INTERNATIONAL JOURNAL OF OPTIMIZATION IN CIVIL ENGINEERING
Int. J. Optim. Civil Eng., 2020; 10(1):53-70

VISCOUS DAMPER PLACEMENT OPTIMIZATION IN CONCRETE STRUCTURES USING COLLIDING BODIES ALGORITHM AND STORY DAMAGE INDEX

M.R. Hashemi ,R. Vahdani[*, †], M. Gerami and A. Kheyrodin
Civil Engineering Departement, Semnan University, Semnan, Iran

ABSTRACT

Dampers can reduce structural response under dynamic loads. Since dampers are costly, the design of structures equipped with dampers should make their application economically justifiable. Among the effective cost reduction factors is optimal damper placement. Hence, this study intended to find the optimal viscous damper placement using efficient optimization methods. Taking into account the nonlinear behavior of structure, this optimal distribution can be determined through meeting story-wise damping requirements such that the structure provides the minimum dynamic response and becomes economically justified. To compare the effect of different damper placement layouts on structural response and determine the objective function of optimization, the ratio of peak structural displacement to yield displacement was used as the damage index and objective function of optimization. Colliding Bodies' Optimization (CBO) algorithm was used for optimal damper placement. In this study, the 3- and 4-story concrete frames with different damper placement conditions were studied. Results confirmed the efficiency of the proposed method and algorithm in optimal viscous damper placement in each story. It was also discovered that the application of dampers on higher stories partially uniforms height-wise damage distribution and works towards the design goals.

Keywords: viscous damper; damage index; optimization; optimal position; nonlinear analysis

Received: 4 August 2019; Accepted: 20 November 2019

1. INTRODUCTION

Today, the application of dampers is among the most common methods for structural control. These systems are used to improve structural performance and reduce structural

---

[*]Corresponding author: Civil Engineering Departement, Semnan University, Semnan, Iran
[†]E-mail address: rvahdani@semnan.ac.ir (R. Vahdani)

damage under major earthquakes. Construction cost is a key factor in designing different structures. As a result, they should be designed to exhibit the best performance in an earthquake at the same cost as conventional structures. Despite the advantages of dampers in reducing structural response during earthquake, their relatively high cost necessitates a method for damper placement optimization by minimizing their numbers to achieve the best structural performance in nonlinear surfaces. Many methods have been proposed for story-wise damper placement, most of which try to find mathematical relationships between different structural parameters through reasonable assumptions and solving those relationships using damper placement optimization methods. Although different methods have been proposed by various studies for damper placement, each method is applicable in a certain condition and cannot be generalized. In addition, the majority of valid codes lack a certain method for precise story-wise damper placement. The Simplified Sequential Search Algorithm (SSSA) is a well-known method for structures with linear dampers [1]. Different mathematical methods have been proposed for optimal damper placement and distribution to reduce structural displacement. A very common method, used as a basis by many studies for damper placement was proposed by Takewaki [2, 3]. This method relies on the minimization of total story drift using the displacement function based on the natural frequency of an undamped structure. Among other researchers who proposed relevant methods is Filiatrault et al. [4] who proposed a method for optimal damper distribution on the stories by considering different structures and performing dynamic time history analysis assuming that the structural elements remain elastic. To this end, they used an algorithm which was based on the minimization of strain energy in key structural elements. They also proposed simplified slip-load design spectra method for optimal distribution of sip-load through parametric studies on natural vibration period and earthquake frequency content [5]. Another study in 2009 proposed a method for optimal viscous damper placement and size, using genetic algorithm. Results suggested comparable performance of this method to existing methods [6]. Lopez et al. investigated the effectiveness of a simple damper placement method in a Multi-Degree-Of-Freedom (MDOF) structure. Results showed that the best response of a structure with uniform stiffness is achieved by adding dampers to lower stories [7]. Moreschi et al. optimized design parameters of fluid (yielding) metallic dampers and friction dampers in moment resisting frames. These parameters included slip-load, damping system stiffness, and yield displacement. They investigated optimal distribution of height-wise dampers using Genetic Algorithm (GA) by defining an objective function based on the peak story acceleration response [8]. Lavan et al. studied damper placement and concluded that Li et al. succeeded in optimization of friction damping system parameters in elastic structures. Since SSSA and GA are time-consuming methods, their study used a method based on story-wise shear loads to determine the optimal number and position of dampers [9]. The active control techniques for optimal damper placement are less efficient than inactive control techniques [10]. Apostolakis et al. studied optimal design of moment resisting frames with damper and cross brace assuming damper slip-load as the optimization variable. They used GA and square root of the sum of story acceleration for solving the optimization problem and assessing seismic response, respectively [11]. Shin et al. proposed a method for optimal viscous damper placement that provides life safety structural performance level (LSSPL) and minimum structural damage. This study used GA to optimize three different danger levels in the USA. Their findings suggested that the objective function size effectively reduced at all danger levels [12]. Considering the size of their high-rise structure and the many design variables, Yan et al. investigated the optimal viscous damper size and position using GA [13]. They also investigated the automatic generation of smart earthquake-resistant building system in structures with hybrid system of base-isolation and fixed-based [14]. Saitura et al. investigated an optimal damper distribution in a real 26-story structure using an approach based on an optimization problem and considering other damper properties, except damping. They found that the determination of optimal damper distribution is more efficient based on the cost criterion relative to other conventional criteria [15]. Lucalandi investigated the effect of vertical distribution of damping coefficients of a nonlinear viscous damper for seismic reinforcement of multistory reinforced concrete frames. This study used two energy methods and a simplified sequential search algorithm to determine the optimal distribution, and then compared them. Results showed that the energy methods produced good results in terms of cost reduction, distribution efficiency, and simplicity, as compared to more effective yet complex methods [16].

