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The optimal TADAS damper placement in moment resisting steel structures based on a cost-benefit analysis

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Abstract

In this paper, the optimal location and characteristics of TADAS dampers in moment resisting steel structures, considering the application of minimum number of TADAS dampers in a building as an objective function and the restriction for destruction of main members is studied. Genetic algorithm in first generation randomly produces different chromosomes representing unique TADAS dampers distributions in structure and the structure corresponding to each chromosome is time history analyzed. Then the damage index for each member and the average weighted damage index for all members are determined. Genetic algorithm evaluates the fitness of each chromosome then selection and crossover as logical operators and mutation as random operator effect the current generation's chromosomes according to their fitness and new chromosomes are generated. Accordingly, successive generations are reproduced in the same way until the convergence condition is fulfilled in final generation and four distributions are suggested as better options. Since these proposed distributions are selected under the one earthquake, therefore, it is better that the four new structures are cost-benefit analyzed in different earthquakes. Finally, the optimal placement for dampers is compared and selected based on a benefit to cost ratio, drift stories and the number of different TADAS types of such structures. The increase in amount of energy dissipated via dampers located in different floors as well as the status of plastic hinges in main members of the structure strengthened with optimum option are the proof of the optimal placement and suitable characteristics for dampers.

Keywords:Optimal location; TADAS dampers; Destruction of main members; Genetic Algorithm; Cost-benefit analyze; Dissipation energy;

1. Introduction

The effectiveness of dampers is now well recognized for consuming much of earthquake-induced energy in disposable elements which are not part of the gravity framing system. To develop in using these devices, researchers have a more focus on the behavioral aspects of the half-scale model of the existing structures equipped with dampers [1] and also on the optimal distribution and characteristics of these sacrificing members.

As mentioned above, for finding an optimal solution, many studies on the problem of selecting the positions of dampers and actuators have been carried out. For example, Li and Liu used two control algorithms, optimal control and acceleration feedback control, to optimize the number and configuration of the actuators [2]. With respect to the solution procedure of the optimum problem, a multi-level optimization model is proposed. To solve the multi-level optimization problem, a multi-level genetic algorithm is applied. Yang and Lin applied active control theories to determine the optimal locations of the passive energy dissipation devices and the corresponding capacities [3]. Emphasis is placed on the application of linear matrix inequality for the effective design of passive EDDs. Mahendra and Moreschi used a genetic algorithm to find the optimal size and location of the dissipation devices that were considered as frequency-dependent and -independent viscous and VEDs in the structure [4]. Moreschi and Singh dealt with the optimal design for yielding metallic and friction dampers together [5]. They considered the device yielding level, device stiffness and brace stiffness for the yielding metallic dampers and the slip load level and brace stiffness for the friction dampers as design variables. Martinez-Rodrigo and Romero presented a simple methodology leading to an optimum retrofitting option with nonlinear fluid viscous dampers [6]. They developed a performance index in order to numerically compare the different retrofitting options

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and a force index for discarding the inadmissible force in the devices. Ji-Hun et al., studied a gradient-based simultaneous optimization procedure for both VEDs and supporting braces added in a structure [7]. They showed that the size of the supporting brace could be reduced without significant increase in the size of VEDs by the simultaneous optimization procedure. Lee et al., presented the optimum sizes and locations of VEDs which were proposed using the eigenvalue assignment technique [8]. A convex model was determined to realize a given target response based on natural frequencies and model damping ratios. Pourzeynali emphasized the combined application of genetic algorithm and fuzzy logic (GLFC) to design and optimize the different parameters of the active tuned mass control scheme for getting the best results in the reduction of the building response under the earthquake excitations [9]. Then, the results obtained from GLFC are compared with those obtained from the tuned mass damper and linear quadratic regulator control methods. Aydin and Boduroglu chose the transfer function amplitude of the base shear force as an objective function for determining the damping coefficients of the added viscous dampers [10]. An active constraint on the sum of the damping coefficients of added dampers and the upper and lower bounds for each damper are taken into consideration.

In this study, optimal TADAS dampers distribution in moment resisting steel structures is searched, using genetic algorithm considering that each proposed dampers distribution should exactly model in initial structure and that the new structure is time history analyzed. For this purpose, API is used as a new feature in Sap2000. Consequently, searching process is carried out, considering the direct role of dampers on the seismic rehabilitation of structures.

Also, unlike the standard genetic algorithm which determines a unique solution for the problem, this program suggests the four better solutions and the best of them is selected via cost-benefit analysis among the solutions for 3 earthquake ground motion records.

2. Genetic Algorithm

In this section, a short introduction on genetic algorithm is provided. Genetic algorithm is a powerful optimization method that works both randomly and logically, and its workability in continuous and discrete domains has been proved [11, 12, 13, and 14]. Here, all design variables are coded into one binary string known as chromosome. The genetic algorithm uses three basic operators: selection, crossover and mutation.

Selection of chromosomes is a random-logical process. To do this, the chromosomes are first evaluated by fitness function. The fitness function is the combination of objective function and constraint. The shape of fitness function for the optimal dampers distribution in steel structures will be described later. In crossover, the two new chromosomes are generated by cutting the two already existing ones at a random location called crossover point and exchanging their right parts. Crossover guarantees convergence for genetic algorithm.

