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Optimal Design of Mixed Structures under Time-history Loading Using Metaheuristic Algorithm

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Abstract

In this paper, an optimum design of concrete-steel mixed frames under time-history loadings was formulated as an optimization problem. The behavior of a mixed structure is different from the steel and reinforced concrete structures because of vertically irregular in their mass, stiffness and damping of each part. Moreover, current codes and available commercial software packages do not present solutions for such structures. Researches have indicated that the structures exhibit higher-mode effects and responses that are sensitive to the relative stiffness and mass of the two parts of the structures. Thus, the equivalent static analysis is not applicable, a dynamic analysis has to be performed to analyze and design such structures. Therefore, the optimum design of mixed structures under an earthquake can be relatively complicated and time-consuming. Because the design methods for these structures are iterative and dynamic. The main objective is to find the minimum cost of the structure under time-history loadings while satisfying all design constraints. The results show that the proposed optimization procedure is ideal to obtain the optimum design for a mixed structure subjected to time-history loadings. Also, for comparison, the optimal design of reinforced concrete (RC) frames and steel frame are presented using the algorithm.

Keywords

mixed structures, structural optimization, improved plasma generation optimization (IPGO) algorithm, time-history analysis

1 Introduction

Due to reduced costs and faster time, designers select novel structural systems that are not well-addressed by the current codes. Specifically, mixed structures are a vertical combination of seismic force-resisting systems, in which a stiff and massive lower structure (e.g., reinforced concrete frames) is used to support a less massive, less stiff upper tower structure (e.g., steel frames). These structures are vertically irregular in their stiffness, mass and damping thus the analysis of the structures under a stimulation earthquake can be very complicated if they are designed according to design codes. Because the design methods for these structures are iterative and dynamic. The codes recommend only that irregular structures be preferentially designed using dynamic analysis but give no further guidance regarding the expected behavior. Researches has demonstrated that the structures exhibit higher-mode effects and responses that are sensitive to the relative stiffness and mass of the two parts of the structures. Research has observed that higher mode effects are potentially more substantial for irregular structures than regular structures, particularly as the extent of the irregularity increases. The modal periods depend on the distribution of mass and stiffness in the structure, this means that the shear of the storeys may be amplified relative to those predicted by the first mode alone. The equivalent static analysis is not applicable, a computer-based dynamic analysis has to be conducted for analyzing and designing such structures. The static procedures are generally applicable only to the first mode vibration of regular structures, and therefore less accurate as the degree of irregularity and thus the significance of higher-mode effects increases [1]. Specifically, an enhancement of the irregularity effect on the higher-mode response, and just in some specific conditions is the first mode dominant. In general, the equivalent static force method does not use for irregular structures, it is appropriate for regular structures [2, 3]. But the two-stage procedure is used for the podium and tower of setback structures in two separate structures and the equivalent static loads are used for each structure [4].

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Researches have used different terminology for irregularity structures, some studies refer to these structures as (vertically) mixed structures [5–8], other studies refer to hybrid, podium and setback structures, and vertical combination of the systems [9–11]. The current study will use mixed structures. There are in general three aspects of continuing interest in research: 1) experimental and numerical examples of the structural behavior; 2) characterization of strength, ductility and damping; 3) The analysis methods to evaluate structural demands. Few studies investigated experimental and numerical tests. The shake table tests of the 3-storey wood-concrete structure are investigated by Xiong et al. [9]. They apperceive that the structure responses increase with reduction of the stiffness ratio. Lu et al. [12] designed a 12-storey frame with a four-storey steel structure, a seven-storey concrete and a one-storey transition storey. They apperceive that the stiffness ratio influences the acceleration of the structure [12]. Maley et al. [13] performed nonlinear time-history analysis, displacement-based design and equivalent static method for numerical examples. They apperceive that the response (drifts and deformations of the higher mode) of mixed structures is sensitive to the inelastic behavior changes. Chen and Ni [14] designed wood-concrete structures and they found that the two-step analysis procedure is used in the design of these structures when the stiffness ratio is greater than 10 times the mass ratio. Fragility curves of the mixed concrete-steel structures are developed by Pnevmatikos et al. [15] and parametric numerical results for these mixed structures are presented and discussed.

