Earthquakes and Structures, *Vol. 14, No. 1 (2018) 1-10*
DOI: https://doi.org/10.12989/eas.2018.14.1.001

Comparison between uniform deformation method and Genetic Algorithm for optimizing mechanical properties of dampers

Reza Karami Mohammadi[*1], Maryam Mirjalaly[1], Masoud Mirtaheri[1a] and Meissam Nazeryan[2b]

[1]*Department of Civil Engineering, K.N. Toosi University of Technology, 470 Mirdamad Ave. West, Tehran, Iran*
[2]*Department of Civil Engineering, Sharif University of Technology, Azadi Ave., Tehran, Iran*

(Received November 11, 2017, Revised January 22, 2018, Accepted January 23, 2018)

Abstract. Seismic retrofitting of existing buildings and design of earth-quake resistant buildings are important issues associated with earthquake-prone zones. Use of metallic-yielding dampers as an energy dissipation system is an acceptable method for controlling damages in structures and improving their seismic performance. In this study, the optimal distribution of dampers for reducing the seismic response of steel frames with multi-degrees freedom is presented utilizing the uniform distribution of deformations. This has been done in a way that, the final configuration of dampers in the frames lead to minimum weight while satisfying the performance criteria. It is shown that such a structure has an optimum seismic performance, in which the maximum structure capacity is used. Then the genetic algorithm which is an evolutionary optimization method is used for optimal arrangement of the steel dampers in the structure. In continuation for specifying the optimal accurate response, the local search algorithm based on the gradient concept has been selected. In this research the introduced optimization methods are used for optimal retrofitting in the moment-resisting frame with inelastic behavior and initial weakness in design. Ultimately the optimal configuration of dampers over the height of building specified and by comparing the results of the uniform deformation method with those of the genetic algorithm, the validity of the uniform deformation method in terms of accuracy, Time Speed Optimization and the simplicity of the theory have been proven.

Keywords: metallic-yielding damper; optimal outline configuration of dampers; optimal retrofitting; uniform deformation method; Genetic Algorithm

1. Introduction

Seismic design methods based on displacement control are considered as one of the basic branches of performance-based design, in which the maximum displacements of different points of a structure are considered as the main design parameters. In this method, first, different levels are introduced for the seismic performance of structures. Then to maintain the structure in each of these levels, Allowable amounts for the maximum values of structural parameters are introduced. Many researches have been performed to determine allowable amounts of structural parameters at different seismic performance levels (Wen 2001). Therefore, in seismic design of structures under design base earthquake, displacements must not exceed the allowable values (Fajfar and Krawinkler 1997).

To achieve this objective, various tools and techniques are used such as energy dissipating systems. These systems are used to improve performance of structures and also to control their damage during earthquakes. One of these systems categorized among the passive control of structures is the metallic-yielding damper. This passive control device is used to improve the structure ductility by modifying the stiffness, strength and damping simultaneously with the aim of meeting performance design requirements (Tsuji and Nakamura 1996). Energy dissipating capacity of dampers, their number and their detailed properties all impact their ability to reduce response and achieving optimum design objectives. So, intelligent and optimal installation of them plays an important role in improving the structure performance. An optimal structural system is a system with the best performance while its members should be selected in a way that the maximum capacity, stress, deformation, etc. are used under various loading conditions.

In the research conducted by Connor and Clinics (1996), during solving the vibration equation of an elastic system against seismic stimulation, distribution of flexural and shear stiffness of structure has been determined in a way that the distribution of shear and bending displacements in the various stories are uniform (Connor and Clinics 1996). Gantes *et al.* (2000) investigated the optimal distribution of shear and flexural elastic stiffness of braced moment-resisting steel frames (Gantes *et al.* 2000). In these researches, the behavior of braced frame has been simulated with a Timoshenko beam with the same shear and flexural stiffness and the problem is solved analytically while earthquake force was assumed as triangular force. Singh and Moreschi (2001) found the optimized size and location of damper systems with the help of genetic algorithm

∗Corresponding author, Associate Professor
E-mail: rkarami@kntu.ac.ir
[a]Associate Professor
E-mail: mmirtaheri@kntu.ac.ir
[b]M.sc.
E-mail: Meissamnazeryan@gmail.com

Copyright © 2018 Techno-Press, Ltd.
http://www.techno-press.com/journals/eas&subpage=7
ISSN: 2092-7614 (Print), 2092-7622 (Online)

(Singh and Moreschi 2001). In their work, the energy dissipation system was considered as a viscoelastic damper dependent upon frequency and independent of viscosity. In the studies of (Gong *et al.* 2003), a method for seismic design of steel frames was introduced, in which, by limiting the stories relative displacements, the desired performance levels were maintained (Gong *et al.* 2003).

Park *et al.* (2004), presented simultaneous optimization process based on the gradient concept. The dimensions of structural members, the position of viscoelastic dampers and their number were considered simultaneously as design parameters and their optimum amounts were calculated using the genetic algorithm. Uniform deformation method was also the other optimization method which was introduced by Karami Mohammadi and Moghaddam (2001). They successfully used the mentioned method on a shear-building model of frames to determine the optimal distribution of stiffness in frames equipped with passive dampers (buckling-restrained brace (BRB)) and showed that seismic performance of structures could be improved by transferring some structural elements from the strongest to the weakest sections (Karami Mohammadi *et al.* 2004). Hajirasouliha and Moghaddam proposed a new technique to accelerate the optimization process in order to eliminate fluctuations in convergence by checking the influence of distribution of resistant factor in structures on their seismic performance and correcting the technique which was mentioned in references (Hajrasouliha 2005).

Rahemi and Moghaddam used the method of uniform distribution of deformations for optimal arrangement of viscous fluid dampers over height, in two-dimensional moment-resisting steel frames under earthquakes (Rahemi 2007). In their research, it was assumed that the original steel moment-resisting frame itself is able to handle gravity loads. Also using the optimal safety criterion, the target failure parameters were taken equal to the mean demand failure parameters of each active story.

Bagheri *et al.* utilized ADAS Metallic-yielding damper in building frames to reduce their seismic response (Bagheri *et al.* 2011). They showed that employing metallic-yielding dampers with identical dimensions in all stories did not lead to uniform distribution of flexibility and consequently optimal design. They optimized seismic response of frames with braced members and ADAS damper systems by introducing a method based on the uniform deformation concept.

Nikfar assessed the performance improvement of steel frames with cartridge dampers using the endurance time method (Nikfard 2010). He determined the optimal arrangement of these dampers over the building height with the help of genetic algorithm.

A method for seismic rehabilitation of existing frames was provided by Benavent-Climent (2011) by adding hysteretic energy dissipating devices (EDDs). This process was based on the balanced energy and the goal was to determine the lateral strength, lateral stiffness and required energy absorption capacity of each damper in different floors to achieve the target performance level for the intended earthquake risk level.

