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Optimum load and resistance factor design of steel space frames using genetic algorithm

M.S. Hayalioglu

Abstract In this paper, an algorithm is presented for the minimum weight design of steel moment-resisting space frames subjected to American Institute of Steel Construction (AISC) Load and Resistance Factor Design (LRFD) specification. A genetic algorithm (GA) is utilized herein as the optimization method. Design variables which are cross-sectional areas are discrete and are selected from the standard set of AISC wide-flange (W) shapes. The structure is subjected to wind loading in accordance with the Uniform Building Code (UBC) in conjunction with vertical loads (dead and live loads). Displacement and AISC LRFD stress constraints are imposed on the structure. The algorithm is applied to the design of three space frame structures. The designs obtained using AISC LRFD code are compared to those where AISC Allowable Stress Design (ASD) is considered. The comparisons show that the former code results in lighter structures for the examples presented.

Key words optimization, space frames, genetic algorithm, AISC, LRFD, AISC, ASD

1 Introduction

A large number of techniques and algorithms have been developed in recent years for the optimum design of structural systems. Most of the algorithms deal with continuous design variables and simple constraints. A few articles deal with the optimum design of structures subjected to actual design constraints of code specifications (Chan 1992; Chan and Grierson 1993; Soegiarso and Adeli 1994, 1997) Mathematical programming techniques and optimality criteria methods with continuous design variables have been used in all these articles. However, the design variables are discrete in most practical design problems. This is due to the availability of standard sizes and their restrictions for construction and manufacturing purposes. The aim of this paper is to develop optimization algorithms for steel structures subjected to the actual constraints of the American Institute of Steel Construction (AISC) Load and Resistance Factor Design (LRFD) and Allowable Stress Design (ASD) specifications (American Institute of Steel Construction 1995, 1989), and also to use actual steel sections as discrete design variables. A number of methods has been reported for the optimum design of discrete structural systems (Templeman and Yates 1983; Zhu 1986; John and Ramakrishnan 1987). Mathematical programming techniques are used in all these methods.

Genetic algorithms (GAs), which are applications of biological principles into computational algorithms, have been used to obtain the optimum structural design solutions in recent years. They apply the principle of survival of the fittest into the optimization of structures. They are also able to deal with discrete optimum design problems and do not need derivatives of functions like mathematical programming methods.

In this paper, a genetic algorithm (GA) is presented for the optimum design of steel space frame structures subjected to AISC LRFD specifications. A set of available steel sections (AISC W-shapes) are used as discrete design variables. The three space frames are optimized under displacement and AISC LRFD stress constraints. The frames are subjected to the horizontal wind loading in accordance with the Uniform Building Code (1991) in conjunction with vertical loads due to dead and live load.

2 Genetic algorithms

GAs were originally put forward by Holland (1975). A broad and useful information can be found in the book by Goldberg (1989). More information can be obtained from some articles associated with this topic (Rajeev and

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M.S. Hayalioglu

Civil Engineering Department, Dicle University, 21280 Diyarbakir, Turkey
e-mail: hsedat@dicle.edu.tr

Krishnamoorthy 1992; Adeli and Cheng 1994; Leite and Topping 1995).

GA can be used as an optimization method so as to minimize or maximize an objective function. In this paper, the GA given by Rajev and Krishnamoorthy (1992) is used. This algorithm has been improved by employing a uniform crossover operator instead of two-point crossover and adding a mutation operator. Fitness scaling as explained by Goldberg (1989) has also been added to the algorithm in order to prevent significant diversity in the population.

GAs are search techniques based on the mechanism of natural genetics and natural selections. They make use of the artificial survival of the fittest concept with genetic operators taken from nature to constitute a strong search mechanism. There are various genetic operators used in GA. The present work employs a GA with reproduction, crossover and mutation operators.

A design variable has a sequence number in a given discrete set of variables in GA. Binary codes are used for these numbers. Individuals in a population are finite length strings formed from either 1 or 0 characters. Individuals and the characters are called chromosomes and artificial genes, respectively, in some literature. A string may contain some substrings so that each of them represents a design variable.

