ÖHÜ Müh. Bilim. Derg. / OHU J. Eng. Sci.

ISSN: 2564-6605

Ömer Halisdemir Üniversitesi Mühendislik Bilimleri Dergisi, Cilt 6, Sayı 2, (2017), 581-592
Omer Halisdemir University Journal of Engineering Sciences, Volume 6, Issue 2, (2017), 581-592

Araştırma / Research

OPTIMAL DAMPER PLACEMENT TO PREVENT POUNDING OF ADJACENT STRUCTURES CONSIDERING A TARGET DAMPING RATIO AND RELATIVE DISPLACEMENT

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Geliş / Received: *07.03.2017*
Düzeltmelerin gelişi / Received in revised form: *09.04.2017*
Kabul / Accepted: *12.04.2017*

ABSTRACT

In this study, viscous dampers are optimally placed between two adjacent structures with the aim of preventing pounding. Governing equations are derived in time domain for the optimization problem. Target damping ratios are obtained for the coupled system and used as active constraints in the numerical optimization stage. The damping coefficients of the dampers are chosen as design variables, and the sum of the damping coefficients is minimized under the constraints. An algorithm featuring numerical optimization and time history analysis is put forward to test the candidate optimal design under the earthquake loads of interest. The relative displacements are checked at all storey levels to ensure that they remain below the target values. Two 4-storey adjacent shear-building models are used in numerical examples to validate the proposed method. The appropriate number and locations of linear viscous dampers between adjacent structures are determined, and their effects on structural behaviour are evaluated.

Keywords: Pounding, target damping ratio, added dampers, optimal passive control, prevent collision

BİTİŞİK NİZAM YAPILARIN ÇARPIŞMASINI ÖNLEMEK İÇİN BİR HEDEF SÖNÜM ORANI VE RÖLATİF DEPLASMAN DÜŞÜNÜLEREK OPTİMUM SÖNÜMLEYİCİ YERLEŞİMİ

ÖZ

Bu çalışmada, bitişik nizam iki yapı arasına, sönümleyiciler çarpışmayı önlemek için optimum olarak yerleştirilir. Optimizasyon problemi için yönetici denklemler zaman tanım alanında türetilir. Hedef sönüm oranı girişimli sistem için bulunur ve sayısal optimizasyon aşamasında aktif kısıtlamalar kullanılır. Sönümleyicilerin sönüm katsayıları tasarım değişkeni olarak seçilir ve sönüm katsayılarının toplamı kısıtlamalar altında minimize edilir. Deprem yükleri altında aday optimum tasarımı test etmek için zaman tanım alanında analizleri ve sayısal optimizasyonu içeren bir algoritma gösterilir. Bütün katlarda rölatif deplasmanların hedef değerlerin altına düşüp düşmediği kontrol edilir. Amaçlanan metodun geçerliliğini göstermek için 4 katlı bitişik nizam kayma çerçeveleri sayısal örnek olarak kullanılır. Bitişik yapıların arasına lineer viskoz sönümleyicilerin uygun yerleri ve sayıları hesaplanır ve onların yapısal davranış üzerindeki etkileri araştırılır.

Anahtar Kelimeler: Çekiçleme, hedef sönüm oranı, ek sönümleyiciler, optimum pasif kontrol, çekiçlemenin önlenmesi

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1. INTRODUCTION

As development occurs, cities have grown increasingly crowded. This phenomenon has caused land values to increase and the construction of adjacent structures to become a necessity. The dynamic characteristics of entirely independent structures are generally different, and pounding effects may occur during earthquakes. Collisions may occur due to different storey levels of adjacent buildings and from their tilting to one side, which causes hitting of these adjacent structures. Collisions commonly are seen following earthquakes result in serious damage and collapses in problematic buildings. This problem can be solved by adopting new passive, active, or semi-active technological systems.

Collision of structures during earthquakes is an urgent problem that must be solved by engineers. The simplest way to prevent collisions is to construct buildings far apart from each other. Constructing adjacent buildings produces pounding issues. The dynamic characteristics of these structures differ because they are generally built at different times under different regulation terms using designs independent of each other. The out-of-phase characteristics of adjacent structures cause collision.

The nature of collision is highly complex and presents an engineering problem that remains difficult to address. Pounding of structures with great masses causes impact forces that cannot be predicted. These forces can pull down structures that are not going to collapse. Anagnostopoulos [1] provided an account of dangerous events owing to pounding. Several other reports on structural damage resulting from pounding of the adjacent structures have been published in the literature [2, 3]. Damage statistics has revealed that pounding occurred in over 330 collapsed or severely damaged structures; for at least 15% of these structures, pounding was the primary reason collapse and severe damage [4].