Haji Rasouliha (2011) offered a practical method for performance-based design of reinforced concrete (RC) buildings under seismic stimulations (Hajirasouliha 2011). This study has indicated that efficient design was performed by transfer of materials from the stronger parts to the weaker parts of the structure, as long as the uniform deformation criteria are maintained. A.Martínez *et al.* (2014) studied optimal placement of nonlinear hysteretic dampers on the planar structures under seismic excitation. Zhang and Xia (2017) proposed an improved PSO algorithm (PARTICLE SWARM OPTIMIZATION) for parameter identification of nonlinear dynamic hysteretic models in order to reduce the influence of randomness caused by using the PSO algorithm. Kandemir-Mazanoglua and Mazanoglu (2017) conducted an optimization study for viscous dampers between adjacent buildings.

In severe earthquakes, the deformation demand in some parts of the structure passes through the permissible seismic capacity, meaning that the material capacity is not fully exploited. Therefore, it can be assumed that the uniformity of the demand for deformation will lead to the optimal use of materials in the structure. The concept of uniform distribution of deformation can be easily adopted to find the optimum design of different types of structural systems (Karami Mohammadi, 2001, Karami Mohammadi *et al.* 2004). In this way, in order to achieve the best design solution, inefficient materials gradually move from strong to weak parts of a structure until a uniform deformation or damage occurs. Uniform distribution of deformation algorithms have been used in various studies to obtain optimal seismic design in shear buildings (Karami Mohammadi *et al.* 2004, Moghaddam and Hajirasouliha 2006, Moghaddam and Hajirasouliha 2008, Hajirasouliha and Moghaddam 2009), concentrically braced frames (Moghaddam *et al.* 2005), eccentrically braced frames (Karami Mohammadi and Moussavi Nadoushani 2012, Karami Mohammadi and Sharghi 2014), reinforced concrete frames (Hajirasouliha *et al.* 2012), and truss-like structures (Hajirasouliha *et al.* 2011). In this study, for illustrating the efficiency of the uniform deformation method, the proposed algorithm is used to design optimal steel structures with TADAS dampers and is compared with optimized structures by genetic algorithm. It has been shown that the uniform deformation algorithm can converge with a much smaller number of steps and it is much faster than the genetic algorithm.

In this study, UDD (Uniform Distribution of Deformation Method) and Genetic algorithm are used to find the optimum distribution of dampers in order to maintain the desired performance level. Comparison between UDD and Genetic algorithm proves validity of the uniform deformation method. Krishnamoorty (2001) investigated typical applications of GAs to practical design of structural systems such as steel trusses, towers, bridges, reinforced concrete frames, bridge decks, shells and layout planning of buildings. Karami and Sharghi (2014) presented a practical method for optimization of eccentrically braced steel frames, based on the concept of uniform deformation theory (UDT) performed by gradually shifting inefficient material from strong parts of the structure to the weak areas until a state of uniform deformation was achieved. Babu Desu *et al.* (2007) presented an efficient control strategy to control displacements as well as acceleration responses of asymmetric buildings having asymmetry in both the plan and elevation. Karami Mohammadi and Haghighipour (2017) proposed an algorithm based on Uniform Deformation Theory to mitigate vulnerable buildings using magneto-rheological (MR) damper. Artar and Daloglu presented an optimization process using Genetic Algorithm (GA) that mimics biological processes for optimum design of planar frames with semi-rigid connections. Ying *et al.* (2009) developed a non-clipped semi-active stochastic optimal control strategy for nonlinear structural systems with MR dampers based on the stochastic averaging method and stochastic dynamical programming principle.

Current studies indicate that during strong earthquakes the deformation demand in structures is not expected to be uniform, therefore it can be concluded that the deformation demand in some parts of the structure doesn't reach the allowable level of seismic capacity and therefore the material isn't fully exploited, if the strength of underused element decreases. Incrementally, the deformation would be expected to increase. Hence if the strength decreases we should eventually obtain a status of deformation. At this point, the dissipation of seismic energy in each structural element is maximized and the material capacity is fully exploited. By reducing the material, a structure becomes lighter as deformation is distributed more uniformly. As a result, in general it could be assumed that a status of uniform deformation is a direct consequence of the optimum use of material that is considered as the theory of uniform deformation. Consequently the aim of this study is to verify the validity and efficiency of the proposed method with the genetic algorithm which belongs to the larger class of evolutionary algorithms of optimization.

2. Optimal retrofitting of moment-resisting steel frame

In this study, optimal performance of steel frames is provided by changing the behavioral parameters of dampers utilizing the uniform deformation and genetic algorithms. The model examined in this study has been designed with initial weaknesses. In other words, these structures are designed in such a way that is only capable of bearing their own weight. Thus, under seismic loading, they are more likely to be under nonlinear large deformations. By keeping constant the size of beams and columns, the metallic-yielding dampers with braces are added to two internal spans of moment-resisting frames in order to improve the seismic performance of these frames. Mechanical properties of these dampers during the optimization process are determined in a way to reach the desired performance level.

The uniform deformation theory initially proposed by Karami Mohammadi (2001) is based on the concept that the structural weight of a lateral load resistant system with uniform distribution of maximum deformations will be minimal in compare with the weight of a typical design system, in which uniform deformation is not reached and only some of the structural elements reached its final state. In other words, the structural weight of a lateral load resistant system decreases as deformation approaches into a uniform state. As a result, it can be said that the optimal distribution of materials is related to the optimal performance of the structure during the given earthquake.

According to this theory, inefficient materials should be moved from strong parts of the structure to weak positions. As a result, the structural properties will be updated and the modified structure will behave differently during the design earthquake. Karami Mohammadi *et al.* (2004) showed that if this change is applied continuously, the calculations will lead to a uniform distribution of maximum deformations. In order to achieve convergence conditions, the process of modifying the strength of the structural components should be based on an appropriate algorithm.

The optimization objective is defined as follows:

• Optimization objective:

After retrofitting, the structure should have the minimum required weight, which meets expected performance level in earthquake.

• Design constraints:

The maximum inter-story displacement should not exceed the allowable amount of life safety performance level and also structural elements have to tolerate both gravity and seismic loads according to ASCE 41-13 (2013).

• Design variables:

Mechanical properties of Metallic-yielding dampers are considered as a retrofitting variable and no changes are included in the dimension and size of the initial frame members.

In this study, the target function is considered equal to the total weight of structural elements such as beams, columns, braces and damper resistance. While the initial sections of moment-resisting frames during optimization procedure remain constant, the variable part of the target function is considered as the total of braces' weight and damper resistance that are directly related to the rehabilitation cost of lateral bearing system.

