SEISMIC PROTECTION OF SIMILAR ADJACENT BUILDINGS COUPLED WITH OPTIMAL VISCOELASTIC DAMPERS

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Abstract

Rapid urbanization leads to the increase in high raised buildings. Also due to land and the cost constraints, the space provided between the high raised buildings is very less. These buildings without seismic design can damage each other during an earthquake. Even seismically designed individual buildings are susceptible for damage due to impact from adjacent buildings during an earthquake. Therefore, seismic protection of adjacent buildings is an innovative way has been an interest for researchers from the past two decades. The technique of connecting the adjacent dissimilar buildings through dampers has proven to be efficient. However, adapting the connected control technique to dynamically similar buildings (DSAB) has remained a challenge due to their in-phase behavior under dynamic loads. The present study focuses on the response reduction of dynamically similar adjacent buildings coupled with viscoelastic (VE) dampers under seismic forces. A numerical study has been carried out on the coupled ten storied reinforced concrete DSAB subjected to recorded ground motions. These buildings are numerically modeled as a shear building with lumped mass at each floor level connected with VE dampers. Response reduction of both DSAB using connected control technique with straight and diagonal configuration of VE dampers are considered. Providing dampers at all floor levels of DSAB can become uneconomical. It is possible to find an economical solution with limited number of dampers to connect DSAB at their optimal locations. Hence, this study focuses on optimizing the location of dampers with the best configuration to reduce the seismic response of both DSAB. Multi-objective particle swarm optimization (MOPSO) is used in this study to get the optimum locations of VE dampers by considering all possible locations and configurations. The top floor displacements of both adjacent buildings are considered as two separate objectives functions to be simultaneously minimized by MOPSO. The seismic response obtained from the buildings connected with optimal damper configuration is compared with that of buildings fully connected with dampers. Also, the convergence study has been done to evaluate the number of optimal dampers required to reduce the seismic response of buildings at par with capacity of fully connected dampers. The seismic response of the coupled buildings, with the optimal damper locations, has been reduced considerably compared to that of uncoupled building. The proposed technique is cost-effective in reducing the seismic response of DSAB with the optimal number of VE dampers compared to fully connected dampers.

Keywords: Dynamically similar adjacent buildings; Viscoelastic dampers; Coupled buildings; Optimum location of dampers; Multi-objective particle swarm optimization.

1. Introduction

In most metropolitan cities, the density of buildings is high. Also, due to land and cost constraints, the space provided between structures is limited. During an earthquake event, these structures are damaged by ponding to each other. Although individual structures are designed to inhibit dynamic response, the structures are affected by the lateral movement of the adjacent structure due to seismic forces. For the same earthquake, each building behaves differently because of their distinct structural dynamic properties. But, adjacent buildings with similar dynamic properties vibrate in similar manner during an earthquake, when their spatial variation is neglected. When dynamic properties such as stiffness, mass distribution and inherent structural dampness of two buildings are the same, it leads to the same structural time period. These building built adjacent to each other are termed as dynamically similar adjacent buildings (DSAB). In the early 1970s, connected control technique (CCT) was used to reduce the wind induced response of adjacent structures. Twenty years later, CCT has been expanded to reduce the earthquake-induced shocks of dynamically diverse buildings. The CCT for adjacent dissimilar structures has proven to be an efficient and economical way of reducing vibrations in both buildings rather than improving each building. Furthermore, if dampers are placed at their optimum locations between adjacent buildings, their efficiency is maximized. However, the application of CCT for DSAB is challenging due to in-phase behavior of these building under seismic forces. Also, chances of pounding is minimal when adjacent structures have dynamically similar properties [1].

