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Optimization-Based Design of 3D Reinforced Concrete Structures

H. Dehnavipour[1*], M. Mehrabani[2], A. Fakhriyat[2], A. Jakubczyk-Gałczyńska[3]

1. Ph.D. Student, Faculty of Civil Engineering, Semnan University, Semnan, Iran
2. M.Sc., Department of Civil Engineering, Behbahan Khatam Alanbia University of Technology, Behbahan, Iran
3. Assistant Professor, Department of Construction Management and Earthquake Engineering, Faculty of Civil and Environmental Engineering, Gdansk University of Technology, Gdansk, Poland

Corresponding author: *dehnavipour@semnan.ac.ir*

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ABSTRACT

In the design of reinforced concrete (RC) structures, finding the optimal section of members and the optimal rebar, which is capable of observing building code's requirements, is always the primary concern to engineers. Since an optimal design needs a trial-and-error approach, which designs are almost assumed without this approach, that is unlikely to lead to the best solution. Therefore, in this article, the aim is achieving an optimal structural design that can satisfy the building code's requirements, such as constraints on flexural strength, shear strength, drift, and constraint of construction at the same time. The work is presented in this paper intends to accelerate the process with an optimization system. To do so, a six-story RC structure analyzed by the linear static method and results of the optimization process, done by the Particle Swarm optimization algorithm (PSO), has shown that the weight of the structure optimized and observed limitations.

1. Introduction

In the design of the concrete structures, choosing the section of members, the types of reinforcing bars, and the number of reinforcing bars is three important economical factors. Thus,

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selecting the optimal sections and reinforcing bars, which are proportional to the maximum capacity of members, is the problem that always has challenged engineers. In the past years, some research have been widely carried out in the field of structural optimization. Fadaee and Grierson optimized a single-story three-dimensional structure with and without the shear wall, respectively [1,2]. Kwak and Kim applied a database, including pre-determined sections, to optimize reinforced concrete frames. They used Regression relationships to enhance the convergence rate of the selected algorithm [3]. Fragiadakis and Papadrakakis optimized the design of concrete structures based on performance under dynamic loading. The objective function was the reduction of structural cost and improvement of seismic performance [4]. Kaveh and Zakian evaluated the optimality of shear walls, beams, and columns properties in a concrete frame [5]. Atabay used a discrete genetic algorithm to optimize the size of a non-beam shear wall in accordance with the design requirements of the concrete structures and the displacement limitation [6]. Gharehbaghi and Salajegheh used hysteresis energy as the objective function to optimize moment-framed concrete structures. They studied the effects of hysteresis cycles, which represent the value of energy loss resulted from nonlinear cyclic, displacements of members [7]. In order to reach an optimal moment steel frame, Gong and et al. utilized the time history analysis to determine seismic response and the multi-objective genetic algorithm to solve the problem [8]. Further, Akin and Saka presented the optimization of the reinforced concrete plane frames by the harmony search algorithm. The objective function was the frame cost, including the cost of concrete, framework, and reinforcing steel for each member of the frame [9]. The optimization of the member properties in irregular steel structures has been presented by Aydoğdu et al. using the ant colony algorithm, in which the weight considered as the objective function [10]. Also, a hybrid method of optimality criteria and the genetic algorithm was investigated by Chan and Wong to optimize the properties of steel frame members. The main goal of the research mentioned above was minimizing the size of member sections and reaching the optimal layout of braces by using the topological variables as the on/off status for each pair of the diagonal cross the braces [11]. Kaveh and Ilchi Ghazaan also optimized the irregular structure under dynamic spectral loading, in which structural weight considered as the objective function by modified algorithms, and then compared their responses [12]. Vaez and Qomi indicated the optimization of the shear wall, which its focus was on properties of walls as the only variable. The weight compared by two kinds of variables, continuous and discrete [13]. Siemaszko et al. also considered an optimization problem. Probabilistic methods proposed to estimate the occurrence of paraseismic vibrations [14]. The Bayesian networks, EVSI method, and entropy method compared. The results showed that the use of Bayesian networks was an effective approach to assess the impact of vibrations. An interesting approach to solve this type of problem is also presented in [15]. Khatami et al. proposed an effective formula for the impact damping ratio as a parameter used to study different problems of structural pounding under seismic excitations, and the results confirm the effectiveness of the described method. Farahnaki applied the Particle Swarm algorithm to estimate the strength of reinforced concrete flexural members [16].