3. Modeling and assumptions

3.1 Geometrical properties of structures

The structures used in this study include two-dimensional 5-story steel frames with 5 spans, 9-story steel frames with 4 spans and 5-story irregular steel frames which are placed on ground type D, assuming they are designed in very high risk areas based on standard ASCE 7-10 (ASCE/SEI 7-10 2010). St-37 steel type with yielding stress of 2400 kg/cm^2 is used. The general geometry of all the three frames and position of the dampers are presented in Fig. 1. The height of each story and the length of each span are assumed equal to 3 m and 5 m, respectively. Both regular and irregular five-story frames have 5 spans and the nine-story frame has 4 spans, while 2 middle spans in the entire height of the frames have been braced in order to perform optimization process and adding dampers. Beam and column sections are IPE and HE-B, respectively. Finally, it should be noted that all the supports and connections are fixed.

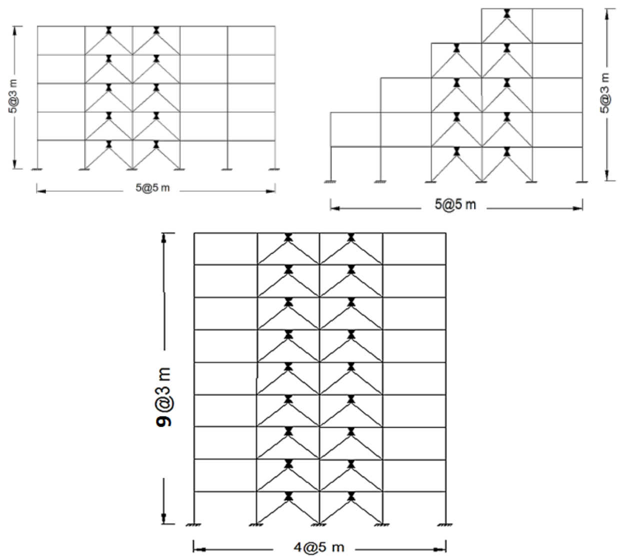

Fig. 1 The geometry of the frames and position of dampers

3.2 Modeling in Opensees

In this work, Opensees 2.2.1 software is used for modeling and performing nonlinear dynamic time history analysis. Nonlinear Beam-Column elements have been utilized for modeling the column and beam elements, considering deflection control. In this element, it is possible to consider extensive plasticity with linear distribution (Mazzoni *et al.* 2007).

Furthermore, uniaxial material hysteretic constitutive model is used for the steel. This model is capable of modeling steel behavior with tri-linear method under both tension and compression while the slope of strain hardening part in tension is considered as 2% of elastic part. Nonlinear zero length spring with elastoplastic behavior, which is connected to Chevron bracing, is utilized for modeling the metallic damper. As is seen in Fig. 2, this nonlinear spring restricts movement in *X* direction between two points, one on top of the Chevron bracing and the other one in the midpoint of beam. Parameters related to this spring are determined during optimization process. It should be noted that for braced sections, column-beam linear elements with square sections are applied. Since, based on the performance criteria of structures with damper, braced members that are used for installing dampers should always remain elastic, for this purpose, the braced elements dimensions are designed proportional to the damping force at each step of optimization in such a way that they always behave linearly.

Zero length elements are utilized for connecting beams to the nonlinear spring elements, springs to Chevron bracings and also bracings to the end of columns. Only the transitional degrees of freedom have been restrained.

4. Optimization process

In this work, the frames designed based on ASCE 7-10 have been modelled in order to perform time history dynamic analysis in OpenSees software. At first, four different seismic records are applied on structures which are placed on ground type *D* and then optimization process is conducted with the help of Matlab software and connecting it to Opensees software the optimal arrangement of dampers is found.

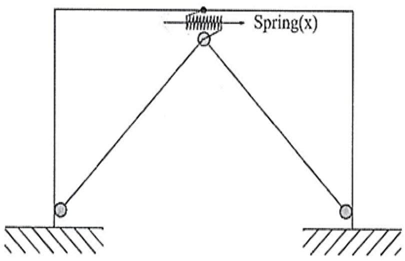

Fig. 2 Modeling of the metal damper

The studied models in this study have initial weaknesses in their design. Optimization procedure is carried out by keeping constant the beams and columns dimensions and adding dampers to the two middle spans and finally finding their optimal parameters. Damper resistance is defined as the maximum force corresponding to the initiation of the damper yielding. The resistance unit is the same unit of force. Therefore, its accumulation with force quantities such as weight can be acceptable.

4.1 Optimization based on uniform deformation method

Optimization based on uniform deformation method is an iterative procedure, which is used to change the behavioral parameters of dampers in a way that provide optimal performance level. Thus, the following steps have been taken in order to improve efficiency of moment-resisting frames against seismic loads.

1. Weak moment-resisting frame structure can be considered as a starting point in the process. It should be noted that the initial frame is capable of carrying gravity loads. However, it does not meet the optimal performance level of structure (LS) based on the criteria considered in the functional regulation of ASCE 41-13.

2. During the optimization process, the structural period is changed. In order to prevent the loss of earthquake input energy and to provide enough energy to cause damage in the structure, the selected earthquakes for conducting dynamic time history analyses are scaled to have spectral acceleration of 0.5 g in a period equal to the first period of the structure.

3. Moment-resisting frames are subjected to scaled seismic excitation records and the relative maximum displacements of each floor, and also the allowable relative displacement of each floor is determined based on the predefined performance levels. In each step, the coefficient of variation (COV) for the maximum relative displacement of each story is also calculated. Coefficient of variation (COV) is defined as the ratio of the standard deviation to the mean. It shows the extent of variability in relation to the mean of the population. The smaller it is, the more equal the population and more uniform the maximum deformations.

4. AT this step, in order to improve the seismic performance of the structures, metallic-yielding dampers are added to the stories that their displacements exceeded the allowable amount given in the code. Considering that the metallic-yielding dampers are usually installed on Chevron bracings, they also should be designed. In this study it is assumed that the bracings always remain elastic so that the dissipated energy in structures is only the result of nonlinear behavior of metal dampers. For this purpose, bracings should be designed in each step of optimization procedure according to their existing forces. Some researchers have shown that for reaching an appropriate convergence, the applied changes to the structure must be gradual (Moghaddam 2002). In this regard, the following equation is used to correct the stiffness of dampers in each step.

$$\left[k_i\right]_{n+1} = \left[k_i\right]_n \left[\frac{\left(\Delta_i\right)_{max}}{\Delta_{all}}\right]^{\alpha} \tag{1}$$

where, k_i, $(\Delta_i)_{max}$, Δ_{all}, n and α respectively represent the stiffness of dampers in ith story, the maximum relative displacement of ith story, the allowable inter-story relative displacement, the number of steps and the convergence power, which is defined based on the structure type, height of stories, loading type, etc.