Viscous dampers have a high energy dissipation capacity and the fastest growth rate for structural application. Despite growing rate of viscous dampers application and the significant role of damper placement in the improvement of seismic response of the structure, there is currently no consensus on the use of a special method for height-wise viscous damper placement. Considering that the majority of studies into optimal damper placement focus on steel structures and there are fewer studies on concrete structures, this study investigated the optimal damper placement in such structures. This study proposed an objective function by using the concept of story-wise damage index based on the peak story drift and yield displacement of structure. For optimal damper placement, dampers are first positioned randomly. Then, nonlinear analysis of time history is applied to the structure using seven pairs of accelerograms. In the next stage, story drift coefficient is calculated. In the second part, a population should be generated for using the CBO algorithm. To this end, a random damping is assigned to each damper. This process is iterated to achieve a large enough population. In each stage, the sum of damping assigned to the dampers is a constant value. In the next stage, the fitness function for each particle of the whole population is calculated and the respective terms are controlled to find the best particles with the least damage index as the story damping. Otherwise, the damper of a story with a drift lower than the total mean drift is removed, and its damping value is added to a story with a drift value higher than the total mean drift. This process continues until the objective function is fulfilled.

This study used 2D 3- and 4-story moment frames for viscous damper placement. To this end, the desired structures were first designed to meet design basis earthquake (DBE) requirements according to the building codes. Then, the nonlinear time history analysis was applied to all models to determine their yield displacement using OpenSees. Since story dampers should be distributed in such a way to produce the most optimal outcome, different story-wise damper placements were done randomly with a uniform distribution. Finally, the optimal damper position is determined by considering all desired limitations using the optimization algorithm and based on an iterative method.

2. OPTIMAL VISCOUS DAMPER PLACEMENT

2.1 Damping coefficient of viscous dampers

The main use of energy dissipation devices in building frames is to reduce frame displacement and damage, which can be done by increasing the frame stiffness and/or damping. Among energy dissipation devices with both stiffness and damping characteristics are metallic yield dampers, friction dampers, and viscous-elastic dampers. On the other hand, viscous dampers, which often have damping characteristics and lack considerable stiffness, can significantly increase energy dissipation in the frame. Adding viscous dampers does not change the force-displacement relationship. In other words, the response curve for a condition with or without a damper is generally similar. The force-displacement relationship for different dampers depends on environmental conditions, seismic load, permanent deformations, and bi-directional deformations. This dependency should be taken into account in seismic design and analysis by considering threshold values, which are related to properties of materials used in the damper. Energy dissipation in a damper on the i*th* story under harmonic cycles and the main frequency is as follows [17]:

$$E_{Di} = \pi c \frac{2\pi}{T} \phi_{ij}^2 \cos^2 \theta_j = \frac{2\pi^2 c \phi_{ij}^2 \cos^2 \theta_j}{T} \tag{1}$$

where, c is the viscous damping, T is natural period of the structure, ϕ_{ij} is displacement of both damper ends, and θ_j is the deviation angle of the damper on the i*th* story. As a result, the effective damping (β_{eff}) of the structure, i.e the ratio of dissipated energy in the structural damper to load acting on the structure in a hysteretic cycle, is expressed as follows:

$$\beta_{eff} = \beta + \frac{T \sum_j C_j \cos^2 \theta_j \ \phi_{ij}^2}{4\pi \sum_i M_i \phi_i^2} \tag{2}$$

where, θ_j is the deviation angle of the jth damper on ith story, ϕ_{ij} is the horizontal displacement of two ends of the damper in the first oscillation mode, and M_i is the seismic weight of each story. The intrinsic structural damping is considered to be 5%.

2.2 Determination of damage index

Damage index measurement is necessary for the assessment of damage to structural elements. The damage indices are generally good criteria for the assessment of structural performance against seismic excitements. The damage indices are a function of structural ductility, dissipated energy, etc. The damage index ranges between 0 and 1, indicating an undamaged structure and a completely collapsed structure, respectively. Dissipated energy is one of the most important damage parameters used for the calculation of structural damage under the influence of seismic loads. This energy is dissipated under damping effect, plastic deformation, and/or hysteretic cycles. This amount of energy represents the damage rate. The non-cumulative damage index is among the simple indices with a suitable behavior. Among these indices are ductility, which is nonelastic deformation of a structure without causing a total collapse or structural strength reduction. This index is defined as follows in terms of displacement:

$$DI = \frac{\Delta m}{\Delta y} \tag{3}$$

where, Δ_m and Δ_y are, respectively, the maximum displacement caused by an earthquake and yield displacement; in addition, DI is the structural damage index. To measure the story-wise damage index and total damage index, Δ_m can be replaced by the peak story drift and/or the peak roof drift [18].

2.3 Formulation of viscous damper placement optimization

An optimization problem includes an iterative solution process. According to these equations, the aim is to find optimal story-wise damper position in such a way that the damage index is minimized. In the optimization process, minimization of the objective function matters the most. In other words, optimization should be done in such a way that the objective function is minimized. Eq. (3) is the objective function for story-wise damper placement. This study used Eq. (3) to evaluate the non-conditional optimization problem based on the CBO algorithm to obtain damping coefficients of each damper. The aim was to determine the damping coefficients and position of each damper in such a way that the damage index of stories does not exceed a certain value. As a result, the following optimization equation was developed:

$$\begin{aligned} &Find: && C^T = \{C_1, C_2, \ldots\ldots\ldots\ldots, C_n\} \\ &Minimize: && F = \text{minimize(DI)} = \frac{\Delta m}{\Delta y} \\ &Where: && 0 \le DI \le 1 \end{aligned} \tag{4}$$

where, C^T is the damping value, which includes the position and damping of a story-wise damper. By minimization of Eq. (4) based on the optimization algorithm, the damping vector is obtained. The amount of C for each damper should be within an allowable range.

$$0 \le C_i \le \bar{C} \tag{5}$$

where, $\bar{C}$ is the upper threshold of damping coefficient obtained from Eq. (2).

