Preventing Seismic Pounding of Adjacent Structures Using Viscous Wall Damper Device

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Abstract Today, a number of researchers are broadly studying the effective implementation of supplemental seismic energy dissipation systems to improve seismic behavior of structures during earthquakes. The current article studies the impacts of employing Viscous Wall Damper devices to couple two adjacent structures on seismic response of the new system. An exclusive finite element algorithm capable of modeling and analyzing structures equipped with special damper systems was used in order to perform a nonlinear time history analysis subjected to seismic excitation. Two ten-story RC framed structures are modeled adjacently in 11 different cases, each representing existence or damping coefficient of the Viscous Wall Damper device. A parametric study has been conducted in each case to assess the effectiveness of implementing Viscous Wall Damper devices on improving seismic behavior of the coupled structure. The considered metrics include rotation and displacement amplitude, plastic hinge formation, and induced element forces. It has been proved that the proposed damper system substantially diminishes and dissipates induced seismic response of the system. Also, it is indicated that the extent to which Viscous Wall Damper device contributes in mitigating seismic responses is highly correlated with the damping coefficient.

Keywords Viscous wall damper · Passive control · Adjacent structures
Seismic response mitigation · Finite element

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1 Introduction

Seismic Pounding is defined as collision of two adjacent buildings during an earthquake [1]. As a couple of structures in close proximity with unlike properties (in terms of heights, structural systems, materials, etc.) are exposed to a quake, there will be a likelihood of occurring pounding within them. Pounding between proximate structures is an extremely complicated fact making the analysis of the equivalent problem tangled. A number of analytical models have been developed to explain the behavior of adjacent structures throughout a ground motion. Wolf and Skrikerud [2] investigated the pounding prompted on account of a small gap between the structure of a nuclear reactor and a nearby construction. Structural pounding issue is rather unfavorable than profitable proved by Efraimiadou et al. [3] when the collision between adjacent reinforced concrete (RC) buildings under multiple earthquakes was examined. Tapashetti and Swamy [1] demonstrated that the use of pounding prevention techniques such as incorporating new RC walls, bracing systems, dampers, combined system of RC wall and bracing, combined system of RC wall and dampers, and combined system of bracing and dampers between adjacent buildings are effective in mitigating the pounding due to earthquakes. Elwardany et al. [4] presented a finite element analysis for multi-story buildings to research the impacts of adding infill panels on the response of imposed mutual pounding of the structures during earthquakes.

An approach to control pounding is to couple adjacent structures via elastic or damping elements. Considering current concerns in earthquake-resistant design approaches, structures are likely to undergo significant damage but prevent collapse. While this attitude has been a standard for many decades, novel design methods and innovative devices are receiving more notice and being developed comparing with conventional approaches. Plenty new mechanical systems have been suggested in last two decades in order to improve structural behaviors during dynamic excitations. They are all recognized as "protective devices" and include supplemental viscoelastic dampers, viscous fluid dampers, frictional dampers, hysteretic dampers, tuned-mass dampers, and base isolation systems. A semi-active control scheme of joined structures has been suggested by Christenson et al. [5], and different coupled structural configurations have been studied and experimentally verified the effectiveness of employing such vibration control systems based on acceleration feedback. The usefulness of implementing evenly distributed viscous dampers between a couple of elastic parallel structures, excited by a same quake, in order to mitigate the consequent responses was investigated by Luco and De Barros [6], Zhang and Xu [7]. It has been confirmed that the seismic behavior of adjacent structures was improved through application of adjoining dampers.

The influence of position, quantity as well as linking arrangements of fluid dampers are investigated by Lu et al. [8] in order to strengthen two adjacent structures against seismic motions. Then, the obtained outcomes are compared with the use case of rigid rods.

Kageyama et al. [9] studied a passive vibration control procedure in which two adjacent structures were interconnected through dampers. Kim et al. [10] researched the impacts of implementing viscoelastic dampers at connections between a building and a sky-bridge as well as across the seismic joints. According to the outcomes of the conducted analysis, they found that the proposed procedure plays a significant role in reducing the displacements while no such improvement was observed considering the base shear. A new adjustable damping device as a coupling component consisting two dampers positioned between two structures was considered in theoretical and numerical simulations in order to verify the positive seismic behavior of the suggested protective system during a series of remarkable quakes [11]. Since a principal aim of proceeding in cutting-edge technologies of structural engineering is to improve the seismic behavior of structures, implementing a suitable supplemental energy dissipation system can contribute to a great deal [12, 13]. The impact of different characteristic parameters of supplemental viscous dampers on the behavior of RC structures was assessed through a parametric study, which preceded a design for an optimum viscous damper based on the anticipated performance to meet the different levels of demand for a given building [14]. Hejazi et al. [15] developed a 3D elastoplastic viscous damper element well-matched with the constitutive model to strengthen RC structures during earthquake excitations by finite element method. Hejazi et al. [16] developed a multi-objective optimization method to be used in structural passive control schemes according to a genetic algorithm. They also applied the model to a 3D RC framed building, whose structural seismic responses have been investigated. Kandemir-Mazanoglu and Mazanoglu [17] developed an optimization technique to determine the capacity of viscous dampers bearing one-sided structural pounding between two adjoining structures under seismic ground motions.