The reproduction operator applies the principle of survival of the fittest in the population. The crossover operator satisfies that individuals from the mating pool recombine genetic information to generate new solutions to the problem. There are several crossover operators existing in the literature. In the present work, uniform crossover is utilized, which is given in detail by Syswerda (1989). The third operator is mutation which preserves diversification in the search. This operator is applied to each offspring in the population with a predetermined probability. The operator flips the gene of an offspring from 1 to 0 and vice versa at random position.

3 Optimum design problem and its formulation

The optimum load and resistance factor design problem of a space frame with displacement and stress constraints can be stated as follows. Find the set of design variables, A_k (cross-sectional area of the member group k) so that the weight of the structure,

$$W(x) = \sum_{k=1}^{ng} A_k \sum_{i=1}^{mk} \rho_i L_i \,, \tag{1}$$

is minimized subject to displacement and stress constraints. In (1), mk is the total number of members in group k, ρ_i and L_i are density and length of member i, and ng the total number of groups in the frame.

The displacement constraints are

$$\delta_{j\ell} - \delta_j^u \le 0 \,, \qquad j = 1, \dots, n \,, \quad \ell = 1, \dots, n\ell \,, \tag{2}$$

where $\delta_{j\ell}$ is the displacement of the j-th degree of freedom due to loading conditions ℓ, δ_j^u is its upper bound, n is the total number of restricted displacements, and $n\ell$ is the total number of loading conditions.

The stress constraints are expressed in terms of the following interaction equations (American Institute of Steel Construction 1995) for members subject to bending and axial force:

$$\frac{P_u}{\phi P_n} + \frac{8}{9}\left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}}\right) \le 1.0$$

$$\text{for } \frac{P_u}{\phi P_n} \ge 0.2 \,, \tag{3}$$

$$\frac{P_u}{2\phi P_n} + \left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}}\right) \le 1.0$$

$$\text{for } \frac{P_u}{\phi P_n} < 0.2 \,, \tag{4}$$

If the axial force is in tension, the terms in (3) and (4) for a member can be defined as: P_u = required tensile strength, P_n = nominal tensile strength, M_{ux} = required flexural strength about the major axis, M_{uy} = required flexural strength about the minor axis, M_{nx} = nominal flexural strength about the major axis, M_{ny} = nominal flexural strength about the minor axis, $\phi = \phi_t$ = resistance factor for tension (equal to 0.90), and ϕ_b = resistance factor for flexure (equal to 0.90).

If the axial force is in compression in (3) and (4), P_u = required compressive strength, P_n = nominal compressive strength, and $\phi = \phi_c$ = resistance factor for compression (equal to 0.85). The notation of the other terms is the same as the previous ones. The nominal compressive strength of a member is computed as

$$P_n = A_g \cdot F_{cr} \,, \tag{5}$$

$$F_{cr} = \left(0.658^{\lambda_c^2}\right) F_y \qquad \text{for } \lambda_c \le 1.5 \,, \tag{6}$$

$$F_{cr} = \left(\frac{0.877}{\lambda_c^2}\right) F_y \qquad \text{for } \lambda_c > 1.5 \,, \tag{7}$$

$$\lambda_c = \frac{KL}{r\pi}\sqrt{\frac{F_y}{E}} \,, \tag{8}$$

where A_g is the cross-sectional area of a member, K is the effective length factor, E is the modulus of elasticity, r is the governing radius of gyration, L is the member length, and F_y is the yield stress of steel. The effective length factor K, for braced and unbraced frames is calculated from the following approximate equations taken from Soegiarso and Adeli (1997):

$$K = \frac{3G_A G_B + 1.4(G_A + G_B) + 0.64}{3G_A G_B + 2.0(G_A + G_B) + 1.28}$$

(for braced frames), (9)

$$K = \sqrt{\frac{1.6G_A G_B + 4.0(G_A + G_B) + 7.50}{G_A + G_B + 7.50}}$$

(for unbraced frames), (10)

