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Optimization of Steel Frame with Genetic Algorithm Using Different Encoding Types

S. Bekiroglu
Karadeniz Technical University, Department of Civil Engineering, Trabzon
Turkiye

Y. Ayvaz
Karadeniz Technical University, Department of Civil Engineering, Trabzon
Turkiye

T. Dede
Karadeniz Technical University, Department of Civil Engineering, Trabzon
Turkiye

Abstract

In genetic algorithms, binary encoding and value encoding are mostly used encoding types to represent structural characteristics of problems. In this study, in addition to these encoding types, effects of different encoding types such as ternary encoding, quaternary encoding, etc. on optimum solution and convergence of the algorithm including these encoding types are discussed. In the design, the specification, AISC-ASD, is taken into account. It is concluded that the use of different encoding types have advantage over using only one encoding type in the genetic algorithm.

Introduction

The genetic algorithm (GA) is a method that becomes gradually robust and efficient device in optimization of structural design. The superiority of GA to the other conventional optimization methods arises from locating globally optimal solution. In the GA that is an evolutionary process, a set of solutions randomly composed evolves into a set of optimal solutions. The GA that employs with populations provides its global exploration in search space, which makes it strong. Since the GA can effectively continue to find application in structural problems and sustain the abilities stated above, other schemes as with adaptive penalty scheme and adaptive operators should be taken into consideration. From this point of view, in this study, in addition to commonly used binary encoding and value encoding that is used by Dede et al. (2003), other types of encoding such as ternary encoding, quaternary encoding, etc. are discussed.

Genetic Algorithm

The concept of GA evolves a set of solution called as a population and directs the population towards optimal solution. The preference of using a population makes selecting random point possible, instead of not moving from a single point to point over a line or curve in search space, where the point may be feasible or infeasible solution. Thus, the information concerning optimal solution in the whole population is almost completely sought by GA having a random mechanism. Hence, GA can be considered as a global optimization method.

GA takes minimization or maximization of the objective function by employing genetic operators as a goal, where the objective function formulates the aim of optimization for a structural problem. The optimization method, firstly, produces initial population from a large number of points randomly distributed over the design space, and then all of the solutions or individuals including design variables in the population are evaluated according to whether or not they satisfy the constraints of a problem by carrying out the objective function. In consequence of the evaluation, the fitnesses are assigned to individuals. Thus, whether or not the individuals in population have characteristics of the optimal solution is determined. The bad individuals are replaced with the reproduction of the individuals having great fitness and mating pool constitutes, where individuals in a population match each other. The aim joins the characteristics of optimal solution together. In accordance with that, the genetic operators such as mutation and crossover operators are used. After that, if the number of the same individuals is equal to 80 percent of population size, the algorithm is terminated.

Mutation Operator

Mutation operator is applied to renew characteristics (i.e. the genetic information) in an individual by changing its variables with other design variables in search space. Mutation operator gives opportunity of survival to an individual having lower fitness than the others in the population by eliminating its bad design variables in the individual. Therefore, mutation operator produces new individuals instead of bad individuals.

The role of mutation operator in GA prevents the premature convergence of the GA to suboptimal solutions by restoring lost or explored genetic material into the population (Srinivas at all, 1994). Moreover, some important regions of the search space may never be explored as this operator is not introduced in GA (Camp at all, 1998). Since these roles of the operator are implemented, the operator must be applied by controlling the degree of goodness (i.e. fitness) in the individuals. That is why mutation operator for having adaptive quality is needed. The adaptive mutation operator (i.e. intelligent mutation operator (Bekiroğlu, 2003 and Jenkins, 2002)), according to the capacity of individual, accomplishes mission of filter by removing bad design variables from the individual. Srinivas et al. (1994) has developed a new method that is used by Yoshimoto et al. (2003) for real encoding. This method is newly modified to be used in all encoding types and it is given as

$$P_m = \begin{cases} 0{,}5\left(f_{max} - f\right) \Big/ \left(f_{max} - \bar{f}\right) & \left(f \geq \bar{f}\right) \\ 1 & \left(f < \bar{f}\right) \end{cases} \quad (1)$$

where f_{max} is maximum fitness in the population, $\bar{f}$ is average of all fitnesses of individuals, and f is fitness of an individual. When the fitness of an individual, f, is smaller than average of all fitness, $\bar{f}$, the probability of mutation, P_m, is equal to 1. P_m is also equal to 0,5 if the value of f is the same of that of $\bar{f}$. Moreover, P_m becomes zero if f comes close to f_{max}. It can be seen that increment of fitness of individual decreases the probability of mutation.