Although the above-mentioned research on mitigation of earthquake-induced pounding of adjacent structures provide some data about the impacts of different damper systems and their associated responses, the importance of the subject prompts a need to investigate the problem in depth, considering state-of-the-art damper systems as well a range of governing parameters. Hence, the current paper studies the effectiveness of implementing Viscous Wall Dampers, as an advanced system, between adjacent structures in order to attenuate the pounding consequences. In particular, this paper conducts a research on the influence of implementing Viscous Wall Dampers with different damping characteristics on a range of certain structural parameters in order to optimize the associated pounding ramifications in design and practice.

2 Nonlinear Analysis of the Adjacent RC Structures

A two-dimensional finite element model considering all nonlinearity possibilities present in the framed structural system has been generated in order to calculate the response of the structure using a combination of incremental iterative approach and

the Newton–Raphson practice. The aim is to investigate the effects of equipping two adjacent structures with Viscous Wall Damper (VWD) device in terms of reduction in dynamic responses due to earthquake excitations. Figure 1 illustrates the geometry and property details of the adjacent structures.

The model is generated in an exclusive finite element algorithm developed for nonlinear analysis of RC structures supplied with earthquake energy dissipation devices exposed to dynamic excitation. The program is capable of modeling and analyzing structures in order to detect plastic hinges in structural members under seismic excitations.

In order to perform a nonlinear time history analysis, the North-South component of El Centro earthquake record has been used as dynamic excitation (Fig. 2). The structures are bearing static loads as well, whose details are presented in Fig. 3. Figure 3 also represents how VWD device is employed to connect the structures in order to improve the seismic behavior of the connected structures. The damping force imposed to a VWD device is calculated by

$$F_{\mathrm{VWD}} = \hat{C}_{\mathrm{VWD}} \times V^{\eta}, \tag{1}$$

where F_{VWD} is the damping force, C_{VWD} stands for the damping coefficient of the VWD device, V represents the relative velocity of the damper, and η is exponential coefficient belonging to velocity. Velocity exponential coefficient of 1 introduces a linear behavior of the VWD device while any other values reveal a nonlinear behavior of the damper.
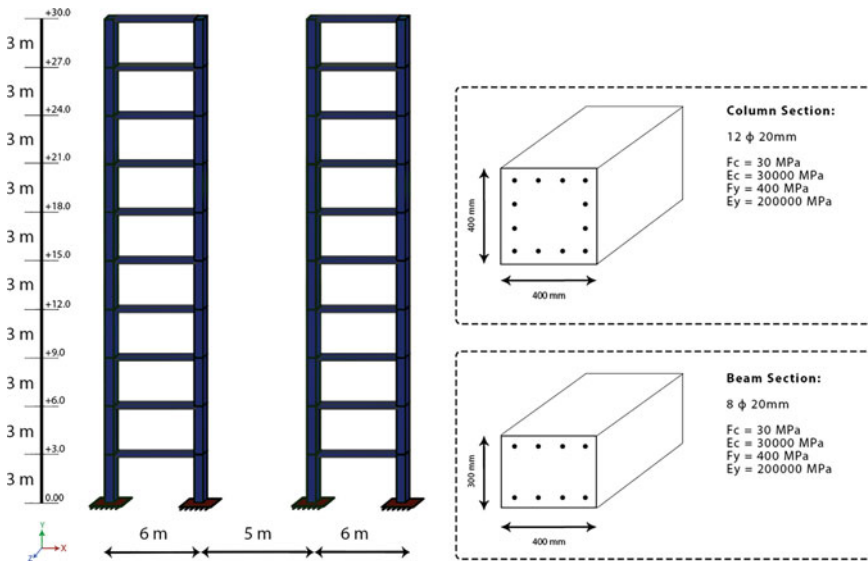