1.1. Research significance

In the majority of research, structures have been assessed in the two-dimension state. On the other hand, a database, including the properties of members, is used in most past research. This approach has two disadvantages; First, according to limitations of time, a few assumed properties can be utilized. Second, these limit databases maybe not considered all optimal solutions and resulted in local optimization. In this article, the concrete structure concerning the equal possibility of properties of members has been optimized.

2. Formulation of optimization for 3D reinforced concrete structure

An optimization problem is consisting of an objective function, design constraints, and design variables. The general form of the problem is expressed in equation (1).

Minimize F(X) $\mathrm{x} = [\mathrm{x}_1, \mathrm{x}_2, \mathrm{x}_3, \ldots, \mathrm{x}_n]^T$

$$\text{Subject to:} \begin{cases} G_m\,(x) \leq 0 & m = 1,2,3 \ldots o \\ h_n\,(x) = 0 & n = 1,2,3 \ldots p \\ X_l^{min} < X_l < X_l^{max} & l = 1,2,3 \ldots q \end{cases} \tag{1}$$

Where X and F(X) represent design variable, the objective function should be minimized, respectively; and also, $G_m(x)$ and $h_n(x)$ describe the inequivalent and equivalent constraints of the problem, which are taken in according to considerations such as seismic and constructional requirements, respectively. X_l^{min} and X_l^{max} are lower and upper bound of variables, respectively. O, p, and q denote the number of inequivalent and equivalent constraints and variables, respectively.

2.1. The objective function

The conventional designs make an acceptable state that can only satisfy the practical requirements of the problem, while the purpose of this article is finding the minimum solution. The optimization methods make it possible to find the best design from the others. Accordingly, it is necessary to exist a criterion that differentiates the best solution of all acceptable ones. This criterion, which problem will be optimized by that, is called the objective function, and it is introduced by design variables. Selecting the objective function depends on the basis of problems.

The considered objective, in this article, is the minimization of the structural cost, and is as follow:

$$Cost = c_c + c_s + c_f \tag{2}$$

In the equation mentioned above, parameters of c_f, c_c, c_s are framework cost, concrete cost, and steel cost, respectively; and are expressed in Eqs (3), (4), and (5).

$$\begin{cases} C_{s_{beam}} = \sum_{m=1}^{n_b} A_{stotal}(m) y_s L_b(m) U_s \\ C_{c_{beam}} = \sum_{m=1}^{n_b} ((b_b(m)\, h_b(m)) - A_{stotal}(m)) y_c L_b(m) U_c \\ C_{f\,beam} = \sum_{m=1}^{n_b} 2((b_b(m)\, h_b(m)) L_b(m) U_f \end{cases} \tag{3}$$

$$\begin{cases} C_{s_{column}} = \sum_{m=1}^{n_c} A_{stotal}(m) y_s L_c(m) U_s \\ C_{c_{column}} = \sum_{m=1}^{n_c} ((b_c(m) h_c(m)) - A_{stotal}(m)) y_c L_c(m) U_c \\ C_{f\,column} = \sum_{m=1}^{n_c} 2((b_c(m) h_c(m)) L_c(m) U_f \end{cases} \tag{4}$$

$$\begin{cases} C_s = C_{s_{column}} + C_{s_{beam}} \\ C_c = C_{c_{column}} + C_{c_{beam}} \\ C_f = C_{f_{column}} + C_{f_{beam}} \end{cases} \tag{5}$$

Where n_b and n_c are the total number of beams and columns, respectively. Value of m is subscript of sections, as well A_{stotal} denotes the total area of reinforcing bars. L_b, L_c, h_b, and h_c refer to the lengths and heights of the beams and the columns, respectively. Furthermore, U_s, U_c, and U_f are steel price per area, the concrete price per area, and framework price per area, respectively. Finally, y_s and y_c are the density of steel and concrete.