Crossover Operator

Another genetic operator, used in this study, increasing variety of solution is crossover operator which is the only operator to be need of a population. Crossover operator is interested in locations of design variables on individuals which are substrings or segments turning out a string called individual. While individuals attain their fitnesses, that is, they are evaluated concerning their abilities to be optimal solution, design variables are also assessed at their own locations. As crossover operator is applied for each parent, its randomly selected substrings are switched between parents at their own locations. Thus, crossover operator deals with putting the most suitable design variables trained at their own locations together over optimal solution. As considered from this point of view, crossover operator actually requires a population and searches with the population to find optimal solution.
Since the productivity of GA is based on the capabilities of the operators, as in the adaptive mutation operator, the crossover operator is also developed. The probability of crossover, which determines the number of exchanged segments, is commonly given by user by depending on its experience. Nevertheless, the adaptive crossover is operated by fitness of individuals, but not with experience of user. Srinivas et al. (1994) has also developed another new method that is used by Yoshimoto et al. (2003) for real encoding. This method similar to multi-point (flexible) crossover in view of style of application is newly arranged for being used in other encoding types. In the method number of selected variables randomly not determined as in multi-point (flexible) crossover. However, the number is defined with probability of crossover in relative to fitnesses of individuals in the population. The probability of crossover, P_c is formulated as

$$P_c = \begin{cases} \left(f_{max} - f'\right) \Big/ \left(f_{max} - \bar{f}\right) & \left(f' \geq \bar{f}\right) \\ 1 & \left(f' < \bar{f}\right) \end{cases} \tag{2}$$

where f' is the lowest fitness between parents. The probability of crossover, P_c, decreases if the fitnesses of parents are getting more.
The use of adaptive crossover operator and mutation operator carries out that the individual having the greatest fitness is placed in next generation, which can be viewed as elitist strategy. The adaptive crossover operator and adaptive mutation operator were preferred in this study.

Encoding Strategies

In genetic algorithm, possible solution of problems is represented in the two ways which are fenotype and genotype. While the fenotype form of solution of problems is

used for indicating cross-section used in the design variables set that is considered for solution of problem, the genotype form is used for applying genetic operators including crossover and mutation. According to numbers of design variables, the genotype form can be coded in value or binary notation. In the binary encoding, design variables consist of substring of uniform numbers in the interval [0, 1]. However, in the value encoding, design variables do not constitute numbers in certain interval. Instead, design variables refer to integer numbers, i.e., 1, 2, 3, 4, ..., nv, where nv is the number of cross-sections under consideration. Therefore, different representation of the genotype can be used. The representations are given in Table 1.

Table 1. Fenotype and genotype forms of individuals in the population whose size is 20.

Encoding Type	Fenotype	Number of Individual	Genotype
Binary Encoding	22 51 241 4	1	00010101 00111010 11110000 00000011
	18 50 166 23	2	00010001 00111011 10100101 00010110
	37 48 121 34	3	00100100 10111001 10100101 00010110
	… … … …	..	…….. …….. …… ……
	198 89 107 8	20	11000101 01011000 01101010 00000111
Quaternary Encoding	22 51 241 4	1	0111 0303 3300 0003
	18 50 166 23	2	0100 0301 2211 0112
	37 48 121 34	3	0210 0300 1320 0201
	… … … …	..	…. …. …. ….
	198 89 107 8	20	3011 1120 1222 0013
Value Encoding	22 51 241 4	1	22 51 241 4
	18 50 166 23	2	18 50 166 23
	37 48 121 34	3	37 48 121 34
	… … … …	..	… … … …
	198 89 107 8	20	198 89 107 8
Real Encoding		1	41,87 85,81 631,61 22,9
		2	36,26 85,16 345,81 41,87
		3	65,52 81,29 216,13 58,84
		..	…… ….. ….. ……
		20	445,16 145,81 187,74 28,45