Fig. 1 Adjacent structures 2D geometric model and section properties

Fig. 2 Earthquake acceleration record (North–South component) of El Centro (Imperial Valley Irrigation District, USA-1940)
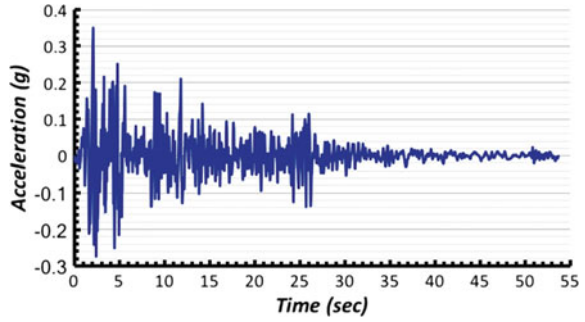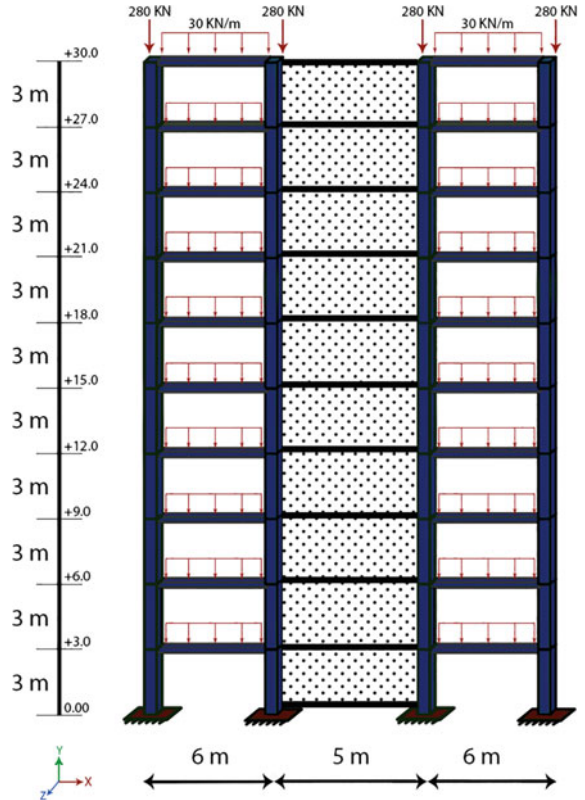

Fig. 3 Static loading details and coupling details of the two adjacent structures

According to the above-mentioned equation, the governing factor to relieve the seismic responses of such structures is the damping coefficient. Thanks to the existence of dampers with a wide range of damping coefficients, there are options for implementing a proper damper with a given damping coefficient based on the requirement of structural design process.

3 Verification of the Developed Numerical Model

In order to verify the current numerical model of VWD device in terms of its influence on seismic behavior of a given system, two entirely identical 3D RC structures, which were investigated in an experimental study by Lu et al. [18], as seen in Fig. 4a, have been nominated for nonlinear dynamic analysis. The considered excitation for dynamic analysis has been El Centro earthquake record with an acceleration amplitude of 0.05 g as an intensity factor. The two structures of 1:2 length scale were built, one with VWD device implemented and the other without any; in order to compare the effectiveness of implementing such device with the case of no supplemental damping device employed. Among the two models, the second one was empowered with VWD device whose damping coefficient was 20 KN s/m. Furthermore, in order to assess the mechanical performance of the proposed device an exclusive test setup was designed and built, as seen in Fig. 5.

The three-story RC structures consisted of a single bay along the X direction and two bays along the Y direction, forming a plan of 2.4 m × 3.6 m. Elevation-wise, the buildings contained three stories of 2 m height. The geometrical properties of the frame are depicted in Fig. 4b. Furthermore, the section dimensions of considered columns are 150 mm in width and 150 mm in height, while beams are formed as a cross-section of 80 mm in width and 150 mm in height and each floor plates have a thickness of 55 mm. The exceptions are the beams connected to VWD
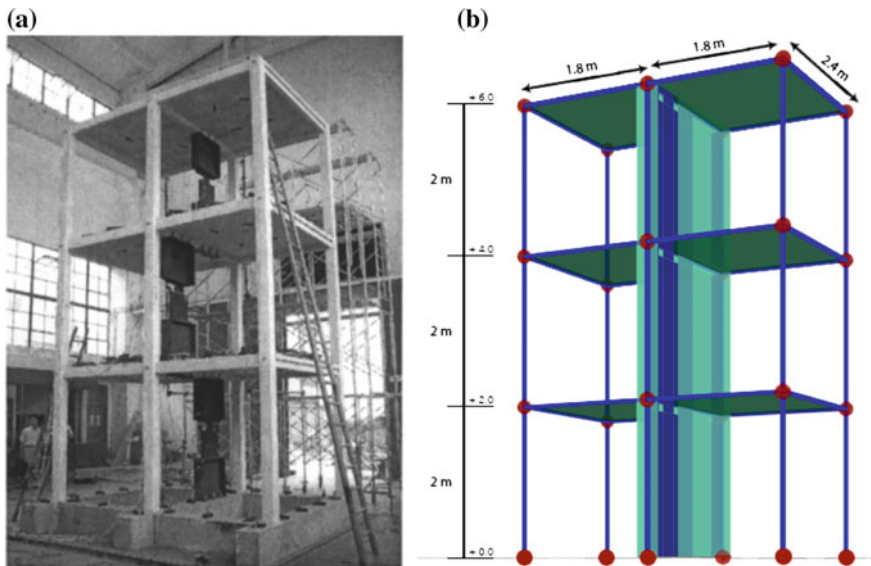