2.4 CBO algorithm

Colliding bodies' optimization (CBO) algorithm is a metaheuristic algorithm developed by Kaveh and Mahdavi [19] using the laws of physics. This algorithm is based on one-dimensional collision of particles. The collision between bodies' is based on the laws of momentum and energy. There are no external force on the particles, and the momentum of all the particles before and after the collision are equal, (Fig. 1).

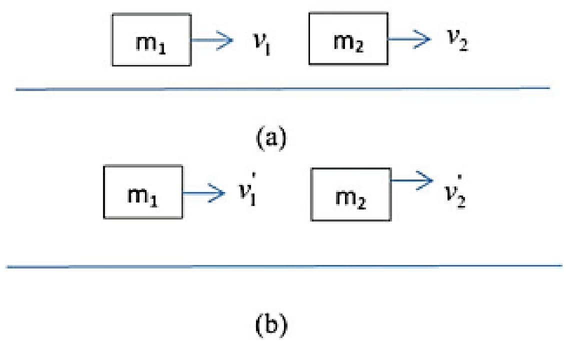

Figure 1. The collision between two particles. (a) before the collision and (b) after the collision

Therefore can be expressed by the following equation:

$$m_1 v_1 + m_2 v_2 = m_1 v_1^{'} + m_2 v_2^{'} \tag{6}$$

where V_1 and V_2 are the initial velocity of the first and second particles before collision, $V_1^{'}$ and $V_2^{'}$ are the final velocity of the first and second particles after collision. m_1 and m_2 are the mass of the first and second particles. The equations for the velocities after a one-dimensional collision are:

$$\begin{aligned} v_1^{'} &= \frac{(m_1 - \varepsilon m_2)v_1 + (m_2 + \varepsilon m_2)v_2}{m_1 + m_2} \\ v_2^{'} &= \frac{(m_2 - \varepsilon m_1)v_2 + (m_1 + \varepsilon m_1)v_1}{m_1 + m_2} \end{aligned} \tag{7}$$

where ε is the coefficient of restitution of the two colliding bodies, the ratio can be expressed by the following equation:

$$\varepsilon = \frac{\left|v_2^{'} - v_1^{'}\right|}{\left|v_2 - v_1\right|} = \frac{v^{'}}{v} \tag{8}$$

In this algorithm, each structure is regarded as a massed particle, which can be a solution in the optimization problem. Each particle has an initial mass and speed before colliding with another particle. After the collision, each particle is separated with a certain speed and moves towards its secondary position. The secondary position can be more or less fit than the initial position. A summary of the mechanism of this algorithm is as follows [20].

In this algorithm, the number of design variables in the search space is equal to the number of desired dampers and each particle represents a structure. Therefore, some particles with random values are first generated as the design variables. Then, a mass is assigned to each particle based on the fitness value and the particles are ordered downward based on their fitness value. Next, particles were divided into two groups, that the first group included stationary particles and the second group included moving particles. The fitness values of moving particles are lower than those of the stationary particles. The moving particles collide with the stationary particles and change their position in the search space. The speed of moving and stationary particles is determined as follows:

$$\begin{cases} V_i = 0 & i = 1, 2, 3, \dots, \frac{np}{2} \\ V_i = X_{i-\frac{np}{2}} - X_i & i = \frac{np}{2}+1, \frac{np}{2}+2, \dots, np \end{cases} \tag{9}$$

where np stands for the number of particles, X_i is the position of i*th* particle, and V_i is the speed of the *i*th particle. According to the laws of physics, when two objects collide, the momentum of all particles before the collision is equal to their momentum after the collision. As a result, when the kinetic energies before and after the collision are equal, the speed of stationary and mobile particles after the collision ($V_i^{'}$) is as follows:

$$\begin{cases} V_i^{'} = \dfrac{\left(mp_{i+\frac{np}{2}} + (\mu)\left(mp_{i+\frac{np}{2}}\right)\right)V_{i+\frac{np}{2}}}{mp_i + mp_{i+\frac{n}{2}}} & i = 1, 2, 3, \dots, \frac{np}{2} \\ V_i^{'} = \dfrac{\left(mp_i - (\mu)\left(mp_{i-\frac{np}{2}}\right)\right)V_i}{mp_i + mp_{i-\frac{np}{2}}} & i = \frac{np}{2}+1, \frac{np}{2}+2, \dots, np \end{cases} \tag{10}$$

where mpi is the mass of i*th* particle defined as Eq. (11).

$$mp_i = \frac{\frac{1}{fit(i)}}{\sum_{k=1}^{np} \frac{1}{fit(k)}} \quad i = 1, 2, 3, \dots, np \tag{11}$$

where $fit(i)$ is the value of the objective function of i*th* particle. For better exploration of the search space, μ is used as Eq. (12) in Eq. (10).

$$\mu = 1 - \frac{iter}{iter_{\max}} \tag{12}$$

where iter is the current iterative number and $iter_{max}$ is the total iterations in the optimization process. Finally, the new position of each particle considering their post-collision speed is obtained from Eq. (13).

$$X_i^{new} = \begin{cases} X_i + rand\, V_i' & i = 1, 2, 3, \ldots, \frac{np}{2} \\ X_{i-\frac{np}{2}} + rand\, V_i' & i = \frac{np}{2} + 1, \ldots, np \end{cases} \tag{13}$$

where, rand is a random number between 0 and 1, and X_i^{new} is the new position of the i*th* particle after the collision. Different applications of the CBO and ECBO can be found in [21].