Mutation in a binary string is the random changing of 1s to 0s and vice versa. Therefore, this process helps to prevent the genetic algorithm from being trapped in a local minimum [15].

3. TADAS Dampers

Initial stiffness and yield force of TADAS dampers considering the dimensions and the number of plates can be given as follows:

$$K = \frac{NEbt^3}{6h^3} \tag{1}$$

$$F_y = \frac{Nf_y bt^2}{6h} \tag{2}$$

Equations (1) and (2) have been given by Tsai, where N, h, b, t are the number, height, width and thickness of plates, respectively [16].

4. Problem Description: A Standard Optimization Form

To define the optimal location of dampers in a structure issue as a standard optimization form, design variables, constants, objective function and constraints need to be specified.

4.1. Design Variables

"The number of main variables is equal to the number of the spans in the steel structures in which the TADAS dampers can be placed.

"The quantity of variables determines the type of dampers to be placed at their corresponding spans. If the quantity of the variable is in the range of [1, n], then a damper will exist at the span, and the type of this damper will be selected as a matching member of TADAS dampers type collection, otherwise there will be no damper at this span.

"The domain for variables is a natural number which depends on the number of the dampers types that can be used here. The above mentioned can be expressed as follows:

$$D_i=\{x_i \in N \mid 1 \leq x_i \leq 2n\} \tag{3}$$

In which, n is the maximum TADAS dampers types used in the problem.

4.2. Objective Function

The aim in optimizing the dampers' locations in structures is to use the minimum number of dampers. Thus, objective function at these problems could be shown as Eq. (4):

$$\begin{cases} f(x_1,...,x_i,...,x_{m1}) = \sum_{i=1}^{m_1} y_i \\ y_i = \begin{cases} 1 & 1 \leq x_i \leq n \\ 0 & n \prec x_i \leq 2n \end{cases} \end{cases} \tag{4}$$

4.3. Constraints

Constraints exist in the optimization of any practical issue. Determining maximum or minimum solutions is meaningful by defining these constraints. Here, constraints such as restriction on destruction of the main frames, restriction on drift stories, and restriction on the maximum relative deformation of the two ends of the dampers could be defined. In this study, only the constraint of restriction on the destruction in main members is considered.

To define this constraint, first the damage index for each member is given as Eq. (5) [17]:

$$DI = [(1-\alpha_1)\frac{(\mu-\mu_e)}{(\mu_{mon}-1)}] + \alpha_1 \frac{E_H}{E_{Hmon}} \quad (5)$$

in which $\alpha_1=0.206$, $\mu_{mon}=8$ [18].

The maximum damage index is determined for each frame by using the output results for the defined plastic hinges of the members. Then the average weighted damage index for all members is calculated as follows:

$$\overline{DI} = \frac{\sum_{k=1}^{N} DI_k w_k}{W} \quad (6)$$

in which w_k , DI_k refer to the weight and damage index of k^{th} member, and N, W are the number and weight for all the main frames.

Consequently, the constraint of restriction for average weighted damage index is defined as Eq. (7):

$$g = \overline{DI} \le G \quad (7)$$

in which G is the maximum amount expected for average weighted damage index for all the main members.

5. Problem Description as a Genetic Algorithm Form

5.1. Chromosome

Each design variable is coded in a binary substring. The length of this substring is chosen in a way that could cover the whole domain of the corresponding variable. Thus, this length must be chosen as the smallest natural number in Eq. (8):

$2n \le 2^{m2}$, n = the maximum TADAS dampers types used in the problem (8)

Now the length of chromosome for the problem in Eq. (9) is presented:

$m=m_1.m_2$ (9)

in which m1, m2 and m are the number of main variables, length of substring and length of chromosome respectively.

5.2. Fitness Function

Fitness function is formed by combining the objective function and the constraint based on the penalty function method. In this study, the fitness function is defined as in Eq. (10):

$F(v)=1.0 -\alpha.g_n(1-\alpha).f_n$ (10)

where is the effective coefficient for the constraint, and are the normalized objective function and $.f_n$, g_n constraint that are presented in Eqs. (11), (12):

$$f_n(v_j) = \frac{f(v_j)}{m_1} \quad (11)$$

$$g_n(v_j) = \frac{g(v_j)}{G} \quad (12)$$

6. Sensitivity Analysis

The rate and type of crossover operator, rate of mutation operator and the effective coefficient for constraint are important parameters in converging and preventing from being trapped in local optimum points chosen through sensitivity analysis. In this study, sensitivity analysis is done separately for the above parameters which needs a lot of time history analyses for each case. Results for sensitivity analysis are summarized below:

- Rate of crossover and mutation operators are 0.4 and 0.01, respectively.
- Type of crossover operator is two-cut.
- Effective coefficient for the constraint is 0.3.

7. Numerical Examples

7.1. Six-story Moment Resisting Steel Structure

This building with typical plan as shown in Fig. 1 is designed as a SMRF system and according to seismic code. The columns sections are selected from the square boxes collection as follows: {(20, 1cm), (18, 0.8cm), (16, 0.6cm)}, and the beams sections are selected from the following collection: {IPE160, IPE200, IPE240}. It is expected that the use of TADAS dampers decreases the excess of drift stories from the allowed amounts.