As seen from this table, in the population whose size is 20, each individual which is solution of the structural problems is shown as a string. The solution strings as for each encoding type constitute substring of uniform numbers in the interval [0, 1], [0, 1, 2], [0, 1, 2, 3], ..., [0, 1, 2, 3, 4, ..., n], where n is the number that calls encoding type, as consisting of integer numbers. Encoding type using uniform numbers in the interval [0, 1, 2] and [0, 1, 2, 3] can also be called as ternary and quaternary encoding, respectively. Moreover, as used real encoding, the solution string consists of real numbers which are cross-sections. In the table, each individual is carried out by four design variables. While the genotype of the first individual in binary notation is,

00010101 00111010 11110000 00000011

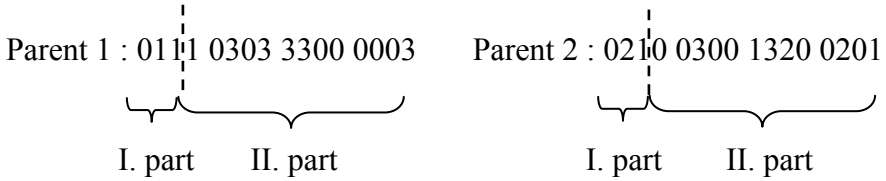
other solution strings of the same individual are represented in the value notation as

22 51 241 4.

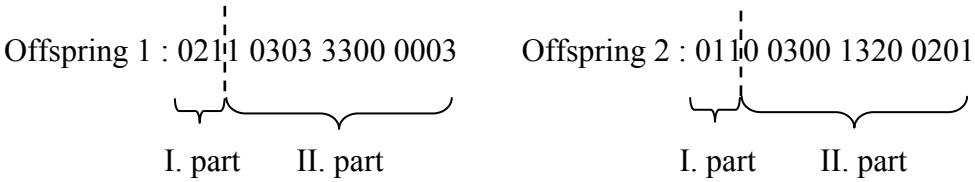
It is also shown in the encoding type having the interval [0, 1, 2, 3] (i.e. quaternary encoding) as

0111 0303 3300 0003.

As mentioned above, the genotype forms of individuals that have the same fenotype forms can be indicated by different representations. There are some advantages of using different representations for genotype. An encoding type for a structural problem is governed by the number of its member. If the number of member increases, the length of solution string is wanted to decrease (notably when the number of substring, that is, the number of design variable is getting more). So, encoding type can be decided as to the number of member.
The use of various encoding type sustains diversity of genetic operators such as crossover operator and mutation operator. When the interval [0, 1, 2, 3] is considered in two point-crossover, both of the matching pair is divided into two parts at crossover point selected at random along the string as seen below,



The design variables between the crossover points are swapped between parents. A crossover operation is carried out in the following example.



While determining crossover point, the point may be selected either the interval of segments or over the each segment. In the example above, the crossover point is over a segment. Hence, design variables not existing in the both of parents occur in the both of parents, where the crossover operator behaves the mutation operator. Moreover, the use of the other encoding types except value encoding and real encoding makes the abilities stated above possible because, in the encoding type having an interval, the design variables consist of a substring but not a number. The same situation is valid in three point-crossover and multi point-crossover.
When mutation is carried out in the value encoding and real encoding, the selected design variables are completely changed, but in the other encoding types including numbers uniform in a certain interval, only a bit in the substring of the design variables can be changed. Notably when size of database of cross-sections is large, implementation of mutation in the encoding type such as value encoding and real encoding transforms the exploration in search space into a purely random exploration.
An important point about which encoding type is preferred is the size of database concerning the problem. If database size for discrete design is 64, binary encoding, ternary encoding, octal encoding having the interval [0, 1, 2, 3, 4, 5, 6, 7], and the value encoding type can be used.

Design Examples

Using different encoding type obtains some advantage stated above. In this study, a portal frame and three-bay, three-story frame structure taken from literature are designed to be the minimum weight by different encoding type in genetic algorithm. In these two examples, it is considered that sidesway buckling or instability can not occur. A subroutine determining the effective length factor is introduced to the algorithm used in this study. The subroutine has got different formulas developed by GA (Mahfouz, 1999) and by least square method. The sidesway option is controlled by either input control parameter or relative displacements of all columns in the system.

A Portal Frame

A portal frame and its loading condition are given in Figure1.