where subscripts A and B denote the two ends of the column under consideration. The restraint factor G is stated as

$$G = \frac{\sum(I_c/L_c)}{\sum(I_g/L_g)}\,, \tag{11}$$

where I_c is the moment of inertia and L_c is the unsupported length of a column section, I_g is the moment of inertia and L_g is unsupported length of a girder; $\sum$ indicates a summation for all members rigidly connected to that joint (A or B) and lying in the plane of buckling of the column under consideration. The required flexural strength of a beam-column member considering second-order effects is computed from the following relationship:

$$M_u = B_1 M_{nt} + B_2 M_{\ell t}\,, \tag{12}$$

where M_{nt} is the required flexural strength in a member assuming there is no lateral translation of the frame, and $M_{\ell t}$ is the required flexural strength in a member as a result of lateral translation of the frame only. Definitions of the other terms in (12) and details of formulations are given in the AISC LRFD specifications (American Institute of Steel Construction 1995) and repetition will be avoided here.

GA is convenient for unconstrained optimization problems. The present problem described by (1)–(4) is a constrained one and therefore it is necessary to transform it into an unconstrained problem. This is achieved by using a transformation based on the violations of normalized constraints as suggested by Rajeev and Krishnamoorthy (1992). The normalized form of constraints can be expressed as follows:

$$g_{j\ell}(x) = \frac{\delta_{j\ell}}{\delta_j^u} - 1 \le 0\,,$$

$$j = 1, \ldots, n\,, \quad \ell = 1, \ldots, n\ell\,, \tag{13}$$

for $\dfrac{P_u}{\phi P_n} \ge 0.2$,

$$g_{i\ell}(x) = \left(\frac{P_u}{\phi P_n}\right)_{i\ell} +$$

$$\frac{8}{9}\left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}}\right)_{i\ell} - 1.0 \le 0\,,$$

$$i = 1, \ldots, nm\,, \quad \ell = 1, \ldots, n\ell\,, \tag{14}$$

for $\dfrac{P_u}{\phi P_n} < 0.2$,

$$g_{i\ell}(x) = \left(\frac{P_u}{2\phi P_n}\right)_{i\ell} + \left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}}\right)_{i\ell} - 1.0 \le 0\,,$$

$$i = 1, \ldots, nm\,, \quad \ell = 1, \ldots, n\ell\,, \tag{15}$$

where nm is the total number of members in the frame. The unconstrained objective function $\varphi(x)$ is then written as

$$\varphi(x) = W(x)\left[1 + C\left(\sum_{j=1}^{n}\sum_{\ell=1}^{n\ell} v_{j\ell} + \sum_{i=1}^{nm}\sum_{\ell=1}^{n\ell} v_{i\ell}\right)\right]\,, \tag{16}$$

where C is a constant to be selected depending on the problem. A value of 10 was found suitable for C in all design examples presented in this paper. In (16), $v_{j\ell}$ and $v_{i\ell}$ are violation coefficients which are computed as

$$\text{if} \quad g_{j\ell}(x) > 0 \quad \text{then} \quad v_{j\ell} = g_{j\ell}(x)\,,$$

$$\text{if} \quad g_{j\ell}(x) \le 0 \quad \text{then} \quad v_{j\ell} = 0\,,$$

and

$$\text{if} \quad g_{i\ell}(x) > 0 \quad \text{then} \quad v_{i\ell} = g_{i\ell}(x)\,,$$

$$\text{if} \quad g_{i\ell}(x) \le 0 \quad \text{then} \quad v_{i\ell} = 0\,. \tag{17}$$

The minimum of the unconstrained function $\varphi(x)$ will be searched by GA. The algorithm requires a criteria to perform selection among the individuals. This is done in such a way that the fittest individual has maximum fitness. Goldberg (1989) suggests that $\varphi(x)$ should be subtracted from a large constant for the minimization problem. In the present work, an expression for fitness is selected as

$$F_i = [\varphi(x)_{\max} + \varphi(x)_{\min}] - \varphi_i(x)\,, \tag{18}$$

where F_i is the fitness of the i-th individual, $\varphi(x)_{\max}$ and $\varphi(x)_{\min}$ are the maximum and minimum values of $\varphi(x)$ among the current population; $\varphi_i(x)$ is the value of the same function computed for the i-th individual. The individuals with small fitness die off and the others send copies to the mating pool proportional to their fitness. After the mating pool is created, individuals are coupled randomly and crossover is applied to them.