Fig. 4 Three dimensional RC frame equipped with VWD device. **a** Large-scaled model by Lu et al. [18], **b** Numerical model used in verification of the current study and its geometrical properties
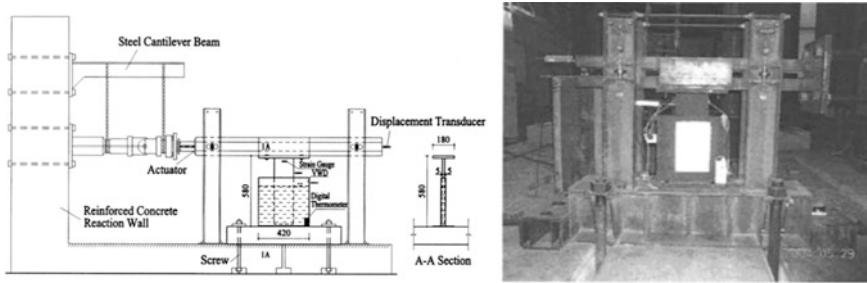
Fig. 5 Exclusive test setup and composition of VWD device

devices, whose dimension includes a width of 100 mm and a height of 150 mm. The geometrical, reinforcement, and material details of structural sections are illustrated in Fig. 6.

The structure enjoys of an inherent damping of 5%, while VWD device roles as an additional damping source. It has been assumed that VWD device functions in a linear behavior, due to taking exponential coefficient equal to one.

In order to verify the results, time history analysis was performed on numerical models of both structures and the subsequent displacements were compared with results of the experimental test by Lu et al. Figure 7a represents the recorded displacement outcomes for both cases of with and without VWD device implemented, achieved in the experiment by Lu et al. Likewise, Fig. 7b displays how both numerical models react to the imposed excitation in each story level. The comparison of the two graphs reveal that the proposed numerical model, to a large extent, is compatible with the experimental test of Lu et al. on the large-scaled structures.

4 Parametric Study

A numerical study has been conducted to assess the effectiveness of adding supplemental damper devices in controlling vibrations and seismic responses of adjoining structures. Hence, the impacts of damper damping coefficient on the mentioned systems have been studied through a nonlinear time history analysis of the simplified system excited by El Centro earthquake. In the current study, 11 different cases of VWD characteristics in terms of damping coefficient have been investigated, as seen in Table 1. Nonlinear time history analysis was performed for all 11 cases and the desired criteria (structural displacement, plastic hinge formation, and induced column forces) were evaluated in details.

$F_c = 20$ MPa $E_c = 25{,}000$ MPa $F_y = 530$ MPa $E_y = 196{,}000$ MPa
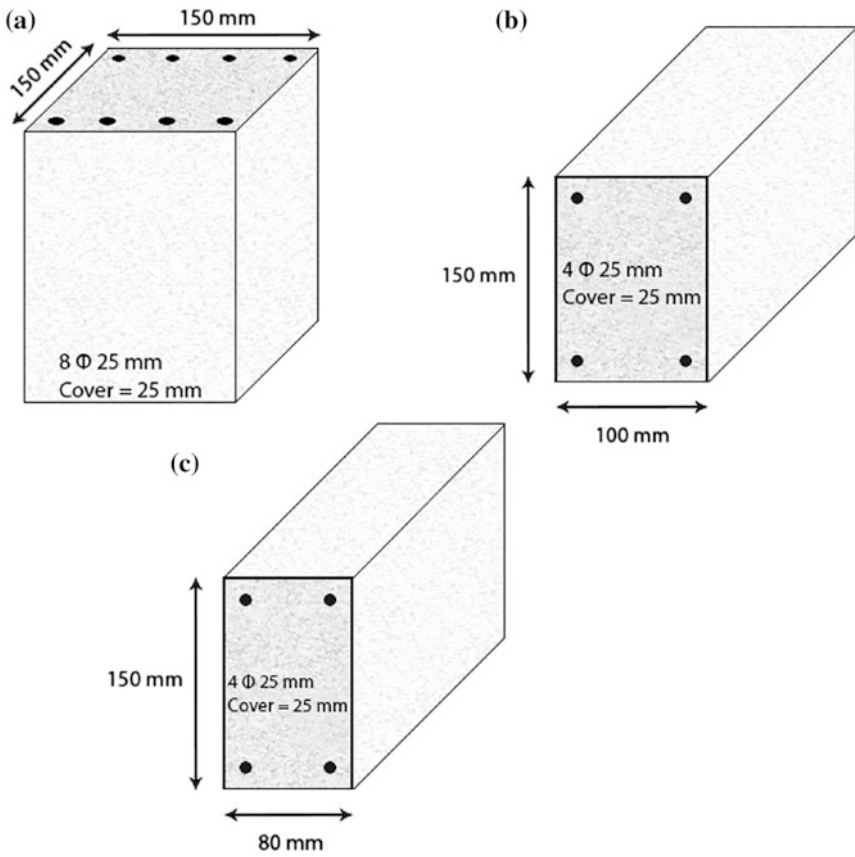