In the beginning, the initial structure under Tabas earthquake with PGA=0.7g, 2% probability of exceeding, is time history analyzed. The plastic hinge formation status of this initial structure is controlled according to Fema356 and is shown in Fig. 2. Some members are collapsed and the structure performance under severe earthquake is not satisfactory. For seismic rehabilitation of this structure, the TADAS dampers are added to steel moment resisting frames.

This structure must be equipped with TADAS dampers in a way that its performance is promoted under severe earthquake. In another word, the amount of main members' destruction under severe earthquakes must be restricted up to an acceptable amount.

For searching the optimum solution, optimizer program starts with a population equal to 7 chromosomes and 4 types of TADAS dampers named: Tadas1, Tadas2, Tadas3 and Tadas4. These 4 types are presented in Table (1) and can be used at any 24 mid spans of outer frames Y1, Y4. The procedure is in a way that the structure equipped with TADAS distribution

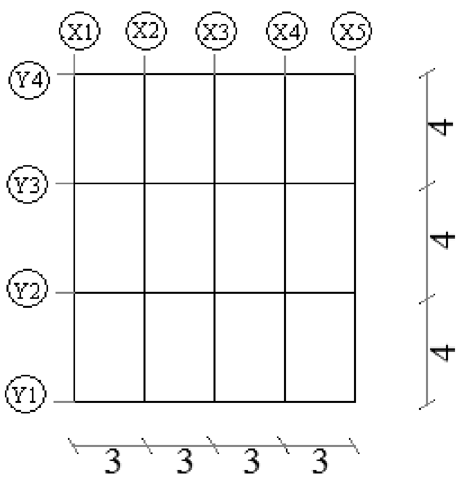

Fig. 1. Typical plan for stories

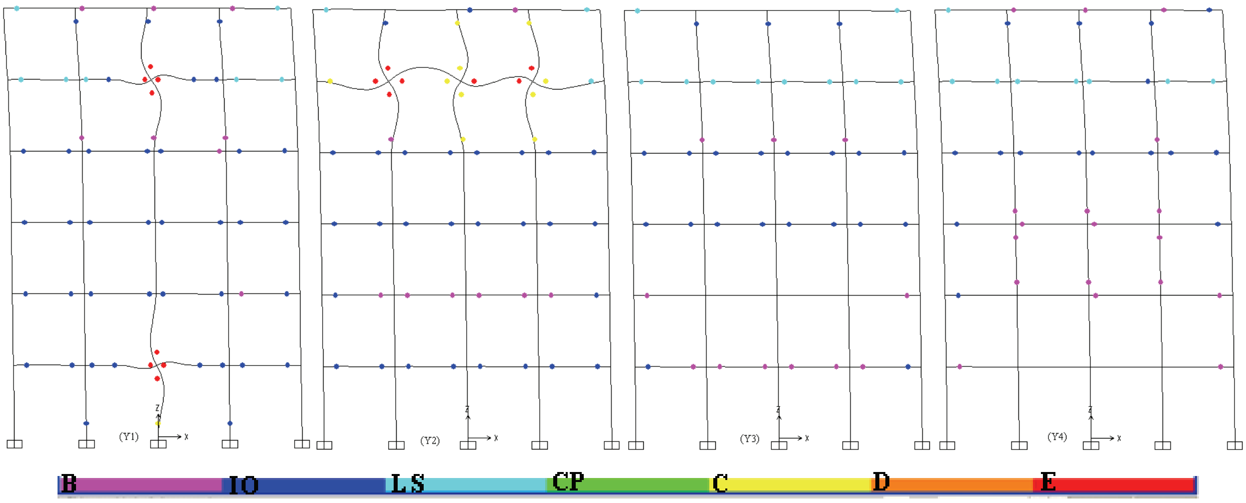

Fig. 2. Plastic hinge formation status in 6 story building under Tabas excitation with PGA=0.7g

which is corresponding to each chromosome is time history analyzed under Tabas Record with PGA=0.525g and the program determines the damage index for each main member according to Eq. (5), using the analysis results for plastic hinges.

Then the average weighted damage index for all members is calculated with Eq. (6) and is restricted to 5%. With restriction of this constraint for Tabas earthquake with PGA=0.525g, it is expected that with PGA=0.7g, plastic hinges status stay in LS mode and the structure performance under severe earthquake is improved. It is pointed that the program considers the maximum amount of constraint for the chromosome which its time history analysis is not converged.

The four resulted distributions are introduced in Table (2) and Fig. 3.

These options are also compared, considering the drift stories and the period for third modes in Tables (3) and (4). Finally, the distribution number 2 is selected as preferred option after cost - benefit analysis. Plastic hinges formation status and the hysteresis behavior of the TADAS dampers located at the 1th and 6th floors of the structure are shown in Figs. (4) and (5).