2.2. The variables of the optimization problem

The optimization problem includes a set of deterministic and variable parameters. Deterministic parameters are constant values, while the variable parameters, called the design variable, are changing in the optimization procedure. The set of these variables are called vector variable. In this article, area sections and bar diameters of beams and columns are the variables.

2.3. The design constraints of the optimization problem

The design constraints used in this article consist of practical constraints such as decreasing the value of properties members, section and reinforcing bars, in upper stories, while each side of a section should not exceed 50 millimeters.

$$G_{b1}(x) = \frac{h_{b\,i+1}}{h_{bi}} - 1 \leq 0 \qquad i = 1, \dots, N_{story} \tag{6}$$

$$G_{b2}(x) = \frac{b_{bi+1}}{b_{bi}} - 1 \leq 0 \qquad i = 1, \dots, N_{story} \tag{7}$$

$$G_{c3}(x) = \frac{h_{c\,i+1}}{h_{ci}} - 1 \leq 0 \qquad i = 1, \dots, N_{story} \tag{8}$$

$$G_{c4}(x) = \frac{b_{c\,i+1}}{b_{ci}} - 1 \leq 0 \qquad i = 1, \dots, N_{story} \tag{9}$$

$$G_{b5}(x) = \frac{d_{b\,i+1}}{d_{bi}} - 1 \leq 0 \qquad i = 1, \dots, N_{story} \tag{10}$$

$$G_{c6}(x) = \frac{d_{c\,i+1}}{d_{c\,i}} - 1 \leq 0 \qquad i = 1, \dots, N_{story} \tag{11}$$

$$G_{b7}(x) = \frac{nd_{bi+1}}{nd_{bi}} - 1 \leq 0 \qquad i = 1, \ldots, N_{story} \tag{12}$$

$$G_{c8}(x) = \frac{nd_{c\,i+1}}{nd_{c\,i}} - 1 \leq 0 \qquad i = 1, \ldots, N_{story} \tag{13}$$

Following geometric constraints are indicated which members should observe the limitation of codes. These constraints are observing the minimum and maximum of longitudinal and stirrups, $A_{sb,min}$ $A_{sb,max}$, $A_{sc,min}$, $A_{sc,max}$, and $A_{v,min}$, in beams; observing minimum and maximum distance between of longitudinal and stirrups in columns and beams, $S_{b,min}$, $S_{vb\,,max}$, $S_{vb\,,min}$, $S_{b,max}$, $S_{c\,min}$, $S_{c\,,max}$, $S_{vc\,min}$, and $S_{vc\,max}$. Finally, the constraint of the ratio between beam width, b_b , to column width, b_c.

$$G_{b9}(x) = \frac{A_{sb\,,min,i}}{A_{sb\,,i}} - 1 \leq 0 \qquad i = 1, \ldots, N_b \tag{14}$$

$$G_{b10}(x) = \frac{A_{sb,i}}{A_{sb,max,i}} - 1 \leq 0 \qquad i = 1, \ldots, N_b \tag{15}$$

$$G_{b11}(x) = \frac{A_{vb\,,min,i}}{A_{vb\,,i}} - 1 \leq 0 \qquad i = 1, \ldots, N_b \tag{16}$$

$$G_{c12}(x) = \frac{A_{sc\,,min,i}}{A_{sc\,,i}} - 1 \leq 0 \qquad i = 1, \ldots, N_{column} \tag{17}$$

$$G_{c13}(x) = \frac{A_{sc\,,i}}{A_{sc\,,max,i}} - 1 \leq 0 \qquad i = 1, \ldots, N_{column} \tag{18}$$

$$G_{b14}(x) = \frac{A_{vc,min,i}}{A_{vc\,,i}} - 1 \leq 0 \qquad i = 1, \ldots, N_{column} \tag{19}$$