5. Using modified dampers, optimization process is repeated until the optimization constraints are satisfied in all stories. Otherwise, the operation is repeated to obtain favorable condition.

6. After completion of the optimization process, stresses in all structural components such as beams and columns are compared to provisions of ASCE 41-13 for nonlinear dynamic analysis.

4.2 Optimization procedure using Genetic Algorithm

In order to improve the optimal behavior of moment-resisting steel frame against seismic loads using genetic algorithm, the following steps have been taken:

1. The weak moment-resisting frame is considered as a starting point in the process.

2. During the optimization process, the structural period is changed. In order to prevent the loss of earthquake input energy and to provide enough energy to cause damage in the structure, the selected earthquakes for conducting dynamic time history analyses are scaled to have spectral acceleration of 0.5 g in a period equal to the first period of the structure.

3. The initial random samples are produced from a wide range of damper stiffness in each story.

4. Time history analysis is carried out with scaled acceleration functions and maximum relative displacements in all stories are determined.

5. Structural performance criteria are controlled based on ASCE7 and penalty function is calculated from the total difference between relative displacement of stories and their allowable amount, of course if they exceed these allowable amounts.

6. Steps 4 and 5 are repeated for the entire population in one generation and then the stopping criterion is controlled. If the optimal result is found, the operation will be stopped, otherwise, the following steps are implemented.

7. New members are generated from the optimal members of the previous generation and removal of the non-optimal members through the crossover and mutation operations.

8. Steps 4 to 7 are repeated again until the optimum solution is reached. The end of operation is the time that the average target function of new generation converges to the optimal target function of the same mentioned generation.

In this algorithm, exploration of the optimal result is carried out according to the fitness of target function. Therefore, choosing appropriate target function which in this study, is the summation of generalized weight and penalty function (Eq. (2)), and dictates the optimal desired path to the optimization procedure. The generalized weight function is equal to the total weight of structural elements, braces, and dampers resistance (Eq. (3)) and the penalty function adds a relatively high expense to the target function based on relative inter-story displacements and also their exceedance of the life safety performance level (Eq. (4)). Finally, the reproductive cycle is repeated until getting optimal result.

$$\text{Objective function} = \text{Generalized Weight} + \text{penalty Function} \tag{2}$$

$$W = W_s + W_b + P_y \,;\, P_y = k \times \Delta_y \tag{3}$$

$$\text{PenaltyFunction} = 1e4 - 1e7 \times \left(\left(\Delta_i\right)_{max} - \left(\Delta_i\right)_{all}\right) \tag{4}$$

Where, W_S, W_b, P_y, $(\Delta_i)_{max}$, $(\Delta_i)_{all}$ are the total weight of structural elements, bracing weight, total resistance of dampers, maximum relative displacement of story *i*, and allowable relative inter-story displacement, respectively.

5. The optimization results

In order to demonstrate the efficiency of the uniform deformation method, optimization procedure is applied on three 5-story regular and irregular moment-resisting frames and 9-story regular frames subjected to four seismic records including El Centro, Morgan Hill, Palm Spring, and Northridge. For brevity, the results of one of them are presented herein.

5.1 Results of optimal retrofitting procedure for 5-story irregular moment-resisting steel frame under Palm Spring record

1. Results of uniform deformation method

5-story irregular frame with initial weakness has a period about 1.54 seconds, which is de-creased to 0.3933 during retrofitting process. Primary studies showed that if the convergence power is selected between 0.4 to 0.8, optimization procedure could have an appropriate convergence speed and also the lowest fluctuations. For these reasons, the convergence coefficient is assumed to be 0.5 in the present study. To reach convergence, 95 cycles

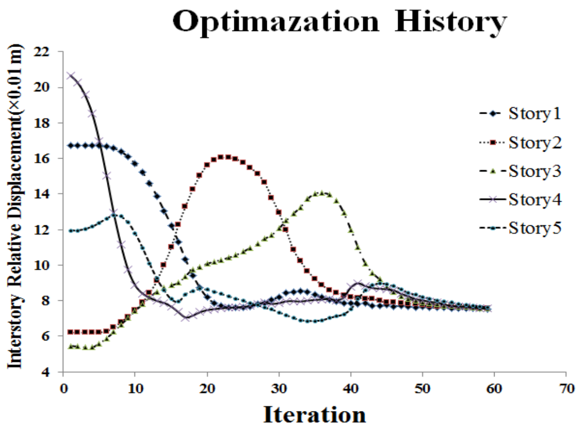

Fig. 3 Trend of variation in maximum relative inter-story displacement of an irregular 5-story frame with damper under Palm spring seismic record in different steps

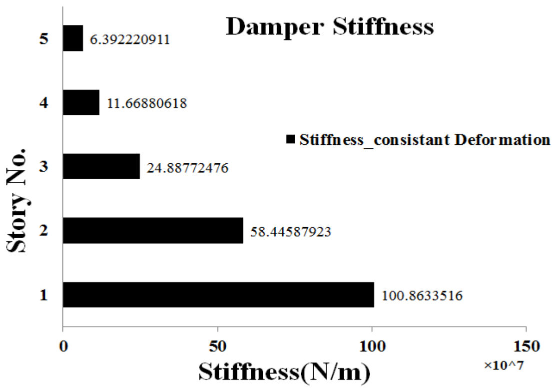

Fig. 4 Optimum arrangement of damper stiffness for irregular 5-story frame under Palm spring seismic record

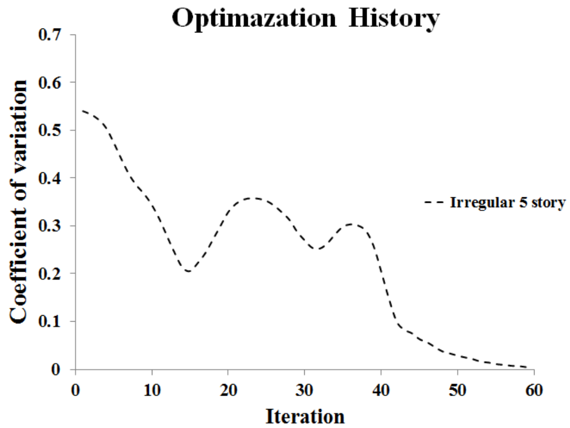

Fig. 5 Coefficient of variation of maximum relative inter-story drifts of an irregular 5-story frame with damper subjected to Palm spring seismic record for different steps

should be repeated. Fig. 3 shows the trend of changes in the inter-story displacement and Fig. 4 depicts dampers arrangements.

Moreover, during the optimization process, the coefficient of variation of maximum relative displacement of stories have been reduced from 0.54 to 0.004599 which implies perfect uniformity in all relative displacements of stories to the allowable amount, as is presented in Fig. 5.