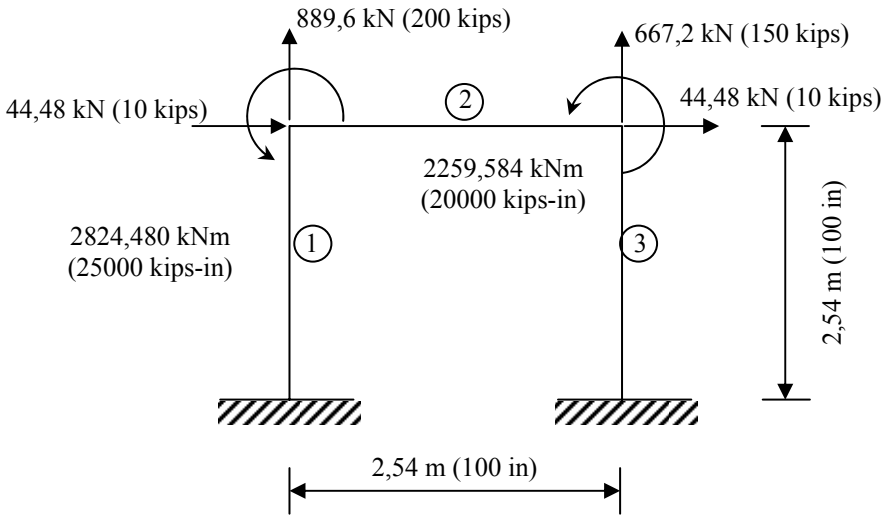
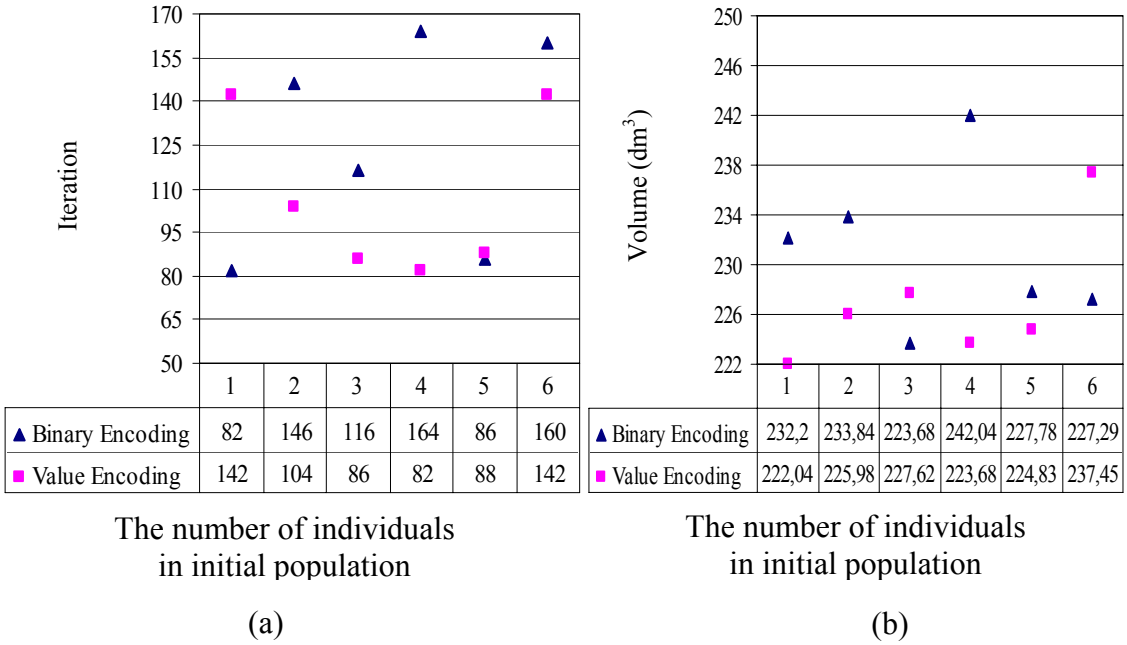


Figure 1. A portal frame and its loading condition

The portal frame was optimized by Tütüncü (1995). In the design, displacement constraint is not applied to the system, and the members are not organized into a group. The modulus of elasticity, E=199,955x10^6 kN/m^2 (29000 ksi), the yield stress, σ_a=248220 kN/m^2 (36 ksi). In the design, coefficient of penalty is equal to, $\bar{f}$, which is average of all fitnesses of individuals except for the first iteration where the coefficient equals to 2. In this design, firstly, 128 AISC W sections including all cross-sections in the sequence of order from 145,806 cm^2 (22,60 in^2) to 521,289 cm^2 (80,80 in^2) are considered. The design results obtained when both binary and value encoding are separately used are given in Figure 2. Population size is 100, which is the same with the initial populations under consideration given in Figure 3. When binary encoding and value encoding are separately used for six different initial populations, the number of iteration in the value encoding is generally smaller than that in binary encoding and the volume of the frame structure in value encoding is smaller than that in binary encoding. The volumes concerning the fifth initial population and the sixth initial population in binary encoding have a little violation, where it is seen that the volume concerning the sixth initial population is larger than that in the value encoding. Secondly, 64 AISC W