Connected control methods are classified based on the type of control technology, type of actuator, type of dampers, type of damper configuration, number of buildings, number of degrees of freedom, etc. Two buildings of different plan dimensions will defiantly have different dynamic behavior. Sometimes, two buildings may look identical but their damage under same earthquake can vary significantly. The possibility of diverse behavior can be due to variation in design, material quality, usage and performance, etc. Such buildings close to each other are termed as dynamically dissimilar adjacent buildings (DDAB). CCT is implemented with liquid dampers for such buildings to minimize seismic response. These damper connections are beneficial for adjacent buildings of the same height rather than different heights [2]. The equation of motion formulated for a multi-level free system with dampers connected to adjacent multistory buildings during seismic excitation. Experimental results have shown that the installation of liquid dampers reduces the seismic responses of both buildings [3]. Shake-table experiments on scaled structural models of two (4-storey and 2-storey) adjacent structures are carried out [4]. The seismic response of two dynamically asymmetric adjacent buildings connected by viscoelastic dampers. Also, viscoelastic dampers are connected between fixed base building and base-isolated building. The effect of viscoelastic dampers as a connected link is more significant in a base-isolated case than a fixed-base buildings case [5]. Friction dampers as a connector between a pair of DDAB has proved to be effective with numerical and analytical studies [6]. Later, the CCT study was done on adjacent buildings linked with magnetorheological dampers and also the seismic behavior of nearby buildings on pile foundations are evaluated [7]. Most of these CCT studies are on DDAB or similar buildings made dissimilar by means of base isolation, bracing, etc. The DSAB connected with low-cost viscoelastic damper with seismic excitation has been carried out. Since the straight damper connection is not effective for DSAB, diagonal damper connection has been used and it resulted in effectively reducing the dynamic response subjected to an earthquake [8].

An economical and effective way to reduce the dynamic response of a structure depends on the type of damper, the optimal number of dampers and their location. Also, proper damper characteristics are required to adopt the coupling method economically. The optimal design strategy for CCT of for two structures that are dynamically identical are studied with cantilever connection [9]. The elastic behavior of two adjacent dynamic analogous structures linked by viscous dampers subjected to different seismic excitations has been studied [10]. The optimized value of the damping coefficient for viscous dampers was obtained by the trial and error process. The two adjacent buildings as a linear discrete system consisting of masses, linear springs and linear passive dampers, which were linked to each floor through optimization with respect to the inter-story drift and optimal damping coefficient are obtained [11]. The effectiveness and performance of buildings with optimal dampers obtained through particle swarm optimization (PSO) algorithm compared to uncontrolled and arbitrary passive viscous damper placement. In another study, PSO was used to appropriately identify magneto-rheological (MR) dampers to improve the seismic response of the structure [12]. To understand the effect of vibration control, experiments are conducted on adjacent steel buildings connected to the MR damper, validating with the control algorithm [13]. It is observed that the MR damper input voltage is affected by the seismic input and its intensity. The seismic performance of adjacent buildings and proper analysis of passive and active control systems are studied [14]. To increase the damper effect, the optimization was performed using a binary and real coded genetic algorithm. Optimal design mechanism of a hybrid control system for two DSAB exposed to seismic excitation to bring about the effective and economic use of the passive and active dampers [15]. PSO is also used to obtain the optimal actuator positions for a combined RC structure with a shear wall [16]. Three optimization methods, Differential Evolution, Nelder Mead, and Simulated Annealing are used to find the optimum positions of the dampers with target damping ratio and cost function as objective functions to dynamically link viscous dampers to adjacent buildings [17]. Optimal damper CCT for DSAB is affected by ground motion, damper configuration, damper locations with limited number of dampers [18]. The adjacent buildings integrated by means of optimal damper configuration with limited number of dampers was observed to be effective to reduce the seismic response.

From the above literature, it is observed that there are limited study on the seismic control of dynamically similar buildings using the connected control technique. Moreover, in most studies, dynamic similar buildings are differentiated by base isolation or bracing. Also, the optimal damper configuration for effective seismic control can be studied for such buildings. Hence, the present study focuses on the method of achieving better performance to CCT for DSAB using Multi-objective particle swarm optimization (MOPSO) to place dampers at optimum locations. Also, the convergence study has been done to evaluate the number of optimal dampers required to reduce the seismic response of buildings at par with capacity of fully connected dampers.

2. Methodology

Two DSAB of RC structures with ten stories are considered and are simultaneously subjected to earthquake excitation in the horizontal direction. The ground levels of both the buildings are considered same and they are close to each other so that the spatial variation of the ground motion can be ignored. At the same time sufficient distance is available between the buildings for the damper installation. The soil structure interaction effect is neglected by considering the buildings to be on a rigid foundation. The inherent damping ratio of the building is taken as 5%. The dead load and live load that contributes to the mass is 64719.4 kg and stiffness is 3.7774×10^8 N/m at each story has to be considered and design is as per the Indian Standards. The buildings are dynamically similar, hence the effect of pounding during the earthquake is not needed. An equation of motion of the building coupled with dampers has been formulated and solved using Newmark-beta method [19]subjected to ground motions.