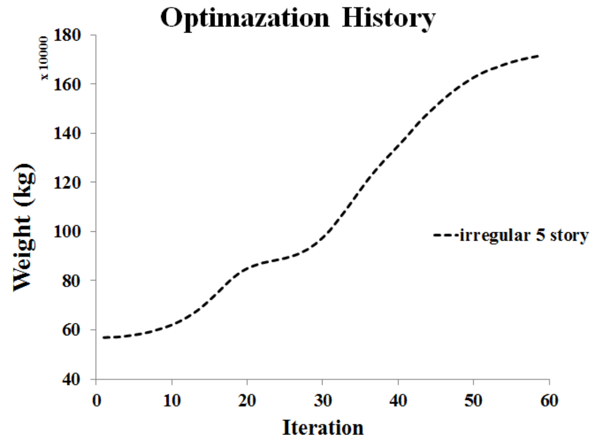

Fig. 6 Variation in generalized weight of an irregular 5-story frame with damper under Palm spring seismic record in different steps

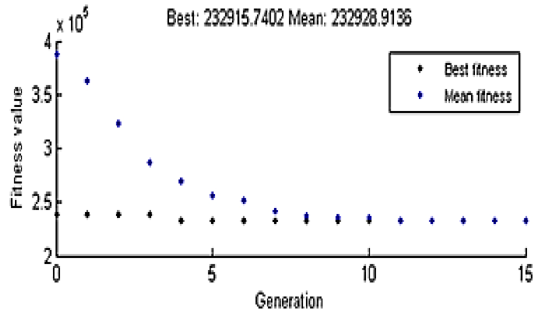

Fig. 7 Optimization trend in objective function of an irregular 5-story frame with damper under Palm spring seismic record by genetic algorithm

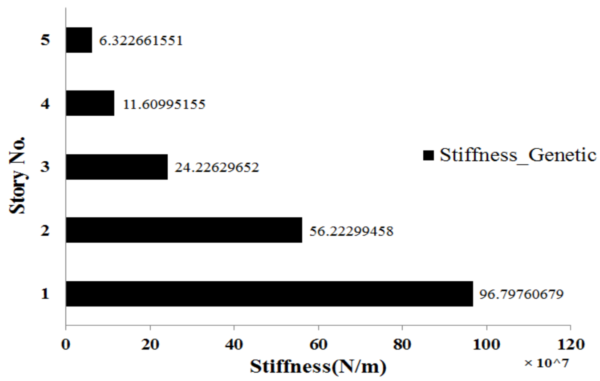

Fig. 8 Optimal arrangement of dampers

Fig. 6 shows the trend of weight variations in different steps, from which, the weight of optimum retrofitted frame is equal to 171.65 kg.

1. Results of genetic algorithms

The initially weak frame had a relative displacement between 5.4 cm to 20.7 cm. This means that the performance levels of stories 2 and 3 were under the benchmark index.

Penalty function was considered equal to $5e4 \times \left(\left(\Delta_i\right)_{max} - \left(\Delta_i\right)_{all} \right)$. Thus, final minimum in the optimization step was acquired after 320 analyses. The

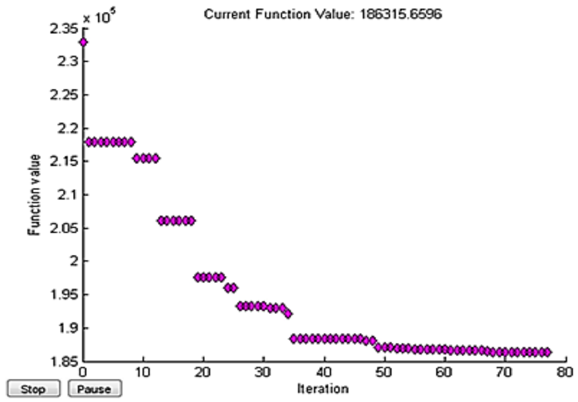

Fig. 9 Optimization trend in objective function of an irregular 5-story frame with damper under Palm spring seismic record by using simple search gradient-based algorithm

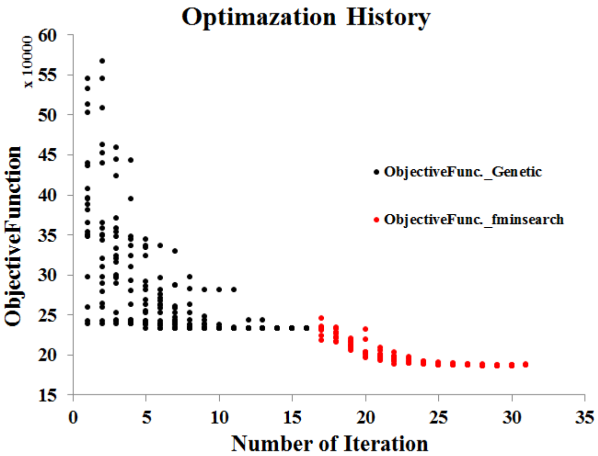

Fig. 10 Optimization trend in objective function of an irregular 5-story frame with damper under Palm spring seismic record by using simple search gradient-based and genetic algorithm

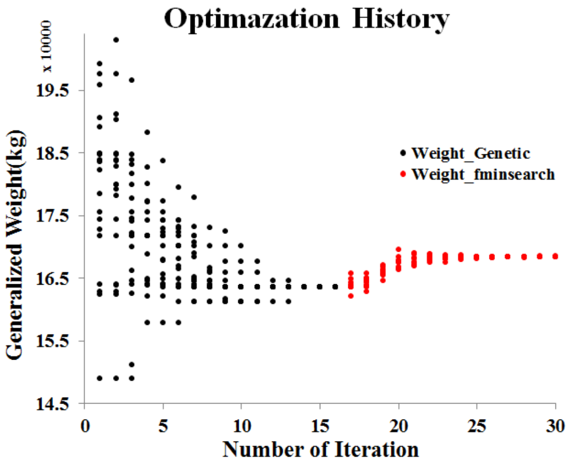

Fig. 11 Variation trend in generalized weight of an irregular 5-story frame with damper under Palm spring seismic record by using simple search gradient-based and genetic algorithm

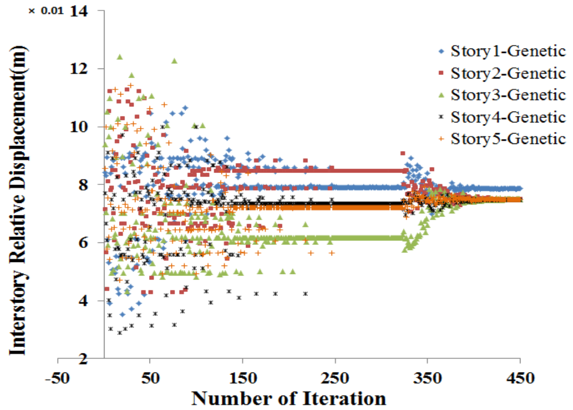

Fig. 12 Variation trend in maximum inter-story displacement of an irregular 5-story frame with damper under Palm spring seismic record by using simple search gradient-based and genetic algorithm

optimum trend in the target function and final minimum are illustrated in Figs. 7 and 8.