2.5 Proposed method for determining damper position and damping

This paper used an iterative process based on structural deformation to determine a proper model for damper distribution, increase structural performance, and achieve a desirable placement. To this end, the structure under investigation was first designed at Design Basis Earthquake (DBE) level to enable it to meet acting loads according to the design codes. Then, the nonlinear time history was applied the structure to determine its yield displacement. Since the story-wise dampers should be distributed in such a way as to obtain the best solution, different layouts of damper displacement are considered. Therefore, a random distribution of story-wise dampers is considered in the first hypothesis, and the structure is subjected to seismic excitements. This study used seven accelerograms. By considering the extent of each story drift and its comparison to the total mean story drift, damper positions are modified to transfer damping from less damaged stories to more damaged stories. A certain value is assigned to the damage index for damper placement in the structure. In this study, the damage index was set at 0.6.

In the optimization process, random damping coefficients are assigned to selected dampers. This damping is measured based on a continuous distribution and peak damping, which can be assigned to the structure. In the next stage, considering the damping values assigned to the structure, nonlinear time history analysis is applied to it under different seismic excitements and the objective function is solved to calculate the damage index. To express the ratio of damage variations to target damage, the coefficient of damage variations is obtained using Eq. (14).

$$COV = \frac{1}{DI_t} \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left(DI_i - DI_t \right)^2} \tag{14}$$

where, DI_t Is the target damage index set at 0.6 and DI_i is the damage index of each story. If the obtained variation coefficient is small, the story-wise damage distribution will be more uniform and closer to the target level. If the coefficient of variations is small, the convergence condition is met and the process is terminated. Otherwise, the optimization algorithm is repeated to determine the damping value of the damper. After several iterations, the desired convergence and optimal damper distribution on the stories are achieved.

3. NUMERICAL EXAMPLES

Three examples with different structural conditions were selected to investigate the efficiency of the proposed method and algorithm. It is worth noting that the above method was validated by comparing its results with an example from [22]. For further study, a 4-story concrete structure was considered. In this study, all examples were investigated and compared according to [22] to investigate the efficiency of CBO method. In the method proposed by [22], the damper with a uniform distribution is placed on all stories and then subjected to nonlinear time history analysis. As a criterion for investigating the need for damper placement on the stories, the extent of drift caused by this story-wise damper placement was compared to the values from undamped structures and the method used in [23].

3.1 Accelerograms

Structural responses to earthquake depend on accelerogram properties, such as frequency content and maximum acceleration. On the other hand, the soil type and distance from the fault can affect the structural response under investigation. This study tried to use acceleration data from various earthquakes in Iran recorded by a set of accelerograms. To this end, seven earthquake records with different PGAs, compared according to the Standard 2800-Fourth Edition, were used. Table 1 represent the properties of the employed accelerograms.

Table 1: Earthquake record specification

NO	Earthquake	Year	Magnitude	PGA(g)	Site
1	BAM	2003	6.5	0.63	**BAM**
2	TEHRAN	2003	4.4	0.17	**TEHRAN**
3	KERMANSHAH	2017	7.3	0.126	**KERMANSHAH**
4	SARPOLE ZAHAB	2017	4.4	0.272	**SARPOLE ZAHAB**
5	ZARAND	2005	6.5	0.329	**ZARAND**
6	TABAS	1978	6.4	0.51	**TABAS**
7	GOLBAF	1981	5.9	0.32	**GOLBAF**

3.2 3Story concrete frame

To investigate the performance of the proposed method and algorithm, the first example investigated a three-story concrete frame based on the assumptions in Ref. [21] (Fig. 2). The finite element model of this structure is comprised of eight nodes and three degrees of freedom. E and p are set at 30,000 MPa and 2,500 kg/m3, respectively. On the other hand, the cross-sections of all elements were set based on the assumption in Fig. 2. To determine the optimal position and damping coefficient of each damper, the story-wise dampers were uniformly distributed according to Fig. 3. Table 2 presents the cross-section of elements.

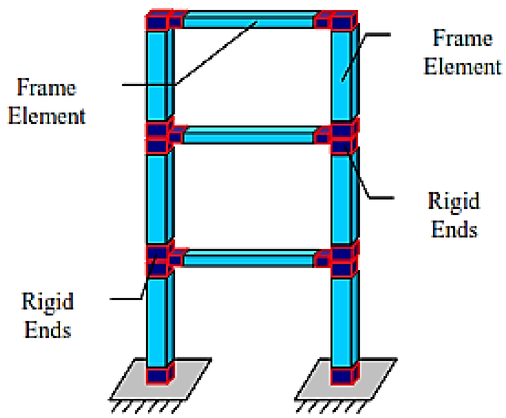

Figure 2. 3story frame example and beam column sections properties [22]

Table 2: The beam column sections properties

Story	Beam	Column	Number of Rebar for Column
1	B40x30	C40x40	12T18
2	B40x30	C40x40	12T18
3	B40x30	C40x40	12T18

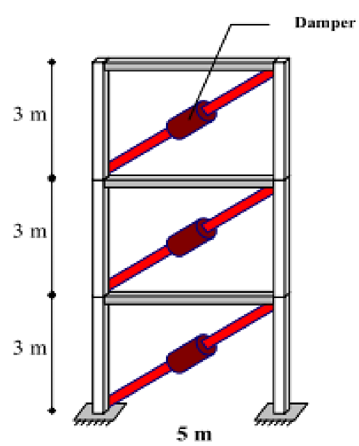

Figure 2. The uniform distribution of damper in the story [22]

The total damping coefficient of dampers in the above structure was calculated based on the target effective damping (β_{eff}), which was set at 20% in this example. According to Eq.2, the damping coefficient of the damper was $C = 80.87\ kg.s/m$. Based on this damping value, a uniform distribution was observed in all stories according to the method in Ref .22 (Table 3). Then, the structure was subjected to time history analysis.