Fig. 6 Geometrical, reinforcement, and material specifications of structural sections. **a** Columns, **b** beams connected to VWD, **c** other beams
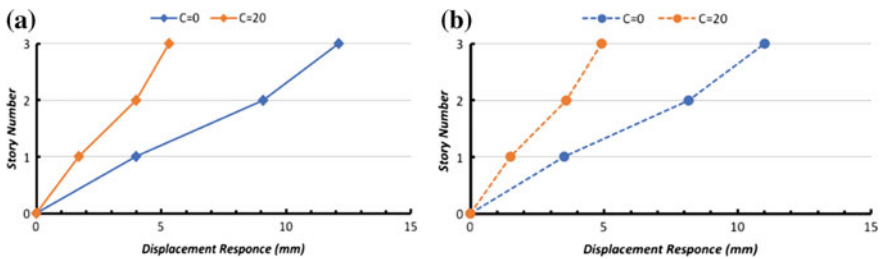

Fig. 7 Verifying the proposed numerical model in terms of displacement. **a** Experimental test by Lu et al. **b** the numerical model proposed in the current study

Table 1 Considered cases of damping coefficient

Case no.	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
Damping coefficient (KN s/m)	0	20	40	60	80	100	150	200	250	300	350

4.1 Structural Displacement Criterion

The maximum structural displacement and rotation is associated with structural element demands. Therefore, the proposed structural system has been investigated under 11 damping characteristic cases. The first case considers the circumstance in which no VWD device is implemented, while other cases are representatives of different characteristics of VWD devices. Figure 8 shows the effectiveness of adapting VWD devices on maximum displacement and rotation at each story level in such proposed structural systems. Furthermore, the detailed values of displacements and rotations are listed in Table 2.

Figure 8 illustrates that the increase in VWD damping coefficient leads to a drop in structural displacement. According to Fig. 8a, VWD devices contributed the structure in decreasing the displacement in X direction. The ultimate reduction was from 39.18 to 14.83 mm while a VWD device with $C = 350$ KN s/m was employed. This represents a total reduction of 62% in structural displacement, as presented in Table 2.

Figure 8b demonstrates the effects of using VWD devices in reducing structural rotation in each story level. The highest reduction was recorded from 0.0019789 to 0.00149478 rad by 24% while a VWD device with damping coefficient of $C = 250$ KN s/m was adopted. Table 2 elaborates on the values concisely.

The comparison of induced displacement as well as rotation in the plain structure and the one equipped with VWD devices with damping coefficients of 20, 100, 200, and 350 KN s/m are demonstrated in Figs. 9, 10, 11, and 12, respectively, in terms of time history based graphs in X and over Z directions. These figures are
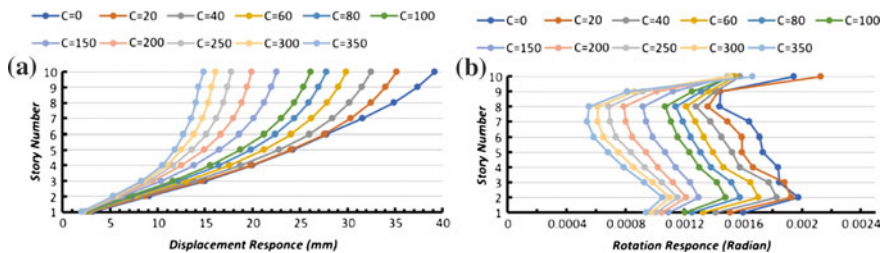

Fig. 8 Maximum displacements and rotations at each story heights: **a** displacement at X direction, **b** rotation over Z direction

Table 2 Displacement and rotation reduction rates in each damping coefficient case

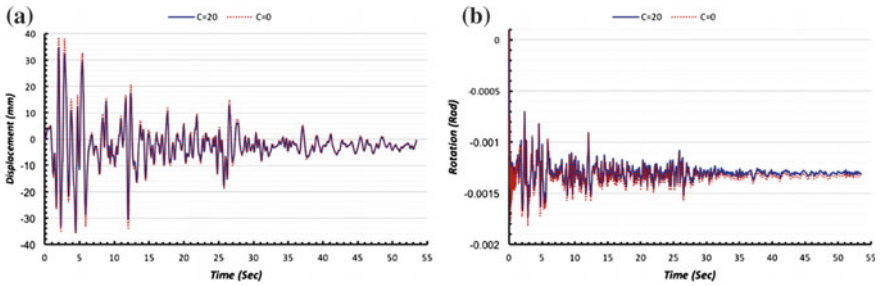| Damping coefficient (KN s/m)	Maximum displacement in X direction (mm)	Displacement reduction in X direction (%)	Maximum rotation in Z direction (rad)	Rotation reduction in Z direction (%)
0	39.1804	0	0.0019789	0
20	35.1529	10	0.00212977	−8
40	32.4729	17	0.00182994	8
60	29.8901	24	0.00170446	14
80	27.7745	29	0.00158127	20
100	26.1154	33	0.00152677	23
150	22.5332	42	0.00150247	24
200	19.8808	49	0.00151433	23
250	17.7346	55	0.00149478	24
300	16.1191	59	0.00151919	23