Then the precise extreme of the whole structure is determined by using a simple search gradient-based algorithm and the result of optimization trend in the target function is shown in Fig. 9, separately. A number of 154 dynamic analyses have been performed in the above method. Of course, as is clear from Fig. 9, the answer has almost become uniform at the end of the operation.

In order to illustrate optimization trends in the target function and weight changes, the integrated results of both methods are provided in Figs. 10 and 11.

The results of time history optimization for maximum relative inter-story displacements are displayed discretely in Fig. 12, Based on this diagram, it is clear that the genetic algorithm has taken a relatively uniform path between steps 250 to 320, which means that the response could not be optimized, however, after step 320 when the simple search gradient-based algorithm works, the performance level of stories can be optimized and finally the target function is reduced.

6. Comparison of optimal retrofitting results of moment-resisting steel frame for uniform deformation method and genetic algorithm

Uniform deformation method utilizes a simple convergence equation for performing optimization process. The general idea is based on using maximum capacity of structures with the help of unifying deformation in all stories.

The genetic algorithm is a mathematical optimization tool, while its target is assigning optimization parameters, in a way that the target function experiences the minimum possible amount and the optimization constraints are satisfied.

Not exceeding the performance level from expected level is considered as optimization constraint in both methods. This means, in uniform deformation method this constraint is introduced as the lower term in optimization loop while in genetic algorithm it is defined as the penalty function in the target function. In this section, the goal is comparing the results of above-mentioned methods.

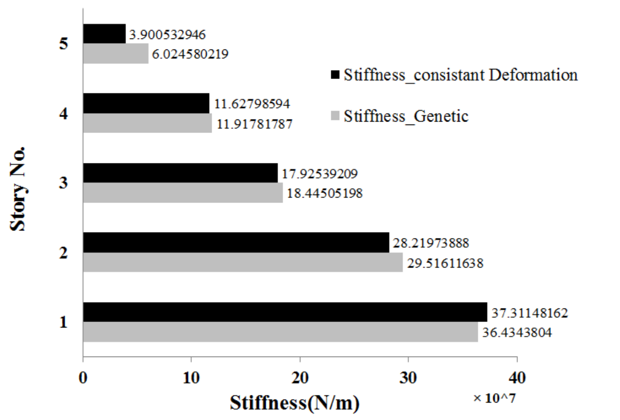

Fig. 13 Comparing optimal arrangement of dampers in irregular moment-resisting 5-storey frame based on two optimization methods, uniform deformation and genetic algorithm

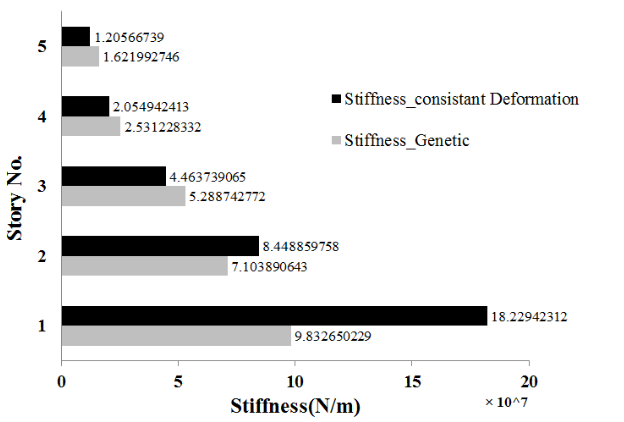

Fig. 14 Comparing optimal arrangement of dampers in irregular moment-resisting 5-storey frame under Morgan Hill earthquake based on two optimization methods, uniform deformation and genetic algorithm

6.1 Comparison of optimal retrofitting results of an irregular 5-story moment resisting frame

In order to compare the results, optimal arrangements of this frame under different seismic records are shown in Figs. 13 to 16. Based on these diagrams, the optimal arrangement in both methods and for all records are almost the same except for Morgan Hill record.

The result from Morgan Hill earthquake shows that there is another maximum point in addition to what is acquired from the uniform deformation method. The diagrams of optimal target functions for both methods in 5-storey irregular moment-resisting frame under four seismic records are depicted in Fig. 17.

It could be stated that according to the obtained results that optimal target functions in Palm spring and Moregen Hill records have minimum amounts using the genetic algorithm. Of course, the difference between the amounts of two methods for the objective function under Palm spring record is very small.

Therefore, it can be concluded that the minimum results of the mentioned records for both methods are in a very

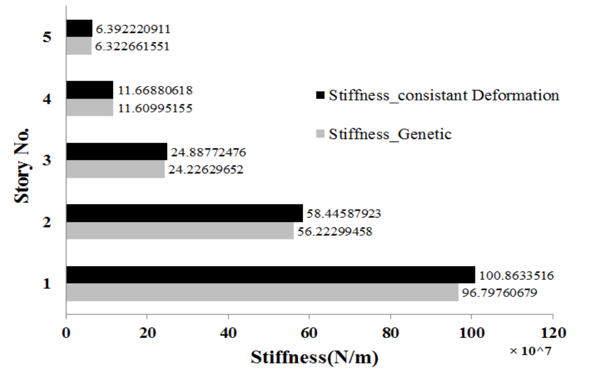

Fig. 15 Comparing optimal arrangement of dampers in irregular moment-resisting 5-storey frame under Palm Spring earthquake based on two optimization methods, uniform deformation and genetic algorithm

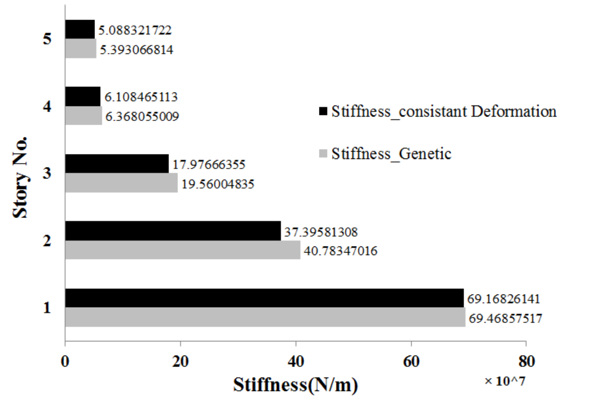

Fig. 16 Comparing optimal arrangement of dampers in irregular moment-resisting 5-storey frame under Northridge based on two optimization methods, uniform deformation and genetic algorithm