It is clear that computation of the fitness of an individual requires the values of displacements and stresses in the frame system. This is achieved by carrying out the linear-elastic analysis of space frame systems.

4
Analysis of space frame systems

Linear-elastic analysis of a rigidly-connected space frame system has been carried out by using the matrix displacement method. Each node or joint has six degrees of freedom and each member has six stress-resultants in the local coordinates. These are axial tension, two moments causing curvature in the (z–y) plane, two moments causing curvature in the (z–x) plane, and twisting moment or torque (x and y are the principal axes of the cross-section and z is the axis along the member length). Applying the known steps of the method, the joint displacements of structure and stress resultants of members are obtained. The other member end forces and span moments are computed depending on these stress resultants.

5
Optimum design algorithm

The optimum AISC LRFD algorithm for space frame structures consists of the following steps.

1. Construct the initial population randomly which comprises binary digits.
2. Decode the binary codes for the design variables of each individual and find their sequence numbers in the available steel section list. Perform the linear-elastic analysis of each space frame which represents an individual in the population subjected to given loading conditions and obtain the response of the frame.
3. Calculate the value of unconstrained function $\varphi(x)$ for each individual using (13)–(17). Find the maximum and minimum values of this function in the population.
4. Calculate the fitness value for each individual from (18).
5. Apply linear fitness scaling to the population as explained by Goldberg (1989) to obtain fast convergence.
6. Apply the reproduction operator. Copy the individuals into the mating pool according to their fitness and couple them randomly. Generate offspring using uniform crossover and thus obtain the new population.
7. Apply mutation to each offspring in the new population.
8. Replace the initial population by the new population and repeat steps 2 to 8 until the distance between the maximum and the average fitness values of current population falls below a certain threshold. In this case, the individual with the maximum fitness value in current population represents the optimum design.

6
Constraints and objective function for optimum AISC – allowable stress design

In the present study, an optimum allowable stress design algorithm has also been developed to compare optimum designs based on AISC LRFD specifications. The equation for the normalized displacement constraint is the same as (13). The combined stress constraints taken from American Institute of Steel Construction (1989) are expressed in the following equations.

For members subjected to both axial compression and bending stresses,

$$g_{i\ell}(x) = \left[\frac{f_a}{F_a} + \frac{C_{mx} f_{bx}}{\left(1 - \frac{f_a}{F'_{ex}}\right) F_{bx}} + \frac{C_{my} f_{by}}{\left(1 - \frac{f_a}{F'_{ey}}\right) F_{by}}\right]_{i\ell} - 1.0 \le 0\,, \qquad i = 1, \dots, nm\,, \quad \ell = 1, \dots, n\ell\,, \tag{19}$$

$$g_{i\ell}(x) = \left[\frac{f_a}{0.60 F_y} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}}\right]_{i\ell} - 1.0 \le 0\,, \qquad i = 1, \dots, nm\,, \quad \ell = 1, \dots, n\ell\,. \tag{20}$$

When $f_a/F_b \le 0.15$, (21) is permitted in lieu of (19) and (20)

$$g_{i\ell}(x) = \left[\frac{f_a}{F_a} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}}\right]_{i\ell} - 1.0 \le 0\,, \qquad i = 1, \dots, nm\,, \quad \ell = 1, \dots, n\ell\,. \tag{21}$$