The seismic performance of dynamically similar adjacent buildings connected with a different configuration of dampers is studied through numerical modelling. These building are modeled using simplified lumped mass shear building model shown in Fig.1. and subjected to time history analysis of ground acceleration. The numerical analysis is carried out by connecting the adjacent similar building models with various possible damper configurations as shown in the Fig.2. The reduction of seismic response of the coupled building can be obtained by solving the equation of motion through numerical integration.

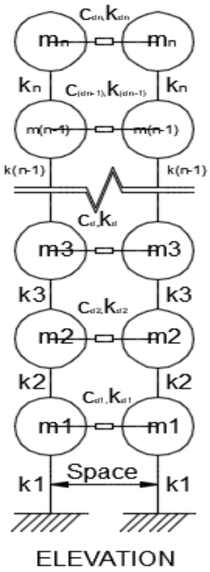

Fig. 1 Schematic shear building model of dynamically similar adjacent buildings

The equation of motion coupled system is given by:

$$M\ddot{X} + (C + C_D)\dot{X} + (K + K_D)X = -MI\ddot{x_g} \quad (1)$$

where, M = Mass matrix of the of the coupled building, K = Stiffness matrix of the coupled building, C = Damping matrix of the coupled building, C_D = Damping matrix of the damper based on configuration, K_D= Stiffness matrix of the damper based on configuration , I = Unit vector depends on direction of ground motion, $\ddot{x_g}$= Earthquake Ground acceleration.

$$[M] = \begin{bmatrix} m_{(n,n)} & 0 \\ 0 & m_{(n,n)} \end{bmatrix} \quad (2)$$

$$[K] = \begin{bmatrix} k_{(n,n)} & 0 \\ 0 & k_{(n,n)} \end{bmatrix} \quad (3)$$

$$[C] = \begin{bmatrix} c_{(n,n)} & 0 \\ 0 & c_{(n,n)} \end{bmatrix} \quad (4)$$

$$m_{(n,n)} = \begin{bmatrix} m_{11} & 0 & 0 & 0 \\ 0 & m_{21} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & m_{n1} \end{bmatrix} \quad (5)$$

$$k_{(n,n)} = \begin{bmatrix} k_{11} + k_{21} & -k_{21} & 0 & 0 \\ -k_{21} & k_{21} + k_{31} & \dots & 0 \\ 0 & \dots & \ddots & \dots \\ 0 & 0 & \dots & k_{n1} \end{bmatrix} \quad (6)$$

$$C_{(n,n)} = \begin{bmatrix} c_{11}+c_{21} & -c_{21} & 0 & 0 \\ -c_{21} & c_{21}+c_{31} & \dots & 0 \\ 0 & \dots & \ddots & \dots \\ 0 & 0 & \dots & c_{n1} \end{bmatrix} \quad (7)$$

$$C_D = \begin{bmatrix} Cd_{(n,n)} & 0 \\ 0 & Cd_{(n,n)} \end{bmatrix} \quad (8)$$

$$K_D = \begin{bmatrix} kd_{(n,n)} & 0 \\ 0 & kd_{(n,n)} \end{bmatrix} \quad (9)$$

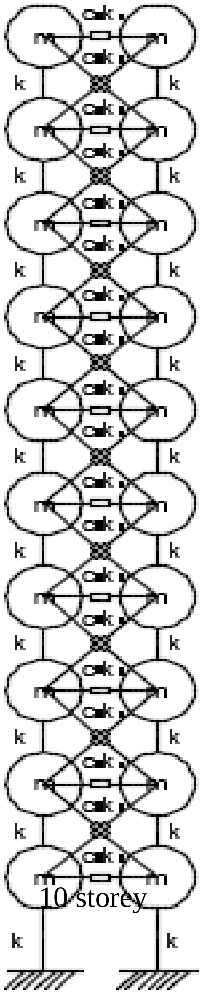

Fig. 2 Possible damper configuration for connecting DSAB

where, $Cd_{(n,n)}$ and $kd_{(n,n)}$ are the damping and stiffness matrixes of dampers in single building. For example adjacent similar buildings connected with diagonal dampers connection, the $Cd_{(n,n)}$ and $kd_{(n,n)}$ matrixes are given by:

$$Cd_{(n,n)} = \begin{bmatrix} cd_1 & 0 & 0 & 0 \\ 0 & cd_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & cd_n \end{bmatrix} \quad (10)$$

$$kd_{(n,n)} = \begin{bmatrix} kd_1 & 0 & 0 & 0 \\ 0 & kd_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & kd_n \end{bmatrix} \quad (11)$$