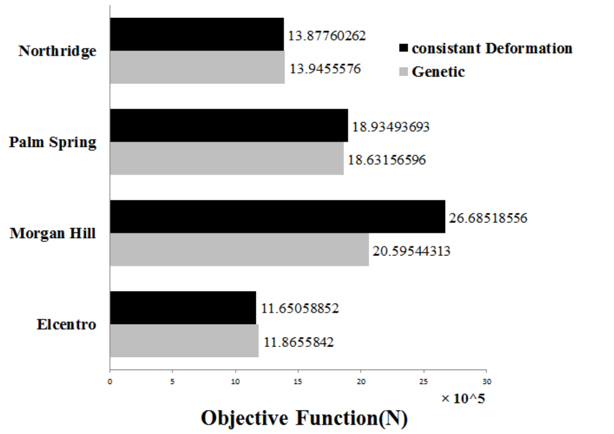

Fig. 17 Comparing optimal objective functions in irregular moment-resisting 5-storey frame under Morgan Hill earthquake based on two optimization methods, uniform deformation and genetic algorithm

close range. While, this frame under Morgan Hill record resulted into a different arrangement of dampers and non-uniform relative displacement with acceptable performance level using the genetic algorithm. This has resulted in target function lower than that of the uniform displacement

Table 1 Comparing the numbers of time history dynamic analyses in irregular 5-storey moment-resisting frame based on uniform deformation and genetic algorithm methods

numbers of time history dynamic analyses		
	Consistent deformation	Genetic
El Centro	59	472
Morgan Hill	42	463
Palm Spring	59	475
Northridge	73	464

method.

In the case of El Centro and Northridge, in comparison to the uniform deformation method, it could be said that the genetic algorithm has not resulted into an optimal solution, although a higher number of analyses and lower speed are associated with the genetic algorithm. In both records, the difference between the target functions is not significant. Results of the number of nonlinear dynamic analyses performed in both methods for achieving convergence are shown in Table 1.

It could be concluded based on Table 1 that the number of required dynamic analyses to reach a desired performance level in the genetic algorithm is about 7 to 11 times greater than that of the uniform deformation method, which means the convergence speed is lower.

7. Verification of uniform deformation method

In order to verify and make conclusion about the uniform deformation method as an optimization procedure, the results of all frames for both methods are presented in Table 2.

According to Table 2, it could be said that the deformation of frames are not uniform in three cases, which all these three frames corresponded to Morgan Hill seismic records. In these cases, COVs are more than 0.2.

Therefore, the genetic algorithm confirms uniform deformation method in about 75% of all cases. It should be noted that in the three above-mentioned cases, only in 2 cases the genetic algorithm works properly and reached the other general minimum, which finally leads to a more optimal target function. Finally, genetic algorithm works better than uniform deformation in just 16.7% of all cases (Fig. 18).

Having higher convergence speed, lower number of analyses and higher consistency with the result of evolutionary genetic algorithm, it could be said that uniform deformation method is a more efficient procedure for retrofitting the existing weak frames.

In this study, the goal was to introduce the uniform deformation method and to compare it with conventional optimization methods. For more reliable conclusions about the efficiency of the method of uniform deformations, more case studies are recommended using different types of structures and the number of more earthquakes, as well as comparison of results with the results of other optimization methods.

Table 2 Comparing the numbers of time history dynamic analyses in irregular 5-storey moment-resisting frame based on the uniform deformation and genetic algorithm methods

Frame Type	Uniform deformation method			
	Earthquake Record	COV	Objective Function	Number of iteration
Regular 5-story	El Centro	0.0965	133611.8	35
	Morgan Hill	0.00009045	238331.8	24
	Palm Spring	0.05169	188968.2	36
	Northridge	0.0159	141983.4	41
Irregular 5-story	El Centro	0.00286	116505.9	59
	Morgan Hill	0.0049	266851.9	42
	Palm Spring	0.00459	189349.4	59
	Northridge	0.0076	138776	73
Regular 9-story	El Centro	0.0971	290014.7	74
	Morgan Hill	0.03574	335601	145
	Palm Spring	0.09431	306000	60
	Northridge	0.05239	258804.2	55
Genetic Algorithm method				
Regular 5-story	El Centro	0.11684	132403.1	316
	Morgan Hill	0.34323	241347	267
	Palm Spring	0.02621	194495.6	396
	Northridge	0.07122	144698.3	456
Irregular 5-story	El Centro	0.10159	118655.8	472
	Morgan Hill	0.31843	205954.4	463
	Palm Spring	0.02207	186315.7	475
	Northridge	0.03518	139455.6	464
Regular 9-story	El Centro	0.08921	291104.1	468
	Morgan Hill	0.20701	298264.6	376
	Palm Spring	0.09052	316041.3	382
	Northridge	0.04853	252007.4	385

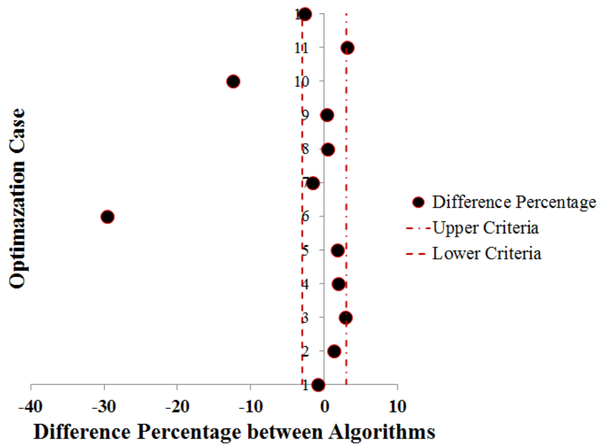

Fig. 18 Comparing differences of objective functions in percent for two optimization methods, uniform deformation and genetic algorithm

8. Conclusions

The idea of uniform deformation method is a way to retrofit existing weak structures or optimal design of new ones. In this study, uniform deformation and genetic algorithm methods are used to retrofit initially weak moment-resisting steel frames. It was shown that the genetic algorithm confirms the results of uniform deformation method in 75% of all cases. Therefore, the uniform deformation method is a more efficient way in rehabilitation of existing structures with minimum weight regarding its higher convergence speed and lower total number of analyses. Additionally, On the other hand it meets the performance needs of designers.

References

Artar, M. and Daloglu, T.A. (2015), "Optimum design of steel frames with semi-rigid connections and composite beams", *Struct. Eng. Mech*., **55**(2), 299-313.

ASCE/SEI 41-13 (2013), Seismic Rehabilitation of Existing Building, American Society of Civil Engineers (ASCE).