For members subjected to both axial tension and bending stresses,

$$g_{i\ell}(x) = \left[\frac{f_a}{F_t} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}}\right]_{i\ell} - 1.0 \le 0\,, \qquad i = 1, \dots, nm\,, \quad \ell = 1, \dots, n\ell\,. \tag{22}$$

In (19)–(22), the subscripts x and y, combined with subscripts b, m and e, indicate the axis of bending about which a particular stress or design property applies, and F_a = axial compressive stress that would be permitted if axial force alone existed, F_b = compressive bending stress that would be permitted if bending moment alone existed, F'_e = Euler stress divided by a factor of safety, f_a = computed axial stress, f_b = computed compressive bending stress at the point under consideration, and C_m = a coefficient whose value is taken as 0.85 for compression members in frames subject to sidesway.

In (22), f_b is the computed bending tensile stress, f_a is the computed axial tensile stress, F_b is the allowable bending stress and F_t is the governing allowable tensile stress. Allowable, $(0.6F_y)$ and Euler stresses are increased by 1/3 in accordance with the specification when produced by wind, acting alone or in combination with the design dead and live loads. Definitions of the allowable and Euler stresses and other details are given AISC ASD specifications (American Institute of Steel Construction 1989) and therefore will not be repeated here.

The same form of the unconstrained objective function as given in (16) is used here providing that (19)–(22) are used instead of (14) and (15).

The same optimum design algorithm as explained in Sect. 5 is used for allowable stress design on the condition that the latest constraints and unconstrained objective function are adopted.

7 Design examples

The algorithm has been applied to the optimum design of three space frame structures. The material is steel with a modulus of elasticity of 200 000 MPa and shear modulus of elasticity of 77 000 MPa. The yield stress and the unit weight of material are 344.8 MPa and 7850 kg/m^3, respectively. Four different types of loads are employed: dead load (D), live load (L), roof live load (L_r), and wind loads (W). Four load combinations are taken into account, per AISC LRFD specification: I: ($1.4D$), II: ($1.2D + 1.6L + 0.5L_r$), III: ($1.2D + 1.6L_r + 0.5L$) , and IV: ($1.2D + 1.3W + 0.5L + 0.5L_r$).

The same material properties are used and only a load combination is considered, per AISC ASD specification: ($D + L + Lr + W$). The values of 2.78 kPa for dead load (D), 2.39 kPa for live load (L), and 2.39 kPa for roof live load are considered in the three design examples.

The maximum drift is restricted to $0.004H$ ($H =$ total height of the structure) for designs based on AISC ASD specification. This value is increased by 30% to 0.0052 to include the effect of the coefficient 1.3 in the LRFD wind load combination. AISC (W) shapes are used as steel sections in all design examples considered in the present study. Wind loading is obtained from the Uniform Building Code (1991) using the equation $p = C_e C_q q_s I$, where p is design wind pressure; C_e is combined, height, exposure, and gust factor coefficient; C_q is pressure coefficient; q_s is wind stagnation pressure; and I is importance factor. Assuming exposure B a value of 0.7 is used for C_e. The value of C_q for inward face is 0.8 and for outward face is 0.5. The value of qs is 0.622 kPa assuming a basic wind speed of 113 km/h (70 mph) and the importance factor is assumed to be one.

7.1 Design of single-storey 8-member space frame

The one storey 8-member frame shown in Fig. 1 is the first example. The members of the frame are divided into three groups as shown in Fig. 1. The horizontal loads due to wind act in the z-direction at each unrestrained node. The displacement constraints are given as (± 2.34 cm in the z-direction for each unrestrained node (equal to $0.0052H$). The displacement constraints are taken as ± 1.8 cm (equal to $0.004H$) for allowable stress design. The population size, linear fitness scaling multiplier (Goldberg 1989), crossover and mutation probability are selected as 60, 2.0, 0.99, and 0.002, respectively. A minimum weight of 1299.5 kg is found after 60 generations for AISC LRFD with a maximum storey drift of 0.64 cm. The minimum weight is also obtained as 1812.9 kg after 50 generations for AISC ASD with 0.72 cm maximum story drift. The displacement values are quite below their upper bounds and this indicates that stress constraints govern the designs for both codes of practice. The optimum design variables for member groups are given in Table 1 for the two design codes.

