The flexibility of connections affects on force, drift and stiffness matrix of the frame.

The AISC-Allowable Stress Design (ASD) specification (AISC, 1989) describes three types of steel frames: simple framing, rigid framing and semi-rigid framing (partially restrained). This specification requires that the connections should be partially restrainted. Also, Eurocode 3 (1992) describes three types of connections: pinned, rigid and semi-rigid.

In recent years, some researchers have attended to the design of steel frame with semi-rigid connections (Kameshki and Saka, 2001; Hayalioglu and Degertekin, 2005; Oskouei and Sarioletlagh, 2011). In some of the researchs, mathematical programing techniques are used to obtain optimum design (Simões, 1996). Due to the extensive parameters, mathematical methods are not practically used because of their complication.

Kameshki and Saka (2001) cosidered both rigid and semi-rigid type of connections and they obtained minimum weight of frames using a genetic algorithm. Hayalioglu and Degertekin (2004) obtained minimum cost of frames by using the genetic algorithm. Hayalioglu and Degertekin (2005) compared optimal designs to AISC-ASD and AISC-Load and Resistance Factor Design (LRFD) methods. They used uniform crossover in genetic algorithms. Kripakaran *et al.* (2011) investigated rigid connections behaviors. All connections were considered fully rigid or pined. Optimum number of rigid connections was obtained that was in the rang of 6-12. Oskouei and Sarioletlagh (2012) for optimization process in their studies utilized stress and displacement constraints and limited the number of plastic hinges.

In the present work, combination of genetic algorithm

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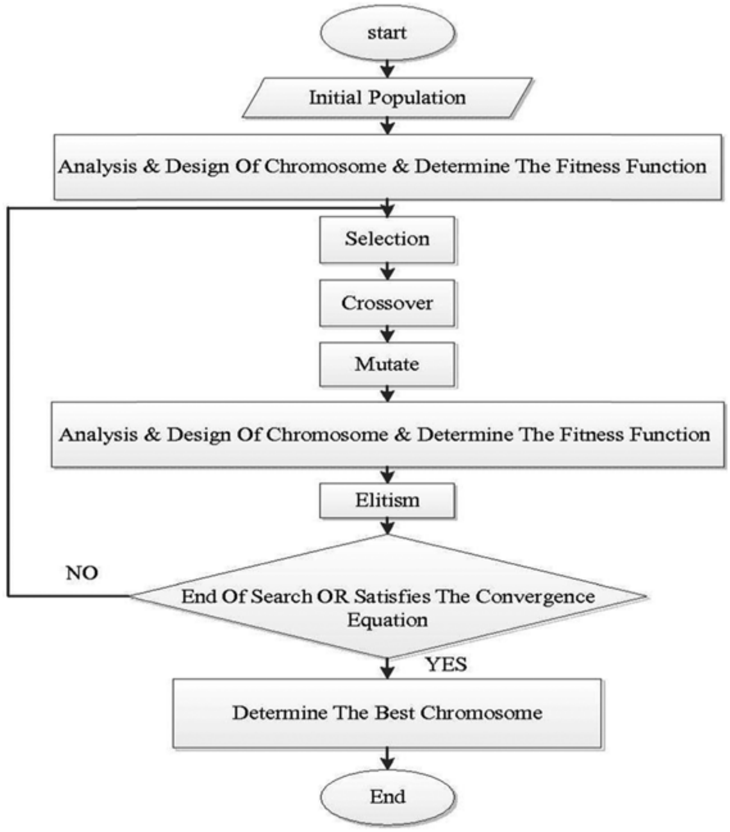

Figure 1. The proposed algorithm of optimization process.

and fuzzy logic is used for optimum design of steel frames with semi-rigid connections. Fuzzy logic provides fast convergence with better solutions. In addition, the proposed algorithm considers an appropriate fitness function which leads to faster convergence. Here, binary coding is employed and uniform crossover has been employed in order to have a better investigation for the purpose of a driving optimum solution. Frames are subjected to displacement and stress constraints. Optimum design is obtained for three frames with various types of connections.

2. Genetic Algorithms

Genetic algorithms are search techniques based on the mechanism of natural genetics and natural selection. There are various genetic operators used in genetic algorithms.The present work employs a genetic algorithm with crossover, mutation and elitism. Genetic algorithms are used as an optimization method in order to minimize or maximize an objective function. Optimization process consists of several iterations. In each iteration which is called a generation, a number of the populations under test are evaluated to complete each other for the purpose of participating in production of new populations. Populations consisting several choromosomes and each choromosome consist of several genes. Each gene expresses single parameter in genetic algorithm. There are several crossover operator in the genetic algorithm for example single-point, two-point, multiple-point and uniform crossover. Crossover and mutation prevents optimization process to get trapped in the local optimum. In this paper, we have employed uniform crossover operator using binary coding.

3. Alghoritm for Least Weight

In this section, the explanation of the proposed algorithm will be presented. Steps of the algorithm can be expressed as:

Step 1. The initial population is constructing.

Step 2. The binary codes become decoded and frames are specified. These frames are analyzed. The joints displacement and member forces are obtained from the analysis (Eqs. 4 to 7). The fitness function for each chromosome is calculated using the Eq. (1).

Step 3. From the fitness value, the best populations are selected.

Step 4. At this stage, crossover and mutation are applied on the chromosomes.

Step 5. Repeat step 2 for these chromosomes.

