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Multi-objective Optimization of Steel Frames with Added Viscous Dampers Using Imperialist Competitive Algorithm

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ABSTRACT

Optimization is a big challenging task for engineers and designers. In practice, almost all of the engineering problems have more than one objective function, criterion to be optimized, therefore, multi-objective optimization procedure is necessary for many optimization problems. In this study, we presented the development of the Imperialistic Competitive Algorithm (ICA) to multi-objective optimal design of steel frames with dampers. Semi-active liquid viscous dampers are added to the steel frames to reduce the seismic response of structures subjected to earthquake loadings. The number and position of the dampers are considered as the design variables and the structural responses such as the acceleration of each floors, the maximum displacement of the top roof and the maximum relative displacement of the floors are the objective functions to be minimized simultaneously. A seven-story and a twelve-story 3D buildings are selected as the numerical examples to test the developed algorithm. The resultant Pareto-front sets are reported and discussed for the numerical examples. The obtained trade-offs demonstrate very smooth and reliable sets for all case studies. Meanwhile, the results indicate that the position of the dampers directly influences their effectiveness in decreasing the seismic response of structures. The maximum top floor displacement, the maximum story drifts and the maximum acceleration of each story have reduced in comparison to the uncontrolled condition, by respective values of 44.9%, 43.2% and 11.8%, for seven-story case study.

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1. Introduction

Mathematical optimization approaches are only capable of solving simple problems with explicit objective functions; therefore, the difficulties arise when the objective functions are implicit or discrete design variables appear in an engineering optimization problem. To overcome these problems, evolutionary algorithms have been developed to optimize problems with non-differentiable functions, including genetic algorithm (GA) [1], imperialistic competitive algorithm (ICA) [2,3], differential evolution (DE) [4], and many others.

Through the practical optimization, engineers have to solve the problems with multiple conflicting objective functions. Although a few studies have been carried out for multi-objective optimization of structures with dampers, there are many studies in the literature on the optimal design of steel and reinforced concrete structures with static loads. Non-dominated sorting genetic algorithm (NSGA-II) is one of the most famous approaches for multi-objective optimization, which developed by Deb et al. [5]. Babaei and Mollayi developed a none-dominated sorting genetic algorithm (NSGA-II) to the multi-objective optimal design of RC frames, where the total weight and the maximum displacement were the objective functions [6]. A comparative study between GA and DE is implemented for multi-objective design of RC frames and interesting results are reported in [7].

A comprehensive list of methods on multi-objective optimization using evolutionary algorithms are presented by Deb [8]. A hybrid genetic and ant colony optimization algorithm was applied for multi-objective optimization of steel braced frames, where the structural weight and the maximum displacement were the conflicting objective functions [9]. In another work, optimal number and location for steel outrigger-belt truss system is investigated to minimize simultaneously weight and the roof displacement of the structures [10].

In the duration of an earthquake, structures are subjected to a large amount of energy. The absorption and dissipation of that great energy in its elastic deformations region is irrational, since designing to such measures is not only uneconomical, it also interferes with the architectural requirements of the structure. Therefore, the main purpose of a structural engineer has always been to design structures with the ability to dissipate inelastic earthquake energy, in a manner so that when confronting strong dynamic loads, such as earthquakes, the structure enters in the plastic region to form plastic hinges, where the seismic energy is absorbed and dissipated through inelastic cyclic deformations within the members. In the recent decades many attempts have been made to utilize innovative methods and technologies in designing against the earthquake loads.

One of the most important techniques is the use of control systems in reducing the seismic vibration of structures. The main purpose of control systems is to reduce vibrations either through absorbing the earthquake energy or by changing its frequencies. Tuned mass damper (TMD) is one of the vibration control system which has been studied and improved to find optimal parameters for structures under critical earthquake [11–13]. In another study, advantages of the friction TMD over conventional TMD is studied and very important issues are reported [14]. Tuned liquid damper is another system to control the vibration of the structures and is very efficient when it is modified [15].

In this article, semi-active liquid viscous dampers are employed to reduce the seismic structural vibrations. The Imperialistic Competitive Algorithm (ICA) is developed to multi-objective optimal design of steel frames with dampers, where the structural responses such as maximum displacement, drift and acceleration are considered as three independent objective functions. The number of the dampers and their locations are considered as the design variables. To show the effectiveness and efficiency of the algorithm, a seven-story and a twelve-story 3D steel buildings are selected as the numerical examples.

In section 1, liquid viscous dampers are introduced and their behavior is formulated. Section 2 presents the displacement function of a structure including semi-active viscous dampers. Optimization of the semi-active control forces using linear quadratic regular (LQR) algorithm is investigated in section 3. In order to find the optimal number and position of viscous dampers, optimal design of structures using imperialistic competitive algorithm (ICA) is developed and presented in section 4. In section 5 three dimensional numerical examples are tested by utilizing the developed algorithm and section 6 concludes the paper.

2. Viscous dampers

Liquid viscous dampers are energy absorbent systems which, considering their physical size, provide high levels of energy absorption. As a result, they can be utilized to eliminate the effects of earthquake energy in structures. These dampers consist of a hydraulic cylinder and a stainless steel piston rod with a bronze cap. A hole is situated in the cap so that when the piston reciprocates, the liquid passes through the slot with pressure which in return causes energy dissipation in the form of heat.

In order to improve the behavior of viscous dampers, controllable models of these dampers, known as semi-active viscous dampers have been introduced. These dampers are very similar to their non-active counterparts with the exception of having an external passage ring which joins the liquid inside the cylinder from either sides of the piston cap. The ring has an adjustable valve which controls the current inside the damper. Thus, these dampers increase the liquid pressure during the movement of the piston and can, resultantly, create very large damping forces, diminishing a considerable amount of earthquake energy.

As previously noted, one of the characteristics of such dampers is their dynamism and capability of adapting to the structure's behavior in order to withstand earthquake loads. Hence, they recognize the seismic loads when the earthquake initiates and apply the required forces to confront them. Additionally, external energy is merely used to adjust the valves in these systems and, therefore, the dampers do not require a large source of external energy, which makes them very reliable [16]. The simplest model to illustrate the behavior of such dampers is the Maxwell model with a time dependent damping coefficient of [17]:

$$p(t) = C_0(t)\dot{u}(t) \tag{1}$$

where, $p(t)$ is the external damping force, $C_0(t)$ is the time dependent damping coefficient, which, based on the status of the control valve (open/closed), can vary between a minimum and a maximum amount, and $\dot{u}(t)$ is the speed of movement of the piston cap. Figure 1 illustrates the Taylor liquid viscous damper. An important advantage of these dampers is their reliability characteristic due to their independence of high external forces. In addition, the small size and light weight of these components allows for their use in larger numbers within a structure.