Various impact analytical models have been developed to define the structural response of adjacent structures during an earthquake [5]. Stavroulakis and Abdalla [6] provided optimal conditions by minimizing the potential energy of adjacent structures with the intent of resolving the separation distance between them under equivalent static horizontal forces. With the intent of determining the required separation distance and preventing pounding, Jeng et al. [7] advanced the Spectral Difference Method and Double Difference Combination rule based on random vibration theory. Lin [8] suggested a statistical method of the mean and standard deviation of the separation distance of adjacent buildings based on random vibration theory to prevent pounding. Valles and Reinhorn [9] worked on a pounding problem based on the pseudo energy radius; these researchers calculated the minimum separation distance and adopted a novel prevention technique to avoid pounding.

Luco and De Barros [10] calculated the optimal number of interconnecting dampers uniformly distributed over two structures to minimize the transfer function amplitude of the top displacement of the taller building. Zhang and Xu [11] found the optimal values of visco-elastic dampers to reduce the maximum seismic response to values below the random seismic response. Abdullah et al. [12] favoured a shared tuned mass damper attached to adjacent structures to avoid potential pounding and reduce the vibration of structures. Lin and Weng [13] considered pounding at the top storey level of a short building and determined the pounding probabilities of adjacent buildings separated by a minimum code-specified gap to prevent pounding. Zhu and Xu [14] introduced analytical formulas in an attempt to obtain the optimal parameters of Maxwell model defining fluid dampers used to link two adjacent structures. Zhu et al. [15] produced three control strategies indicating optimum passive control, active control, and semi-active control to prevent pounding. Aldemir and Aydin [16] also proposed an active control algorithm for adjacent structures. Kasai et al. [2] proposed a method called the “spectral difference (SPD) method,” which was based on the spectrum approach, and described simplified rules to predict the inelastic vibration phase. The group then verified the accuracy of the SPD method to explain the effects of various parameters on the relative displacement via a closed-form solution.

Damper elements are known to develop the seismic behaviour of the structures in which they are installed. The passive damping elements used most often for seismic control of structures is viscous and visco-elastic dampers. The pounding effect, which is due to out-of-phase vibrations, can be simulated. When the separation distance between adjacent structures is short, the high positive value of the relative displacement indicates increased pounding risk. The vibration characteristics of adjacent structures lead to changes in relative displacement between them. In this study, two adjacent structures are modelled as single degree-of-freedom systems. While the adjacent structures are not linked to structural elements, each building changes according to variations in their stiffness at every step of optimization. Linear time history analysis is conducted using the ground motion of the El Centro NS earthquake to obtain the maximum positive value of the relative displacement between adjacent structures. The relative displacement spectra are plotted according to the period ratios of the adjacent structures. These period ratios can cause pounding and are investigated.

Pounding risk is simulated by adopting a high value of the relative displacement response spectrum. In previous applications, a viscous damper was linked between adjacent structures to avoid structural pounding. The optimal damping and stiffness values of the passive coupling element are calculated according to the method of Zhu et al. [15]. Time history analyses are conducted once more, and the maximum relative displacements are plotted by the period ratio of the adjacent structures in the case where adjacent structures are linked by a viscous damper. For different engineering disciplines, damping within a structural system may present different importance. Damping can mean only a reference note on a seismic or wind spectral plot, 5% damped spectra being the most commonly known parameter among the civil engineering community. For most structural engineers, damping refers to changes in overall stress within a structure that is subjected to shock and vibration. Experts frequently argue whether a structure should have 2%, 3%, or 4%, but not more than 5%, structural damping.

The concept of installing supplemental dampers within a structure proposes that these damping elements will absorb part of the input energy. The damping level of buildings can be increased to range from 20% to 40% by adding dampers. A supplemental damper is an element that can be added to a system to enable withstanding of forces resulting from vibrations and energy dissipation. Application of supplemental dampers has gone through various applications like from protection related structures to commercial applications on building structures and bridges exposed to seismic or wind loads. Fluid damping technology has been proven to be reliable and robust in all aspects of implementation to structures. A fluid viscous damper is one of the most well-known passive dampers currently available. Fluid viscous devices including a cylindrical piston immersed in a viscous fluid are broadly used in aerospace and the military, and they have been recently used in building applications [17]. The main characteristics of these devices are a linear viscous response obtained over a broad frequency range, insensitivity to temperature, and compactness in comparison with the stroke and output force they can produce. Absorption of energy by the damper occurs through movement of the piston in a highly viscous fluid. The output force of the damper is directly proportional to the velocity of the piston if the fluid is purely viscous.

When damper allocations are considered, several optimal damper procedures based on active control theories have been developed [18-26]. A number of optimal passive damper procedures have been published in the literature [12, 27-64].

In the Turkish Earthquake Code [65], the buildings do not include structural control systems. It needs a new regulation for controlled structures. The explanations in the Turkish Earthquake Code are given as follow:

Earthquake Gaps, apart from the effect of temperature changes due to basic displacement and rotations due to different floor levels, the conditions for gap spaces to be left only for earthquake effects between building blocks or existing buildings and new buildings are stated below:

- Unless a more unfavourable result than next item is obtained, the gaps shall not be less than the squares root of the sum of the squares of the displacements obtained in adjacent blocks or buildings for each storey multiplied by the coefficient α defined below. The floor displacements to be taken into account will be the averages of the reduced ($u_i^{(x)}$) displacements calculated in the nodes at which the columns or curtains are connected. If it is not possible to make an account for the existing old building, the location of the old building will not be taken smaller than the values calculated for the new building on the same floor.