Part of the studies of the mixed structures is about the characterization of strength, ductility and damping. Papageorgiou and Gantes [16] presented a semi-empirical error minimization method for obtaining the equivalent damping ratio. Lee et al. [17] calculated the equivalent damping ratio by adding dampers to SDOF structure and substituting multi-storey structure. Fanaie and Shamlou [18] investigated seismic characteristics such as period, ductility factor and response modification factor for the mixed structures. Farghaly [19] obtained the equivalent damping ratio for different heights of the structure and different types of the structural system and he introduced the structural system with the most energy amortization. Kaveh and Ardebili [20] investigated 12 mixed structures in two categories with different numbers of concrete and steel storeys. They suggested an equivalent damping ratio for mixed structures in different soil types and storeys number of the concrete and steel.

The previous studies are not the scope of this paper. The final part of studies for vertical mixed structures concerns the simplified methods for the analysis and design of these structures. The solutions of the problems are divided into two groups while both of them use an equivalent 2DOF model. One part of the method is more approximate and practical, code-specified design [10], while the other part is concerned with simplifying nonlinear analysis rather than immediate application to design [21]. Ugel et al. [22] designed a four-storey concrete and steel structure according to Venezuelan seismic codes. They designed all structural elements with the linear analysis but the demands and performance of the elements were calculated with push-over analysis, the calculation of over strength, ductility and displacements with dynamic analysis, and fragility curves with incremental dynamic analysis. Also, Yuan & Xu presented the design of mixed concrete and cold-formed steel. If the lateral stiffness ratio of the lower to upper structures is large, the evaluation of the seismic load is performed by a two-stage lateral force method that is prescribed in ASCE 7. They found that the design of the two stage analysis method may be uneconomical and unsafe [10].

In the past decades, the optimal design of the structures has been investigated that the main goal of the optimization is to use minimum weight of the materials, optimum size of the large-scale steel structures, minimum cost of the reinforced concrete frames [23–25] and control the plastic behavior of reinforced concrete [26] by different metaheuristic algorithms for example genetic algorithm (GA) [27], simulated annealing optimization (SAO) [28], particle swarm optimization (PSO) [29], ant colony optimization (ACO) [30], enhanced colliding bodies optimization (ECBO) [31], vibrating particles system (VPS) [32], harmony search (HS) [33], big bang–big crunch (BB-BC [34], charged system search (CSS) [35], teaching–learning-based optimization (TLBO) [36], bi-directional evolutionary structural optimization (BESO) [37], plasma generation optimization (PGO) [38], and improved plasma generation optimization (IPGO) [39] but all of them the previous studies are about the optimum design of the steel structures and reinforced concrete (RC) frame structures.

In this paper, the optimum design of the steel-concrete mixed structures is investigated by improved plasma generation optimization (IPGO). Also, previous researches of mixed structures have identified the risk of higher-mode effects arising due to the interaction of different modes of vibration. Studies have identified that this is sensitive to numerous design variables, notably the number of storeys, and the mass and stiffness attributed to each of the upper and lower structures. The main aim of the study is to find the most economical design of the steel-concrete mixed structure. In the following section, the formulation of the steel and RC frame optimization is described. The section databases and constraints of the beams and columns are provided in Section 3. The IPGO algorithm is briefly introduced in Section 4. The numerical example of the moment frame mixed structure is represented in Section 5. Finally, the concluding remarks are outlined in Section 6.