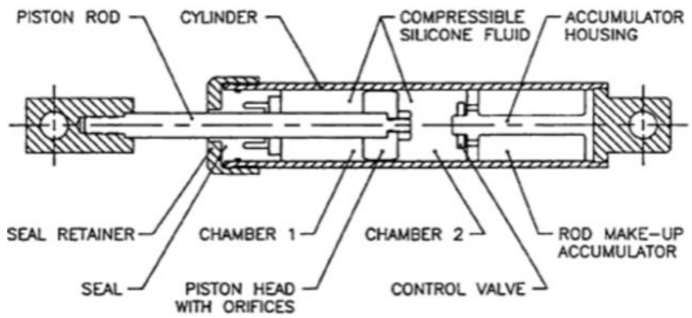


Fig. 1. Taylor liquid viscous damper [18].

3. Structural displacement function including semi-active viscous dampers

To form the displacement function of a structure, considering the presence of a semi-active viscous damper, the model can consist of a damper, parallel to a spring. Assuming rigid levels, the displacement function of a structure with a damper j located in the x-y plane, at a distance $(e_{yj})_i$ from the center of mass of the i[th] story and between the floor i-1 and i would be as follows [19]:

$$M\ddot{x} + C\dot{x} + kx + \begin{Bmatrix} 0 \\ M \\ -1 \\ +1 \\ 0 \\ M \\ 0 \\ -(e_{yj})_{i-1} \\ (e_{yj})_i \\ 0 \\ M \\ 0 \end{Bmatrix}_{n\times 1} f_j = -M\{r\}\ddot{x}_g(t) \quad (2)$$

In Eq. (2) the matrices M, K and C are, respectively, the mass matrix, the stiffness matrix and the structure's damping matrix and $\dot{x}, x$ and $\ddot{x}$ are the structure's displacement, velocity and acceleration, respectively. In matrix $\{r\}$ the components related to the degrees of freedom in the direction of the earthquake equal 1 and the rest of the components are 0. In addition, $\ddot{x}_g(t)$ is the horizontal acceleration of the earthquake, obtained from accelerograms. In the above equation, f_j is the force of the damper, which for a damper with an angle of α to the horizontal could be obtained as:

$$f_j = C_{dj}(t)\cos^2(\alpha)[-(\dot{u}_x)_{i-1} + (\dot{u}_x)_i - (e_{yj})_{i-1}(\dot{u}_\theta)_{i-1} + (e_{yj})_i(\dot{u}_\theta)_i] \tag{3}$$

The above equation can be written as:

$$M\ddot{x} + C\dot{x} + Kx = D\{f\} - M\{r\}\ddot{x}_g(t) \tag{4}$$

From Eq. (4) matrix D can be calculated based on the location and number of dampers. Vector $\{f\}$ includes damping forces with time dependent indeterminate elements since the coefficient of each damper, $C_{dj}(t)$, is indeterminate and a function of time:

$$f = \begin{bmatrix} f_{x,1} \\ f_{x,2} \\ M \\ f_{x,m} \\ f_{y,1} \\ M \\ f_{y,k} \end{bmatrix}_{(m+k)\times 1} \tag{5}$$

4. Optimization of the semi-active control forces

Control algorithms are of significance in structural control systems. In fact, the intelligent controllers, that compute the required control loads based on the information transferred from the sensors, use control algorithms. In this article linear quadratic regular (LQR) optimal control algorithms are employed to calculate the control forces of the semi-active liquid viscous dampers. This algorithm affects the variables space obtained from the dynamic functions of the structure. In the LQR method, the optimum control forces are calculated so the efficiency index J is minimized. To compute the values of the semi-active control forces using these algorithms, Eq. (4) should be rewritten in state space [20]:

$$\dot{u} = Au + Hf + Bw \tag{6}$$

In the above equation $\{f\}$ is the control force vector and the rest of the variables can be defined as follows:

$$H = \begin{bmatrix} 0 \\ -[M]^{-1}[D] \end{bmatrix}, \{z\} = \begin{Bmatrix} \{x\} \\ \{\dot{x}\} \end{Bmatrix}, B = \begin{bmatrix} 0 \\ I \end{bmatrix}$$

$$A = \begin{bmatrix} 0 & I \\ -[M]^{-1}[K] & -[M]^{-1}[C] \end{bmatrix}, w = -\{r\}\ddot{x}_g(t) \tag{7}$$

Also, to minimize the efficiency index J:

$$J = \int_0^\infty \left[u^T Q u + f^T R f \right] dt \tag{8}$$

The weight matrices R and Q in the above equation are defined as [21]:

$$Q = \begin{bmatrix} Q_V & 0 \\ 0 & 0 \end{bmatrix}, \; Q_V = \mathrm{diag}(1), R = 10^{-q}\mathrm{diag}(1) \tag{9}$$

Here q is an unknown which, with its increase, the structural responses decrease and the value of damper forces increase. The most practical approach to determine q is to perform a number of trial and error method analyses for various q values and to compare the outcomes to find the q that would keep the damping forces below the allowable limit of 1000 kN. Substituting for the weight matrices of Eq. (9) in Eq. (8) and solving the problem results in the Riccati equation, as follows:

$$PA + A^T P + Q - PHR^{-1}H^T P = 0 \tag{10}$$

Solving the Riccati equation above, matrix P can be found and the control force vectors of the dampers would be:

$$f = -R^{-1}H^T P u = -Gu, G = \left[G_d \quad G_v \right] \tag{11}$$

Matrix G is known as the feedback matrix which calculates the control forces based on displacement and velocity. Assuming that the information obtained from the control system sensors only contains velocity, G_d in the above equation will be zero and the feedback matrix will be:

$$G = \left[0 \quad G_v \right] \tag{12}$$

By substituting Eq. (11) in Eq. (6), the deferential equation below is obtained and solving it results in the structural behavior:

$$\dot{u} = (A - HG)u + Bw \tag{13}$$

5. Optimization using imperialist competitive algorithm (ICA)

With increasing input and output variables and in more complex problems, the use of traditional optimization methods becomes impractical and time consuming. Accidental and innovative algorithms are appropriate, practical and simple alternatives that require no differentiation processes. Limited works have utilized these artificial algorithms for optimal design and placement of viscous dampers [22,23].

One of the most recent and powerful optimization approaches is the imperialist competitive algorithm, introduced in 2007 by Atashpaz and Lucas [1]. This algorithm is a new optimization strategy, formed based on the socio-political characteristics of imperialism, which, despite its limited application in the structural and earthquake engineering, successful results have been reported on its use in solving a great number of engineering problems. Amini and Bagheri (2012) used this approach for active optimal control of structures [24].

Similar to other evolutionary algorithms, this algorithm begins with a number of random initial populations, each known as a country. Then some of the best population elements (equivalent to elites in the genetics algorithm) are chosen as the imperialist countries. The rest of the population will count as colonies. Depending on their power level, the imperialists attract the colonies towards themselves using the absorption policy. The total power of each empire depends on both of its components; the imperialist country as the main core and its colonies. Figure 2 illustrates the general scheme of the imperialist competitive algorithm.

With the formation of the initial empires, the imperialistic competition commences amongst them. Any empire that fails to perform successfully in the imperialistic competition (or at the least, fails to prevent influence loss); will be wiped off the competition ground. Therefore, the survival of an empire is dependent on its power in absorbing the colonies of the competitor empires. Hence, during imperialistic competitions, larger empires gradually become more powerful and weaker empires will be gone. To increase their power, the empires will also have to develop their own colonies.