$$G_{b15}(x) = \frac{S_{b\,,min,i}}{S_{b\,,i}} - 1 \leq 0 \qquad i = 1, \ldots, N_b \tag{20}$$

$$G_{b16}(x) = \frac{S_{vb\,,min,i}}{S_{vb\,,i}} - 1 \leq 0 \qquad i = 1, \ldots, N_b \tag{21}$$

$$G_{b17}(x) = \frac{S_{vb\,,i}}{S_{vb\,,max,i}} - 1 \leq 0 \qquad i = 1, \ldots, N_b \tag{22}$$

$$G_{c18}(x) = \frac{S_{c\,,min,i}}{S_{c\,,i}} - 1 \leq 0 \qquad i = 1, \ldots, N_{column} \tag{23}$$

$$G_{c19}(x) = \frac{S_{c\,,i}}{S_{c\,,max}} - 1 \leq 0 \qquad i = 1, \ldots, N_{column} \tag{24}$$

$$G_{c20}(x) = \frac{S_{vc\,,min,i}}{S_{vc\,,i}} - 1 \leq 0 \qquad i = 1, \ldots, N_{column} \tag{25}$$

$$G_{c21}(x) = \frac{S_{vc\,,i}}{S_{vc\,,max,i}} - 1 \leq 0 \qquad i = 1, \ldots, N_{column} \tag{26}$$

$$G_{j22}(x) = \frac{W_{b\,,i}}{W_{c\,,i}} - 1 \leq 0 \qquad i = 1, \ldots, N_{joint} \tag{27}$$

Moreover, other constraints are controlling the flexural capacity of beams and columns, $\emptyset M_{nb}$ and $\emptyset M_{nc}$, respectively; controlling the shear capacity of beams and columns, $\emptyset V_{nb}$ and $\emptyset V_{nc}$, according to ACI318-14 [17]; and controlling the elastic of each story based on the exact computed fundamental period of the structure without any upper limit according to ASCE7-16 [18].

$$G_{b23}(\mathrm{x}) = \frac{|\mathrm{M}_{\mathrm{u}b,(\mathrm{i,j})}|}{|\emptyset \mathrm{M}_{\mathrm{nb},\mathrm{i}}|} - 1 \leq 0 \qquad \mathrm{i} = 1, \ldots, \mathrm{N}_{\mathrm{beam}} \tag{28}$$

$$G_{c24}(\mathrm{x}) = \frac{|\mathrm{M}_{\mathrm{uc},(\mathrm{i,j})}|}{|\emptyset \mathrm{M}_{\mathrm{nc},\mathrm{i}}|} - 1 \leq 0 \qquad \mathrm{i} = 1, \ldots, \mathrm{N}_{\mathrm{column}} \tag{29}$$

$$G_{b25}(\mathrm{x}) = \frac{|\mathrm{V}_{\mathrm{ub},(\mathrm{i,j})}|}{|\emptyset \mathrm{V}_{\mathrm{nb},\mathrm{i}}|} - 1 \leq 0 \qquad \mathrm{i} = 1, \ldots, \mathrm{N}_{\mathrm{beam}} \tag{30}$$

$$G_{c26}(\mathrm{x}) = \frac{|\mathrm{V}_{\mathrm{uc},(\mathrm{i,j})}|}{|\emptyset \mathrm{V}_{\mathrm{nc},\mathrm{i}}|} - 1 \leq 0 \qquad \mathrm{i} = 1, \ldots, \mathrm{N}_{\mathrm{column}} \tag{31}$$

$$G_{j4}(\mathrm{x}) = \frac{\Delta_{\mathrm{i}}}{\Delta_{\mathrm{a,i}}} - 1 \leq 0 \qquad \mathrm{i} = 1, \ldots, \mathrm{N}_{\mathrm{column}} \tag{32}$$

In the equation mentioned above, G denotes constraints.