2 Formulation of the mixed frame optimization

The general optimization problem of the structure can be stated as follows:

$$\begin{aligned}&Find\left\{\boldsymbol{X}\right\}=\left\{\boldsymbol{x}_1,\boldsymbol{x}_2,\ldots,\boldsymbol{x}_{ng}\right\}\quad \boldsymbol{x}_{i,\min}\leq \boldsymbol{x}_i\leq \boldsymbol{x}_{i,\max},\\&To\ minimize\ f\left(\left\{\boldsymbol{X}\right\}\right),\\&Subject\ to\ g\left(\left\{\boldsymbol{X}\right\}\right)\leq 0\quad j=1,2,\ldots,n.\end{aligned}\tag{1}$$

Where $\{\boldsymbol{X}\}$ is a vector of design variables; $f(\{\boldsymbol{X}\})$ is the objective function; ng is the number of element groups; $\boldsymbol{x}_{i,\min}$ and $\boldsymbol{x}_{i,\max}$ are the two vectors of the lower and upper bounds of the design variable $\boldsymbol{x}_i$, respectively. $g_j(\{\boldsymbol{X}\})$ is the constraints of the design and n is the number of the constraints. In this paper, the objective function is considered the total cost of the mixed structure. It means that the costs of concrete, steel and framework are calculated. Thus, the objective function of the mixed structure can be defined as the following equations [38, 39]:

$$\begin{aligned}f_{conc}=&\sum_{i=1}^{n_{bc}+n_{cc}}\{C_c b_i h_i+C_s A_{si}\gamma_s\}\\&+\sum_{i=1}^{n_{bc}}\{C_f\left(b_i+2\left(h_i-t_i\right)\right)+C_t b_i\}L_i\\&+\sum_{i=1}^{n_{cc}}\{2C_f\left(b_i+h_i\right)\}L_i,\end{aligned}\tag{2}$$

$$f_{steel}=\sum_{i=1}^{n_{bs}+n_{cs}}C_s\times A_{si}\times L_i\times\gamma_{si},\tag{3}$$

$$f_{obj}=f_{conc}+f_{steel}.\tag{4}$$

Where f_{obj} is the objective function of the mixed structure (€); f_{conc} is the cost of the concrete elements of the structure; f_{steel} is the cost of the steel elements of the structure; n_{bc} and n_{cc} are the number of beams and columns of the concrete elements, respectively; n_{bs} and n_{cs} are the number of beams and columns of the steel elements, respectively; C_c, C_f and C_s, are the unit cost of concrete, formwork and steel, respectively; C_t is the unit rate of scaffolding; b, h, L are dimensions of the concrete elements (m); A_{si} is the area of the bars of each section of the concrete elements and the section area of the steel elements (m^2); γ_s is the density of steel as 7849 (kg/m^3). A cross-section database is considered for RC structural elements because the dimensions of the design variables are large, and the computational cost and complexity of the optimization process increase. The IPGO algorithm uses the discrete design variable in the section database to obtain the optimum solution. Also, for steel elements, the 11 discrete design variable is considered discrete design variable that all of them are selected from 267 predetermined W-shaped cross sections. The design variables are defined for calculation of the objective function that includes dimensions of the cross sections, area and number of top and bottom steel bars in cross section. The constraints of the concrete structural elements are derived from the ACI 318 building code [40] and the limitation of the steel structural elements are considered according to the AISC-LRFD provisions [41]. For concrete structural elements, the number and diameter of the longitudinal bars varied from four #3 to twenty #11 bars. The depth to width ratio of the beam sections is considered between 1 and 3. The database of the cross-sections is sorted in the ascending cost per unit length. The upper and lower bound of the cross-sectional depth of beams is considered 350 and 1050, respectively; and increments are considered 50 mm. The width of beams is constant at 350 mm. For column sections, the bars in the cross-section are symmetrical. The lower bound, upper bound, and increments of dimensions are considered as 250, 1200, and 50 mm, respectively [42].