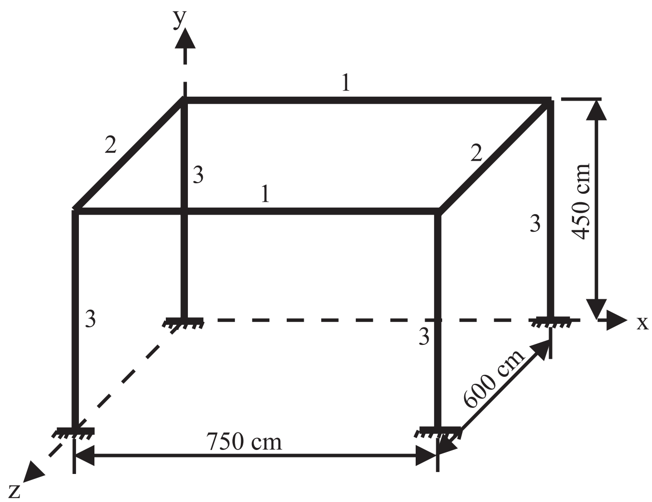

Fig. 1 Single-storey 8-member space frame

Table 1 Optimum design variables for the single-storey space frame

Group No.	Design Variables LRFD	ASD
1	$W12 \times 19$	$W10 \times 26$
2	$W\ 5 \times 16$	$W12 \times 45$
3	$W10 \times 22$	$W\ 6 \times 16$

7.2 Design of 4-storey 84-member space frame

The second example is the 4-storey space frame with a square plan and side view shown in Fig. 2. The structure has 84 members divided into 8 groups of members. The groups are organized as follows: 1-st group: corner columns of 4-th and 3-rd storeys, 2-nd group: outer and inner columns of 4-th and 3-rd storeys, 3-rd group: corner columns of 2-nd and 1-st storeys, 4-th group: outer and inner columns of 2-nd and 1-st storeys, 5-th group: outer beams of top storey, 6-th group: inner beams of top storey, 7-th group: outer beams of 3-rd, 2-nd and 1-st storeys, 8-th group: inner beams of 3-rd, 2-nd and 1-st storeys.