3. Optimal Position of Dampers

The number of possible damper configurations with N_f floors and N_d dampers is N_1 C N_d, where $N_1 = N_f + 2(N_f - 1)$, the first term accounting for configurations with damper ends connecting at same level, and the second term for "diagonal" damper positions in which the left end is at one floor above or below the right end. If N_{total} is sufficiently small, it is possible to obtain the desired maximum displacements (with respect to time) of the top left and top right floors for all damper configurations in a reasonable amount of CPU time. From these results, we can then find the best configurations, i.e., those giving the smallest values for the above displacements. We will refer to this process as "enumeration." For example, with $N_f = 10$, $N_d = 3$, we have $N_1 = 28$, and $N_{total} = 3{,}276$ which is small enough to enable enumeration to be performed in a few minutes on a desktop computer with a 3.3 GHz clock and 4 GB RAM. However, for larger values of N_f and N_d, N_{total} can be impractically large for enumeration to be a viable option. For example, with $N_f = 10$, $N_d = 5$, we have $N_1 = 28$, and $N_{total} \approx 4.6 \times 10^6$. In such cases, enumeration is ruled out, and some optimization algorithm needs to be employed to find the best solutions in a reasonable amount of time.

In this paper, we report displacement values (i.e., the maximum displacements for the top left and top right floors) for all configurations when N_{total} is sufficiently small. This gives a good idea of the spread of the solutions in the (x_L, x_R) space, where x_L and x_R are top-floor maximum displacements for the left and right buildings, respectively. For the same N_f and N_d values, we also obtain the best displacement values using optimization in order to validate the optimization results against the enumeration results. For larger values of N_{total}, we only report the best solutions obtained using optimization since enumeration is not possible in these cases.

The multi-objective particle swarm optimization (MOPSO) algorithm described in [20] is used in this work together with local search [21]. The following PSO parameters were used: inertia weight $W = 0.4$, cognitive and social learning factors $C_1 = C_2 = 2$.The number of particles was 20 for $N_f = 10$. The number of PSO iterations varied from 50 for smaller problems to 500 for the largest problem, viz., $N_f = 20$, $N_d = 5$. A constant mutation probability of 0.2 was used in all cases. Local search was performed once in every 10 PSO iterations. The results of enumeration for all N_d and the best solutions obtained using the above MOPSO algorithm for all other cases are described in the following section.

4. Results and Discussions

Optimal CCT proposed for DSAB with number of floors (N_f) and different number of dampers (N_d) is evaluated here. The VE damper properties such as stiffness and damping values of $K_d = 10^6 N/m$ and $C_d = 10^7 N-m/s$ respectively are used in this study based on the convergence study. Optimal damper configuration is obtained for a set of DSAB with N_f=10 stories and different N_d=3,4 until response match the close to the fully connected dampers through MOPSO.