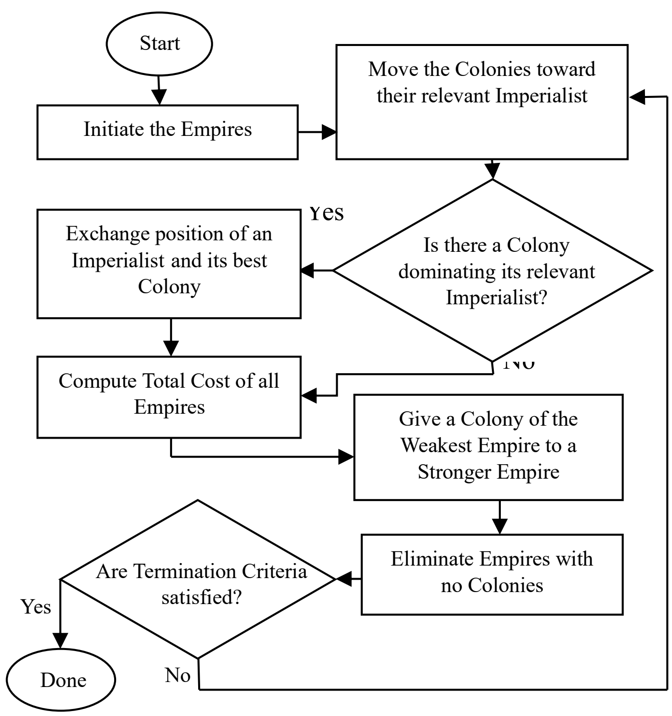


Fig. 2. Imperialist competitive algorithm flowchart.

With time, the colonies will become closer in power to their empires and a type of convergence will take place. Ultimately, the competition will end up in a single empire in the world, with colonies that are, position-wise, very close to the imperialist country.

For the optimized design of the semi-active liquid viscous dampers, the number and placement of the dampers should undergo an optimized selection process. To increase the efficiency of the semi-active control system, the location vectors of the dampers in various levels of the structure should be determined by solving an optimization problem. To perform the optimization equation, an objective function, in the form of a loss function consisting of three objectives, is assumed which should be minimized.

The objectives consist of the ratio of the maximum drift of the levels in controlled vs. uncontrolled modes, the ratio of the drift of the roof in the controlled mode vs. the uncontrolled situation and the ratio of maximum acceleration of the levels in the controlled vs. the uncontrolled mode. All objectives need to be minimized simultaneously.

$$\begin{aligned} &Find \quad W \\ &Minimize \quad F(t) = \alpha \frac{drift_{\max}}{drift_{\max(un)}} + \beta \frac{x_{top}}{x_{top(un)}} + \gamma \frac{\ddot{x}_{\max}}{\ddot{x}_{\max(un)}} \end{aligned} \tag{14}$$

where W is the damper location vector in the structure's levels which counts as the input variable. α, β and γ are constant values which, for the purpose of this research, are assumed to be equal to 0.4, 0.3 and 0.3, respectively. x_{top} is the displacement of the top floor, $drift_{\max}$ is the maximum relative displacement of the floors and $\ddot{x}_{\max}$ is the maximum acceleration of the structure. In addition, $x_{top(un)}$, $drift_{\max(un)}$ and $\ddot{x}_{\max(un)}$ are respectively the displacement of the top floor, maximum drift of the levels and the maximum acceleration, for a non-controlled structure.

6. Numerical studies and discussions

Liquid viscous dampers with a capacity of 200 kN.s/mm and a maximum force of 1000 kN have been selected as samples and used to semi-actively control the structure's vibration. Two structures of 7 and 12 stories have been explored to illustrate the effect of using viscous dampers. The structural response against earthquakes depends on the characteristics of the accelerogram such as frequency content, maximum acceleration and the duration of the earthquake. In addition, the type of soil on which the accelerogram is positioned and its distance from the fault causing the earthquake can also influence the response of the structures under investigation. Therefore, the attempt has been made to use a group of the accelerograms of various natural earthquakes that have occurred in Iran and throughout the world.

All accelerogram have been chosen to be far-field and positioned on stiff soil. The properties of these accelerograms are provided in Table 1. It should be noted the behavior of these dampers has been modeled for both controlled and uncontrolled conditions using MATLAB. There are a maximum of 8 dampers in each story.

Table 1
Characteristics of the selected accelerograms.

Earthquake	Magnitude	PGA(g)	Site
Chi-Chi	7.6 m	0.410	TCU047
Manjil	7.4 mw	0.184	Qazvin
Imperial Valley	6.5 m	0.348	Elcentro
Kern county	7.4 mw	0.180	Taft
N. Palm Spring	6 m	0.254	San Jacinto
Imperial Valley	6.7 m	0.256	LA-Century
Parkfield	6 m	0.357	Cholame5

6.1. A seven-story building

The first example is a 7-story steel structure located in a very high seismic risk zone and designed on stiff soil. The lateral resistance system used in the structure consists of coaxial braced steel frames, it has a height of 22.4 m and plan dimensions of 23.55 m × 16.5 m. The 3D and plan view of this structure are shown in Fig. 3.

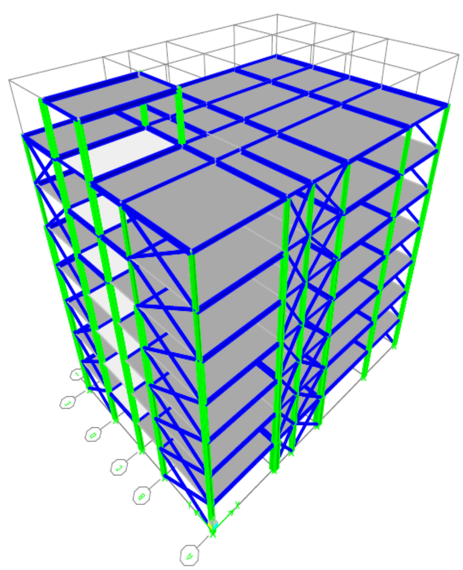


Fig. 3. 3D view of a 7-story building.

A 3D model of the structure has been created in SAP and each floor has been assumed as a rigid diaphragm with flexibility towards out of plane bending. Hence, the degrees of freedom of all nodes located on the plane of a level will be connected to the floor diaphragm and they are reduced to three DOFs of the rigid floor. Therefore, per each floor two lateral and one-rotational degrees of freedom have been defined in the center of mass of the floor. The structure's mass and stiffness matrices are thus obtained with 3N × 3N dimensions, where N is the number of floors.

The multi-objective optimization problem with these accelerograms using imperialist competitive algorithm for up to 30 decades, has been solved several times for the 7-story structure and with every execution of the program it can be seen that the algorithm with various convergence speeds would end in the same result. The convergence pattern of the imperialist competitive algorithm for the Parkfield earthquake has been shown in Fig. 4 for four analyses of the optimization problem.