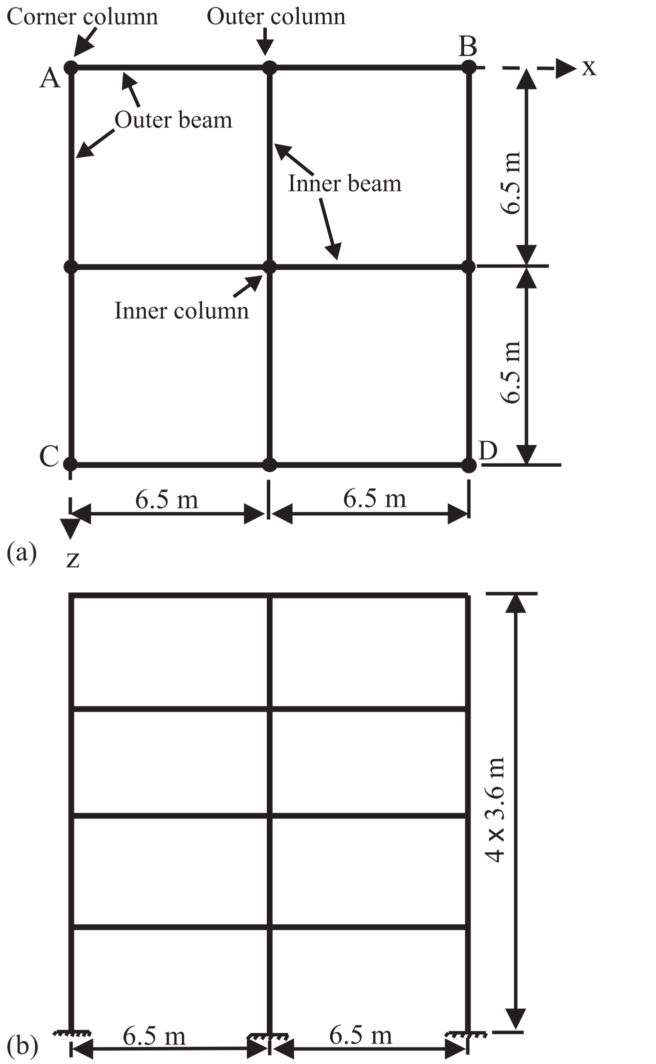

Fig. 2 Four-storey 84-member space frame: (a) plan, (b) side view

The horizontal loads due to wind act in the z-direction at each node on the sides AB and CD. The displacement constraints are given as ± 7.49 cm and ± 5.76 cm in the z-direction for the nodes on the top level for AISC LRFD and ASD specifications, respectively. The population size, linear fitness scaling multiplier, crossover and mutation probability are selected as 60, 2.0, 0.99, and 0.001, respectively. A minimum weight of 16 165.6 kg is found after 83 generations for AISC LRFD with a maximum storey drift of 3.51 cm. The minimum weight is also obtained as 18 371.2 kg after 94 generations for AISC ASD with 2.31 cm maximum story drift. Stress constraints govern again the designs for both codes of practice. The optimum design variables for member groups are given in Table 2 for the two design codes.

Table 2 Optimum design variables for the 4-storey space frame

Group No.	Design Variables LRFD	ASD
1	$W10 \times 19$	$W\ 8 \times 31$
2	$W12 \times 30$	$W10 \times 49$
3	$W\ 6 \times 25$	$W\ 8 \times 35$
4	$W\ 8 \times 31$	$W\ 8 \times 31$
5	$W10 \times 17$	$W\ 8 \times 18$
6	$W\ 8 \times 40$	$W\ 8 \times 35$
7	$W10 \times 22$	$W12 \times 14$
8	$W12 \times 26$	$W12 \times 45$

7.3 Design of 10-storey 130-member space frame

The 10-storey space frame with a rectangular plan and side view shown in Fig. 3 is the third example. The structure consists of 130 members divided into 9 groups. The groups are organized as follows: 1-st group: outer beams of top storey, 2-nd group: inner beam of top storey, 3-rd group: outer beams of storeys from 1 to 9, 4-th group: inner beams of storeys from 1 to 9, 5-th group: outer and corner columns of 10-th and 9-th storeys, 6-th group: outer and corner columns of 8-th and 7-th storeys, 7-th group: outer and corner columns of 6-th and 5-th storeys, 8-th group: outer and corner columns of 4-th and 3-rd storeys, 9-th group: outer and corner columns of 2-nd and 1-st storeys.

The horizontal loads due to wind applied in the z-direction at each node on the sides AB and CD. The displacements are restricted to ± 18.72 cm and ± 14.4 cm in the z-direction for the nodes on the top level for AISC LRFD and ASD specifications, respectively. The population size, linear fitness scaling multiplier, crossover and mutation probability are selected the same as those of the previous example. A minimum weight of 40 976.3 kg is found after 101 generations for AISC LRFD with a maximum storey drift of 18.71 cm. The minimum weight is also obtained as 41 280.2 kg after 97 generations for AISC ASD with 14.23 cm maximum story drift. Displacement constraints govern the designs for both code specifications. The optimum design variables for member groups are given in Table 3 for the two design codes.