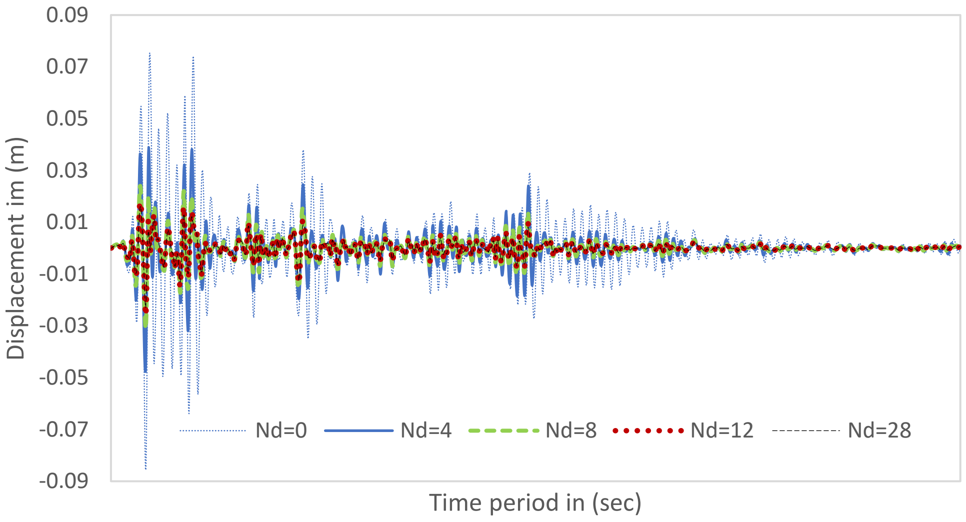

Fig. 3, Top floor displacement of DSAB with and without dampers

Initially, seismic response of DSAB's are observed without dampers ($N_d = 0$) and with fully connected dampers ($N_d = 28$, Fig. 2), and the corresponding top floor displacement time history response is shown in the Fig. 3. To reduce the cost of the CCT for DSAB, the number of dampers is to be minimized using MOPSO for different cases. The optimal damper configurations of DSAB is obtained by considering $N_f = 10$ and $N_d = 3,4,5 \ldots.$ until 14 are with constant damping and stiffness value of external VE Damper. The optimal locations of dampers for each case of $N_d = 3,4,5 \ldots.$ until 14 are shown in Fig. 5 respectively. For each case the Pareto front of both the objectives has been determined using MOPSO and it is shown in the Fig.4. It can be observed that, for each case there can be many optimal solutions with variation in top floor displacements of left and right building.