Fig. 9 Induced displacement and rotation versus time in X and over Z directions for $C = 20$ KN s/m **a** displacement, **b** rotation
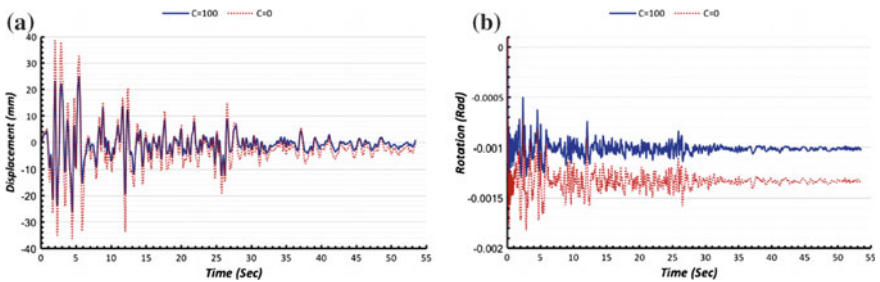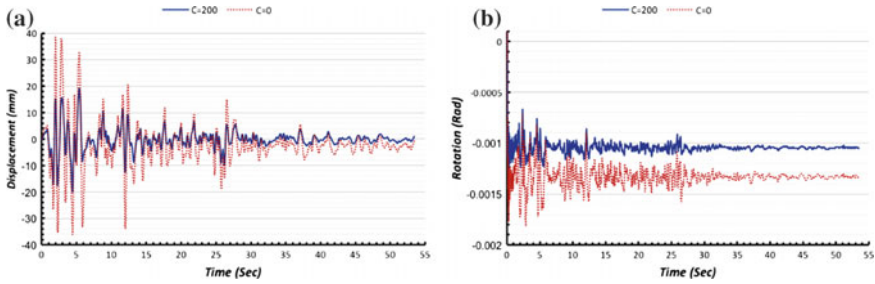

Fig. 10 Induced displacement and rotation versus time in X and over Z directions for $C = 100$ KN s/m **a** displacement, **b** rotation

Fig. 11 Induced displacement and rotation versus time in *X* and over *Z* directions for *C* = 200 KN s/m **a** displacement, **b** rotation
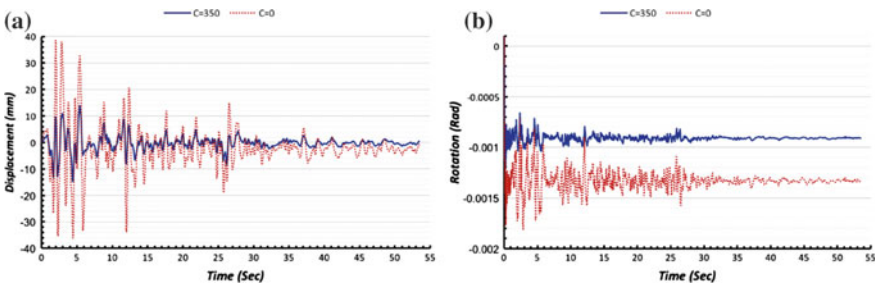

Fig. 12 Induced displacement and rotation versus time in *X* and over *Z* directions for *C* = 350 KN s/m **a** displacement, **b** rotation

confirming the efficiency of VWD device regarding the decrease in structural displacement amplitude and rotation.

4.2 Plastic Hinge Formation Criterion

This criterion studies the number of structural members undergone a plastic hinge, i.e., a failure due to the earthquake excitation.

Figure 13 exhibits the number of sections which experienced a plastic hinge (as distinct structural members) as well as the total number of induced plastic hinges (as summation of all plastic hinges) in all structural members during the excitation while VWD devices with distinctive characteristics of damping coefficient were mounted.

According to Fig. 13, increasing damping coefficient decreases the number of sections experiencing a plastic hinge from 24 in the unreinforced frame to 20 in the frame enhanced by a 20 KN s/m VWD, while further increase in damping coefficient to 40 KN s/m leads to a higher number of sections endured plastic hinge. As the damping coefficient rises to 200 KN s/m, the graph represents a descending
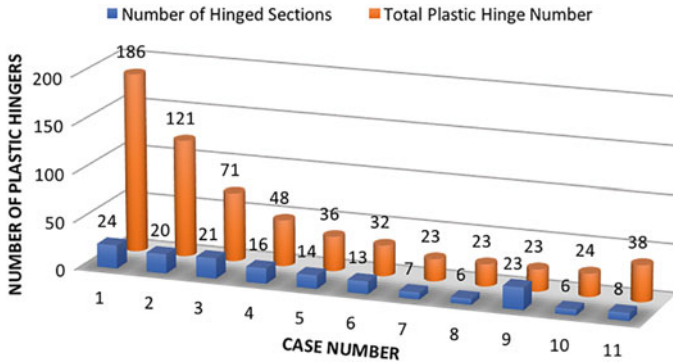
Fig. 13 Number of distanced hinged members and summation of all plastic hinge formations for different cases

trend reaching to a minimum of 6 hinged sections, which shows a 75% decrease in comparison with the case 1. Afterwards, a sudden surge in the number of hinged sections is recorded at $C = 250$ KN s/m. The graph ends up by a fluctuation at higher damping coefficients.