(a) If the floors of neighbouring buildings or building blocks are at the same level on all floors, α=0.25 (R/I) shall be taken.

(b) If the floors of neighbouring buildings or building blocks are of different levels, even on some floors, α=0.5 (R/I) for the whole building shall be taken.

- The minimum amount of gap to be released shall be at least 30 mm up to 6 m height and at least 10 mm for every 3 m height after 6 m.

- The joints between the building blocks shall be arranged in such a way that the blocks in the earthquake can operate independently of each other in all directions.

- In the event that two separate blocks of building or a building are connected to each other by a different element and the like, the displacement capacity of the movable bearing on one of the blocks connected to the element is in the direction of the two earthquake orientations and directions, Shall be at least 1.5(R/I) times the sum of the absolute values of displacements calculated for reduced earthquake loads.

In this study, the placement of linear viscous dampers in two shear frames is modelled in an attempt to prevent collisions during earthquakes and improve the earthquake behaviours of the resulting structures. To this end, equations of the uncoupled and coupled motions of the adjacent structures are formed, and their behaviours with and without dampers are determined. Where to locate dampers and how many of them should be installed into a structure present an important problem. In this study, a target damping ratio developed by Aydın [31] is applied to observe the optimal damper distribution in shear frames, and an algorithm aiming to reach the target inter-storey drift ratio is used in order to obtain the optimal distribution of dampers placed between adjacent structures. The proposed method shows that dampers placed at optimal positions between structures are able to reduce the relative displacement between adjacent buildings to the desired level and eliminate collision risk during earthquakes.

2. MATERIAL AND METHODS

2.1. Formulation of the Problem

Consider two s-storey, adjacent shear frames with floor pounding at the same level (Figure 1). By adding fluid viscous dampers between the structures, their collision can be prevented. Equations of motion belonging to structures A and B are provided in uncoupled form in the case without added dampers.

$$\boldsymbol{M_A}\boldsymbol{\ddot{U}_A}(\boldsymbol{t}) + \boldsymbol{C_A}\boldsymbol{\dot{U}_A}(\boldsymbol{t}) + \boldsymbol{K_A}\boldsymbol{U_A}(\boldsymbol{t}) = \boldsymbol{M_A}\boldsymbol{r}\ddot{U}_g(t) \quad (1)$$

$$\boldsymbol{M_B}\boldsymbol{\ddot{U}_B}(\boldsymbol{t}) + \boldsymbol{C_B}\boldsymbol{\dot{U}_B}(\boldsymbol{t}) + \boldsymbol{K_B}\boldsymbol{U_B}(\boldsymbol{t}) = \boldsymbol{M_B}\boldsymbol{r}\ddot{U}_g(t) \quad (2)$$

In Figure 1, $\boldsymbol{U_A}(\boldsymbol{t})$ and $\boldsymbol{U_B}(\boldsymbol{t})$ stand for the displacement vectors and $\boldsymbol{\dot{U}_A}(\boldsymbol{t})$ and $\boldsymbol{\dot{U}_B}(\boldsymbol{t})$ stand for the velocity vectors of structures A and B, respectively. $\boldsymbol{\ddot{U}_A}(\boldsymbol{t})$ and $\boldsymbol{\ddot{U}_B}(\boldsymbol{t})$stand for the acceleration vectors and $\ddot{U}_g$ stands for the ground acceleration. In the same way, $\boldsymbol{M_A}$ and $\boldsymbol{M_B}$ are symbols for mass, $\boldsymbol{C_A}$ and $\boldsymbol{C_B}$ stand for structural damping, and $\boldsymbol{K_A}$ and $\boldsymbol{K_B}$ stand for the stiffness matrices of structures A and B, respectively. As well, *r* refers to the impact vector, the elements of which correspond to a degree of freedom of 1 in the direction of the earthquake motion. When the vibrations of structures A and B are modelled together, the equation of motion for the situation without dampers can be written as follows

$$\boldsymbol{M}\boldsymbol{\ddot{U}}(\boldsymbol{t}) + \boldsymbol{C}\boldsymbol{\dot{U}}(\boldsymbol{t}) + \boldsymbol{K}\boldsymbol{U}(\boldsymbol{t}) = \boldsymbol{M}\boldsymbol{r}\ddot{U}_g(t) \quad (3)$$