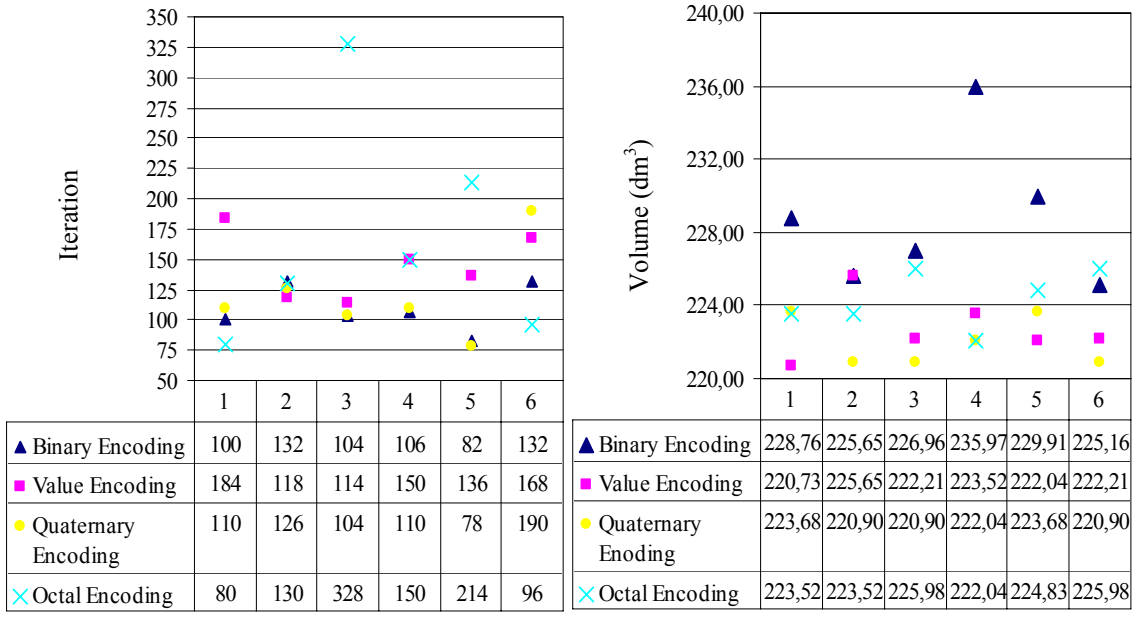


	1	2	3	4	5	6
Binary Encoding	82	146	116	164	86	160
Value Encoding	142	104	86	82	88	142

	1	2	3	4	5	6
Binary Encoding	232,2	233,84	223,68	242,04	227,78	227,29
Value Encoding	222,04	225,98	227,62	223,68	224,83	237,45

Figure 2. Comparison of design results obtained by using different initial population versus (a) iteration number and (b) volume of the portal frame

sections that are subset of the 128 AISC W sections are considered with the same of six initial populations. The design results obtained are shown in Figure 3.



	1	2	3	4	5	6
Binary Encoding	100	132	104	106	82	132
Value Encoding	184	118	114	150	136	168
Quaternary Encoding	110	126	104	110	78	190
Octal Encoding	80	130	328	150	214	96

	1	2	3	4	5	6
Binary Encoding	228,76	225,65	226,96	235,97	229,91	225,16
Value Encoding	220,73	225,65	222,21	223,52	222,04	222,21
Quaternary Enoding	223,68	220,90	220,90	222,04	223,68	220,90
Octal Encoding	223,52	223,52	225,98	222,04	224,83	225,98

Figure 3. Comparison of design results obtained by using different initial population versus (a) iteration number and (b) volume of the portal frame

In the results shown in this figure, the volumes in value encoding are smaller than those in binary encoding, but certain superiority for the number of iteration is not seen in comparison with each other. Moreover, when quaternary encoding is selected as

encoding type, the volumes have the smallest values. In Figure 3, the volume in the first initial population violates the constraints in a little rate. The volumes of design results in binary encoding are larger than those in the other encoding types. The volume concerning the sixth initial population in binary encoding has a little violation. Although the number of sections is not considered as many as in the literature, the design results in this study are similar to that in the literature and they are presented in Table 2.