Step 6. From the fitness function value, the best chromosome of the previous population is replaced with the worst chromosome of this population.

Step 7. In this section, end of search or the equation of

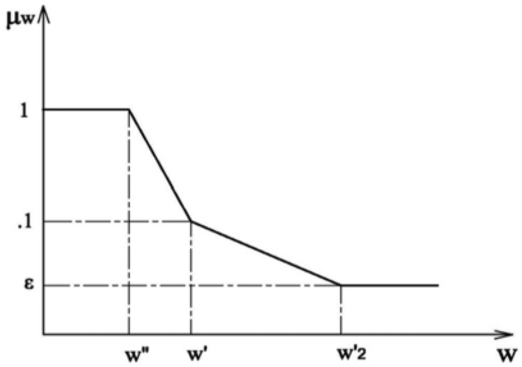

Figure 2. Membership function.

convergence criterion is checked.

Step 8. If convergence criterion is satisfied, the algorithm ends, otherwise the re-selection process is carried out (step 2 to 7).

The proposed algorithm of optimization process is shown in Fig. 1.

4. Optimization of Frames

The total weight of a frame consists of weight of beams and columns. In optimization procedure, we used fitness function having the following form (Ashtari and Barzegar 2012):

$$\text{Maximize } \varphi(x)=L_s\lambda-\alpha \text{ penalty} \tag{1}$$

L_s is a scale factor and λ is overall satisfaction parameter.

$$\lambda=\min(\mu_w, \min(\mu_{\sigma i}^a), \min(\mu_{dj})) \tag{2}$$

where μ_{dj}, $\mu_{\sigma i}^a$ are membership functions for displacement and limit stress constraints.

μ_w is membership function for the objective function (Fig. 2). W'' is lower limit of objective function and W'$_2$ is upper limit of objective function. W' can be selected as the best value obtained in previous work. W' is equal to W''+Δg that Δg is the magnitude of relaxation of the constraint, and W'$_2$ is equal to n×W'' that n>1.

The proposed penalty function is defined as:

$$\begin{aligned}&\text{Penalty}=\max(0,\ 0.1/\mu f(x)-1)\\ &+\Sigma_{i=1}^{noe}\max(0,\ 0.1/\mu\sigma(x)-1)\\ &+\Sigma_{j=1}^{nod}\max(0,\ 0.1/\mu dj(x)-1)\end{aligned} \tag{3}$$

noe is the number of elements and *nod* represents the number of degree of freedom and $\mu f(x)$ is membership function for the objective function. In this paper $\mu f(x)=\mu_w$.

In this paper, in order to have better convergence, we assume L_s=n and α=5n, where n equals to the number of elements group. Here, L_s and α are adding to the bothsides of negative in equation (1) with the purpose of balancing two terms of the equation. In this research, these parameters are obtained after 450 analysis.

4.1. Displacement and stress constraints

4.1.1. Displacement constraint

The story drift is defined as relative lateral displacement of two adjacent story. The maximum interstory drift and deflection of a building is restricted by Iranian earthquake resistant code (BHRC, 2005).

$$\text{IF } T\le 0.7\rightarrow\frac{\delta_{n+1}-\delta_n}{h}\le\frac{0.025}{0.7R} \tag{4}$$

$$\text{IF } T\ge 0.7\rightarrow\frac{\delta_{n+1}-\delta_n}{h}\le\frac{0.02}{0.7R} \tag{5}$$

where $\delta_{n+1}-\delta_n$ is the difference of two adjacent story displacements and h is the story hight. T is the principal period and R is the structure response modifiction factor (BHRC 2005).

4.1.2. Stress constraint

The stress constraints are expressed in terms of the following interaction equations:

$$\frac{f_a}{F_a}>0.15\rightarrow\frac{f_a}{F_a}+\frac{C_{mx}f_{bx}}{\left(1-\frac{f_a}{F'_{ex}}\right)F_{bx}}\le 1 \tag{6}$$

$$\frac{f_a}{F_a}\le 0.15\rightarrow\frac{f_a}{F_a}+\frac{f_{bx}}{F_{bx}}\le 1 \tag{7}$$

where f_a=axial stress; F_a=allowable axial stress; f_b= bending stress; F_b=allowable bending stress and F_e can be expressed as:

$$F_e'=\frac{105\times10^5}{\lambda^2} \tag{8}$$

where, λ is slenderness ratio. F_e is the Euler stress divided by a factor of safety. *x* indicates the axis of bending about which a particular stress or design property is applied. C_{mx} is a coefficient whose value is taken 0.85 for compression members in unbraced frames.

$$\lambda\le C_c\rightarrow F_a=\frac{1}{F\cdot S}\left[1-0.5\left(\frac{\lambda}{C_c}\right)^2\right]F_y \tag{9}$$

$$F\cdot S=1.67+0.375\left(\frac{\lambda}{C_c}\right)-0.125\left(\frac{\lambda}{C_c}\right)^3 \tag{10}$$

$$C_c=\sqrt{\frac{2\pi^2E}{F_y}} \tag{11}$$

where E is modulus of elasticity and F_y is yield stress of steel.