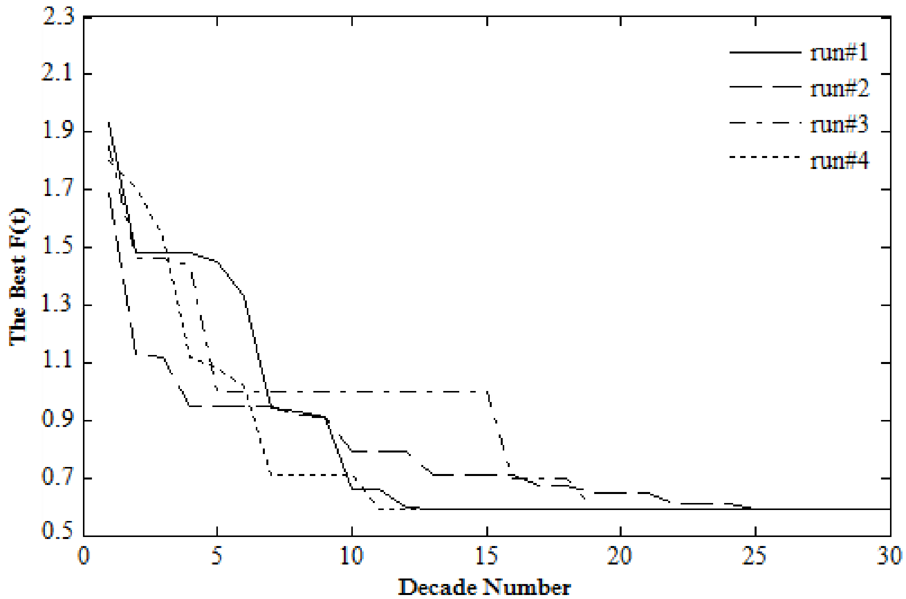


Fig. 4. Convergence history of ICA for four individual runs of the algorithm under Parkfield earthquake.

Ultimately, after executing the algorithm for all of the selected accelerograms, the results of the optimum number and location of the dampers have been shown in Table 2.

Table 2
Optimum number and position of the dampers for the 7-story structure.

Story	1	2	3	4	5	6	7
Wchi-chi	1	0	1	0	1	1	1
Wmanjil	0	1	0	1	1	1	1
Wimperialvalley	1	1	0	1	0	1	1
Wkern county	1	0	0	1	1	1	1
WN.PalmSpring	1	0	1	1	1	1	0
WImperial Valley	1	1	0	0	1	1	1
WParkfield	1	0	1	1	1	1	0

According to the optimal placements obtained for each accelerogram, as shown in Table 2, the reduction values of the structure's vibration responses are as illustrated in Figure 5.

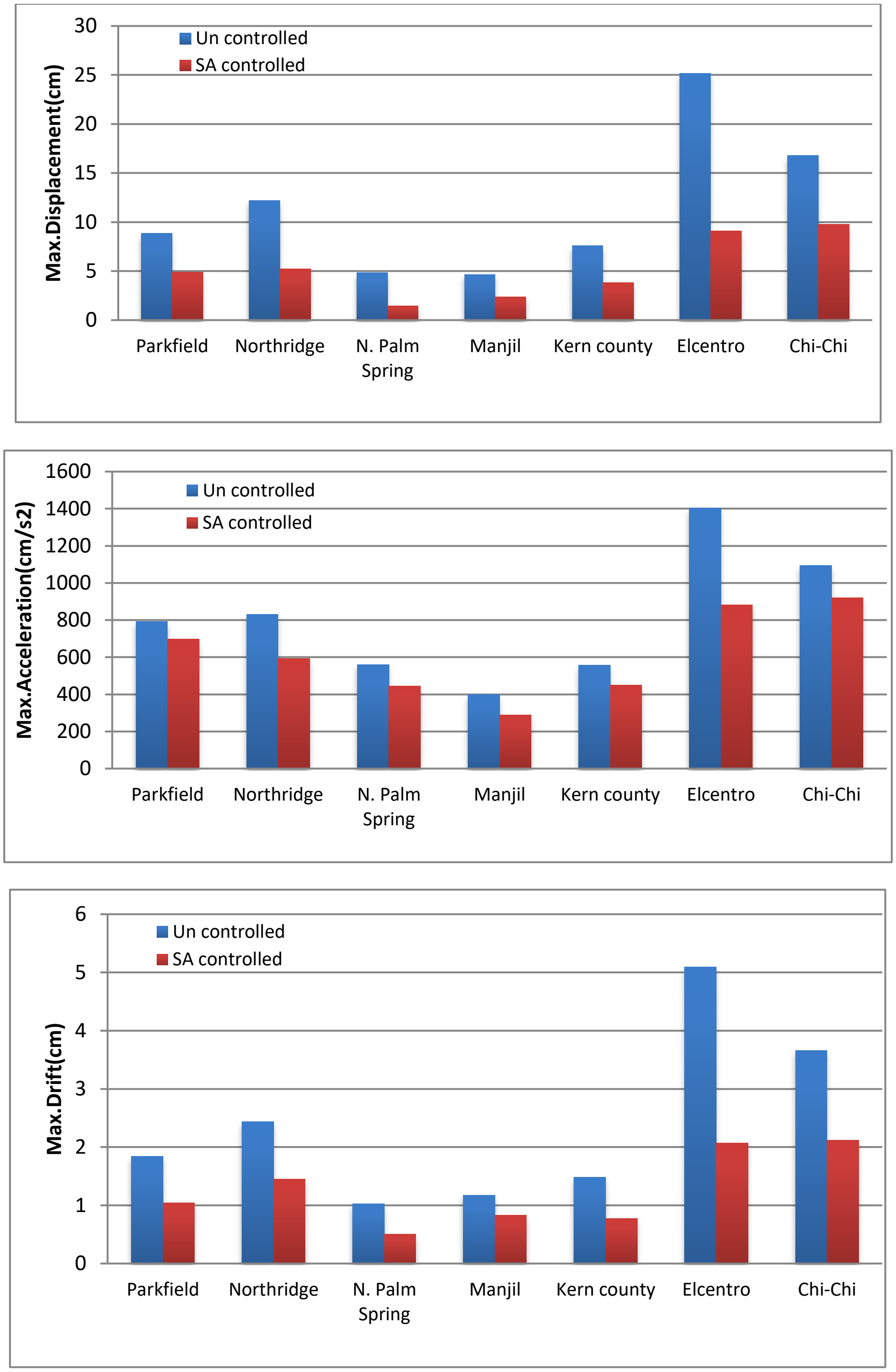


Fig. 5. Comparison values of responses for the 7-story structure.

In the images below, the diagrams of top floor displacement results, the maximum relative drift of the stories and the maximum acceleration of the floors for both controlled and uncontrolled conditions, have been shown for the 7-story structure under the influence of the Parkfield earthquake. In addition, in semi-active control systems, the control force of each damper can be obtained as a function of time, using Eq. (11). The result is a vector and each member of this vector is the force of one damper. Moreover, from the force of each damper, its damping coefficient can be achieved from Eq. (3). For example, these values are shown in Figure 6 for the damper located on the 6th floor.