3 The constraints of the beams and columns for steel and concrete frames

Constraints of the concrete beams and columns were obtained from the provisions of the ACI 318 design code [40]. The constraints include the load capacities of the column and beam sections, limitation of reinforcements in sections, the minimum depth of beams, the compressive stress block in beams, minimum clear spacing between reinforcement bars, and the limitation dimensions of the sections. The constraints of the RC columns and beams are presented in Table 1 and Table 2, respectively.

Where M_u and M_n are the ultimate applied moment and nominal bending moment capacity; $\varnothing = 0.9$ is the strength reduction factor; f_c' is compressive strength of concrete

Table 1 Constraints of the RC beams

Positive and negative bending moments	$g_1 = \frac{\lvert M_u \rvert - \varnothing M_n}{\varnothing M_n}$
Minimum reinforcements in sections	$\rho_{min} = \frac{\sqrt{f_c'}}{4 f_y} \geq \frac{1.4}{f_y}, \ g_2 = \rho_{min} - \rho$
Maximum reinforcements in sections	$\rho_{max} = 0.85 \beta_1 \frac{f_c'}{f_y} \frac{600}{600 + f_y}, \ g_3 = \rho - \rho_{\max}$
Minimum thickness of beams	$h_{min} = \frac{L}{21}, \ g_4 = \frac{h_{min} - h}{h_{min}}$
Compressive stress block	$g_5 = \frac{a - d}{d}$
Minimum clear spacing	$s_{min} = \max(d_b, 1in), \ g_6 = \frac{s_{min} - s}{s_{min}}$

Table 2 Constraints of the RC columns

Combination of moment and axial force	$l_u = \sqrt{(P_u)^2 + (M_u)^2}$, $l_n = \sqrt{(\varnothing P_n)^2 + (\varnothing M_n)^2}$, $C_1 = \frac{l_u - l_n}{l_n}$
Minimum longitudinal bars	$C_2 = \frac{0.01 \times A_g}{A_s} - 1$
Maximum longitudinal bars	$C_3 = \frac{A_s}{0.08 \times A_g} - 1$
Minimum clear spacing	$s_{min} = \max(1.5 d_b, 1.5in), \ C_4 = \frac{s_{min} - s}{s_{min}}$
Depth of the column section	$C_5 = \frac{b_T}{b_B} - 1$
Width of the column section	$C_6 = \frac{h_T}{h_B} - 1$

and f_y is the yield strength of steel; d and a are the effective depth of the beam and the height of the compressive stress block, respectively; d_b is the diameter of reinforcement bars; M_u and P_u are applied moment and axial force of columns; and M_n and P_n are nominal flexural and axial strength of columns, respectively. A_g is the total area section; A_s is the area of the longitudinal bars in the section; the depth (h) and width (b) of the column in the top storey (T) should be smaller than the bottom one (B).

Displacement of the roof and inter-storey displacements and strength constraints of the steel elements are presented according to the LRFD-AISC provisions [40]. The constraints are defined in the following:

$$\frac{\Delta_T}{H} - R \leq 0 \tag{5}$$

$$\frac{d_i}{h_i} - R_i \leq 0, \quad i = 1, 2, \ldots, ns \tag{6}$$

$$\frac{P_u}{2\phi_c P_n} + \left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} \right) - 1 \leq 0 \quad for \ \frac{P_u}{2\phi_c P_n} < 0.2 \tag{7}$$

$$\frac{P_u}{\phi_c P_n} + \frac{8}{9} \left(\frac{M_{ux}}{\phi_b M_{nx}} + \frac{M_{uy}}{\phi_b M_{ny}} \right) - 1 \leq 0 \quad for \ \frac{P_u}{2\phi_c P_n} \geq 0.2 \tag{8}$$