7.2. Ten- story Moment Resisting Steel Structure

This case is defined by increasing the number of stories in the previous example to 10. The columns sections are selected from the square boxes collection as follows: {(22, 1.2cm), (20, 1.0cm), (18, 0.8cm), (16, 0.6cm)}, and the beams sections are selected from the following collection: {IPE160, IPE180, IPE200, IPE220, IPE240}. It is expected that the use of TADAS dampers decreases the excess of drift stories from the

Table 1. Initial stiffness and yield force for the used dampers

Type	Initial K(kg/cm)	Yielding force(KG)
TADAS1	5748.92	4979
TADAS2	7186.15	6223.75
TADAS3	8623.38	7468.5
TADAS4	11497.84	9958

Table 2. Number of different types of TADAS dampers in 6 story building for proposed distributions

Number of dampers	Case 1	Case 2	Case 3	Case 4
Tadas1	2	1	2	1
Tadas2	4	2	1	3
Tadas3	2	2	4	4
Tadas4	2	6	4	3
Sum	10	11	11	11

Table 3. Drift (cm) for all stories of 6 story building for proposed distributions

story	Without Dampers	Case 1	Case 2	Case 3	Case 4
1	2.0619	1.2931	1.3705	1.3165	1.4575
2	5.2612	3.8206	3.4243	3.0641	3.9145
3	8.9138	6.6074	6.0229	5.7007	6.1684
4	12.1027	9.0313	7.7597	7.8285	7.8973
5	15.6012	10.833	9.2089	9.3227	9.3141
6	17.9255	11.745	10.122	10.314	10.122

Table 4. Periods (s) for three modes of 6 story building for proposed distributions

mode	Without damper	Case1	Case2	Case3	Case4
1	2.05724	1.8973	1.8973	1.8973	1.8973
2	1.89737	1.7240	1.6137	1.6030	1.6180
3	1.78350	1.5353	1.4265	1.4648	1.4775