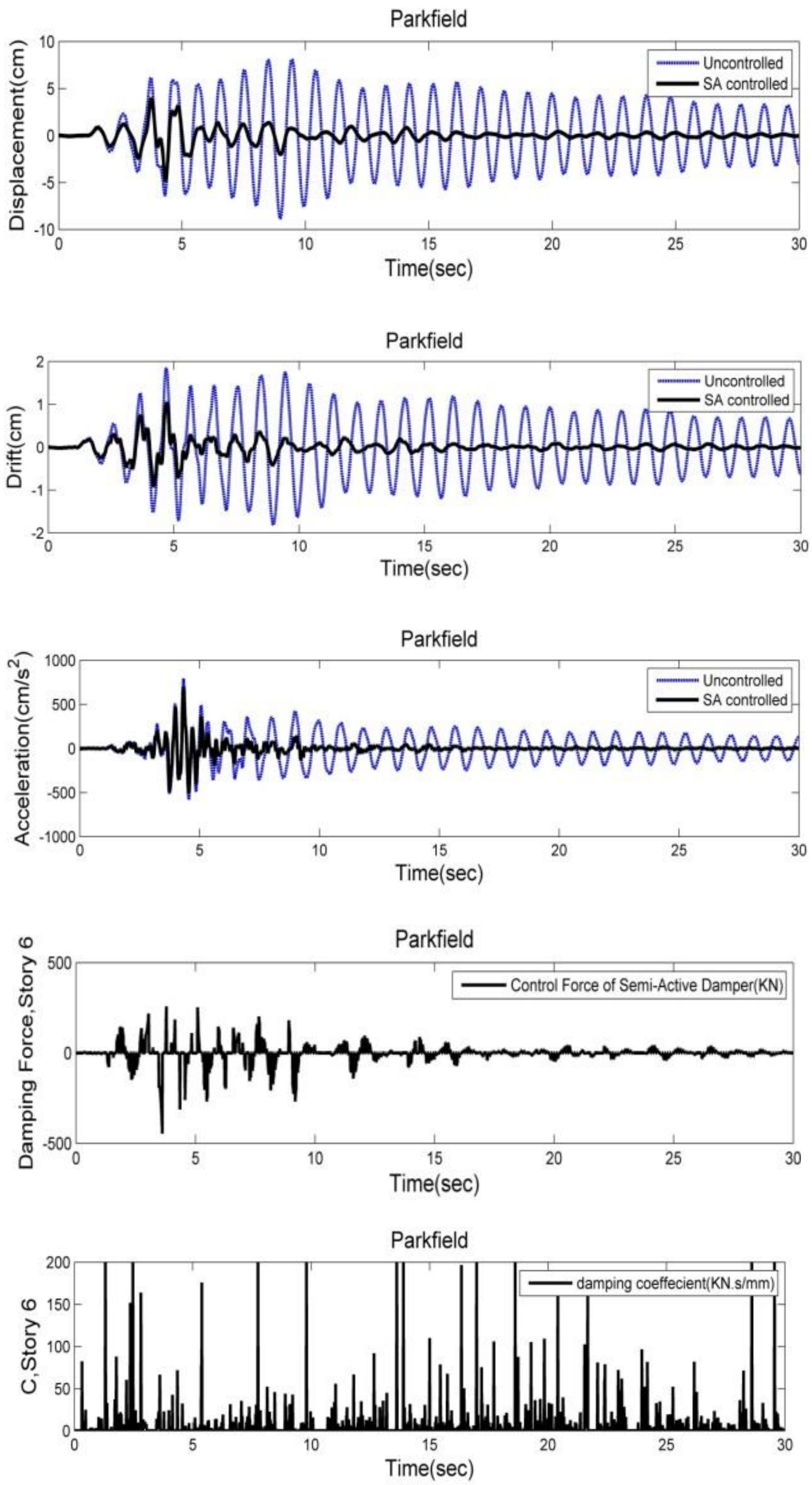


Fig. 6. Time-history structural responses of the 7-story structure for Parkfield earthquake.

Considering the graphs of Figure 5, the structural response reduction values of the semi-active liquid viscous damper can be compared to the uncontrolled condition. As it can be seen, for the Parkfield earthquake, for instance, the displacement values of the top floor, the maximum drift of the stories and the maximum acceleration of each story have reduced in comparison to the uncontrolled condition, by respective values of 44.9%, 43.2% and 11.8%.

To evaluate the inter-influence of the problem's various objectives and their effect of the structure's response, the weighted sum method of optimization is used. Since this method requires a great length of optimization time, therefore, in this method, 42 members with a number of repetitions have been utilized.

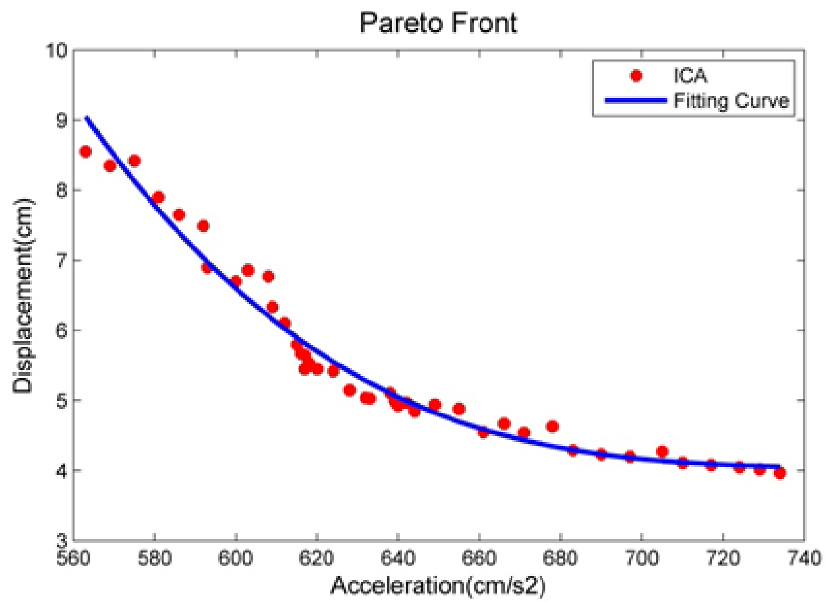


Fig. 7. Pareto set for maximum acceleration of stories and top floor displacement.