Table 3: The damping value in the story

Story No.	Damping
1	34.8347
2	34.8347
3	34.8347

According to the proposed method in [23], a certain damping ratio should be assigned to achieve a desired story-wise response, which makes the structure very costly. Therefore, the optimum damping for a given story is achieved using the proposed algorithm for determination of optimal story-wise damping with an effective damping value of 20%, assuming a random story-wise damper distribution (Table 4). Damping assigned to the stories are as follows:

Table 4: The damping values allocated to the story according to the proposed algorithm

Story No.	Damping
1	0
2	3.3576
3	77.5109

Fig. 4 shows the damping values from [21] and the proposed algorithm:

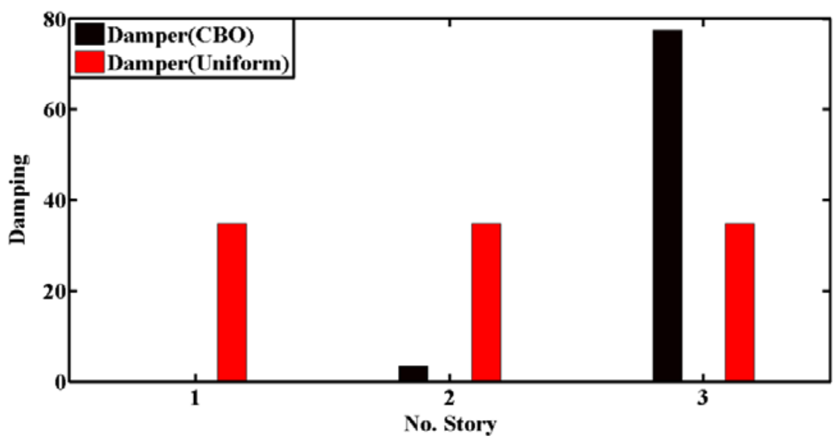

Figure 4. Optimum coefficients for minimization of story damage index

According to Fig. 4 the proposed method assigned a zero or very small damping to the stories with damage index lower than the reference damage index; whereas, [22] considered a constant damping for all stories to reduce story drift using the damping distribution model in [22]. In the proposed method, the third story accounted for a considerable amount of the total damping. Therefore, the difference between the proposed method and [23] in damper assignment can be attributed to the story-wise damage index. Considering the optimal damper layout, story drift variations Fig. 5 are as follows:

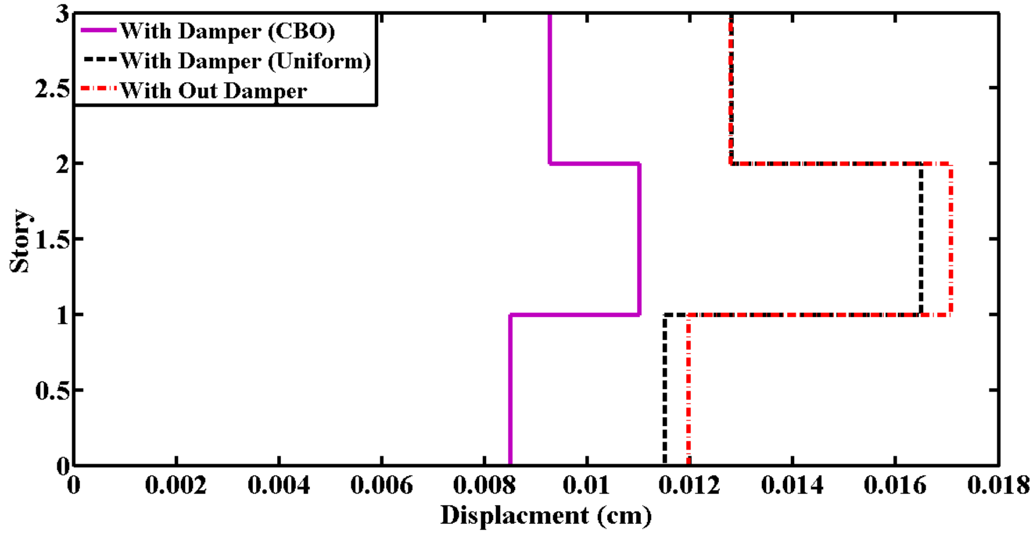

Figure 5. Maximum displacement of each story with various damper damping

According to Fig. 5, using dampers on the stories with more critical damage index can reduce the total vulnerability of the structure; in addition, the structural response can be reduced by assigning a certain damping value to the desired story. Fig. 6 also show that the optimal story-wise damping distribution, based on the damage index, reduced the extent of damage by approximately 38%. Fig. 7 shows the optimal story-wise damper positions.