$$\lambda>C_c\rightarrow F_a=\frac{105\times10^5}{\lambda^2} \tag{12}$$

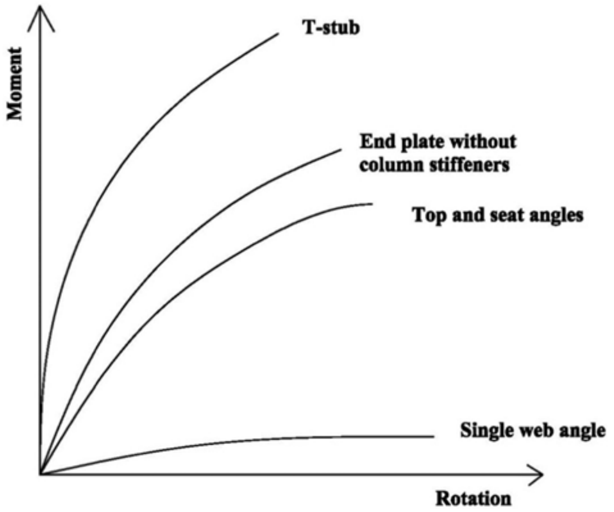

Figure 3. Connections moment-rotation curves.

Definitions of the allowable and Euler stresses and the other details are given by AISC-ASD specifications and therefore will not be repeated here.

5. Connection Modeling

A connection rotates through an angle θ as a result of an applied moment M. This is the angle between the beam and column from their original positions. Several moment-rotation relationships have been derived from experimental studies for modeling semi-rigid connections of steel frames. Moment-rotation curves of various types of connections are shown in Fig. 3 (Chen *et al*., 1996).

Semi-rigid end connections of a beam can be represented by rotational springs as shown in Fig. 4. θ_{rA} and θ_{rB} are the relative spring rotations of both ends and K_A and K_B are the corresponding spring stiffness, expressed as:

$$K_A = \frac{M_A}{\theta_{rA}} \tag{13}$$

$$K_B = \frac{M_B}{\theta_{rB}} \tag{14}$$

The stiffness matrix of beam member(i), with semi-rigid end connections in global coordinates is represented by (Dhillon and OMalley, 1999):

$$[K]_i = \begin{bmatrix} b_1 & & & & & \\ b_3 & b_2 & & & & \\ -b_4 & b_5 & b_6 & & & \\ -b_1 & -b_3 & b_4 & b_1 & & \\ -b_3 & -b_2 & -b_5 & b_3 & b_2 & \\ -b_7 & b_8 & b_9 & b_7 & -b_8 & b_{10} \end{bmatrix} \tag{15}$$

where

$$b_1 = \frac{AE}{L}\cos^2\alpha + \frac{12}{K_R}\left(\frac{EI}{L^2}\right)^2\left(\frac{L}{EI} + \frac{1}{K_B} + \frac{1}{K_A}\right)\sin^2\theta$$

$$b_2 = \frac{AE}{L}\sin^2\alpha + \frac{12}{K_R}\left(\frac{EI}{L^2}\right)^2\left(\frac{L}{EI} + \frac{1}{K_B} + \frac{1}{K_A}\right)\cos^2\theta$$

$$b_3 = \frac{AE}{L}\sin\alpha\cos\alpha - \frac{12}{K_R}\left(\frac{EI}{L^2}\right)^2\left(\frac{1}{EI} + \frac{1}{K_B} + \frac{1}{K_A}\right)\sin\alpha\cos\alpha$$

$$b_4 = \frac{12}{K_R}\left(\frac{EI}{L}\right)^2\left(\frac{1}{2EI} + \frac{1}{K_B}\right)\sin\alpha$$

$$b_5 = \frac{12}{LK_R}\left(\frac{EI}{L}\right)^2\left(\frac{1}{2EI} + \frac{1}{K_B}\right)\sin\alpha\cos\alpha$$

$$b_6 = \frac{12}{K_R}\left(\frac{EI}{L}\right)^2\left(\frac{1}{2EI} + \frac{1}{K_B}\right)$$

$$b_7 = \frac{12}{LK_R}\left(\frac{EI}{L}\right)^2\left(\frac{1}{2EI} + \frac{1}{K_A}\right)\sin\alpha$$

$$b_8 = \frac{12}{LK_R}\left(\frac{EI}{L}\right)^2\left(\frac{1}{2EI} + \frac{1}{K_A}\right)\cos\alpha$$

$$b_9 = \frac{2EI}{LK_R}$$

$$b_{10} = \frac{12}{K_R}\left(\frac{EI}{L}\right)^2\left(\frac{L}{3EI} + \frac{1}{K_A}\right)$$

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

$$\{r_F\} = [0 \;\; V_{FA} \;\; M_{FA} \;\; 0 \;\; V_{FB} \;\; M_{FB}]$$

$$M_{FA} = \frac{M_{FA} + 6\alpha_B M_{FB}}{(1 + 4\alpha_A + 4\alpha_B + 12\alpha_A\alpha_B)}$$

$$M_{FB} = \frac{M_{FB} + 6\alpha_A M_{FA}}{(1 + 4\alpha_A + 4\alpha_B + 12\alpha_A\alpha_B)}$$

$$\alpha_A = \frac{EI}{LK_A} \text{ and } \alpha_B = \frac{EI}{LK_B}$$

where E is the modulus of elasticity, A is the cross section area, I is the moment of inertia and L is the length of beam and α is the angle between the global and local coordinate system.

$\{r_F\}$ is the fixed-end force vector in member coordinates due to in-span gravity loads on beam with semi-rigid connections. M_{FA} and M_{FB} are fixed end moments for the member with fixed connections. The fixed-end shears V_{FA} and V_{FB} are obtained from the equilibrium of the member.