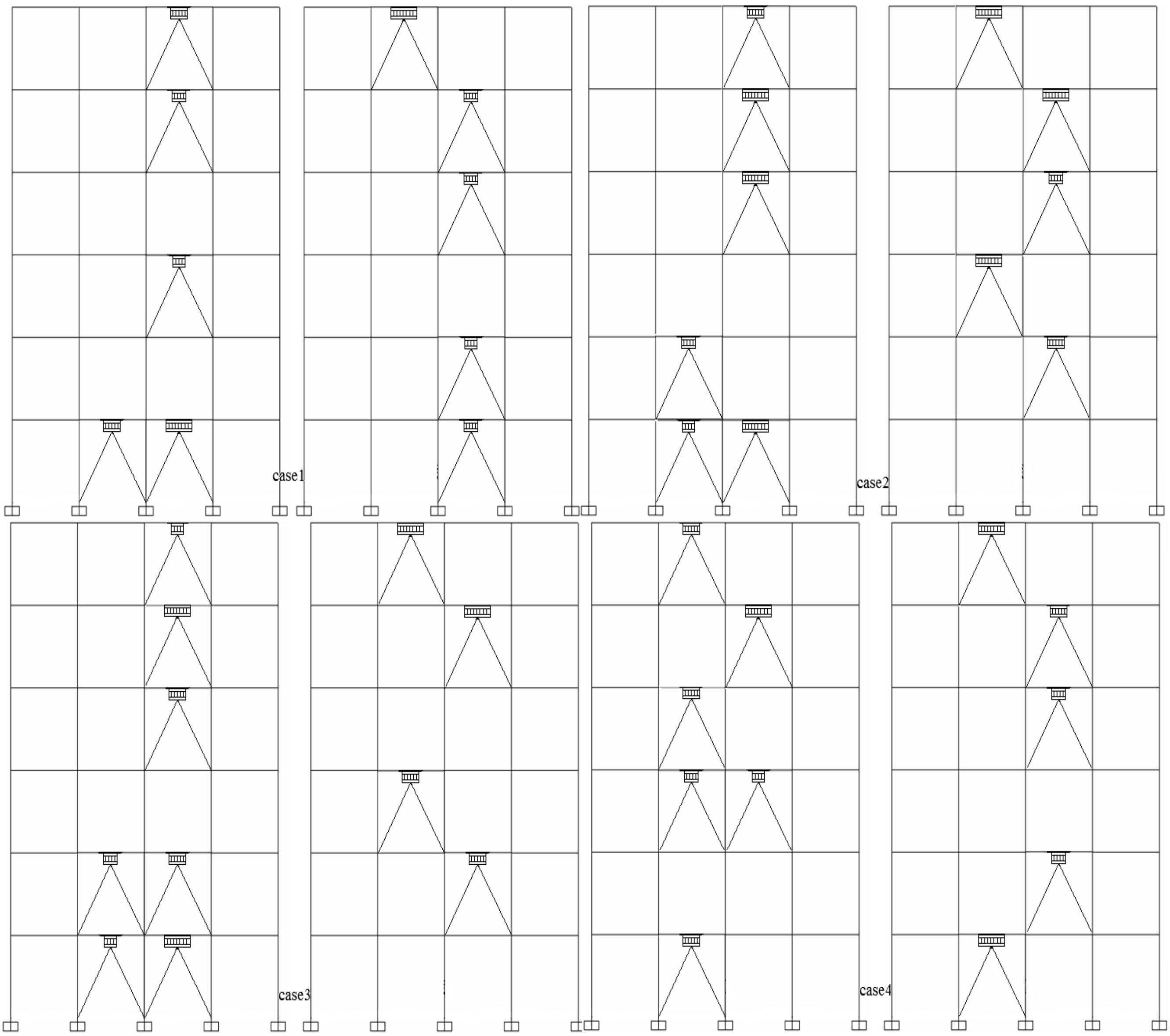

Fig. 3. The proposed four distributions of TADAS dampers in 6 story building

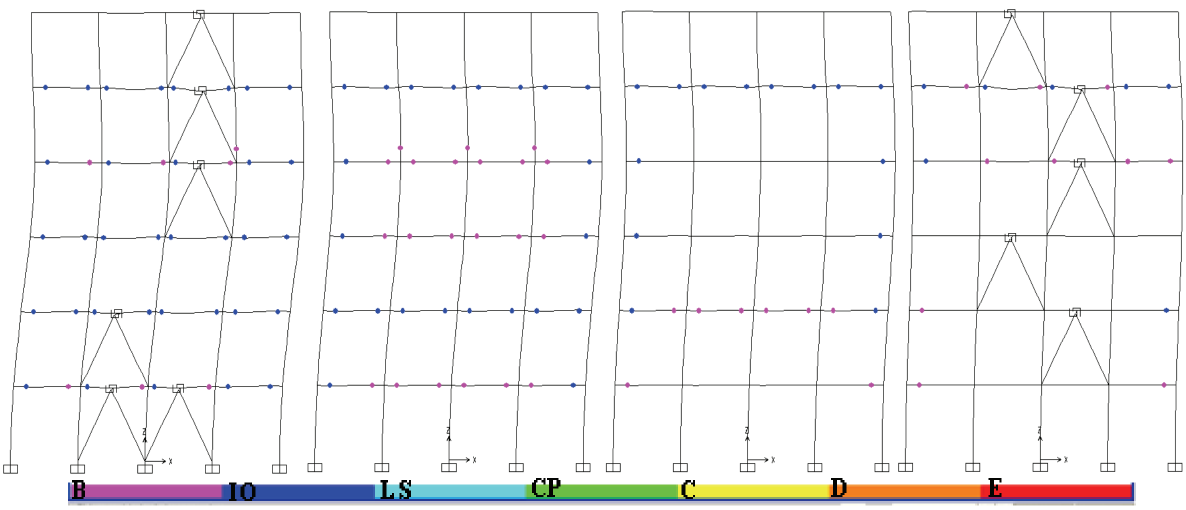

Fig. 4. Plastic hinge formation status in 6 story building equipped with optimal distribution of TADAS dampers under Tabas excitation with PGA=0.7g

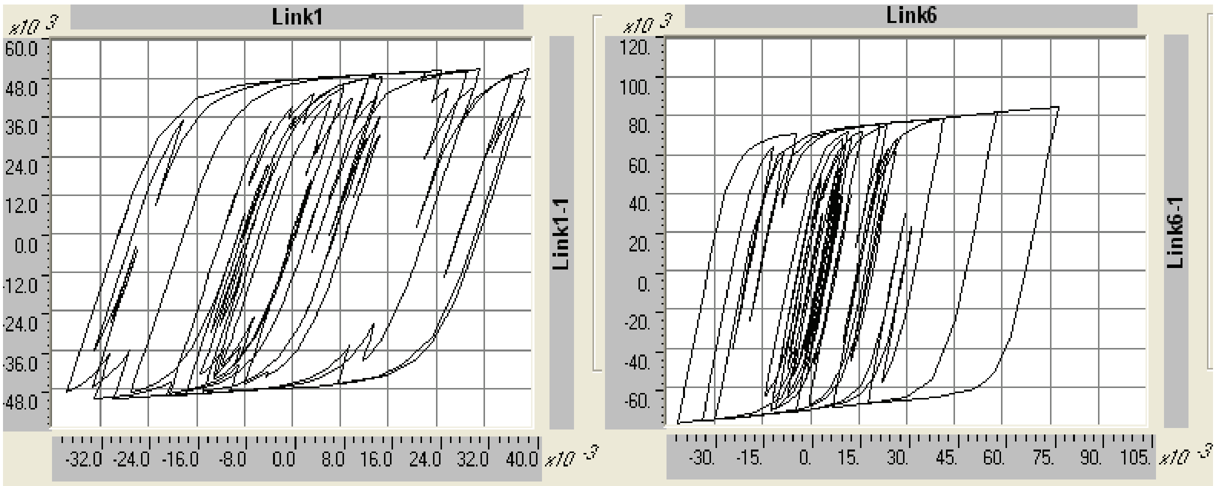

Fig. 5. The hysteresis behavior for the TADAS dampers located at the first and 6th floors of 6 story building