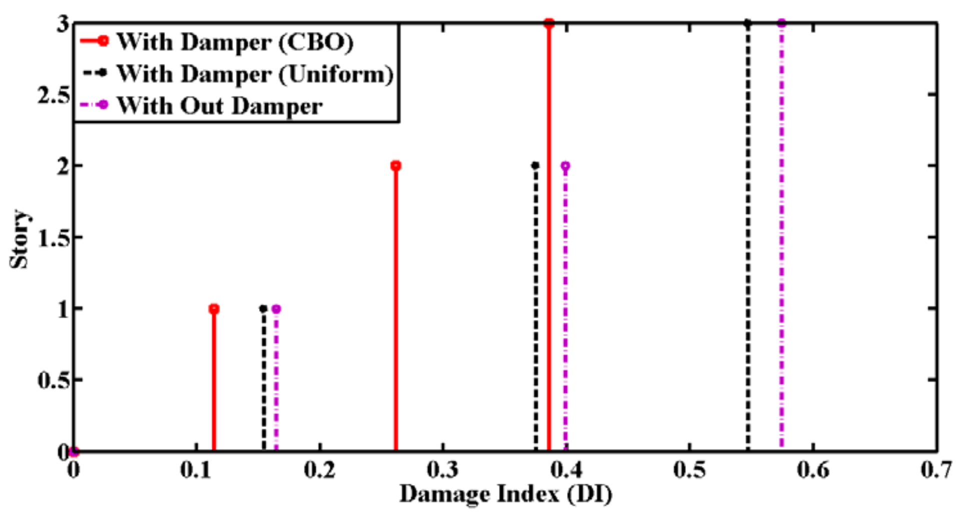

Figure 6. Damage index value of each story

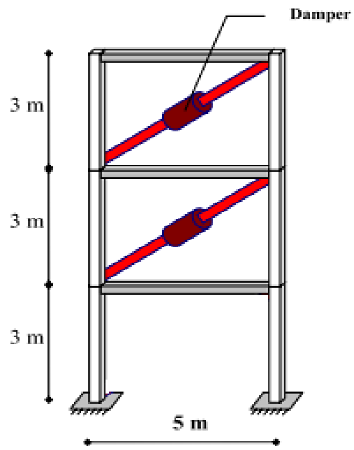

Figure 7. Optimal placement of damper according to proposed method

In addition, the performance of the placement algorithm can be analyzed by drawing the structure capacity diagram. According to Fig. 8, optimal damper placement was partially effective in increasing the energy dissipation in low-rise structures by increasing the capacity of the damper in absorbing the input energy acting on the structure. As a result, it is likely that optimal damper placement can be more effective in high-rise structures.

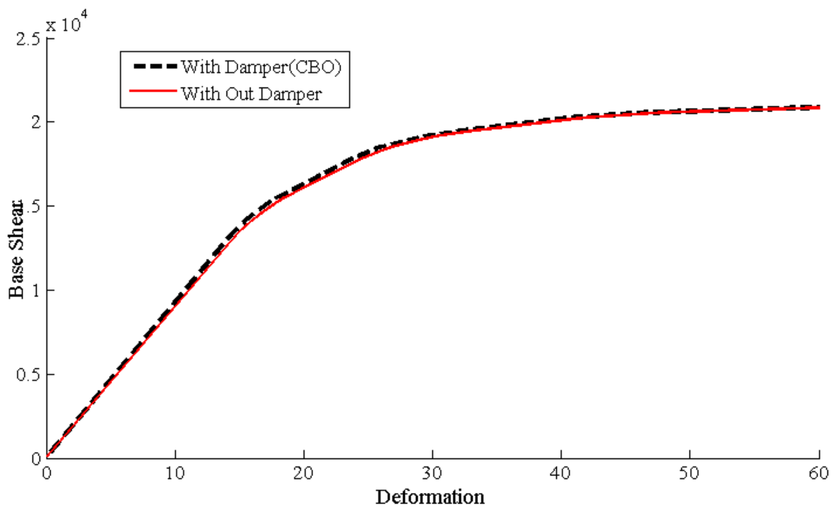

Figure 8. Structure capacity diagram for 3-story concrete frame

3.3 4Story concrete frame

This study examined a concrete plane frame with 44 elements to investigate the efficiency of the proposed method. This frame is a structure with five spans and four stories Fig. 9. The frame was designed and analyzed under a DBE earthquake condition. E and p are set at 26,517.5 MPa and 2,500 kg/m3, respectively. The compressive strength of the concrete was assumed 25MPa. Table 5 presents the cross-section of all elements.

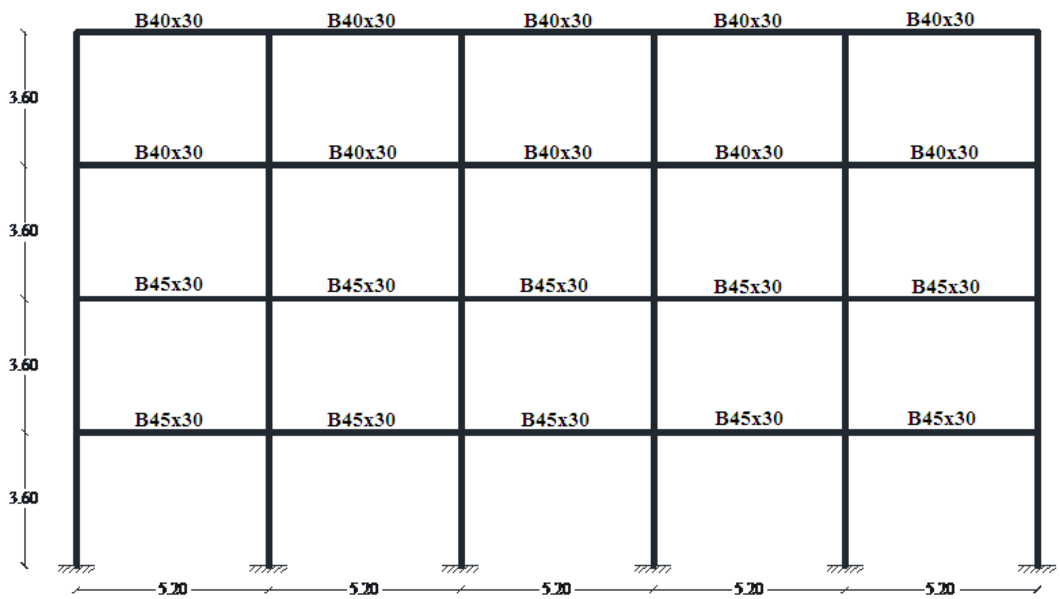

Figure 9. 4story conceret frame

Table 5: The beam column sections properties

Story	Beam	Column	Number of Rebar for Column
1	B45x30	C45x45	12T22
2	B45x30	C45x45	12T22
3	C40x30	C40x40	12T22
4	C40x30	C40x40	12T22

With an initial story-wise damper distribution and assuming a 15% effective damping, the total damping was obtained at $C = 1236.5 \ kg.s/m$. With the application of time history analysis to a structure with dampers, the peak story displacement was calculated for each earthquake record. Then, the story displacement was obtained by taking the average of all seven earthquake records. All story displacements are compared with the total mean displacement for all stories, the stories that drifted less than the total mean were less likely to be selected for damper placement. In this way, an initial story-wise damper layout can be determined. According to the proposed flowchart, the damage index is calculated and compared to the assumed value by determining the total damping based on the new story-wise damper layout. If the required convergence is not achieved, the process is repeated by applying CBO algorithm and setting new damping values. As a result, the optimal solution and optimal damper distribution were obtained with 10 iterations. For comparison, a uniform damping distribution on the stories was considered using the method in [23]. Fig. 10 shows the comparison between uniform damping distribution with the proposed algorithm.