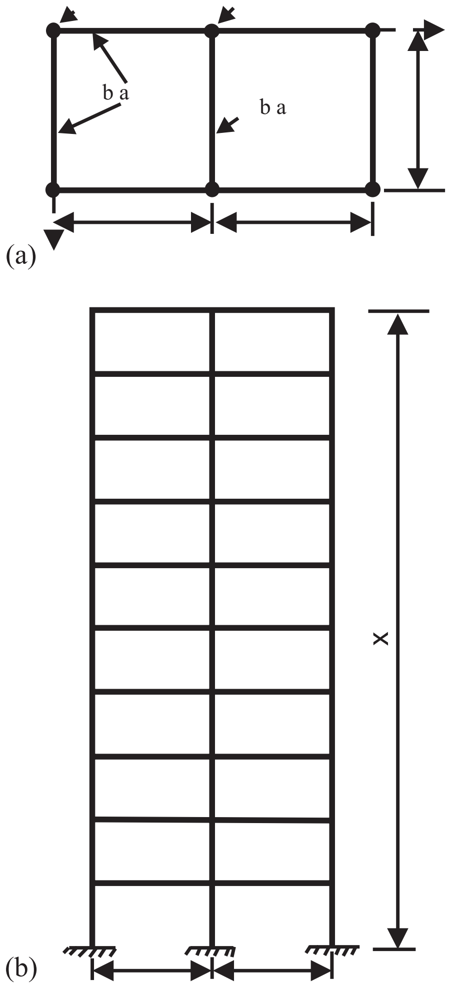

Fig. 3 Ten-storey 130-member space frame: (a) plan, (b) side view

Table 3 Optimum design variables for the 10-storey space frame

Group	Design Variables	
No.	LRFD	ASD
1	$W14\times26$	$W14\times38$
2	$W12\times40$	$W14\times26$
3	$W12\times35$	$W12\times35$
4	$W12\times35$	$W12\times40$
5	$W10\times22$	$W12\times35$
6	$W12\times35$	$W12\times40$
7	$W14\times68$	$W14\times68$
8	$W14\times68$	$W12\times53$
9	$W14\times82$	$W14\times68$

8 Conclusions

A genetic algorithm based optimum design approach is presented for steel moment-resisting space frames subjected to both AISC LRFD and ASD specifications. GAs are quite convenient for practical optimum structural designs, since they treat discrete design variables. Design variables are discrete in nature in most of structural design problems. In most mathematical programming techniques and in the optimality criteria approach, an approximation is made by assigning the obtained optimum continuous design variables to close standard sections. Approximate relationships may also be used between the cross-sectional properties of real standard sections in these methods. However, GA removes all these approximations and obtains real discrete sections in a given set of standard sections. GA is also general and can be applied to any discrete set of sections produced in accordance with different standards.

The following conclusions are reached from the design examples presented, when using GA in the optimum AISC LRFD and ASD of space frame structures.

- The population size plays an important role in the value of the minimum weight and in the number of generations produced. The increase in population size yields the production of more generations. A population size between ℓ and 2ℓ, where ℓ is the chromosome length, produces adequate results as mentioned by Reeves (1993). The chromosome lengths are 18, 48 and 54 for the first, second and third design examples of the present study and therefore a population size of 60 is used for all of them.
- Fitness scaling and higher crossover probability increase the speed of convergence. Linear fitness scaling with a value of 2.0 of the multiplier is included the algorithm and a value of 0.99 is used for crossover probability. Small mutation probabilities such as 0.001 or 0.002 are found suitable in the examples considered, since greater values of this probability cause significant diversity within the population. The following terminating criterion is used in the genetic algorithm: $(F_{\max} - F_{\text{avg}})/F_{\max} \le \varepsilon$, where $F_{\max}$ and F_{avg} are the maximum and average fitness values in the current population, and ε is a prescribed small number. Selecting smaller values for ε causes delay in convergence, but larger values for ε yields premature convergence. Values between 0.01 and 0.015 are found appropriate in the design examples presented.
- The three space frames are designed according to both AISC LRFD and AISC ASD specifications and the results are compared. Savings in weight for designs based on LRFD when compared with designs based on ASD are 28%, 12%, and 0.7% for the first, second and third examples, respectively. It appears from the results that the optimum designs based on LRFD yields lighter frames providing that stress constraints are dominant in designs. Almost the same optimum weights have been obtained for the two design codes when displacement constraints govern the designs in the third example.

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