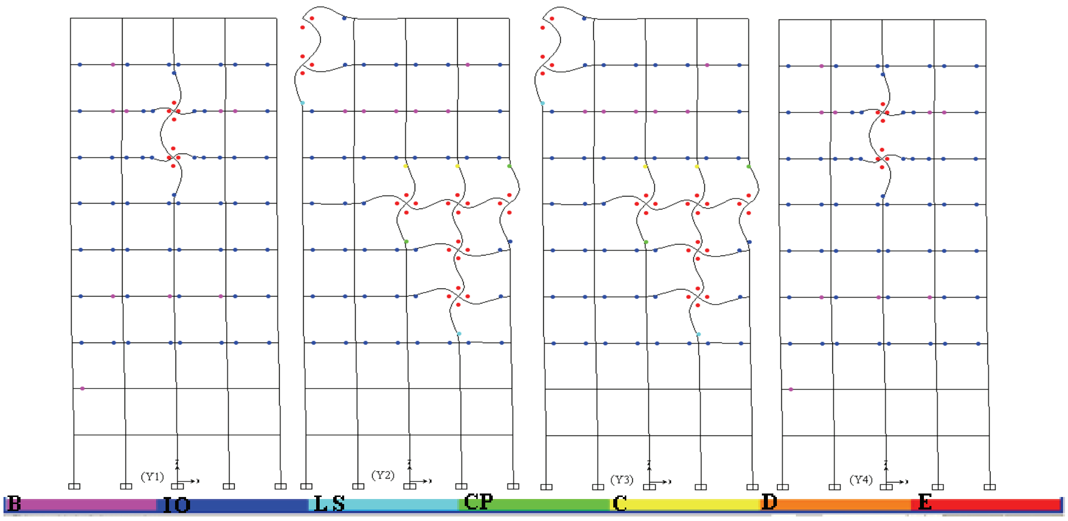

Fig. 6. Plastic hinge formation status in 10 story building under Tabas excitation with PGA=0.7g

allowed amounts.

In the beginning, the initial structure under Tabas earthquake with PGA=0.7g, %2 probability of exceeding, is time history analyzed. The plastic hinge formation status of this initial structure is controlled according to Fema356 and is shown in Fig. 6. Some members are collapsed and the structure performance under severe earthquake is not satisfactory. For seismic rehabilitation of this structure, the TADAS dampers are added to steel moment resisting frames.

Searching process for optimum solution is the same in section 7.1. , only the number of spans in which the dampers can be installed changes to 40 spans.

The four resulted distributions are introduced in Table (5) and Fig. 7. These options are also compared, considering the drift stories and the period for third modes in Tables (6) and (7). Finally, the distribution number 2 is selected as preferred option after cost - benefit analysis. Plastic hinges formation status and the hysteresis behavior of the TADAS dampers located at the 3th and 10th floors of the structure are shown in Figs. (8), (9).

Table 5. Number of different types of TADAS dampers in 10 story building for proposed distributions

Number of dampers	Case 1	Case 2	Case 3	Case 4
Tadas1	4	4	5	4
Tadas2	5	6	5	7
Tadas3	4	3	3	4
Tadas4	1	1	2	1
Sum	14	14	15	16

Table 6. Periods (s) for three modes of 10 story building for proposed distributions

Mode	Without dampers	Case 1	Case 2	Case 3	Case 4
1	2.86761	2.7881	2.7881	2.7881	2.7881
2	2.78817	2.4733	2.4721	2.4091	2.3831
3	2.49265	2.1395	2.1629	2.1285	2.1203