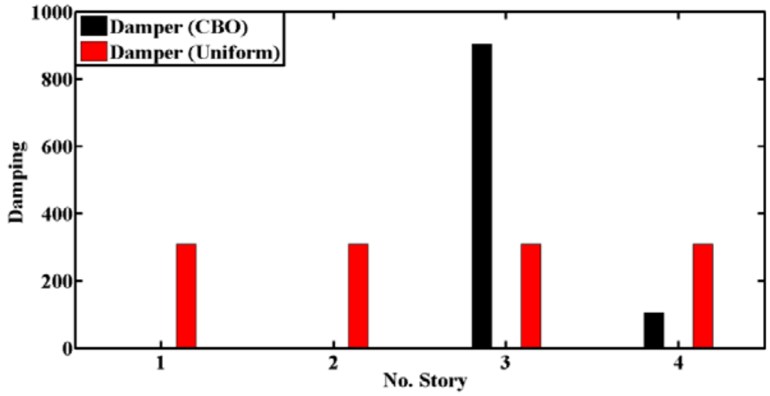

Figure 10. Optimum coefficients for minimization of story damage index

Table 6 shows the damping values assigned to the stories using the proposed algorithm:

Table 6: The damping values allocated to the story according to the proposed algorithm

Story No.	Damping
1	0
2	0
3	903.4742
4	105.8561

According to this figure, the proposed algorithm cumulates damping values on stories with greater vulnerability based on the damage index of the stories. As a result, the maximum damping capacity can be used for minimization of the objective function with optimal damper distribution. Fig. 10 shows the story drift diagram:

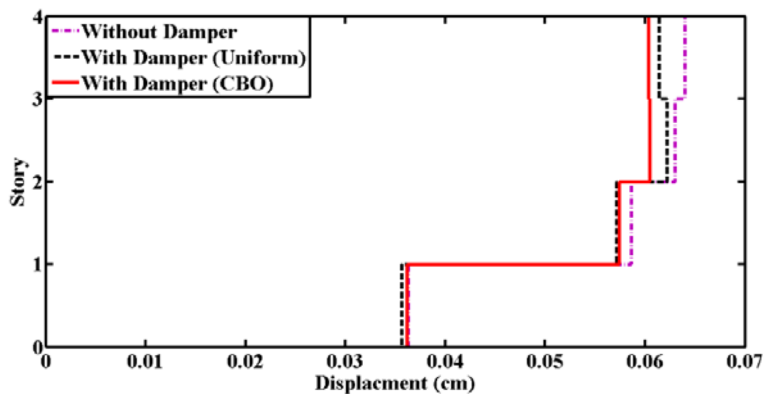

Figure 10. Maximum displacement of each story with various damper damping

According to Fig. 10, the story drift significantly reduced with the application of the proposed algorithm relative to a uniform damping distribution. Similarly, using damper in lower stories does not have much impact on their responses. The proposed algorithm produced better results by using damping only for higher stories. In other words, damping distribution optimization for specific stories reduced story drift only slightly. On the other hand, it led to a nearly 40% reduction in the extent of damages and uniformity of the relative drift and damage. According to these figures, two structures with similar damping values may significantly differ in damage index because of differences in damping distribution. Fig. 11 shows the optimal damper positions.

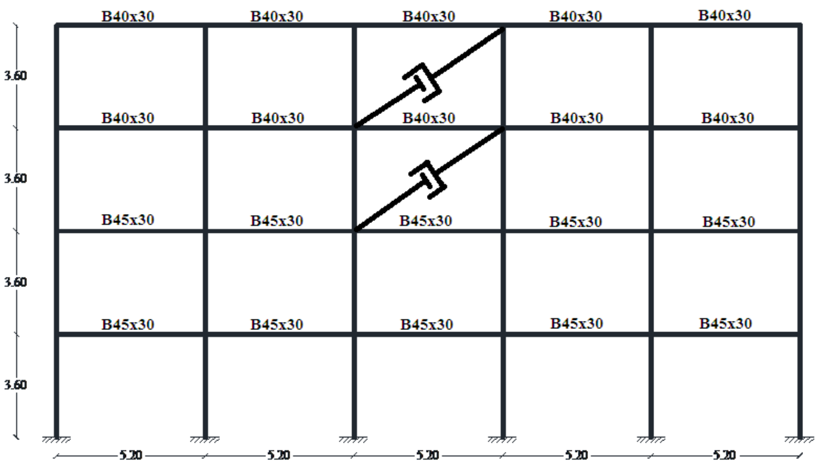

Figure 11. Optimal placement of damper according to proposed method

Considering the damper placement in certain areas of the structure, the controlling function of the dampers prevents any damage to other parts through changing dynamic properties and concentration of energy absorption in certain points. In fact, the earthquake energy is absorbed after acting on the structure. According to diagram Fig. 12 which shows the capacity of the structure with and without dampers, a structure with an optimal story-wise damper distribution has a greater energy absorption capacity than a structure with uniform story-wise damper distribution.