3. The penalty function

Generally, there are two ways to solve constrained problems. First, the constrained problem turns into an unconstrained state; And second, solving the problem directly. Since the structural problems are nonlinear and solving them are complex, thus, here is used the first approach, which is called the penalty method. Accordingly, the objective function will be summed with all violations caused by those constraints that did not observe the limitations.

$$g_j(X) = \frac{g}{g_{max}} - 1 \tag{33}$$

$$\mathrm{M(X)} = Cost + R_P \sum_{m=1}^{n} \max(0, g_j(X))^2 \tag{34}$$

Where M(x) is the new objective function; R_P is the penalty factor, assumed a constant value; n denotes the number of violated constraints; and g_{max} is the maximum constraint value of g.

3.1. Particle swarm algorithm

The particle swarm algorithm is a metaheuristic algorithm. PSO algorithm treats as species of animals, such as birds and fish, that they have a social life, and make a decision. In general, it can be said that this algorithm is based on plural intelligence [19]. PSO consists of particles that represent an m-dimensional vector in the space search, and each particle has a specific velocity, which relatively moves in the search space to improve its position in the set. This vector is included in three-dimensional:

First, the position vector of x_t^i, in which located particle; second, the vector of the best previous position of g_t ; and third, velocity vector of v_t^i. The algorithm evaluates its current position, and then, if a better position has found the coordinate of the new position will be saved in the vector of g_t . In fact, the purpose is saving the best positions, and updating the vector of g_t and the value of g_t^{i} . By adding the coordinate of v_t^i to x_t^i, new points will be generated. The position vector of x, depended on the ith particle, is improved in the iteration of t+1 by Eq (35).

$$x_{t+1}^{i} = x_{t}^{i} + v_{t+1}^{i} * \Delta t \tag{35}$$

x_{t+1}^{i} is referred to as the second velocity, and Δt is the value of the time step, which is considered equal to one. The velocity vector of each particle is as follow:

$$v_{t+1}^{i} = w * v_{t}^{i} + c_1 r_1 * \left(g_t^{i} - x_t^{i}\right)/\Delta t + c_2 r_2 * \left(g_t^{g} - x_t^{i}\right)/\Delta t \tag{36}$$

v_t^i is referred to as the velocity vector of each particle in the Tth iteration. r_1 and r_2 are uniformly distributed random variables between 0 and 1. g_t^{i} represents the best position of ith particle, and g_t^{g} represents the best position of ith particle the generation. Other parameters are dependent, for instance, $c_1$and c_2 are reliability parameters indicate the amount of reliability to the treatment of particles or movement of the generation. Parameter W has an essential role in algorithm convergence, such that large amounts of W can increase the values of the velocity vector, particularly in the last iterations.

4. Design example and results

In this article, a six-symmetric-story structure is used, which its 3D model is shown in fig (1). The height of each story is the same and is equal to 3 meters. The frames in both directions were moment-resisting, and all joints were rigid. The flooring system considered to be a two-way slab. Lateral forces are affecting the frames applied at the center of the mass of each story. Furthermore, in order to consider the effect of cracking, the moment of inertia of the cross-section for each member is calculated according to ACI 318 code [17] using the equations shown in Eqs. (37) and (38).

$$I_{\mathrm{Beam}} = 0.35\, I_{\mathrm{g}} \tag{37}$$

$$I_{\mathrm{Column}} = 0.7\, I_{\mathrm{g}} \tag{38}$$

where I_{g} is the gross moment of inertia of the section of the beam or column.

The equivalent static analysis applied for determining structural demands via OpenSees [20] software. In order to consider arrangements of bars, fiber sections defined by using nonlinear beam-column elements with elastic behavior. These are programmed to change adaptively for each section. Other computer program, optimization procedure, are coded in MATLAB [21] software. Therefore, the interference between the software of MATLAB and OpenSees is accomplished for the optimization process.

Both beams and columns are classified into three groups, not only in the elevator but also in the plan. The grouping members are shown in fig (2). Also, the two-way slab is used for the rigid diaphragms.

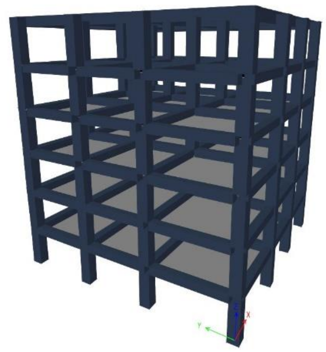

Fig. 1. The 3D model of the six-story structure.