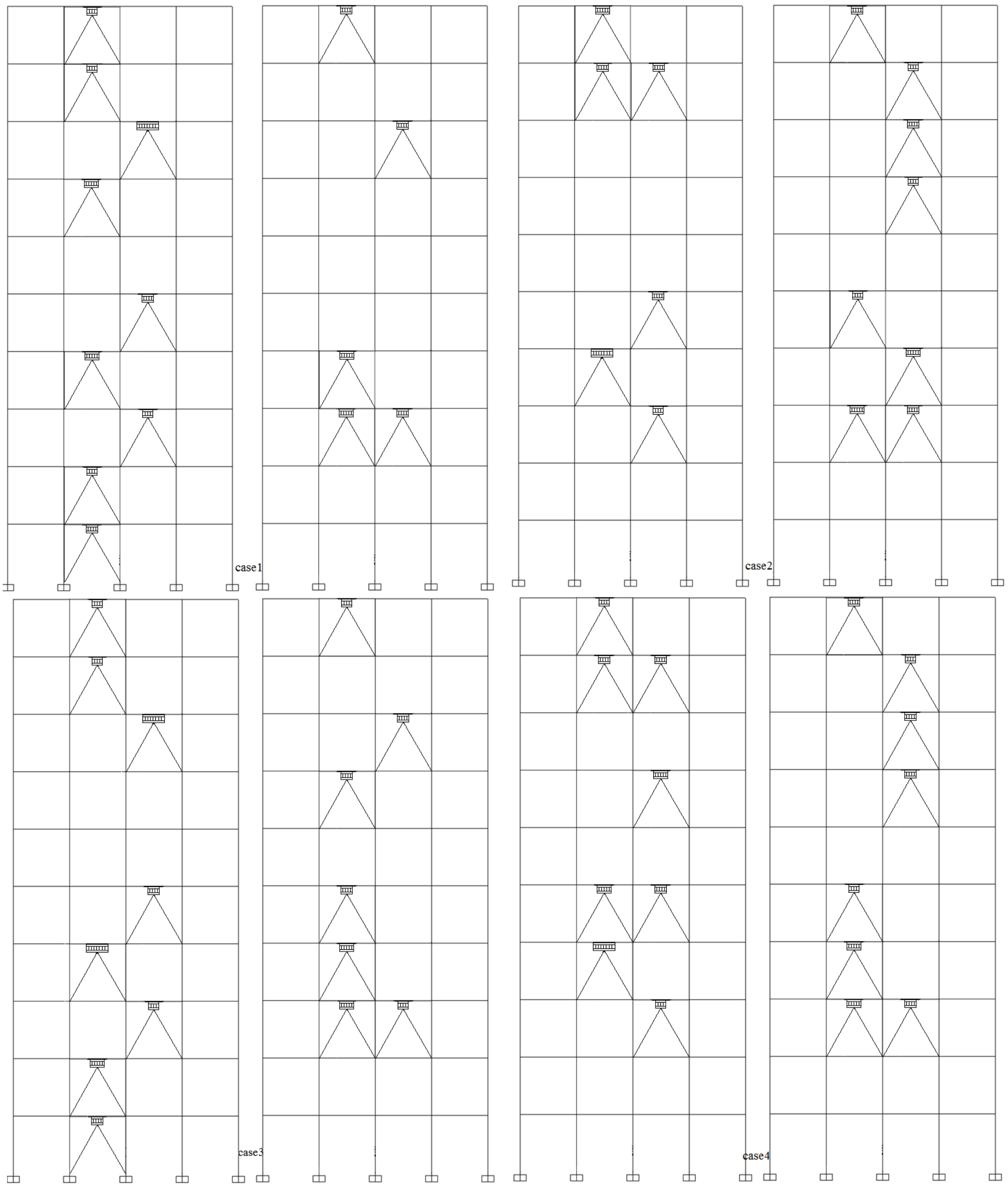

Fig. 7. The proposed four distributions of TADAS dampers in 10 story building

Table 7. Drift (cm) for some stories of 10 story building for proposed distributions

story	Without dampers	Case 1	Case 2	Case 3	Case 4
1	1.3189	1.1429	1.2935	1.1287	1.2930
3	6.1374	4.6094	5.0072	4.5247	5.0065
5	11.8901	8.6420	8.6764	8.2030	8.3731
7	18.3949	13.738	14.260	13.507	12.965
9	24.0455	16.913	17.599	16.671	16.083
10	25.8159	17.844	18.296	17.621	16.857

Table 8. PGA in different probability of exceeding

Probability of exceeding	PGA
50%	0.21g
20%	0.32g
12%	0.38g
10%	0.44g
6%	0.54g
2%	0.70g

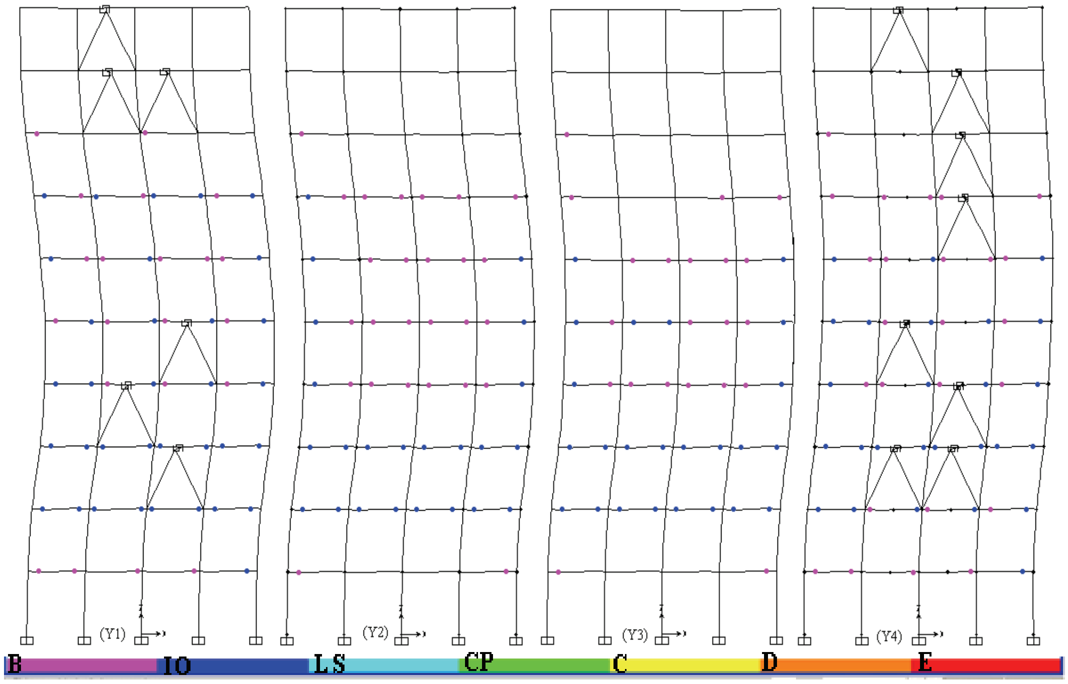

Fig. 8. Plastic hinge formation status in 10 story building equipped with optimal distribution of TADAS dampers under Tabas excitation with PGA=0.7g