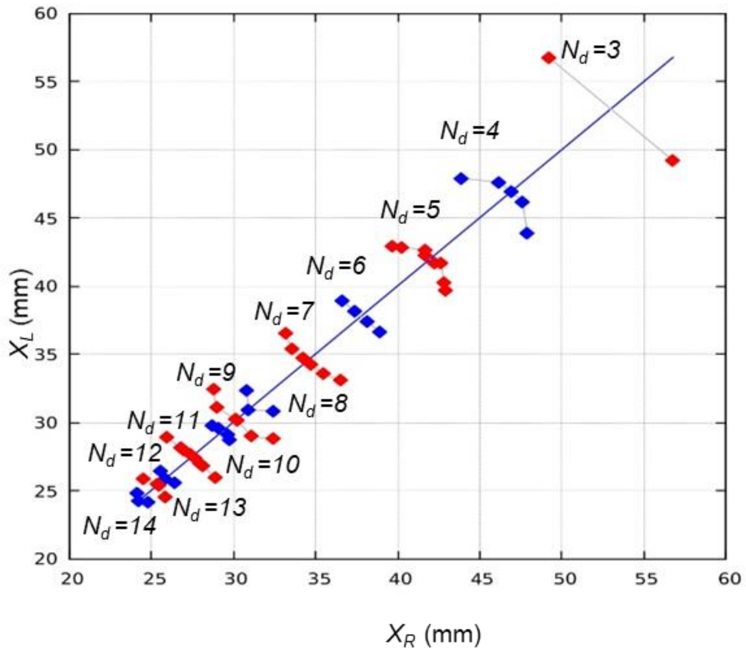

Fig. 4 Optimal displacement of both DSAB

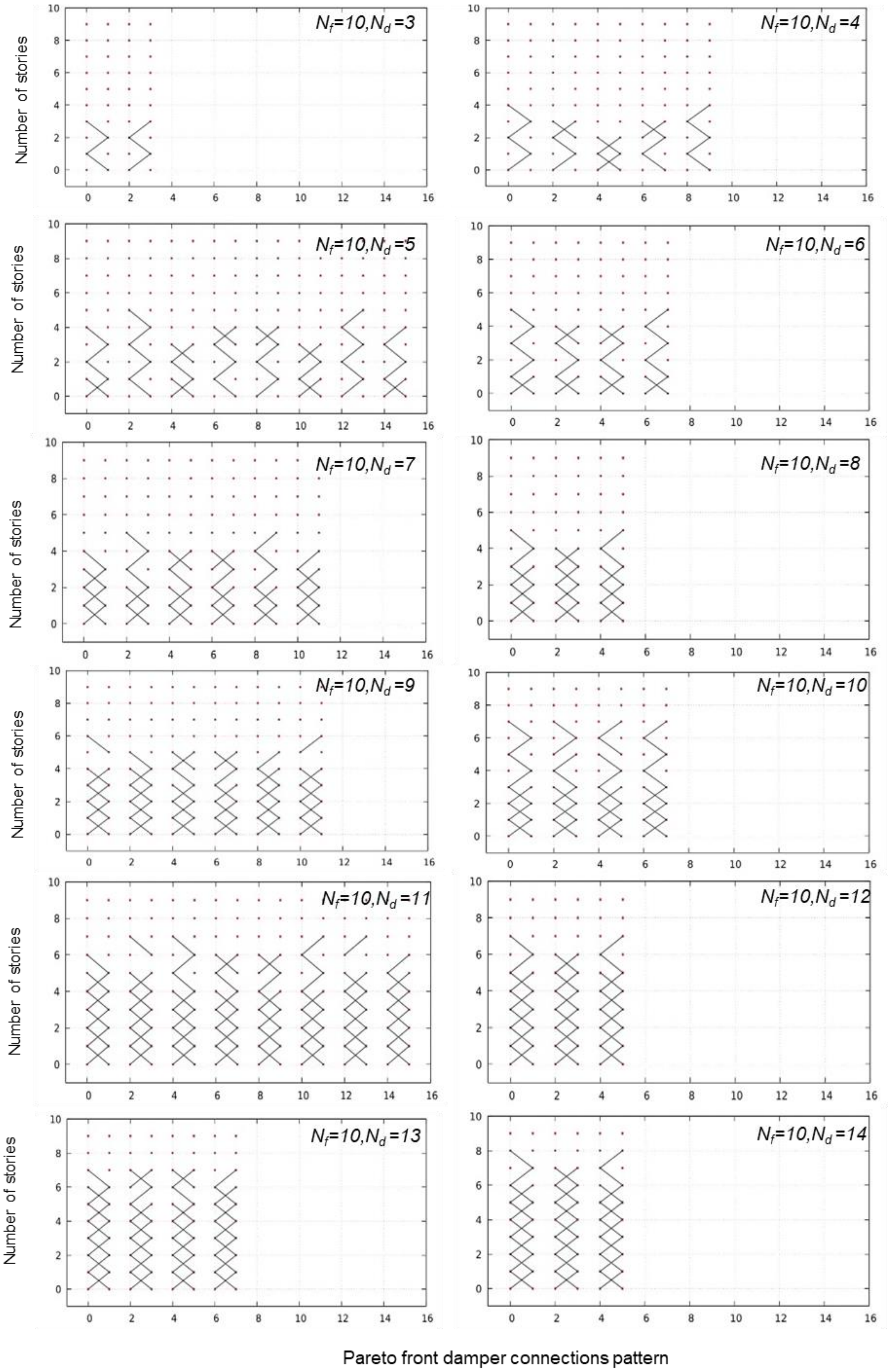

Fig. 5 Optimal damper configurations for connecting DSAB

It is to be noted that for symmetrical configuration of dampers, the left and right building displacement response reduction is equal. With the increase in number of dampers placed optimally, the response of building reduces to greater extent. As the number of dampers $N_d = 12$,13, 14 the improvement in response reduction slows down reaching towards convergence. The efficiency of optimal location of dampers is compared with filly connected dampers through a time history response plot shown in Fig.3. It shows the top floor displacement of DSAB for $N_d = 4$, 8, 12 with symmetrical distribution of dampers. It is observed with placement of dampers the seismic response is reduced to great extent compared to building without damper. Most important observation is that the response of DSAB with $N_d = 12$ is very close to that of building with fully connected dampers ($N_d = 28$). Also, the MOPSO is competent enough to simultaneously reduce the top floor displacement of left and right buildings with slight variation between them for asymmetrical damper configuration.

5. Conclusion

The response reduction of two DSAB connected with viscoelastic damper is investigated under earthquake excitation, assuming a linear elastic behavior of the structures. The governing equations of motion are formulated for the viscoelastic damper connected to two dynamically similar adjacent buildings. The viscoelastic damper is found to be very effective to control the earthquake responses of the DASB. In order to reduce the total cost of VE dampers to connect DSAB, the investigation on finding the optimal location with limited number of dampers is carried out. In order to obtain the simultaneous reduction in response of both buildings, MOPSO is used with two objective functions as top floor displacements of DSAB. With optimal connection of limited number of dampers, the response reduction of DSAB is efficiently achieved compered to fully connected dampers, thereby saving the cost. Hence, it is not necessary to connect the dampers throughout the DSAB but at optimal locations with limited number of dampers.

6. Acknowledgements

The research described in this paper was financially supported by the “Department of science and technology (DST)-Science and Engineering Board (SERB), India”.

we acknowledge the facility provided by the “Department of science and technology (DST)- Fund for Improvement of S&T Infrastructure in Higher Educational Institutions (FIST), India”.

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