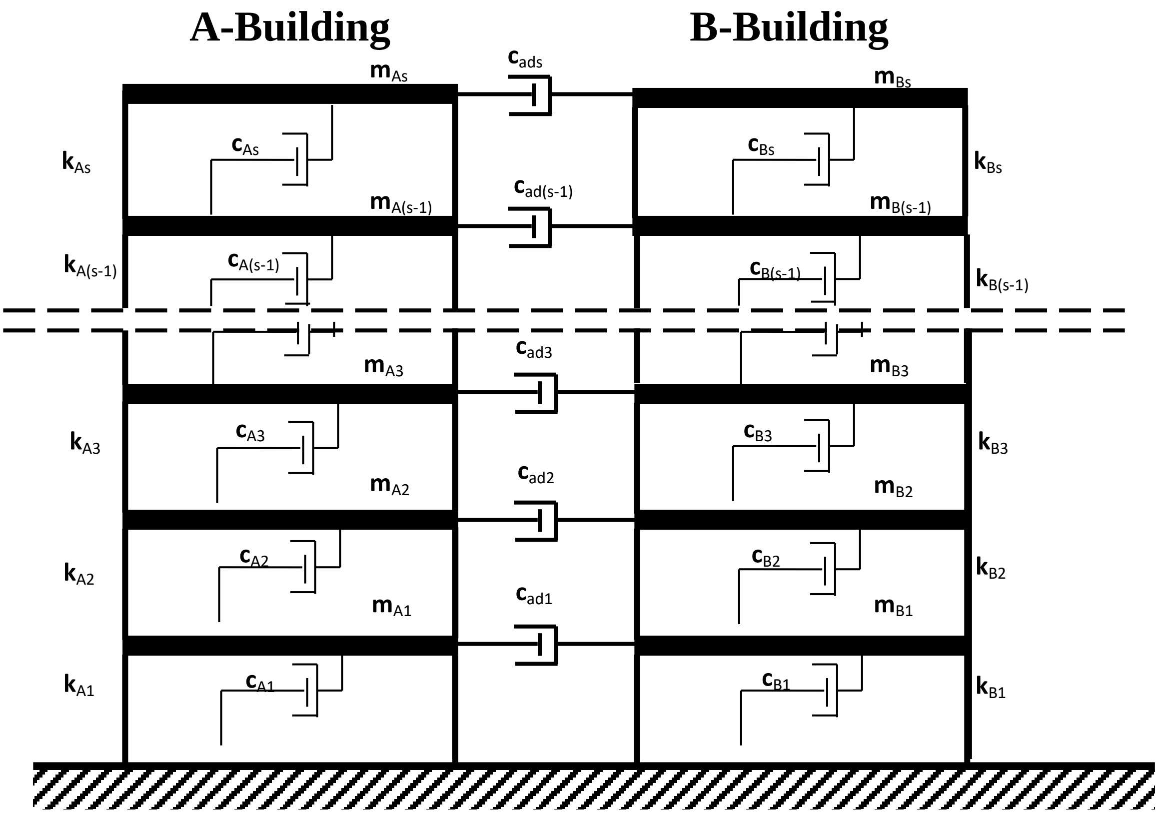

Figure 1. Adjacent model structures

Here, the mass, structural damping, and stiffness matrices of a coupled system can be given as

$$\boldsymbol{M} = \begin{bmatrix} M_A & 0 \\ 0 & M_B \end{bmatrix} K = \begin{bmatrix} K_A & 0 \\ 0 & K_B \end{bmatrix} C = \begin{bmatrix} C_A & 0 \\ 0 & C_B \end{bmatrix} \quad (4)$$

The structural damping matrix, C can be calculated in proportion to only the mass matrix, only the stiffness matrix, or a linear combination of mass and the stiffness matrices. The equation of motion can be written as follows when dampers are placed between structures.

$$\boldsymbol{M}\ddot{\boldsymbol{U}}(\boldsymbol{t}) + (\boldsymbol{C} + \boldsymbol{C_{ad}})\dot{\boldsymbol{U}}(\boldsymbol{t}) + \boldsymbol{K}\boldsymbol{U}(\boldsymbol{t}) = \boldsymbol{Mr}\ddot{U}_g(t) \tag{5}$$

where $\boldsymbol{C_{ad}}$ denotes the damping coefficient of the manufactured viscous damper. This type of damper is added to each storey in a shear building. $\boldsymbol{C_{ad}}$ is a non-proportional damping matrix that should be optimally designed to minimize a target. The matrix, $\boldsymbol{C_{ad}}$ can be decomposed into corresponding added viscous dampers and is written as

$$\boldsymbol{C_{ad}} = c_1\boldsymbol{C_1} + c_2\boldsymbol{C_2} + \cdots + c_s\boldsymbol{C_s} \tag{6}$$

where c_i $(i = 1,2,\ldots,s)$ corresponds to the damping coefficient of the i$^{\text{th}}$ added damper and $\mathbf{C_i}$ $(i = 1,2,\ldots,s)$ signifies the location matrix of the i$^{\text{th}}$ added damper. The location matrix is also equal to the partial differential of $\boldsymbol{C_{ad}}$ regarding i$^{\text{th}}$ added damping coefficient of dampers as