Where Δ_T is the lateral displacement of the roof (max); H is the structure height; R is the maximum drift index as 1/300; d_i is the inter-storey drift; h_i is the storey height of the ith storey; ns is the total number of storeys; R_i is the index of inter-storey drift (1/300); P_u is the required strength (tension or compression); P_n is the nominal axial strength (tension or compression); ϕ_c is the resistance factor (ϕ_c = 0.9 for tension elements, ϕ_c = 0.85 for compression elements); M_u is the required flexural strengths; M_n is the nominal flexural strengths; and ϕ_b is the flexural resistance reduction factor (ϕ_b = 0.9). Due to the good performance of the optimization algorithm, a penalty function $f_{penalty}(\{\boldsymbol{X}\})$ is used to the constraints (g_i) of the optimization problem that is defined in the following:

$$f_{penalty}(\{X\}) = W(\{X\}) + \sum_{i=1}^{m} \vartheta_i \times \max(0, g_i), \tag{9}$$

where m is the number of the constraints and ϑ_i is the penalty parameter corresponding to the ith constraint.

4 Optimization algorithm

Plasma generation optimization (PGO) is a new meta-heuristic algorithm introduced by Kaveh, et al. [38] and its performance of this has been investigated in [43]. To improve the result of the PGO algorithm, Improved Plasma Generation Optimization (IPGO) is developed to obtain reliable solutions and fast convergence. A comparative study of these algorithms is presented for steel and concrete structures [39]. In the IPGO algorithm, plasma memory (PM) is used to save the best solutions obtained at the previous population in each iteration and their values of the objective function. The electrons of the PM memory are replaced with the worst electrons in the current population. Then, electrons are sorted by their values of the objective function. In the improved version of the PGO algorithm, to determine the step size of each electron, the excitation and de-excitation processes or ionization process should be occurred for each electron and the step size of the electron according to the excitation and de-excitation processes or ionization process is obtained, the new position of the electrons is calculated, but in the IPGO, $x_{rc,j}$ is considered the best electron in each iteration (x_{best}). Therefore, $\Delta x_{i,j}$ is formulated for the mathematical representation of moving forward to the new position around the best electron as follows:

$$\Delta x_{i,j} = x_{best} - x_{i,j} \ . \tag{10}$$

5 Numerical examples

This study designed a five-level moment frame according to ACI and AISC codes. The mixed structure consists of three RC frames storeys and two steel frames storeys. This frame has 15 beams and 20 columns arranged in 10 groups for columns and 5 groups for beams shown in Fig 1. The height of the storeys and length of the bays is considered 3 (m) and 5 (m). Static loads include live and dead loads distributed for all spans and effects of the earthquake load are considered dynamic loads. The uniform static load is considered 30 kN/m on all of the beams. The linear time history analysis is performed to design the elements of the structure. The Imperial Valley earthquake at El Centro station in 1940 is chosen for time history analysis [44]. The detail of the analysis and a flowchart of the optimization process is said in [39] which is about the optimum design of the concrete frame under time history analysis. The damping matrix is calculated by Rayleigh's method and an equivalent damping ratio is calculated based on a semi-empirical error minimization method for mixed structures [20]. Mass and stiffness matrices of the moment frames are presented by Clough and Penzien [45]. The static and dynamic analysis, also optimization processes are programmed in MATLAB [46].

For steel part of the structure, the modulus of elasticity is 200 GPa and the yield stress is 248.2 MPa. The effective length factor of the elements in a sway-permitted frame is calculated as $k_x \geq 0$ and the out-of-plane effective length factor is considered as $k_y = 1$. Each column is considered as non-braced along its length, and the non-braced length for each beam member is specified as one-fifth of the span length. For RC part of the structure, the yield strength of steel (f_y) is 500 MPa; the Compressive strength of concrete (f_c') is 40 MPa; unit weight of steel (γ_s) and concrete (γ_c) are 7849 and 2450, respectively. Limitations and constraints of the steel and RC frames and the sections of them are said previous sections. The values of the required parameter of the examples are provided in Table 3. The population size is selected as 30 and maximum iteration number is 3000 and the parameters of the algorithm include nPM = 15, EDR = 0.5, DR = 0.3, and DRS = 0.1. The optimal design of the frame is executed by the IPGO algorithm. To reduce computational effort, the solutions of each iteration are firstly controlled by constraints that do not require structural analysis. Therefore, the optimization procedure found the best solution after a limited number of time history analyses. The optimum design of the IPGO algorithm can be seen in Table 4.