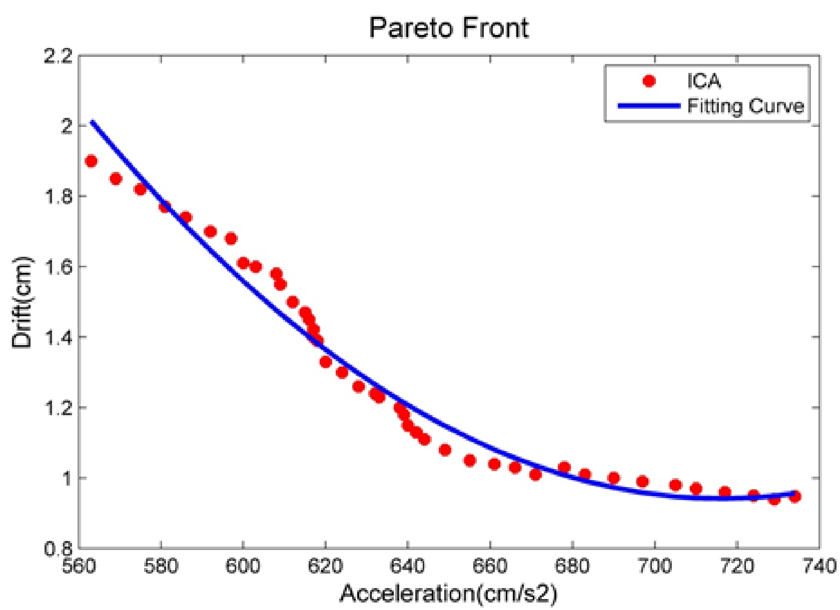


Fig. 8. Pareto set for maximum acceleration of stories and maximum drift of floors.

As it can be seen, where the weight coefficient of the maximum acceleration is approximately set to be 1, solving the optimization problem results in a placement of dampers that does not significantly reduce the maximum drift of the floors or the displacement of the roof (max of 25%). In addition, when the weight coefficient of the maximum drifts and roof drift is set to be 1, the optimal placement of dampers would not greatly reduce the maximum acceleration of the floors.

6.2. A twelve-story building

The second example is a 12-story steel structure located in a relatively high risk area and on stiff soil. The resistance system against lateral forces is a co-axial steel braced bending frame with a height of 38.4 m and a plan dimension of 16 m × 15 m. The 3D and plan views of this structure are shown in Fig. 9.

A maximum number of 8 dampers can be positioned per floor. To optimize the considered problem, 100 countries are primarily selected, 10 of which are imperialists and the remainder are colonies, to form the initial empires.

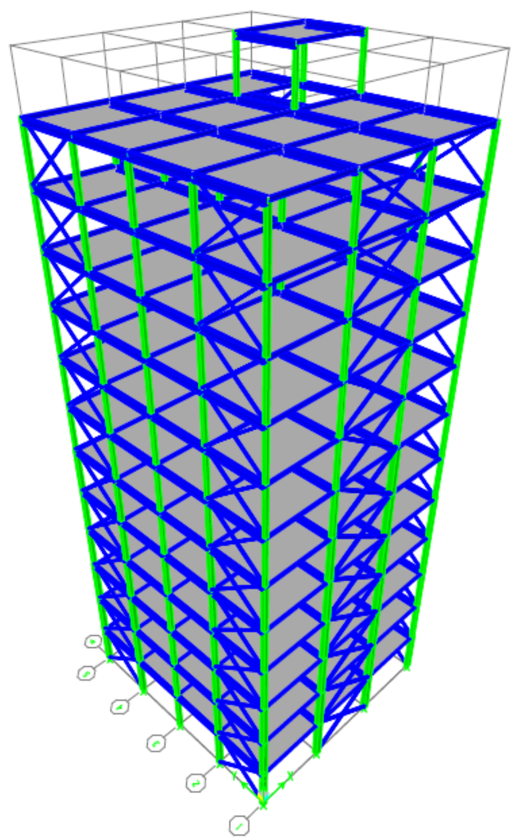


Fig. 9. Three dimensional and plan views of a 12-story structure.

Multi-objective optimization problem under these accelerograms is analyzed up to 30 decades for the 12-story structure, using the imperialist competitive algorithm, and with every execution of the problem, it can be observed that at various convergence speeds, the algorithm reaches similar outcomes. The convergence approach of the imperialist competitive algorithm under the Imperial Valley earthquake is shown in Figure 10 for four times solving of the optimization problem.

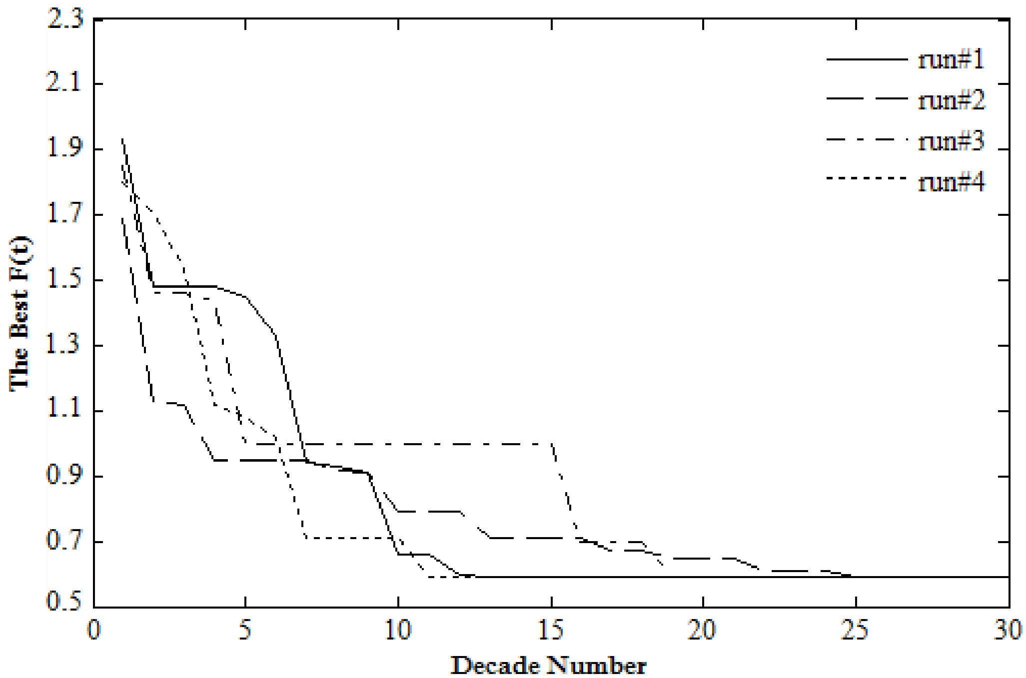


Fig. 10. Convergence history of ICA for four individual runs of the algorithm under Imperial Valley earthquake.