Similarly, the total number of plastic hinges signifies a sloping trend from 186 at case 1 leading to a constant value of 23 at the damping coefficients of 150, 200, 250 KN s/m. Ultimately, an escalating trend in the total number of plastic hinges is seen reaching to 38 at $C = 350$ KN s/m.

In nutshell, VWD devices with low values of damping coefficient show almost no significant improvement in the seismic behavior of the structure. This might be in accordance with an increase in the weight of the structure due to implementing VWD devices. However, higher values of damping coefficient improve performance and efficiency of VWD devices in diminishing induced forces due to seismic excitations.

4.3   Induced Column Forces

As identified in Fig. 14, a corner column has been selected to investigate the effectiveness of adopting VWD devices in dissipating induced column forces, including axial force, bending moment, and shear force.

Figures 15, 16, and 17 illustrate the efficiency of supplemental VWD devices with different damping coefficients in terms of diminishing imposed axial force, bending moment, and shear force, respectively.

According to Fig. 15, it can explicitly be outlined that low values of damping coefficient not only does not moderate the induced axial force, but also may magnify the axial force in some circumstances. However, higher values of damping coefficient lead to a sliding trend in induced axial force, although with little absolute impacts.
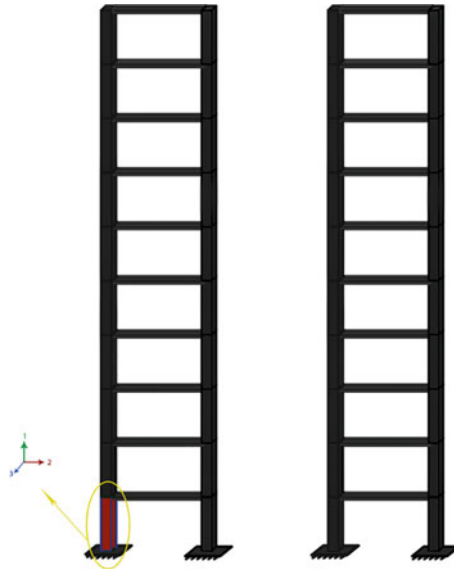
Fig. 14 The considered column of the structure and local coordinate system
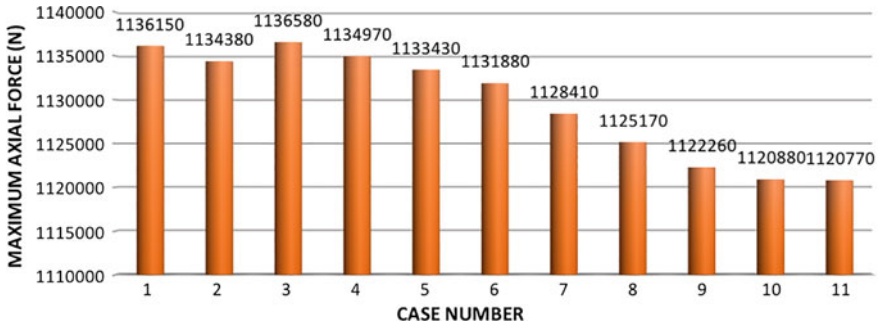