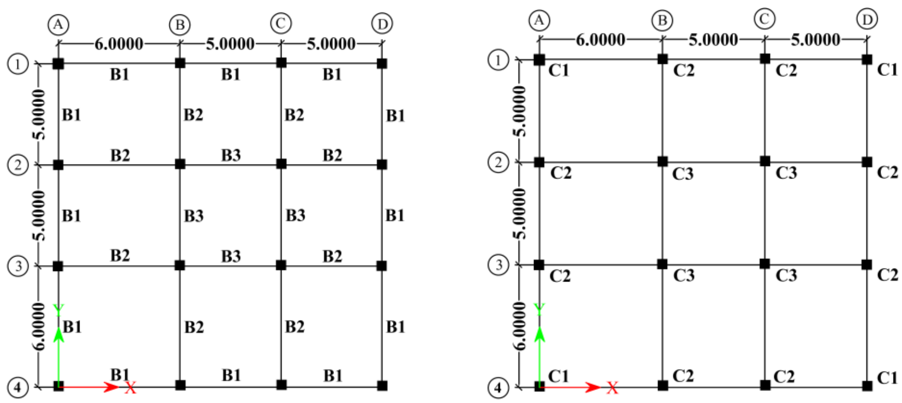

Fig. 2. Member grouping in plan.

Compression strength of f_c = 25 MPa; yield stress of F_y = 400 MPa; and modulus of elasticity for the bar is equal to E_s= 20000 MPa, and for concrete calculate by Eq (39) [16].

$$E_c = 4700\sqrt{f_c'} \tag{39}$$

Steel weight and steel weight per unit volume of ρ = 7,850 kgf/m^3, and concrete weight per unit volume of ρ = 2,450 kgf/m^3. The cover of concrete was taken as c = 40 mm. For column sections, a symmetrical pattern for bars was considered. In this study, the minimum diameter of transversal steel is considered as ϕ10. Width, depth, and interval values for columns are as: 300 < b_c < 750 is the width domain of columns with 50 mm interval value. Width, depth, and interval values for beams are as: 250 < b_b < 700 is the width domain of beams with 50 mm interval value; 350 < h_b < 850 is the depth domain of the beams. The structural characteristics of the frames include a service dead load of D = 5.9 kN/m^2, and uniform service live load of L = 2 kN/m^2. Load combinations are based on the ACI 318-14 code [17] as:

$$U = 1.4\,D$$
$$U = 1.2\,D + 1.6\,L$$
$$U = 1.2\,D + 1.0\,L + E$$

where D, L, and E are the assumed dead, live, and lateral loads, respectively. Allowable drift ratio is considered as 0.0045, according to ASCE7-16 [18]. At the beginning of the optimization procedure, some parameters are indicated in the table (1).

Table. 1
PSO parameters.

Parameters	Iteration	knop	C1	C2	Alfa
Values	150	10	2	2	0.9

Since this study is not used a database, the programming is scripted that the beams of the first story generate between allowed interval, then other beams in structure, and all columns will be generated relatively to satisfy the limitations. This approach to generating the variables not only reduces the time duration of the optimization procedure, but it also will be resulted in optimal design. Therefore, three design variables as the unit cost of members are included.

The convergence curve of the optimization algorithm is demonstrated in Fig. 3.