$$\boldsymbol{C_i} = \frac{\partial \boldsymbol{C_{ad}}}{\partial c_i} \tag{7}$$

In the fundamental mode for a coupled system, the following equation can be written;

$$2\zeta_1\,\omega_1 = \frac{\boldsymbol{\phi_1^T}(\boldsymbol{C}+\boldsymbol{C_{ad}})\boldsymbol{\phi_1}}{\boldsymbol{\phi_1^T M \phi_1}} = \frac{\boldsymbol{\phi_1^T C \phi_1}}{\boldsymbol{\phi_1^T M \phi_1}} + \frac{\boldsymbol{\phi_1^T C_{ad}\,\phi_1}}{\boldsymbol{\phi_1^T M \phi_1}} \tag{8}$$

where ζ_1 is the damping ratio observed after dampers are inserted into the structure, $\boldsymbol{\phi_1}$ denotes the normalized fundamental mode vector, and ω_1 signifies the undamped natural circular frequency of the coupled system. The first term on the right side of Equation (8) corresponds to the proportional damping matrix. No coupling exists between the first mode and any of the other modes. This situation is given as follows

$$\frac{\boldsymbol{\phi_1^T C \phi_i}}{\boldsymbol{\phi_1^T M \phi_i}} = \begin{cases} 2\zeta_{st}\,\omega_1 & i = 1 \\ 0 & i \neq 1 \end{cases} \tag{9}$$

where ζ_{st} denotes the structural damping ratio for the fundamental mode. The second term on the right side of Equation (8) includes the non-proportional damping matrix. However, to simplify the damper design, we can conveniently assume that

$$\frac{\boldsymbol{\phi_1^T C_{ad}\,\phi_i}}{\boldsymbol{\phi_1^T M \phi_i}} = \begin{cases} 2\zeta_{ad}\omega_1 & i = 1 \\ 0 & i \neq 1 \end{cases} \tag{10}$$

where ζ_{ad} signifies the added damping ratio for the fundamental mode. By using Equations (9) and (10), Equation (8) can be rewritten as follows

$$2\zeta_1\,\omega_1 = 2(\zeta_{st} + \zeta_{ad})\omega_1 \tag{11}$$

Therefore,

$$\zeta_1 = \zeta_{st} + \zeta_{ad} \tag{12}$$

The structural damping ratio ζ_{st} is generally adopted for different types of structures. When the dampers are inserted into the structure, the parameter ζ_1 signifies the desired value of the damping ratio. The parameter ζ_{ad} occurring because of the effects of the added dampers is the added damping ratio. If we know the structural damping ratio and the desired total damping ratio, the desired ζ_{ad} can be determined from Equation (12). Therefore, the desired added damping ratio is calculated as follows

$$\zeta_{ad} = \zeta_1 - \zeta_{st} \tag{13}$$

Equation (8) can be rewritten for the added damping ratio as

$$2\zeta_{ad}\,\omega_1 = \frac{\boldsymbol{\phi_1^T C_{ad}\,\phi_1}}{\boldsymbol{\phi_1^T M \phi_1}} = c_1\,\frac{\boldsymbol{\phi_1^T C_1\,\phi_1}}{\boldsymbol{\phi_1^T M \phi_1}} + c_2\,\frac{\boldsymbol{\phi_1^T C_2\,\phi_1}}{\boldsymbol{\phi_1^T M \phi_1}} + \cdots + c_s\,\frac{\boldsymbol{\phi_1^T C_s\,\phi_1}}{\boldsymbol{\phi_1^T M \phi_1}} \tag{14}$$

where the coefficient μ_i can be written as follows

$$\mu_i = \frac{\boldsymbol{\phi_1^T C_i\,\phi_1}}{\boldsymbol{\phi_1^T M \phi_1}} \tag{15}$$

By using Equations (14) and (15), the formula for the desired added damping ratio for the fundamental mode can be written as follows

$$\zeta_{ad} = \frac{1}{2\omega_1}(\mu_1\,c_1 + \mu_2\,c_2 + \cdots + \mu_s\,c_s) = \frac{1}{2\omega_1}\sum_{i=1}^{s}\mu_i\,c_i \tag{16}$$

2.2. Definition of the Optimal Damper Problem for Adjacent Shear Buildings

Different objective and constraint functions are used in the optimal design of structures. Objective functions are used to minimize or maximize the total weight of a structure and or various behaviours. In this study, the objective function is chosen to minimize the total damping ratio of dampers placed between two structures; this function is defined as follows

$$\text{Min. } f = \sum_{i=1}^{s} c_i \tag{17}$$

The total damping coefficient of the added dampers is indicated by the cost function, which will be minimized in Equation (18). In terms of the added damping ratio, Equation (16) can be rewritten as an equality constraint as below

$$\zeta_{ad} = \frac{1}{2\omega_1}(\mu_1\,c_1 + \mu_2\,c_2 + \cdots + \mu_s\,c_s = \frac{1}{2\omega_1}\sum_{i=1}^{ns}\mu_i\,c_i \tag{18}$$