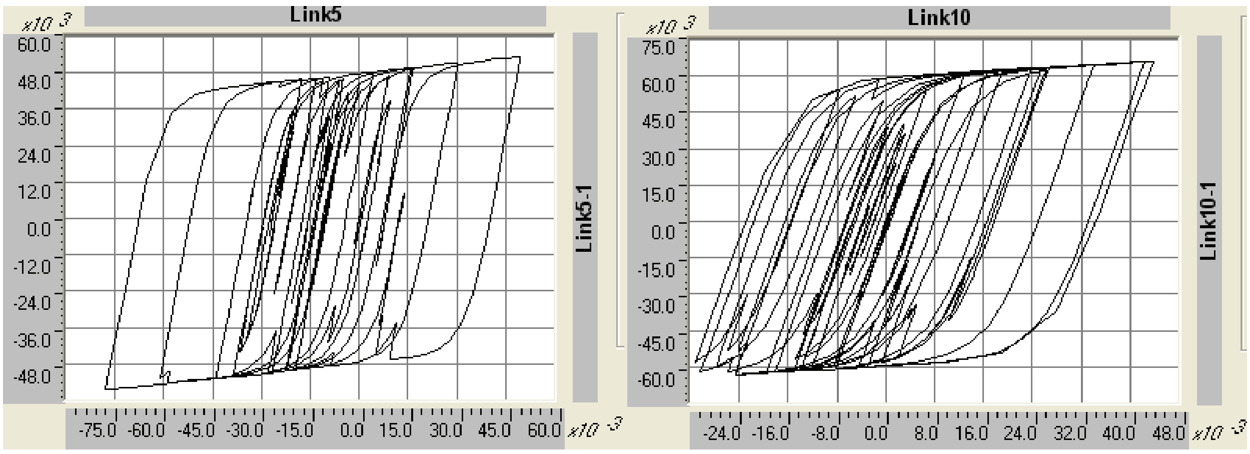

Fig. 9. The hysteresis behavior for the TADAS dampers located at the third and 10th floors of 10 story building

8. Cost-Benefit Analysis

As mentioned before, this program proposes the four better dampers distributions considering the minimum destruction under Tabas earthquake with specific PGA, and using the least TADAS dampers. So cost-benefit analysis of these four options for the following 3 records like Tabas, Naghan and Northridge is advisable.

The following steps should be taken to analyze cost-benefit:

1.Maximum acceleration for different probabilities of occurrence in 50 years (γ_i) is determined by risk analysis. The probabilities of occurrence chosen by Eq. (13) are presented in Table (8). It is pointed that the selection of PGA= 0.7g, 2% probability of exceeding, causes the benefit to cost ratio of these proposed dampers distributions in structure to be more distinctive.

$$\sum_{i=1}^{n} \gamma_i = 1 \tag{13}$$

2. The time history analysis of structure is performed with PGAs specified in step 1. Then, the amount of destruction in main members of structures is determined by Eq. (8).

3. The amount of damage to each frame is estimated according to its destruction with an engineering outlook, and consequently the direct damage for the entire structure is evaluated. Finally, the potential future avoided damage B_i is accounted for by Eq. (14).

$$B2i - B1i = Bi \tag{14}$$

in which are the amounts of damage to the entire structure with and without dampers, respectively

4. The whole benefit earned from applying dampers in proportion to project cost is calculated as follows:

$$B = \sum_{i=1}^{n} B_i \gamma_i \tag{15}$$

In specifying the total benefit, the damage resulted from destruction in nonstructural parts and interruption in serviceability of structure is not accounted for.

5. The relative benefit to cost (BCR) is calculated from Eq. (16). The amount of BCR for the four dampers distributions in 6 and 10-story structures under Tabas, Naghan, and Northridge events are included in Tables (9) & (10).

$$BCR = \frac{B}{C} \tag{16}$$

9. Summary and Conclusions

In this article, genetic algorithm is applied to determine the optimal location and characteristics of TADAS dampers in moment resisting steel structures which theirs performance under severe earthquake aren't satisfactory. If the destruction in main members of the structure equipped with optimal placement of TADAS dampers under severe earthquake is low, then the genetic algorithm and its application method is effective for finding the optimal TADAS dampers placement in such structures.

1. Genetic algorithm searches and proposes the four better dampers distributions in buildings with moment resisting steel frames which fulfill the restriction for the destruction of main members.

2. Optimal distribution for TADAS dampers is determined with comparing the average of benefit to cost ratios, the number and type of TADAS dampers, drift stories and period of structures among the four proposed options by this program.

Table 9. Benefit to cost ratio for 6 story building equipped with four distributions of dampers under different earthquakes

Benefit to cost ratio	Case1	case2	Case3	case4
Tabas	21.1595	22.7023	22.1939	21.5573
Naghan	9.80701	10.2350	10.2146	10.2008
Northridge	9.89387	10.0417	10.0511	10.0464
Average	13.6201	14.3263	14.1532	13.9348

Table 10. Benefit to cost ratio for 10 story building equipped with four distributions of dampers under different earthquakes

Benefit to cost ratio	case1	case2	Case3	case4
Tabas	1.9113	2.5235	2.3345	2.3943
Naghan	3.3799	3.4099	3.4125	3.4255
Northridge	1.8845	1.8514	1.8834	1.8860
Average	2.3919	2.5950	2.5435	2.5686

3. Plastic hinge formation status in building with and without optimal TADAS dampers distribution under Tabas earthquake with PGA=0.7g are compared, in order to determine the performance of dampers located on optimal placements. In case the status of all plastic hinges is within LS mode, then we can say that the destruction in main members under severe earthquake is low and the constraint is fulfilled.

4. On the other hand, if the amounts of energy dissipated via dampers located in the structure equipped with the optimal dampers distribution are significant, then it is concluded that the location and characteristics of these dampers for dissipating the input energy of earthquake are well selected.

5. Also, the better performance of these structures with optimal TADAS dampers distribution in comparison with the performance of the same structures by equal distribution, assuming that the number and characteristics of dampers for two distributions are the same, is another proof of the effective performance of the method.

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