ASCE/SEI 7-10 (2010), Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers (ASCE).

Babu Desu, N., Dutta, A. and Deb, S.K. (2007), "Optimal assessment and location of tuned mass dampers for seismic response control of a plan-asymmetrical building", *Struct. Eng. Mech*., **26**(4), 459-477.

Bagheri, S., Hadidi, A. and Alilou, A. (2011), "Heightwise distribution of stiffness ratio for optimum seismic design of steel frames with Metalic-Yielding dampers", *Procedia Eng.*, **14**, 2891-2898.

Benavent-Climent, A. (2011), "An energy-based method for seismic retrofitFrames using hysteretic dampers", *Soil Dyn. Earthq. Eng*., **31**, 1385-1396.

Connor, J.J. and Klink, B.S.A. (1996), *Introduction to Motion Based Design*, Computational Mechanics Publications, Boston. USA.

Fajfar, P. and Krawinkler, H. (1997), "Seismic design methodologies for the next generation of cods", *Proceeding of International Workshop on Seismic Design Methodologies for the Next Generation of Codes*, Balkema, Rotterdam, Slovenia, Bled, June.

Gantes, C.J., Vayas, I., Spiliopoulos, A. and Pouangare, C.C. (2000), "Optimum bending and shear stiffness distribution for performance based design of rigid and braced multi-story steel frames", *Behavior of Steel Structures in Seismic Areas*, Rotterdam, 585-592.

Gong, Y., Grierson, D.E. and Xu, L. (2003), "Optimal design of steel building frameworks under seismic loading", *Response of Structures to Extreme Loading (XL2003)*, Canada, Toronto.

Hajirasouliha, I. (2011), "An efficient performance-based seismic design method for reinforced concrete frames", *Earthq. Eng. Struct*., **41**(4), 663-679.

Hajirasouliha, I. and Moghaddam, H. (2009), "New lateral force distribution for seismic design of structures", *J. Struct. Eng.*, **135**(8), 906-915.

Hajirasouliha, I., Asadi, P. and Pilakoutas, K. (2012), "An efficient performance-based seismic design method for reinforced concrete frames", *Earthq. Eng. Struct. Dyn.*, **41**(4), 663-679.

Hajirasouliha, I., Pilakoutas, K. and Moghaddam, H. (2011), "Topology optimization for the seismic design of truss-like structures", *Comput. Struct.*, **89**(7), 702-711.

Hajrasouliha, I. (2005), "Evaluating the effect of bearing elements distribution in the structure on its seismic performance", PhD Dissertation, Sharif University of Technology, Tehran.

Kandemir-Mazanoglu, E.C. and Mazanoglu, K. (2017), "An optimization study for viscous dampers between adjacent buildings", *Mech. Syst. Signal Pr.*, **89**, 88-96.

Karami Mohammadi, R. (2001), "Effects of shear strength distribution on the reduction of seismic damage of structures", Ph. D. Thesis, Dept. of Civil Engineering, Sharif University of Technology, Tehran, Iran. (in Persian)

Karami Mohammadi, R. and Haghighipour, F. (2017), "Implementation of uniform deformation theory in semi-active control of structures using fuzzy controller", *Smart Struct. Syst.*, **19**(4), 351-360.

Karami Mohammadi, R. and Sharghi, A.H. (2014), "On the optimum performance-based design of eccentrically braced frames", *Steel Compos. Struct*., **16**(4), 357-374.

Karami Mohammadi, R., El Naggar, M.H. and Moghaddam, H. (2004), "Optimum strength distribution for seismic resistant shear-building", *Int. J. Solid. Struct*., **41**, 6597-6612.

Krishnamoorty, C.S. (2001), "Structural optimization in practice: Potential applications of genetic algorithms", *Struct. Eng. Mech.*, **11**(2), 151-170.

Martínez, C.A., Curadelli, O. and Compagnoni, M.E. (2014), "Optimal placement of nonlinear hysteretic dampers on planar structures under seismic excitation", *Eng. Struct.*, **65**, 89-98.

Mazzoni, S., McKenna, F., Scott, M.H., Fenves, G.L. and Jeremic, B. (2007), *Opensees Command Language Manual*, Pacific Earthquake Engineering Research (PEER) Center.

Moghaddam, H. (2002), *Earthquake Engineering-Theories and Application*, Jahad Daneshgahi Publication, Sharif University of Technology, Iran.

Moghaddam, H. and Hajirasouliha, I. (2006), "Toward more rational criteria for determination of design earthquake forces", *Int. J. Solid. Struct.*, **43**(9), 2631-2645.

Moghaddam, H. and Hajirasouliha, I. (2008), "Optimum strength distribution for seismic design of tall buildings", *Struct. Des. Tall Spec. Build.*, **17**(2), 331-349.

Moghaddam, H., Hajirasouliha, I. and Doostan, A. (2005), "Optimum seismic design of concentrically braced steel frames: concepts and design procedures", *J. Constr. Steel Res.*, **61**(2), 151-166.

Mohammadi, R.K. and Nadoushani, Z.M. (2012), "Optimum design of eccentrically braced frames using endurance time method", *15WCEE*, Lisboa, Portugal.

Mohammadi, R.K. and Sharghi, A.H. (2014), "On the optimum performance-based design of eccentrically braced frames", *Steel Compos. Struct.*, **16**(4), 357-374.

Nikfard, F. (2010), "Assessment of seismic performance of steel frames having metallic-yielding cartridge dampers using endurance time method", M.Sc. Thesis, Sharif University of Technology, Tehran.

Park, K.S., Koh, H.M. and Hahm, D. (2004), "Integrated optimum design of viscoelastically damped structural systems", *Eng. Struct.*, **26**, 581-591.

Rahemi, M.A. (2007), "Optimal seismic performance-based design of moment resisting steel frames", M.Sc. Thesis, Sharif University of Technology, Tehran.

Singh, M.P. and Moreschi, L.M. (2001), "Optimal placement of dampers for passive response control", *Earthq. Eng. Struct. Dyn*., **30**, 553-572.

Tsuji, M. and Nakamura, T. (1996), "Optimal viscous dampers for stiffness design of shear buildings", *Struct. Des. Tall Build.*, **3**(5), 217-234.

Wen, Y.K. (2001), "Reliability and performance-based design", *Struct. Saf*., **23**, 407-428.

Ying, Z.G., Ni, Y.Q. and Ko, J.M. (2017), "A semi-active stochastic optimal control strategy for nonlinear structural systems with MR dampers", *Smart Struct. Syst.*, **5**(1), 69-79.

Zhang, J. and Xia, P. (2017), "An improved PSO algorithm for parameter identification of nonlinear dynamic hysteretic models", *J. Sound Vib.*, **389**, 153-167.

CC