where ζ_{ad} is a fixed damping ratio that can be given as the desired damping ratio. The fundamental natural circular frequency, μ_i, is a known parameter from the vibration characteristics of the structure. Either the objective function or the equality constraint is the linear function of the design parameters. When we take into account the inequality constraints on the upper and lower boundaries of the damping coefficients of every added damper, the following result is obtained

$$0 \le c_i \le \bar{c}_i \qquad (i = 1,2,\ldots,s) \tag{19}$$

where $\bar{c}_i$ stands for the upper limit of the damping coefficient of the damper in the i^{th}storey. In practical applications, a damper capacity and size corresponding to the upper boundary of the added damper should be restricted because of commercial and manufacturing limitations. The effects of the upper limit values of the damping coefficients upon the proposed optimal damper problem were investigated and were presented as a set of optimal damper designs with respect to various upper limits of the dampers. All of optimal designs obtained from the proposed method satisfied the constraints of the RDs under El Centro earthquake. Designers can choose a solution among the sets of the optimal design. These optimal designs were discussed in terms of the cost function value, added damping value and RDs in section. The upper bound on each damping coefficient plays an important role in the proposed optimal damper design. The damper capacity and location in a storey is generally chosen among available dampers and their locations in practical applications.

2.3. Proposed Algorithm

Many optimization tools have been developed to solve the damper optimization problem. Solving the proposed optimization problem is easy because the objective and constraint functions are simple and linear functions of the design variables. In this optimal damper problem, the numerical minimization module of Mathematica 5.0 [66] is applied to calculate optimal damper coefficients under specific constraints to minimize the total damping cost. Three numerical minimization methods, i.e., Differential Evolution, Nelder Mead, and Simulated Annealing, which are well known in the optimization literature, are adopted to solve the optimization problem.

The procedure considering the optimal placement of added dampers in a shear-building frame is given as follows:

Step 1. Read the input data to construct the stiffness matrix (K), and mass matrix (M), and then calculate the first natural circular frequency of the total system (ω_1), the first mode vector, and the structural damping matrix (C). Select a design earthquake for linear time history analysis. Select an upper limit of the design variable, $\bar{c}_i$.

Step 2. At the beginning of the algorithm, iteration number=1.

Step 3. Calculate a new target added damping ratio from the equation $\zeta_{ad}^{new} = \zeta_{ad}^{old} + 0.01$. Consider $\zeta_{ad}^{old} = 0$ in the first iteration. ζ_{ad} is increased by 1% for every iteration in this study.

Step 4. Minimize the cost function defined in Equation (17) in accordance with the constraints of Equations (18)–(19). Adopt the numerical minimization module of Mathematica 5.0 (Wolfram Research 2003) to solve the linear optimization problem by conducting three different methods, i.e., Differential Evolution, Nelder Mead, and Simulated Annealing. Find a candidate optimal damper design.

Step 5. Test the candidate optimal damper design achieved in Step 4 by conducting time history analysis and calculating the peak relative displacements for all storeys as $RD_i = \{U_{Ai}(t) - U_{Bi}(t)\}^{peak}$ for i=1,…s, where $U_{Ai}(t)$ signifies the displacement of the ith storey in structure A. Stop the iteration if all Relative Displacements (RDs) calculated in this step are below the allowable level (assumed to be 0.05 m in this study). Otherwise, return to Step 3, increase the iteration number (as iteration number=iteration number+1) and compute a new target added damping ratio.

This paper is concerned only elastic shear building structures. Moreover, the elastic behavior is taken into account in the study. In case of the strong earthquake, it should be used nonlinear time history analyses. May be, a nonlinear time history analyses under the strong earthquakes can be added to the snap back test stage in the proposed algorithm. In this paper, El Centro (NS) earthquake record is used only. The effects of the selected design earthquakes considering the proposed method should be investigated. It can be apply new earthquake data to the examples provided in the paper.

If all the design variables attain to the upper limit in Step 4 and any one of RD (calculated in Step 5) is not below the allowable level, optimization will not satisfy convergence in Step 4. In this case, one should return to Step 1 and to increase upper limit of the design variables.

3. RESULTS AND DISCUSSION

3.1. Numerical Example

Figure 2 shows two 4-storey structures and the dampers placed between them. The storey rigidity and mass of structure A are uniformly chosen as 3.0×10^7 N/m and 3.2×10^4 kg, respectively, while the storey rigidity and mass of structure B are uniformly chosen as 1.0×10^7 N/m and 6.4×10^4 kg, respectively. The ratio of periods for A and B are determined to be 2.45. Differences in the dynamic characteristics of the structures cause out-of-phase behaviours during earthquakes and, in turn, collisions. Dampers are added at each storey level as depicted in the figure, and the optimal designs of these dampers are found using the proposed algorithm.