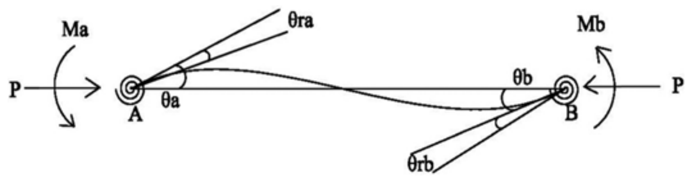

Figure 4. Beam with rotational springs.

Table 1. Rotational stiffness of semi-rigid connections

Semi-rigid connection type	K (N·cm/rad)
1	833×10^7
2	2766×10^7
3	3325×10^7
4	4434×10^7

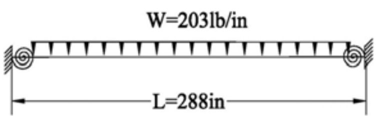

Figure 5. Beam with rotational spring.

6. Design Examples

Three types of examples are chosen for the weight optimization. Design of examples with rigid connections has been compared with semi-rigid connections. The length of each span is 5 m and story height is 3.2 m for all the frames. The modulus of elasticity is 2.1 Gpa in all the examples. The values of dead and live loads are considered as 5,886 N/m^2 and 1,962 N/m^2, respectively and the value of live load for roof level is considered as 1,471.5 N/m^2. The steel density is 77,008 N/m^2. Beams and columns sections are selected from a standard set of steel sections such as American Institute of Steel Construction (AISC) wide-flange (W) shapes. Two different catalogue values were determined for beam and column sections. For seismic load, the Iranian Code of Practice for Seismic Resistant Design of Buildings (standard 2800-05-3rd edition) is employed which is almost the same as UBC

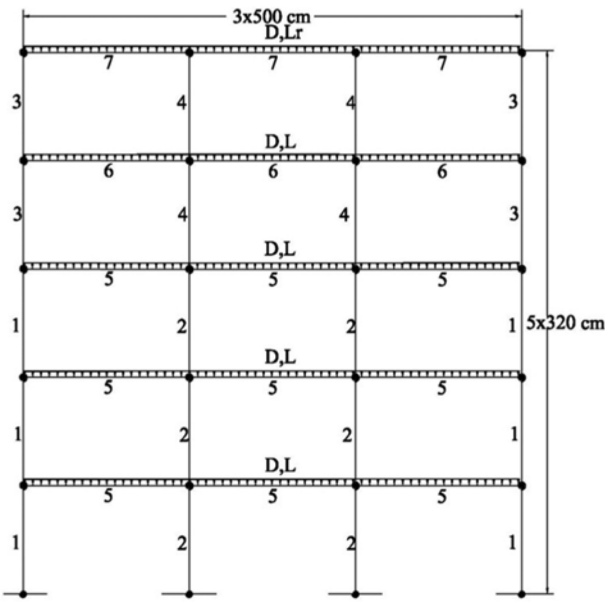

Figure 6. Three-bay five-story frame.

(Uniform Building Code, UBC 1997). In this code, seismic base shear is defined as:

$$V = C.W \tag{16}$$

where C is the seismic response coefficient and W is the effective seismic weight of frame. C is determined in accordance with:

$$C = ABI/R \tag{17}$$

where A is peak ground acceleration (PGA), B is spectral response factor, I is building importance factor and R is

Table 2. Results for spring verification

reference	Section	I (in^4)	Ki	M_u (k·in)	E (k·in^2)
Abdul-Rassak	W8×21	75.3	27795	406	29000
Vatani Oskouei	W8×21	75.3	27795	405.53	29000
In this research	W8×21	75.3	27795	405.852	29000

Table 3. Results for frame verification

reference	Frame	Simple GA		Fuzzy GA	
		Weight (ton)	Top story sway (cm)	Weight (ton)	Top story sway (cm)
Hayalioglu	Nine-story, single-bay	11.794	7.87	-	-
In this research	Nine-story, single-bay	11.745	7.96	11.571	8.12

the response modification factor of structure.

The possibility of mutation is assumed to be 0.005 and the size of population is considered to be 30. OpenSees software (2012) is utilized for modeling and analysis of the frames. The rotational stiffness values of different semi-rigid connections are shown in Table 1 (Hayalioglu, 2005).

For verifying frame with semi-rigid connection in OpenSees, beam with springs under uniform loading is considered and the result is compared with Abdul-Rassak Sultan (2007) and Vatani and Sarioletlagh (2012). This comparison is shown on Table 2.

For verifying the genetic algorithm in Matlab, two examples are constructed and the result was compared with Hayalioglu (2005). This comparison is shown on Table 3.