For comparison of the cost of the structures, in this section, the cost of the steel and reinforced concrete structure are investigated that they are similar to the mixed structure. These examples include a 3-bay 5-story steel frame and 5-story RC frame structures. The design constraints of steel frames are imposed according to the provisions of LRFD-AISC. The RC frames are designed according to the ACI 318-8. The RC frame and steel frame geometry and grouping details are shown in Figs. 2 and 3. The results of the algorithm for the RC frame can be seen in Table 5. The results indicate that the total cost of the RC frame are different from the mixed frame. According to the results, the cost of the RC frame is 21363 Euro while the cost of the mixed frame is 28366 Euro. The cost of the optimum design of the mixed structure is 32.78% higher than the RC structure. Mixed structures are used to make a lighter structure and a faster construction than the RC structures while the cost of the optimum design of them is higher than the RC frames corresponding the obtained design.

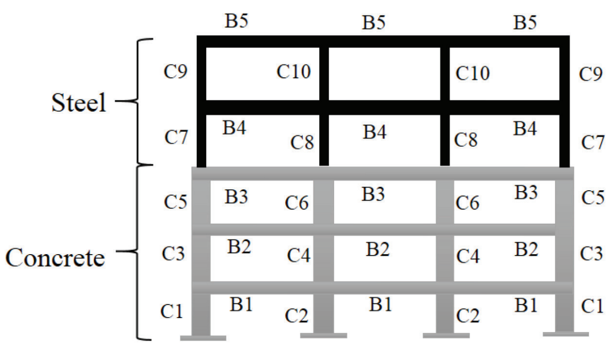

Fig. 1 Steel and concrete structure

Table 3 The detail of the costs

		Unit	Value
Cost of concrete (C_c)	Beam	€/m³	105.93
	Column	€/ m³	105.17
Cost of steel (C_s)	Beam	€/ton	1300
	Column	€/ton	1300
Cost of formwork for RC frames (C_f)	Beam	€/ m²	25.05
	Column	€/ m²	22.75
Cost of scaffolding for RC frames (C_t)	Beam	€/ m²	38.89
	Column	€/ m²	-

It is necessary to mention that the investigated structure of this paper is low rise building but it is possible that the result of the high-rise building can be different. Also, the mixed structure has complex eigenvalues and it is difficult to obtain the optimum design under time history analysis. In following, the results of the algorithm for the steel structures shown in Table 6. The results indicate that the total cost of the steel frames are higher than the RC frames and lower than the mixed structures. According to the results, the cost of the steel frame is 25136 Euro. The cost of the optimum design of the steel structure is 17.66% higher than the RC structure.

Table 4 The optimization result of the mixed structure under the El Centro earthquake

Frame Type	Member type	Group	Dimensions		Reinforce-ments	
			width (mm)	depth (mm)	As top	As bot
concrete	Beam	B1	350	350	3#3	2#3
		B2	350	350	3#3	2#3
		B3	350	350	3#3	3#3
	Column	C1	1200	1200	20#11	
		C2	1200	1200	20#11	
		C3	1200	1200	20#11	
		C4	750	1050	16#11	
		C5	550	1050	18#8	
		C6	400	500	16#4	
steel	Beam	B4	W 14 × 90			
		B5	W 33 × 201			
	Column	C7	W 8 × 35			
		C8	W 18 × 106			
		C9	W 14 × 145			
		C10	W 10 × 49			
Best cost			28366			