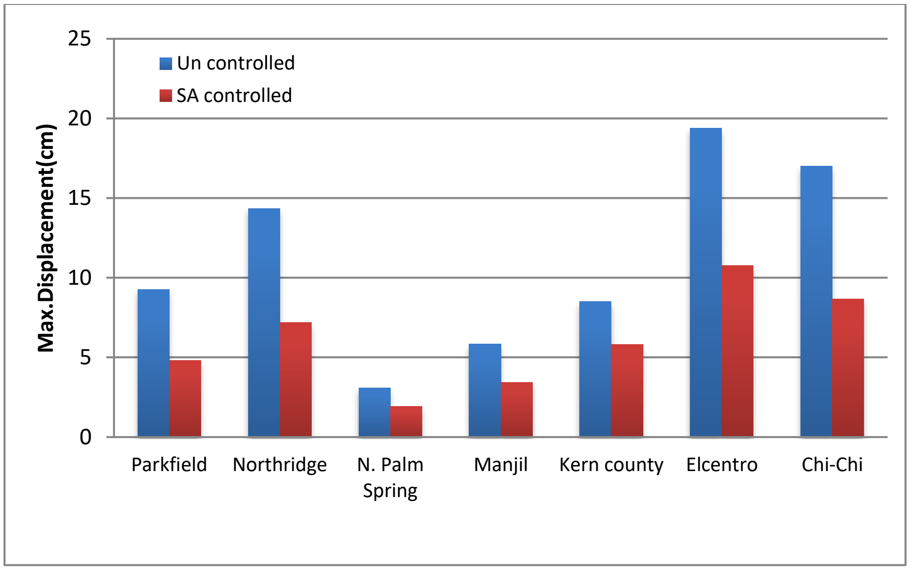
Ultimately, after running the imperialist competitive algorithm for all of the selected accelerograms, the optimum number and position of the damper are resulted as shown in Table 3.

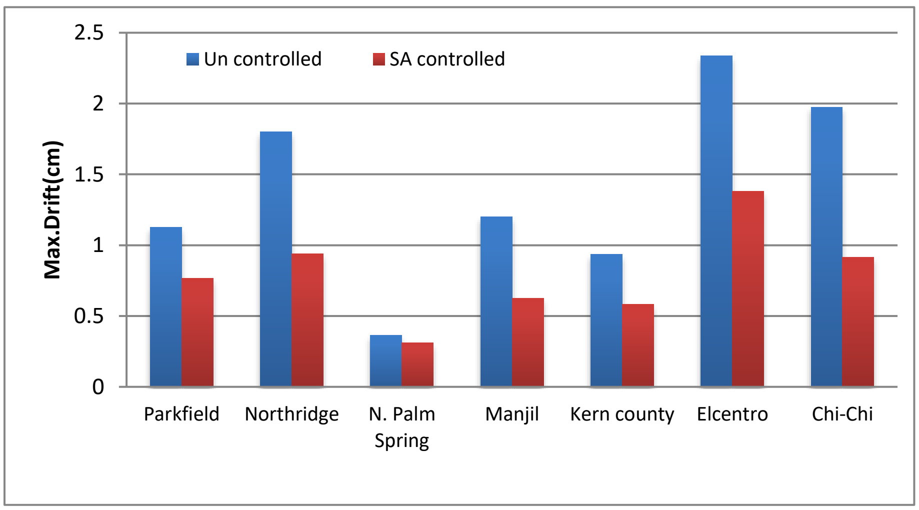
Table 3
Optimum number and position of dampers for the 12-story structure.

Story	1	2	3	4	5	6	7	8	9	10	11	12
Wchi-chi	0	1	0	0	1	1	1	1	1	1	0	0
Wmanjil	0	1	0	0	1	1	1	1	1	1	0	0
Wimp	1	0	1	0	1	1	1	0	0	1	1	1
Wkern	0	1	1	1	0	1	0	1	0	1	0	1
WN.Palm	0	1	0	0	1	1	1	1	1	1	0	0
WNorth	1	1	0	1	0	1	0	1	1	1	1	0
WPark	1	1	1	0	0	1	1	0	1	0	1	0

Based on the optimum placements obtained for each accelerogram (Table 3), the displacement value of the top floor, the maximum drift value of the stories and the maximum acceleration of the stories for the 12-story structure, under both controlled and uncontrolled conditions using the semi-active liquid viscous damper, are shown in Figure 11 for the Imperial Valley earthquake.

In Figure 12, the response diagrams of the top floor displacement, the maximum drift of the stories and the maximum acceleration of the stories, under both controlled and uncontrolled conditions, for the 12-story structure are shown for the Imperial Valley earthquake. The graphs of the control forces, damping coefficient and the semi-active control force for the damper situated on the 11th floor are also shown in Fig. 12.





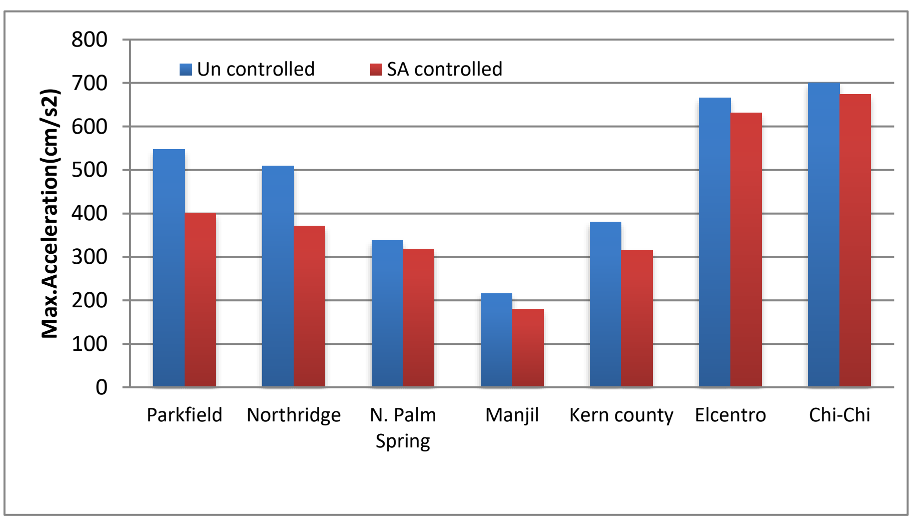


Fig. 11. Comparison values of responses for the 12-story structure.