6.1. Three-bay five-story steel frame

Three-bay five-story steel frame is designed with rigid and semi-rigid connections. Linear analysis was performed. Figure 6 shows the frame topology, dimensions and elements label. The optimum results after 100 generations are presented in Table 4 and Table 5 for simple GA and

Table 4. Optimum results of Three-bay Five-story frame by simple genetic algorithm

Group no.	Semi rigid connection type				Rigid connection
	1	2	3	4	
1	W16X50	W16X50	W16X50	W14X43	W14X53
2	W12X14	W12X14	W12X16	W16X26	W12X22
3	W14X26	W16X26	W14X26	W16X40	W16X31
4	W14X53	W14X43	W14X34	W16X26	W14X30
5	W14X43	W16X50	W14X48	W16X50	W14X61
6	W14X38	W16X36	W14X43	W16X36	W14X43
7	W16X26	W16X26	W14X30	W16X26	W16X26
Total weight (ton)	7.5912	7.8874	7.9050	7.9866	8.2698
Roof displacement (cm)	6.9450	6.5710	6.3265	6.1993	5.6732

Table 5. Optimum results of Three-bay Five-story frame by fuzzy genetic algorithm

Group no.	Semi rigid connection type				Rigid connection
	1	2	3	4	
1	W16X50	W16X50	W14X48	W16X40	W16X40
2	W12X16	W12X16	W12X16	W16X26	W16X26
3	W16X31	W14X34	W14X34	W16X40	W14X38
4	W14X43	W14X43	W16X40	W14X30	W16X26
5	W14X43	W16X40	W16X45	W16X45	W14X48
6	W14X34	W14X34	W14X34	W14X34	W14X38
7	W16X26	W16X26	W16X26	W14X26	W16X26
Total weight (ton)	7.2482	7.3848	7.4434	7.6078	7.7755
Roof displacement (cm)	6.9959	6.7587	6.6899	6.2156	5.3740

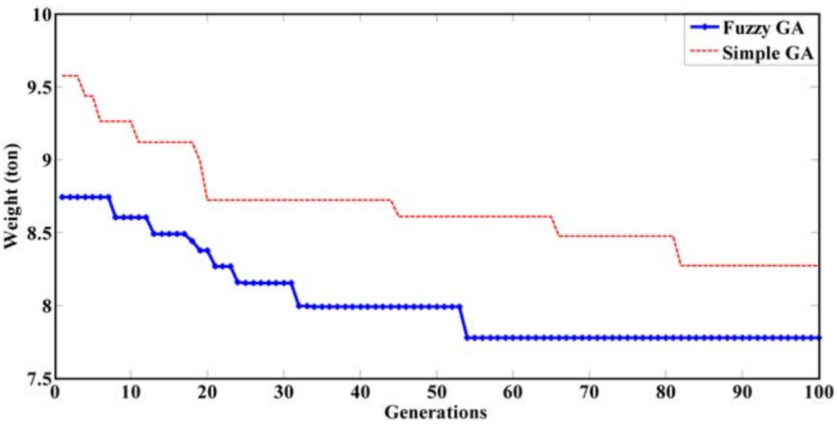

Figure 7. Design history of three-bay five-story frame with rigid connections.

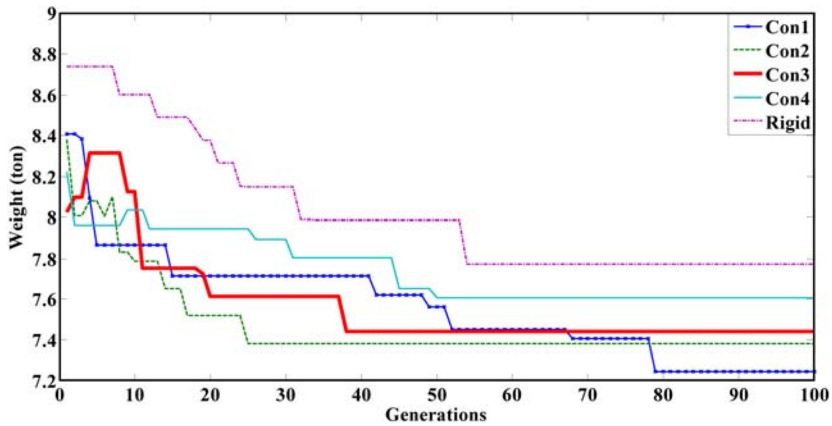

Figure 8. Design history of three-bay five-story frame (fuzzy GA).

fuzzy GA, respectively. The process has been iterated 10 times to obtain lightest weight of the frame. The design history of generations for the optimum linear frame with semi-rigid and rigid connections given in Table 4 and Table 5 is shown in Fig. 7 and Fig. 8. It is apparent that after 55 generations, the minimum weight almost remains the same in fuzzy GA. The result of the optimum design in Table 4 indicates that the frame with semi-rigid connections has 3.5-8.9% lighter weight than the one with rigid connection. Table 5 shows that fuzzy genetic algorithm gives 4.7-6% lighter weight compared to the simple genetic algorithm. The roof lateral displacement in frame with semi-rigid connection is increased by 9.2-22.4% compared to the frame with rigid connection. The rotational stiffness values are presented in Table 1.

6.2. Three-bay nine-story steel frame

A three-bay nine-story frame is designed with rigid and semi-rigid connections. Linear analysis is performed. Figure 9 shows the frame shape, dimensions and elements label. The optimum results after 100 generations are presented in Tables 6 and 7 for simple GA and fuzzy GA, respectively. To obtain lightest weight of the frame, the process has been iterated 10 times. The variation of weight for frame with semi-rigid and rigid connections against the generations during the optimum design process is shown in Figs. 10 and 11, respectively. The result of the optimum design in Table 6 shows that the frame with semi rigid connections has 0.8-5.2% lighter weight compared tothe frame with rigid connection. Table 7 shows the results of fuzzy genetic algorithm having 1-1.5% lighter weight compared to the simple genetic algorithm. The roof lateral displacement in frame with semi-rigid connection is increased by 14.5-19.3% compared to the frame with rigid connection.