Table 2. Design results of the portal frame

Member	Area (cm^2)					
	Briggs ve Willmert (Tütüncü, 1995)	Erbatur ve Al-hussainy (Tütüncü, 1995)	Tütüncü GA (1) (1995)	Tütüncü GA (2) (1995)	Tütüncü GA (3) (1995)	This study
1	127,355	247,096	246,451	160,000	159,355	159,999
2	679,870	493,547	462,580	472,902	469,676	508,386
3	194,387	204,516	210,967	220,645	206,451	201,290
Volume (dm^3)	254,409	240,070	233,680	216,801	212,212	220,090

Three-Bay and Three-Story Frame Structure

Configuration and load conditions of three-bay and three-story frame structure are given in Figure 4.

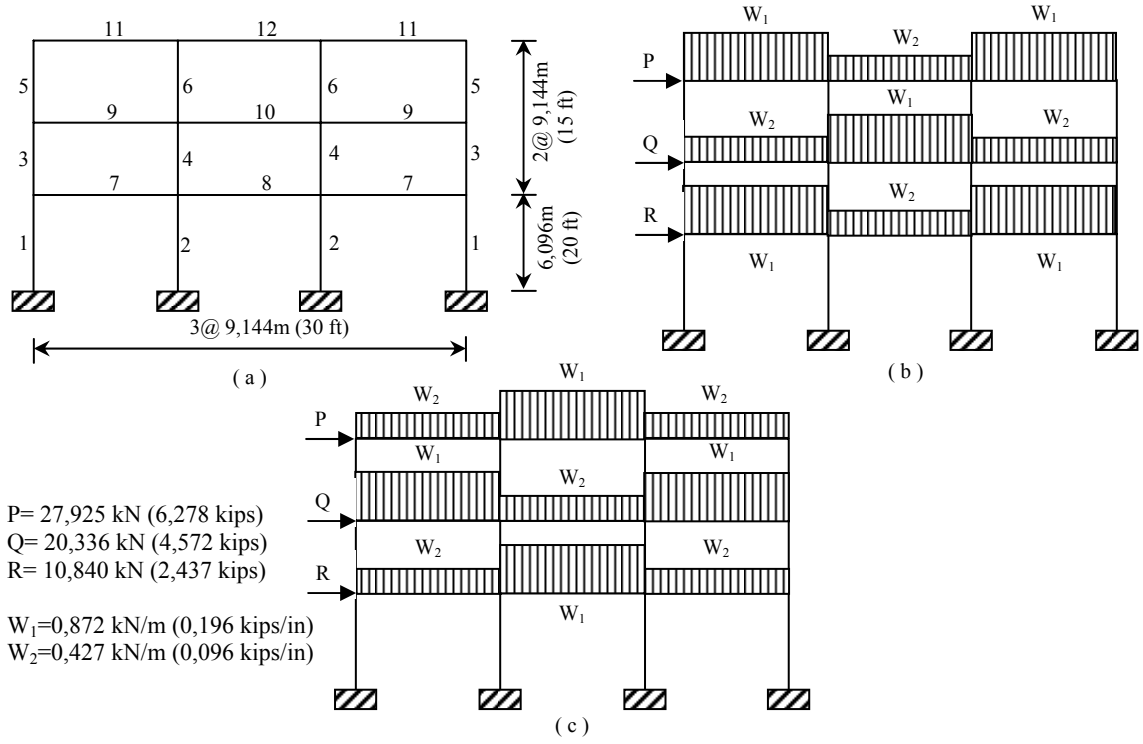
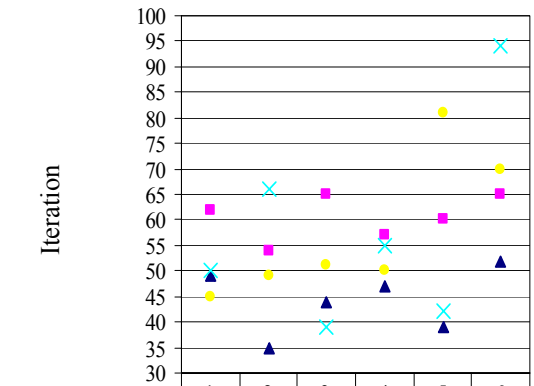