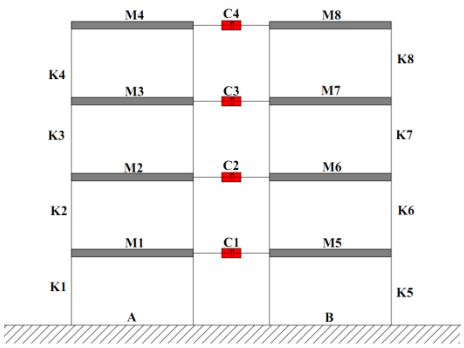

Figure 2. Addition of dampers to each storey level of structures A and B

Separate optimal designs are found in the case where the upper limit of the constraint of the damping coefficient at each storey is $\bar{c} = 2.5\ x\ 10^5$ Ns/m, $\bar{c} = 3.0\ x\ 10^5$ Ns/m, $\bar{c} = 3.5\ x\ 10^5$ Ns/m, $\bar{c} = 4.0\ x\ 10^5$ Ns/m, $\bar{c} = 5.0\ x\ 10^5$ Ns/m, and $\bar{c} = 6.0\ x\ 10^5$ Ns/m. In Figure 3, only the changes in cost function at the 1st, 10th, 20th, and 38th steps of optimization are given for an upper limit of the damping coefficient of $\bar{c} = 3.5\ x\ 10^5$ Ns/m. Changes among three methods are shown. The values of the minimum target function in a step can be seen in the algorithm when the graphs are viewed. Optimal results obtained from the three methods validate the proposed approach.

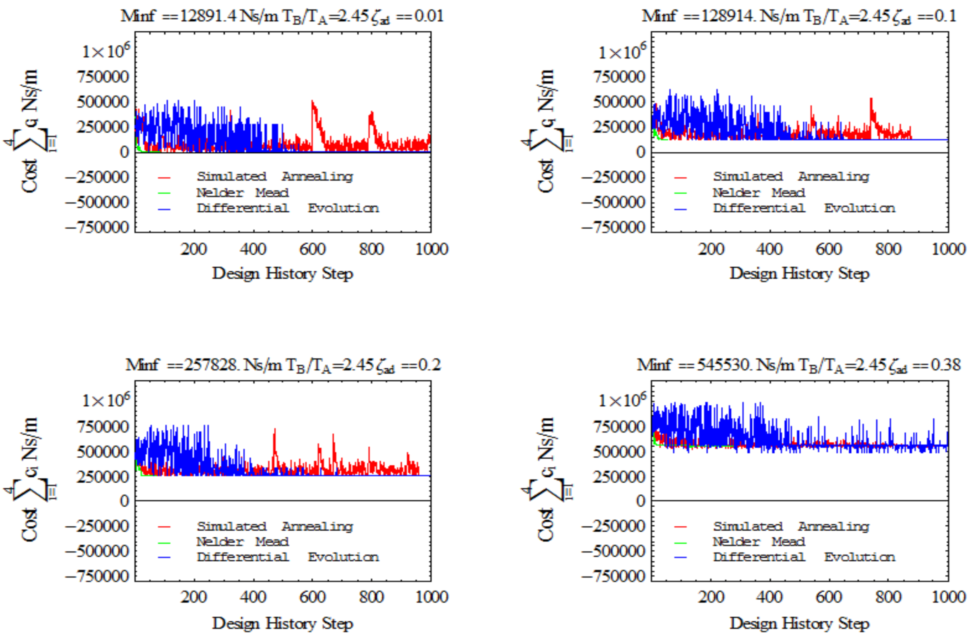

Figure 3. Change in objective function during optimization for the constraint $\bar{c} = 3x10^5$ Ns/m

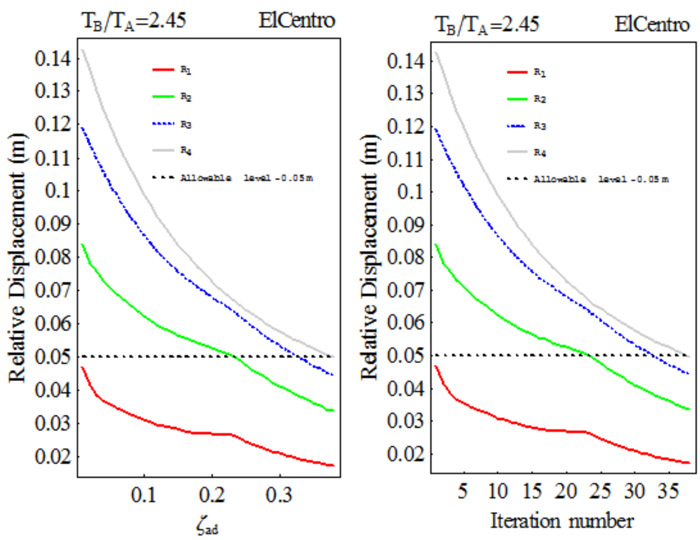

Figure 4. Changes in relative displacement according to the iteration steps and damping ratio during the optimization process for the constraint $\bar{c} = 3\ x\ 10^5$ Ns/m

In the algorithm given in Section 4, optimal designs are found in accordance with different upper constraint values of damping coefficients by using El Centro (NS) earthquake acceleration records. Changes in the iteration phases of the relative displacement and added damping ratio of each storey between buildings are shown in Figure 4 for the constraint $\bar{c} = 3\ x\ 10^5$ Ns/m. The results obtained are below the target of 0.05 m.