6.3. Three-bay three-story steel frame

A three-bay three-story steel frame is designed with rigid and semi-rigid connections. Linear analysis is performed. Figure 12 shows the frame shape, dimensions and elements

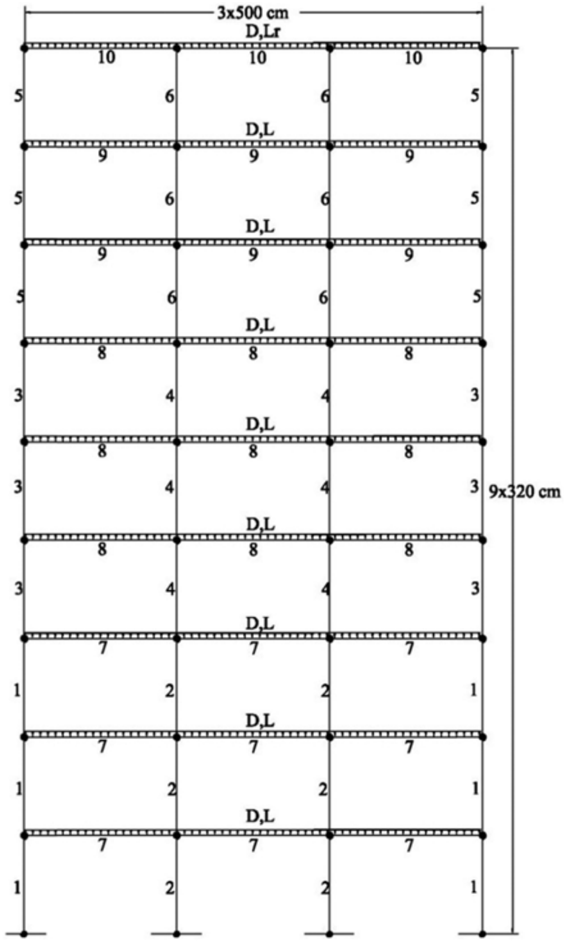

Figure 9. Three-bay nine-story frame.

label. The optimum results after 75 generations are presented in Tables 8 and 9 for simple GA and fuzzy GA, respectively. To obtain lightest weight of the frame, the process has been iterated 10 times. The variation of weight for frame with semi-rigid and rigid connections against the generations during the optimum design process is shown in Figs. 13 and 14, respectively. The result of

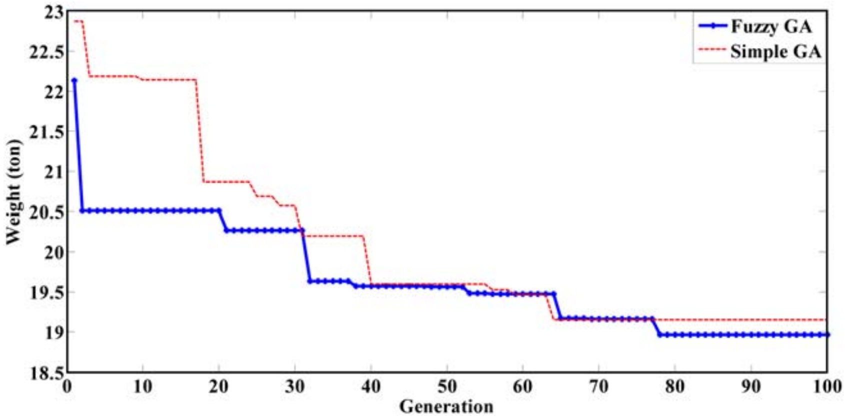

Figure 10. Design history of three-bay nine-story steel frame with rigid connection.

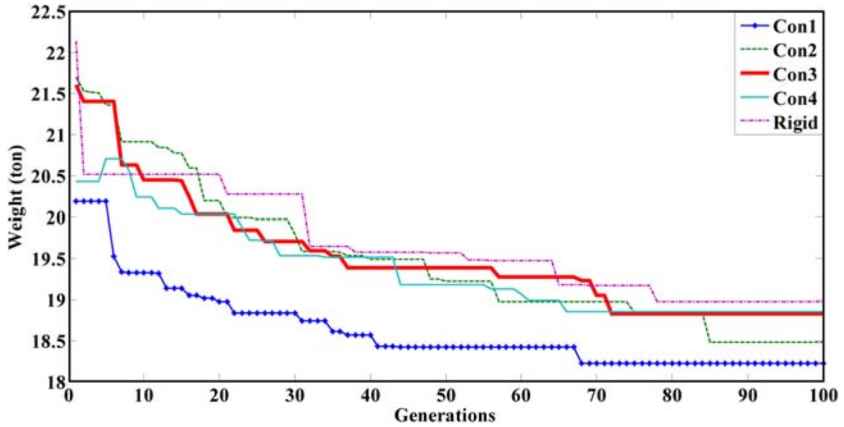

Figure 11. Design history of the three-bay nine-story frame (fuzzy GA).

the optimum design in Table 8 shows that the frame with semi rigid connections has 2.4-11.7% lighter weight compared to the frame with rigid connection. Table 9 shows the results of fuzzy genetic algorithm having 1.2-3.5% lighter weight compared to the simple genetic algorithm. The roof lateral displacement in the frame with semi-rigid connection is increased by 4.2-6.5% compared to the frame with rigid connection.