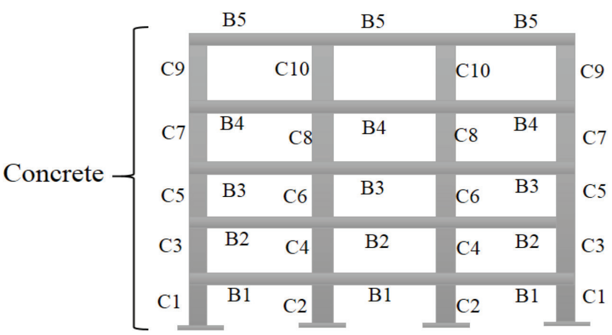

Fig. 2 concrete structure

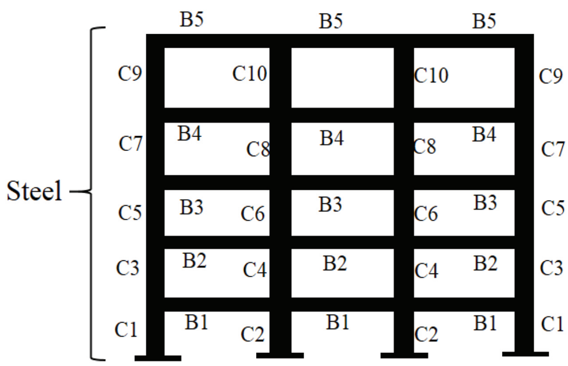

Fig. 3 Steel structure

Table 5 The optimization result of the concrete structure under the El Centro earthquake

Member type	Group	Dimensions		Reinforcements	
		width (mm)	depth (mm)	As top	As bot
Beam	B1	350	350	3#3	2#3
	B2	350	350	3#3	2#3
	B3	350	350	3#3	3#3
	B4	350	650	3#4	4#4
	B5	350	350	3#3	2#3
Column	C1	1200	1200	20#11	
	C2	1200	1200	20#11	
	C3	1200	1200	20#11	
	C4	750	1050	16#11	
	C5	550	1050	18#8	
	C6	400	500	16#4	
	C7	400	600	10#8	
	C8	350	350	6#6	
	C9	300	500	4#9	
	C10	300	300	8#5	
Best cost		21363			

Table 6 The optimization result of the steel structure under the El Centro earthquake

Member type	Group	Optimal cross-section
Beam	B1	W 8 × 24
	B2	W 6 × 9
	B3	W 6 × 9
	B4	W 6 × 15
	B5	W 21 × 93
Column	C1	W 36 × 800
	C2	W 27 × 178
	C3	W 36 × 529
	C4	W 14 × 90
	C5	W 6 × 25
	C6	W 12 × 50
	C7	W 8 × 35
	C8	W 10 × 22
	C9	W 6 × 9
	C10	W 10 × 49
Best cost	25136	

6 Conclusions

This paper used the Improved Plasma Generation Optimization (IPGO) algorithm for the optimization of the steel-concrete mixed structure that is subjected to dynamic loads while the previous studies are about the optimum design of the steel structures and reinforced concrete (RC) frame structures. Mixed structures are a vertical combination of reinforced concrete frames in lower part and steel frames in upper part. For the mixed structures, all of the studies investigated the structural behavior of the mixed structures, characterization of strength, ductility and damping and the analysis methods to evaluate structural demands; but this paper investigated the optimum design of these structures. In the improved version of the PGO algorithm, the electrons escape from local minimum positions shown to accelerate convergence toward the best results. The design constraints of RC and steel frames are imposed according to the standards and limitations of the ACI 318 and LRFD-AISC. The objective function is considered the material and construction cost of reinforced concrete and steel elements. The numerical results demonstrated the performance of the IPGO algorithm for time history analysis and the efficiency of the algorithm for optimum design of the mixed structure. Considering the dynamic load for the design of mixed structures is important. This research provides an ideal and feasible procedure for optimum design of the concrete-steel mixed structure under time history loading by considering the variations in the cross-section of RC and steel frame elements. Also, for comparison, the optimal design of the pure steel and pure reinforced concrete structure are presented under time history analysis that they are similar to the mixed structure.

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