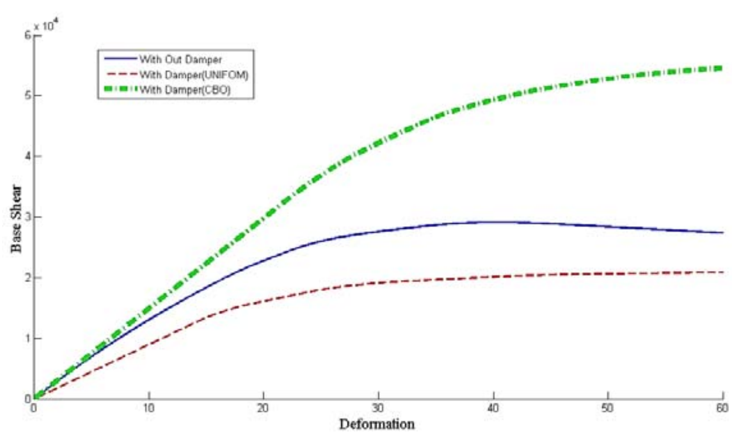

Figure 12. Structure capacity diagram for 4-story concrete frame

4. CONCLUSION

According to the results, the placement of story-wise viscous dampers reduces structural response. Although an optimal story-wise damper placement slightly reduces story drift, this process significantly reduces the extent of the damage and causes uniformity in relative drift and damage. In addition, we can uniform story drifts by limiting the drift in stories with the greatest damage index, which causes uniform damage distribution on all stories. This can be done by optimal application of such structural properties as story damping. Therefore, to achieve an optimal structure, story damping optimization should be done by detecting areas with lower chance of damage and adding those damping to areas with higher chance of damage. To achieve adequate convergence, these changes should be gradually applied and increase energy absorption capacity through an optimal placement. With respect to the position and number of dampers on the stories, as an important factor in structural performance, their optimal function depend on the acting excitement in terms of acceleration and frequency content of earthquake. For better system performance, damper number and layout should be designed optimally in accordance with the earthquake properties.

REFERENCES

1. Whittle JK, Williams MS, Karavasilis TL, Blakeborough A. A comparison of viscous damper placement methods for improving seismic building design, *J Earth Eng* 2012; **16**: 540-60.
2. Takewaki I. Optimal damper placement for planar building frames using transfer functions, *Struct Multidisip Optim* 2000; **20**: 280–7.
3. Takewaki I. *Building Control with Passive Dampers Optimal Performance-Based Design for Earthquakes*, John Wiley & Sons, London, U.K, 2009.
4. Filiatrault A, Cherry S, Efficient numerical modelling for the design of friction damped braced steel plane frames, *Canadian J Civil Eng* 1989; **16**: 211-8.
5. Filiatrault A, Cherry S. Seismic design spectra for friction-damped structure, *J Struct Eng, ASCE* 1990, **116**(5): 1334-55.
6. Kargahiand C, Ekwueme G. Structural optimization of viscous dampers using genetic algorithms for improving seismic performance of existing, *ATC & SEI Conference on Improving the Seismic Performance of Existing Buildings and Other Structures*, 2009.
7. Lopez-Garcia D, Soong TT. Efficiency of a simple approach to damper allocation in MDOF structures, *Struct Cont* 2002; **9**: 19–30.
8. Moreschi MP, Singh LM. Design of yeliding metallic and friction dampers for optimal seismic performance, *Eatrhq Eng Struct Daynam* 2003; **32**: 1291-311.
9. Lee SH, Park JH, Lee SK, Min KW. Allocation and slip load of friction damper for a seismically excited building structure base on storey shear force distribution, *Eng Struct* 2008; **30**: 930-40.
10. Lavan O, Levy R. Simple iterative use of Lyapunov’s solution for the linear optimal seismic design of passive devices in framed buildings, *Earth Eng* 2009; **13**: 650-66.
11. Apostolakis G, Dargush GF. Optimal seismic design of moment resisting steel frames with hystertic passive device, *Earthq Eng Struct Daynam* 2010, **39**(4): 355-76.
12. Shin MP. Minimum failure cost-based energy dissipation system designs for buildings in three seismic regions – Part II: Application to viscous dampers, *Eng Struct* 2014; **74**: 275–82.

13. Yan LW, Wang L, Huang ChJ. Application of improved genetic algorithm in optimum configuration of viscous dampers in tall buildings, *Adv Mater Res* 2014; **1006-7**: 423-6.
14. Kasagi M. Fujita K, Tsuji M, Takewaki I. Automatic generation of smart earthquake-resistant building system: Hybrid system of base-isolation and building-connection, *Heliyon* 2016; 2(2): e00069.
15. Felipe Saitua DG, Alexandros AT, Optimization of height-wise damper distributions considering practical design issues, *Eng Struct* 2018; **173**: 768-86.
16. Luca Landi FC, Pier PD. Effectiveness of different distributions of viscous damping coefficients for the seismic retrofit of regular and irregular RC frames, *Eng Struct*, **100**: 79-93.
17. FEMA-356. Prestandard and commentary for the seismic rehabilitation of buildings, *Federal Emergency Management Agency,* Washington, DC, 2000.
18. Tabeshpour MR, Bakhshi A. An overview of the types of failure indicators, *J Bana* 2004; 34-42.
19. Kaveh A, Mahdavi VR, Colliding bodies optimization method for optimum discrete design of truss structures, *Comput Struct* 2014; 43-53.
20. Kaveh A, Ilchi Ghazaan M. A comparative study of CBO and ECBO for optimal design of skeletal structures, *Comput Struct 2015*; **153**: 137-47.
21. Kaveh A. *Applications of Metaheuristic Optimization algorithms in Civil Engineering*, Springer, Switzerland, 2017.
22. Hejazi F, Noorzaei J, Jaafar MS, Abang AA. *Earthquake Analysis of Reinforce Concrete Framed Structures With Added Viscous Dampers*, World Academy of Science, Engineering and Technology, 2009; **33**: 762-7.
23. Singh MP, Moreschi LM. Optimal placement of dampers for passive response control, *Earth Eng* Struct *Dynam* 2002; **31**: 955–76.