Fig. 15 Induced axial force of the specified column in each case

Considering the impacts on bending moment, Fig. 16 demonstrates a gentle descending trend with a plateau at higher values of damping coefficient. The same trend applies to the impacts of VWD devices on induced shear force. However, the slopping rate proceeds swiftly prior to the plateau bot with lesser positive absolute impacts, as seen in Fig. 17.
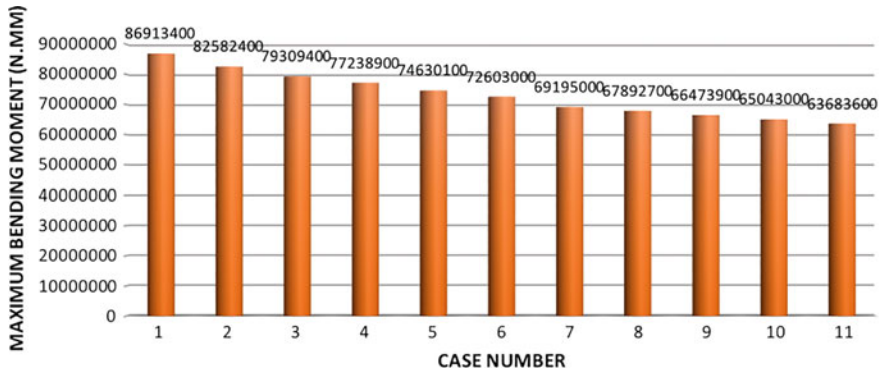
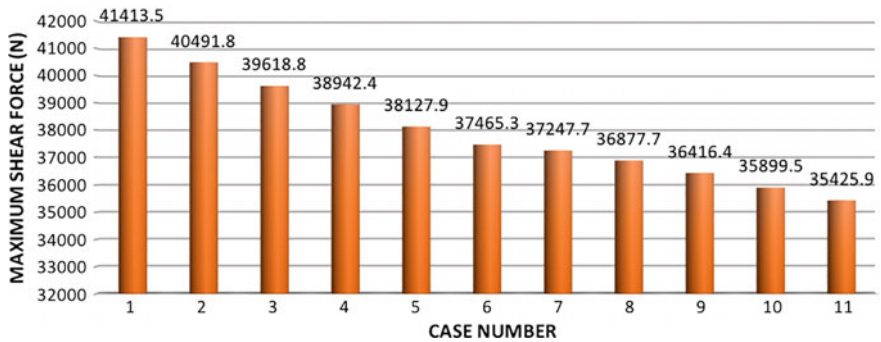**Fig. 16** Induced bending moment of the specified column in each case

Fig. 17 Induced shear force of the specified column in each case

4.4 Overall Performance of VWD Device

Table 3 includes detailed performance index for response of the structures in all defined cases. In addition, an average of reduction for each case is presented based on displacement, rotation, plastic hinge formation, and element forces results. The average of reduction is taken into account as an overall performance of Viscous Wall Damper device.

As tabulated in Table 3, VWD devices with low values of damping coefficient, rolling as connector devices, have partial impacts on the seismic behavior of two adjacent structures. Therefore, higher rates of displacement, rotation, plastic hinge occurrence, and induced element forced are resulted. This mostly applies to VWD devices wither a damping coefficient lower than 60 KN s/m.

Conversely, VWD devices with damping coefficients higher than 60 KN s/m appear to be more impactful in diminishing the seismic behavior of two adjacent structures. Among 11 test cases, the ones with damping coefficients of 200 and

Table 3 Overall performance of Viscous Wall Damper device

Damping coefficient (KN s/m)	Displacement reduction in X direction (%)	Rotation reduction in X direction (%)	Section plastic hinge reduction (%)	Total plastic hinge reduction (%)	Axial force reduction (%)	Bending moment reduction (%)	Shear force reduction (%)	Average of reductions
0	0	0	0	0	0	0	0	0
20	10	−8	17	35	0	5	2	9
40	17	8	13	62	0	9	4	16
60	24	14	33	74	0	11	6	23
80	29	20	42	81	0	14	8	28
100	33	23	46	83	0	16	10	30
150	42	24	71	88	1	20	10	37
200	49	23	75	88	1	22	11	39
250	55	24	4	88	1	24	12	30
300	59	23	75	87	1	25	13	40
350	62	16	67	80	1	27	14	38

300 KN s/m present the most dissipating attribute in terms of seismic responses with average reduction rates of 39 and 40%, respectively.

Table 3 enables determining an optimum option in designing a connector VWD device between two adjacent structures, based on a given metric index, in order to mitigate seismic responses.

5   Conclusion

This study investigates the effectiveness of implementing supplemental Viscous Wall Damper devices to link a couple of adjacent structures in order to relieve seismic responses. Hence, a time history nonlinear analysis of two adjacent ten-story structures excited by a ground motion has been conducted.

The outcomes suggest that connecting adjacent structures with VWD devices lead to a noticeable reduction of seismic responses, including displacement amplitude, rotation, plastic hinge, and induced element forces. Moreover, the correlation between damping coefficient of VWD devices and dissipated seismic energy indicates a direct relationship with two exceptions. The first exception is a fluctuation in seismic responses corresponding with VWD devices with low values of damping coefficient. This might be a result of an increase in structural weight due to implementing VWD devices leading to more seismic demands, which cannot be overcome by little positive impact of VWD devices with low damping coefficient. The second exception occurs while damping coefficient rises so high, where improvements on seismic behavior deteriorate. This might be a result of an over damping circumstance triggered by the higher values of damping coefficient.

Apart from the exceptions, all seven metrics (displacement, rotation, section plastic hinge, total plastic hinge, axial force, bending moment, and shear force) indicate a downward trend. The trends relating to total plastic hinge, bending moment, and shear force relatively drop more swiftly comparing with other trends, which experience gentle cutbacks.

In perspective, employing VWD devices in connecting two adjacent structures successfully diminish earthquake actions and improve seismic behavior of the structure.

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