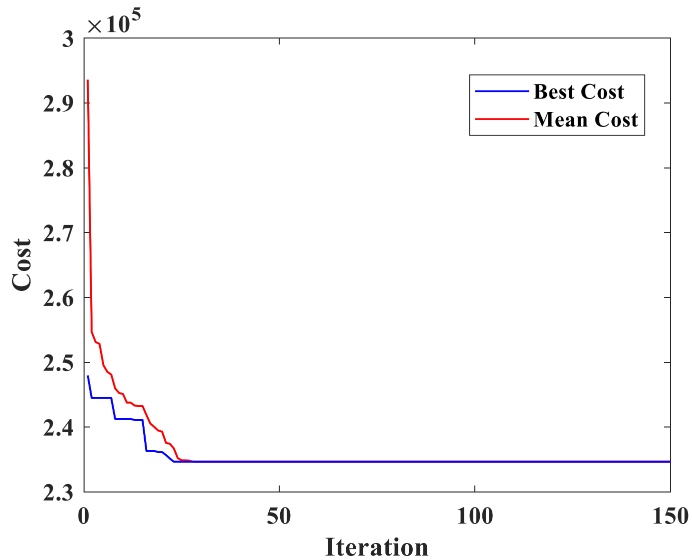

Fig. 3. Convergence curve of PSO for six-story RC structure.

The obtained optimized structural members presented provided in tables (2) and (3).

Table 2
Optimal Beam Properties**.**

Element	Number	Dimensions (mm)		Reinforced (%)		
type	Group	Width	Height	I	Mid	J
B1	1	400	550	0.24	0.61	0.24
	2	400	500	0.23	0.61	0.23
	3	350	400	0.32	1.04	0.32
B2	1	350	500	0.44	0.83	0.44
	2	350	450	0.31	0.83	0.31
	3	300	350	0.43	1.75	0.43
B3	1	400	500	0.26	0.61	0.26
	2	350	400	0.33	1.04	0.33
	3	300	350	0.43	3.28	0.43

Table 3
Optimal Column Properties.

Element	Number	Dimensions (mm)		Reinforced (%)		
type	Group	Width	Height	I	Mid	J
C1	1	550	550	3.45	3.45	3.45
	2	500	500	1.81	1.81	1.81
	3	400	400	1.57	1.57	1.57
C2	1	500	500	1.86	1.86	1.86
	2	400	400	1.79	1.79	1.79
	3	400	400	0.89	0.89	0.89
C3	1	500	500	2.36	2.36	2.36
	2	500	500	1.51	1.51	1.51
	3	500	500	1.13	1.13	1.13

Drift ratios of each story of the frame are plotted in Fig. 4 for the critical load combination.

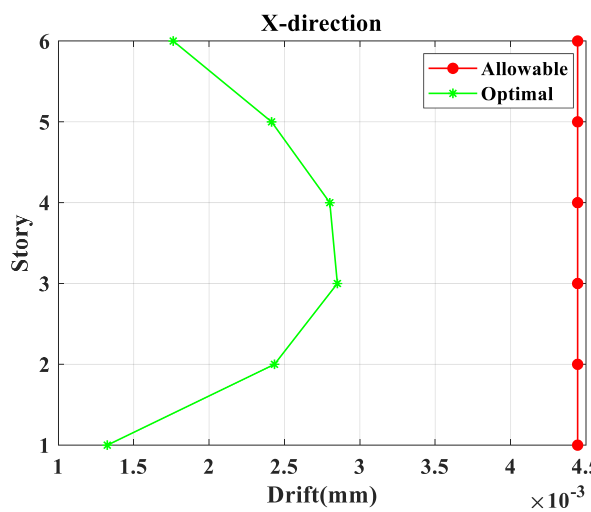

Fig. 4. Drift Ratios of the Attained Optimum six-story structure.

5. Conclusion

In the design of a building, elements should have properties that satisfy requirements and low cost. Accordingly, this approach needs the use of a procedure which converge to optimal solutions. It can be seen that the values of drift are lower than the allowable value; this is because of the effects of other constraints that selected members in this way. An efficient optimal design is a solution that the constraint values be near to their boundaries, minimize the objective function, and simultaneously satisfying the design constraints, which in this article has achieved this goal. In this article, the properties of the structural elements optimized. In order to perform an effective and faster convergence rate in optimization time, the section of columns and beams generated without any database. The principal ordinary and seismic design codes, such as ACI and ASCE codes, are imposed. This procedure helps the engineers to not only reduce the structural cost, and avoid the tedious trial-and-error procedures, but also carry out automatically the optimal seismic design.

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