7. Summary and Conclusion

In this paper, combination of genetic algorithm and

Table 6. Optimum results of three-bay nine-story frame by simple genetic algorithm

Group no.	Semi rigid connection type				Rigid connection
	1	2	3	4	
1	W24X55	W24X55	W24X55	W24X55	W24X55
2	W24X55	W21X62	W27X102	W21X55	W21X55
3	W18X60	W18X60	W18X60	W18X71	W24X62
4	W21X55	W21X55	W24X55	W18X60	W24X55
5	W18X86	W18X71	W24X55	W21X55	W21X55
6	W21X55	W21X55	W24X55	W24X55	W21X55
7	W18X46	W18X50	W18X50	W14X68	W18X50
8	W18X46	W18X50	W18X50	W18X50	W14X68
9	W18X46	W18X46	W18X40	W18X46	W14X48
10	W12X30	W18X46	W18X46	W18X50	W12X30
Total weight (ton)	18.2057	18.8888	18.9883	19.0147	19.1564
Roof displacement (cm)	7.3313	7.2920	7.1709	7.0368	6.1413

Table 7. Optimum results of three-bay nine-story frame by fuzzy genetic algorithm

Group no.	Semi rigid connection type				Rigid connection
	1	2	3	4	
1	W21X55	W21X55	W21X55	W24X55	W21X55
2	W21X55	W21X55	W24X55	W24X55	W24X55
3	W24X62	W24X62	W24X55	W24X55	W24X62
4	W24X62	W21X62	W24X55	W21X55	W21X55
5	W24X55	W24X55	W24X55	W21X68	W21X55
6	W24X62	W21X55	W21X55	W21X101	W21X73
7	W18X50	W18X46	W18X46	W18X46	W18X50
8	W18X46	W18X50	W24X55	W18X50	W18X50
9	W18X40	W18X46	W18X46	W18X46	W18X40
10	W18X76	W14X74	W12X30	W12X30	W18X46
Total weight (ton)	18.2209	18.4792	18.8210	18.8487	18.9703
Roof displacement (cm)	6.7156	6.5056	6.3493	6.0424	5.6339

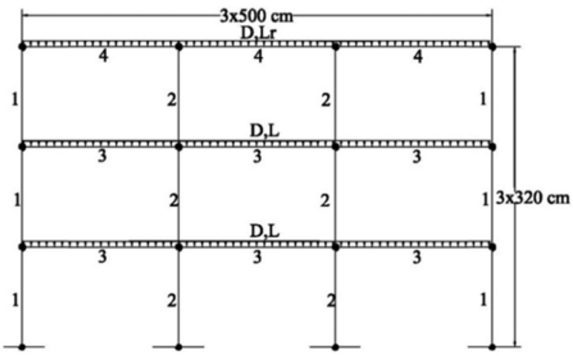

Figure 12. Three-bay three-story steel frame.

fuzzy logic has been employed for weight optimization of steel frames with rigid and semi-rigid connections. Allowable Stress Design (ASD) specifications are imposed on the frames. In the genetic algorithm, uniform crossover operator is employed and also binary coding is used to increase convergence rate. Also, in order to obtain a better convergence, it is proposed to use predefined scale factors in the objective function instead of random values for overall satisfaction parameter and penalty function related to each other (L_s=n, α=5n). These scale factors in the equation of objective function has led to the balance in two terms of the equation.

In tall frames, effect of the displacement constraints is more than other parameters. Also, the difference between the weight of the optimized frames with rigid and semi-rigid connections is small in tall frames.

The following conclusions are extracted from the design examples:

(1) The semi-rigid connections cause an increase of roof lateral displacement compared to rigid connection. These increases in the roof lateral displacements were calculated as 4.2-22.4% in the design examples.

(2) Genetic algorithm with fuzzy logic causes a decrease of the total steel weight compared to simple genetic algorithm. This reduction in the range of 1-6% was obtained.

(3) Genetic algorithm with fuzzy logic provides faster convergence with better solutions compared to simple genetic algorithm.

(4) Increasing the connection stiffness causes a

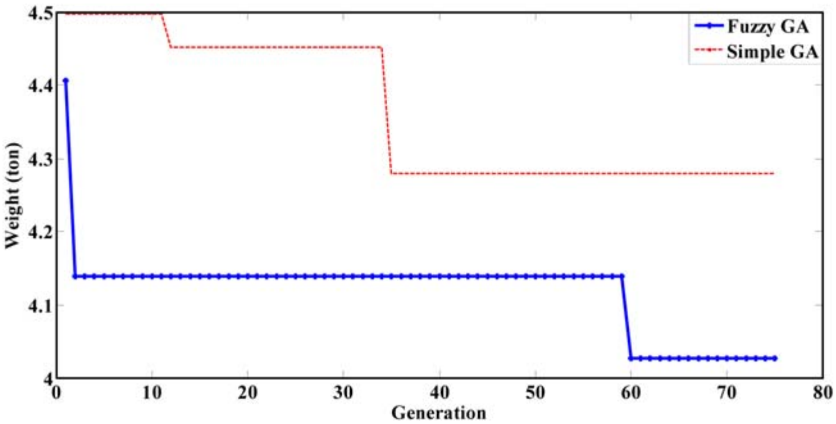

Figure 13. Design history of the three-bay three-story steel frame with rigid connections.