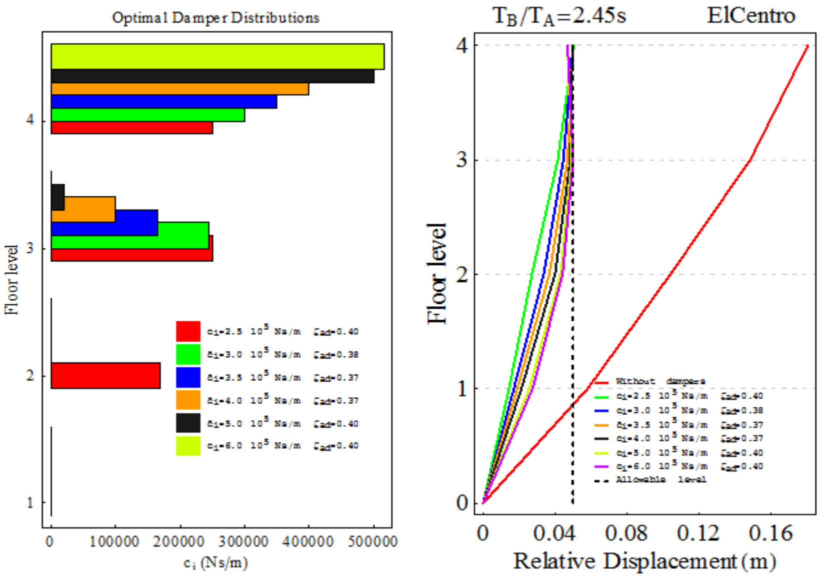

Figure 5. Optimal distributions of dampers and relative displacement profiles corresponding to these distributions for constraints of $\bar{c} = 2.5\ x\ 10^5$ Ns/m, $\bar{c} = 3\ x\ 10^5$ Ns/m, $\bar{c} = 3.5\ x\ 10^5$ Ns/m, $\bar{c} = 4\ x\ 10^5$ Ns/m, $\bar{c} = 5\ x\ 10^5$ Ns/m, and $\bar{c} = 6\ x\ 10^5$ Ns/m

The optimal distributions of dampers and the relative displacement profiles corresponding to these displacements are shown in Figure 5 for constraints $\bar{c} = 2.5\ x\ 10^5$ Ns/m, $\bar{c} = 3\ x\ 10^5$ Ns/m, $\bar{c} = 3.5\ x\ 10^5$ Ns/m, $\bar{c} = 4\ x\ 10^5$ Ns/m, $\bar{c} = 5\ x\ 10^5$ Ns/m, and $\bar{c} = 6\ x\ 10^5$ Ns/m; these values are obtained from the El Centro earthquake. Changes in the damping coefficients of optimal designs corresponding to different constraint situations, the target functions corresponding to these designs, and the resulting damping ratios are given in Table 1. When the distribution of dampers is examined, increases in $\bar{c}$ value cause the optimal distribution to increase. In all relative displacement profiles for all optimal designs in Figure 5, the target relative displacement (0.05 m) is not achieved.

Table 1. Changes in the damping coefficients of optimal designs corresponding to different constraint situations, the target functions corresponding to these designs, and the resulting damping ratios for 4-storey adjacent buildings

Upper Limit of Damping Coefficient Ns/m (10^5)	**Optimal Damping Coefficient Ns/m**				**Minimum Value of Cost Function Ns/m**	**Target Added Damping Ratio (%)**
$\bar{c}_i$	c_1	c_2	c_3	c_4	$\sum_{i=1}^{4} c_i$	ζ_{ad}
2.5	0	169771	250000	250000	669771	40
3.0	0	0	245530	300000	545530	38
3.5	0	0	164203	350000	514203	37
4.0	0	0	99547	400000	499547	37
5.0	0	0	20244.8	500000	520245	40
6.0	0	0	0	515656	515656	40

4. CONCLUSIONS

In this work, addition of optimal linear viscous dampers between structures is investigated with the aim of preventing the collision of two adjacent buildings featuring the same levels and numbers of floors during an earthquake. In the proposed method, dampers are placed between layers of the shear frames of adjacent buildings. The algorithm put forth aims to ensure that the relative displacement measured at different storey levels reaches a specific level. Performing that, a candidate optimum, under upper limit value given for each one of the dampers and under target damping ratio, is found in every step and target given for relative displacements is tested by conducting time history analysis. When the target values are achieved, the algorithm is stopped. Four-storey adjacent shear frames are chosen as numerical examples, and the proposed method is conducted. Some parametrical modifications are also investigated, and effectiveness of the proposed method is demonstrated.

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