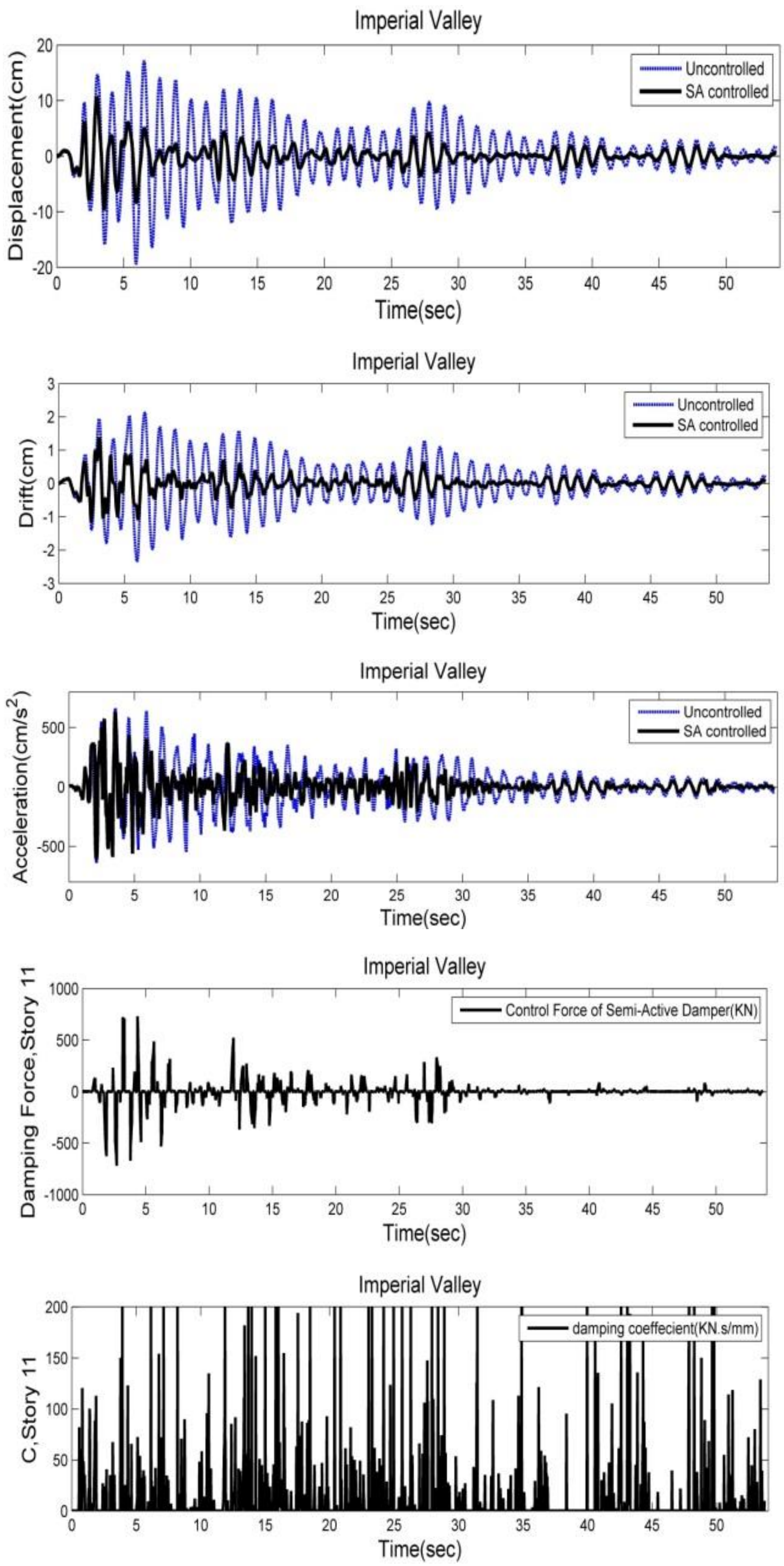


Fig. 12. Time-history structural responses of the 12-story structure for Imperial Valley earthquake.

From the graphs of Fig.11, the reduction values of the controlled structural response using semi-active liquid viscous damper can be observed and compared to the uncontrolled condition. It is evident that, for example, for the Imperial Valley earthquake, the values of the top floor displacement, maximum drift of the stories and the maximum acceleration of the floors show 44.4%, 40.9% and 5.15% reduction, respectively, compared to the uncontrolled condition.

To explore the influence of different objectives on each other and on the structural response, weighted sum method of optimization is employed. In this approach, 42 members with several repeats have been examined and, consequently, the efficient Pareto set for the assumed objectives are shown in figures 13 and 14.

As it can be observed, where the weight coefficient of the maximum story acceleration is assumed to be close to 1, solving the optimization problem results in a placement of the dampers that do not cause a significant reduction in the maximum floor drift or the floor displacement (Max of 22%). In addition, for the condition where the weight coefficient associated with the maximum drift and maximum floor displacement is increased, once again, solving the optimization problem results in a placement of the dampers which has minimal effect on decreasing the maximum acceleration of the floors.

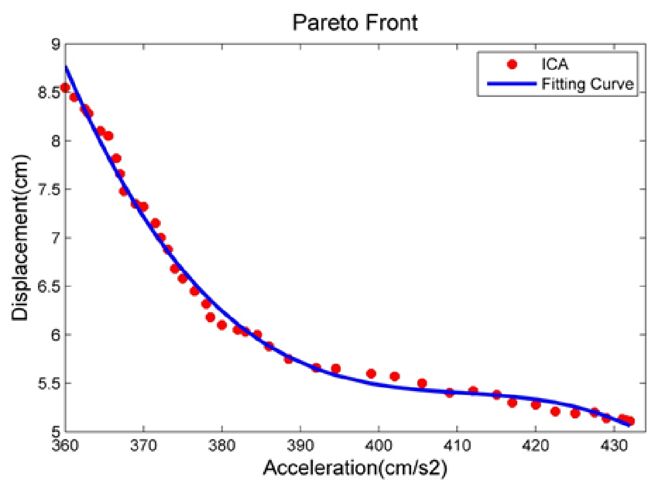


Fig. 13. Pareto set for maximum acceleration of stories and top floor displacement.

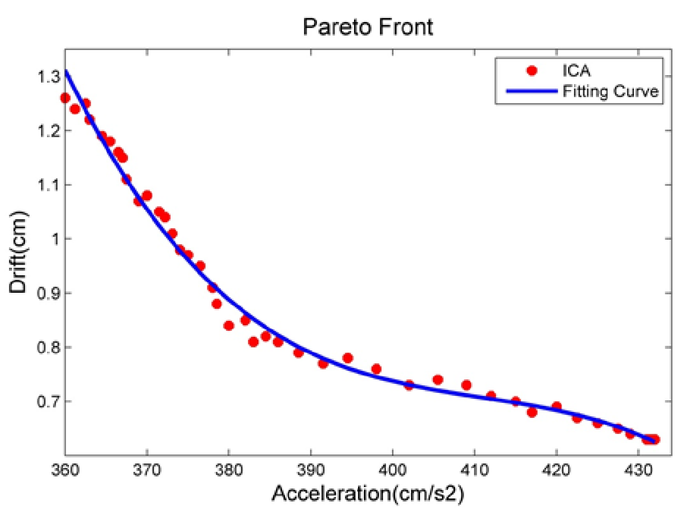


Fig. 14. Pareto set for maximum acceleration of stories and maximum drift of floors.

7. Conclusion

In this research, multi-objective optimal design of steel buildings are performed using the Imperialistic Competitive Algorithm (ICA). This algorithm is developed and applied to seven-story and twelve-story buildings with added viscous dampers as the numerical examples to show the effectiveness and accuracy of the method in finding the best location of dampers. The sample buildings are subjected to the seven benchmark earthquake loadings and the structural responses are set as objective functions. The results are as:

(1) The obtained Pareto-fronts for the objective functions are very smooth and reliable for both case studies.
(2) Location optimization of dampers is very effective, For instance, the displacement values of the top floor, the maximum drift of the stories and the maximum acceleration of each story have reduced in comparison to the uncontrolled condition, by respective values of 44.9%, 43.2% and 11.8%, for seven-story case study.
(3) The obtained Pareto-fronts report interesting results. Increasing the weight coefficient of the maximum story acceleration does not cause a significant reduction in the maximum floor drift or the floor displacement. In addition, increasing the weight coefficient associated with the maximum drift and maximum floor displacement has minimal effect on decreasing the maximum acceleration of the floors.

Conflict of Interest

The authors declare that they have no conflict of interest.

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