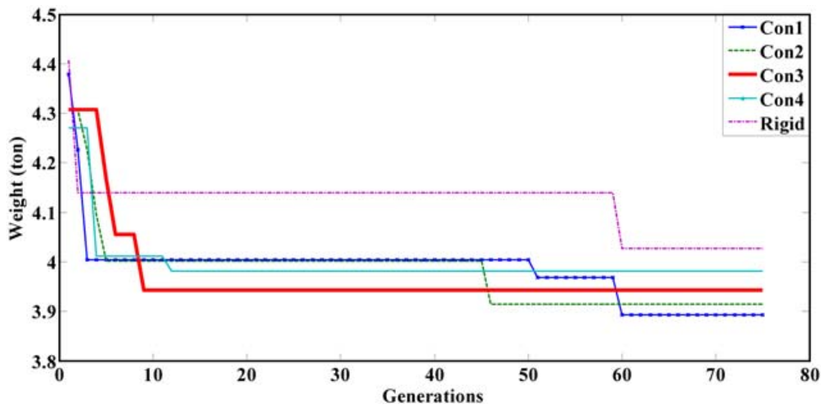

Figure 14. Design history of the three-bay three-story steel frame (fuzzy GA).

Table 8. Optimum results of three-bay three-story steel frame by simple genetic algorithm

Group no.	Semi rigid connectiontype				Rigid connection
	1	2	3	4	
1	W16X26	W16X26	W16X26	W16X40	W12X16
2	W16X31	W16X31	W14X34	W14X53	W16X40
3	W16X36	W16X36	W14X38	W16X36	W14X43
4	W16X26	W14X30	W16X26	W14X30	W14X34
Total weight(ton)	3.8285	3.9174	4.0043	4.1780	4.2795
Roof displacement (cm)	2.6221	2.9294	2.8517	2.5728	2.4702

Table 9. Optimum results of three-bay three-story steel frame by fuzzy genetic algorithm

Group no.	Semi rigid connectiontype				Rigid connection
	1	2	3	4	
1	W16X26	W16X26	W16X31	W12X16	W16X31
2	W14X34	W14X34	W14X30	W16X40	W14X34
3	W14X38	W16X36	W16X36	W16X40	W14X38
4	W16X26	W14X26	W14X26	W16X26	W16X26
Total weight (ton)	3.8925	3.9139	3.9431	3.9817	4.0269
Roof displacement (cm)	2.9517	2.8303	2.6887	2.5960	2.4210

decrease in the roof lateral displacement and increases the total weight of frame. The semi-rigid connection causes a decrease in the weight of frame in the range of 0.8-11.7%.

(5) Genetic algorithm parameters have important role in the converge velocity. The possibility of mutation is obtained 0.005 and a value of 1 is used for the crossover probability.

(6) Population size has an important effect on the values of the optimum weight. An increase in population size causes large increase in the computing time, but a small decrease in the weight of the frame.

References

Abdul-Rassak Sultan, S. (2007). *Performance-based optimal design of semi-rigid connected steel frame under seismic loading*. Ph.D. dissertation, Department of Civil Engineering, The Hong Kong Polytechnic University.

AISC (1989). *Manual of steel construction-Allowable stress design*. American Institute of Steel Construction, Chicago.

Ashtari, P. and Barzegar, F. (2012). “Accelerating fuzzy genetic algorithm for the optimization of steel structures.” *Struct Multidisc Optim Journal*, 45, pp. 275-285.

BHRC (2005) *Iranian earthquake resistant code, standard no 2800. 3rd ed.*, Tehran, Iran.

Chen, W. F., Goto, Y., and Liew, J. Y. R. (1996). *Stability design of semi-rigid frames*. New York, John Wiley & Sons Inc.

Dhillion, B. S. and OMalley, J. W. (1999). “Interactive design of semi-rigid steel frames.” *J. Struct. Eng., ASCE*, 125, pp. 556-564.

Eurocode 3 (1992) *Design of steel structures. Part I: general rules and rules for buildings*. Committee European de Normalization (CEN), Brussels.

Hayalioglu, M. S. and Degertekin, S. O. (2004). “Design of non-linear steel frames for stress and displacement constraints with semi-rigid connections via genetic optimization." *Struct Multidisc Optim Journal,* 27, pp. 259-271.

Hayalioglu, M. S. and Degertekin, S. O. (2005). "Minimum cost design of steel frames with semi-rigid connection and column bases via genetic optimization." *Computers & Structures Journal*, 83, pp. 1849-1863.

Jian-Yi, W. (1999). *Nonlinear behavior of semi-rigid composite joints under lateral loading* (*Experimental and Theoretical Study*). Ph.D. dissertation, Department of Civil and Engineering, The Hong Kong Polytechnic University.

Kameshki, E. S. and Saka, M. P. (2001). "Optimum design of nonlinear steel frames with semi-rigid connections using a genetic algorithm." *Computers & Structures Journal*, 79, pp. 1593-1604.

Kripakaran, P., Hall, B., and Gupta, A. (2011). "A genetic algorithm for design of moment-resisting steel frames." *Struct Multidisc Optim Journal*, 44, pp. 559-574.

OpenSees (2012). *Open system for earthquake engineering simulation. Version 2.2.0.*, OpenSees, Berkeley.

Simões, L. M. C. (1996). "Optimization of frames with semi-rigid connections." *Comput Struct*., 60(4), pp. 531-539.

Vatani, O. A., and Sarioletlagh, S. (2012). "Using genetic algorithm for optimization of seismic behavior of steel planar frames with semi-rigid connection." *Struct Multidisc Optim Journal*, 45, pp. 87-302.