Figure 4. Three-bay and three-story frame structure and its load conditions

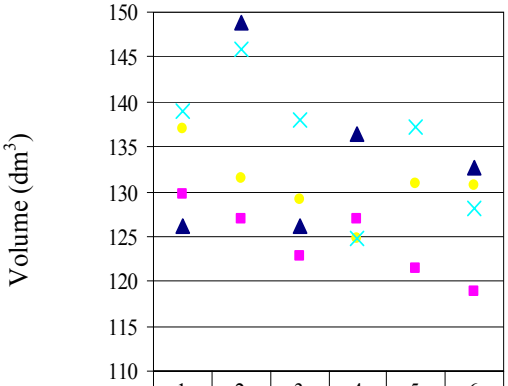
This system was also designed to be minimum weight by Cao (1996). The system consists of 21 members organized into 12 groups. The modulus of elasticity, $E=199{,}955 \times 10^6$ kN/m^2 (29000 ksi), the yield stress, $\sigma_a=248220$ kN/m^2 (36 ksi). Allowable story drift is defined as $0{,}0015h/C_d$, where h is the story height and C_d is

deflection amplification factor and equals to 4,0. 64 AISC W sections including all cross-sections having largest moment of inertia among the same cross-sections in the sequence of order from 47,355 cm^2 (7,34 in^2) to 183,871 cm^2 (28,50 in^2) are taken as profile database. The system is designed for two different load conditions. In the design, quadratic penalty function is chosen. Population size is 50. When the genotype forms of individuals are separately represented with binary encoding, value encoding, quaternary encoding, and octal encoding, the design results obtained are given for six different initial populations in Figure 5.



	1	2	3	4	5	6
Binary Encoding	49	35	44	47	39	52
Value Encoding	62	54	65	57	60	65
Quaternary Encoding	45	49	51	50	81	70
Octal Encoding	50	66	39	55	42	94

The number of individuals in initial population



	1	2	3	4	5	6
Binary Encoding	126,1	148,9	126,1	136,3	154,2	132,7
Value Encoding	129,7	127	122,8	127	121,4	118,9
Quaternary Enoding	137	131,5	129,1	124,8	130,9	130,6
Octal Encoding	139	145,9	137,9	124,9	137,2	128,2

The number of individuals in initial population

Figure 5. Comparison of design results obtained by using different initial population versus (a) iteration number and (b) volume of the three-bay, three-story frame structure

As seen from this figure, the iteration number in the design process is the least in binary encoding. However, the least volumes among twenty four design results are generally obtained for value encoding. The volumes that are of values of 28,819 dm^3, 29,029 dm^3, 29,363 dm^3, 28,343 dm^3, and 29,827 dm^3 have a little percentage of violation. Although the number of sections is not considered as many as in the literature, the design results in this study are similar to that in the literature and they are presented in Table 3.

Table 3. Design results of the three-bay and three-story frame structure

Group No	Area (cm^2)												Weight (kN)
	1	2	3	4	5	6	7	8	9	10	11	12	
Cheng and Juang (Cao, 1996)	155,484	123,226	155,486	100,645	155,486	76,129	104,516	94,839	94,839	94,839	104,516	94,839	123,032
Soda (Cao, 1996)	92,903	143,871	113,548	90,968	113,548	58,903	129,032	113,548	127,097	127,097	129,032	129,032	128,770
Cao	100,645	129,032	85,161	100,645	76,129	76,129	104,516	117,419	104,516	117,419	104,516	104,516	113,139
This Study	92,9	136,129	74,193	100,645	75,484	58,903	129,032	113,548	118,064	127,097	104,516	134,193	118,893

Conclusion

In this study, the application of different encoding types in the GA are discussed and evaluated. Different encoding types such as binary encoding, value encoding, quaternary encoding, and octal encoding are compared with each other. A certain superiority of an encoding type in comparison to each other may not be comprehended as seen from figures. However, it can be stated that when a structural problem is designed by using each of the encoding types mentioned above, it can be found that an encoding type can give the best optimum solution when compared to the results of the others. The use of different encoding types provides some advantages mentioned in the section, Encoding Type.

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