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POUNDING HAZARD REDUCTION USING A COUPLING STRATEGY FOR ADJACENT BUILDINGS

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Abstract

Buildings' pounding is described as the collision between adjacent buildings resulting from certain excitations, and more specifically seismic excitations. Avoiding pounding is a significant challenge especially in metropolitan areas where these buildings are built very close to each other, and where the coast of land is very high. This work aims to reduce the risk of pounding between two adjacent buildings by using a coupling strategy of two adjacent structures with a passive damper used in the control of seismic vibrations. Adopting a coupling strategy allows to transform the two separated structures into one system coupled by a damping device, which result in a synchronised vibrating mode between the two coupled structures. Because of coupling, the structures move in the same direction during the earthquake, this will avoid any unsynchronised vibrations that can cause a potential pounding hazard situation. This can be achieved by using a passive damping device. In this study, two structural configurations presenting a high pounding risk are investigated for this study. It has been found that chances of pounding are reduced along with a reduction regarding top floor displacement. In addition, it has been also observed that the use of a single damping system at the top floor reduces responses and avoids pounding of adjacent buildings.

Keywords: Pounding; adjacent buildings; seismic excitation; coupling buildings; passive control.

1. Introduction

During the past, major earthquakes around the world have caused a large range of damages in civil engineering structures, which reveal the importance of structural control systems for seismic hazard mitigation. Several after effects occur during strong earthquakes. Usually, they are more dangerous and destructive in nature than the earthquake itself. In a cluster of buildings the mutual impacts between adjacent buildings known as pounding or hammering is an after effect phenomenon of strong earthquakes, this has been observed during Mexico City earthquake, 1985, Loma Prieta earthquake, 1989, Kobe earthquake, 1995, and recently Christchurch earthquake, 2011.

This phenomenon has caused several damages to adjacent buildings, especially in metropolitan areas where the buildings are of varying heights and built very close to each other due to the high cost of land and the presence of existing buildings, hence, different dynamics properties and narrow separation gap are created, which induce unsynchronised vibrations and probably mutual impacts between those buildings. Although the codes provide guidelines for sufficient seismic gap to avoiding pounding effects, in realty, they are exists many instances where the gap between two buildings is not adequate to avoid pounding, especially when new building are built next to existing buildings, further minimum gaps just provided for adjacent buildings according to codes may not be sufficient in the long run because of the aging of the structures. Important pounding effects has been realised after Mexico City earthquake; in 1986, Bertero [1] published a report, in which he distinguishes several structural arrangements presenting a high pounding risk, more than 15% of the collapsed buildings during Mexico City earthquake were exposed to important mutual impacts. Anagnostopoulos [2] used a simplified model of multiple structures to study the pounding effect. Considerable damages were observed and even some collapse cases were attributed to pounding, the insufficiency of seismic gap was pointed as one of the main causes of pounding. During Loma Prieta earthquake, more than 200 cases of pounding were observed by Kasai et al. [3]. After Kobe earthquake in 1995, Comartin [4] published a report in which multiple pounding cases especially between buildings constructed in series were noted. A multitude of poundings cases were also observed by Cole et al. [5] during the recent Christchurch earthquake, 2011. Naserkhaki et al. [6] studied the occurrence of pounding between adjacent buildings under based fixed condition and soil-structures interaction condition, in the both cases the seismic response was amplified after the pounding. Zhai et al. [7] investigated the pounding between inelastic multi degrees of freedom building using a dimensional analysis. Jeng, Tzeng [8] determined six possible situations of pounding hazard, after observing the recent mutual impact during the last earthquakes and recommended to avoid those situations if it is possible. Dogan, Gunaydin [9] studied the pounding causes and concluded that the unsynchronised vibration between adjacent buildings is the main reason for mutual impact occurrence. The unsynchronised vibration can be caused by the difference in dynamics characteristics between two adjacent buildings, which are closely related to the mass, rigidity and stiffness of each building. Mate et al. [10] investigated the pounding between adjacent buildings and proposed a various pounding mechanisms.

One of the novel solutions for building response reduction is the coupling of adjacent building. Coupling adjacent buildings with damping devices is a convenient and effective means to reduce building response. Significant researches have been conducted on this area in recent years, and various approaches were proposed by different researchers for coupling adjacent buildings. Kobori et al. [11] proposed bell-shaped hollow connectors to link two adjacent buildings to reduce the pounding hazard. Westermo [12] suggested an articulated link to connect two adjacent building to avoid pounding. Seto [13] has shown that coupling adjacent structure is a viable alternative for the protection of adjacent flexible structures. Zhang, Xu [14] demonstrated the effectiveness of discrete viscoelastic dampers as coupling device connecting adjacent buildings. Zhu, Xu [15] determined optimum parameters of Maxwell model by deriving analytical formulae and defined fluid dampers to link two adjacent structures using the principle of the average vibration energy of either the primary structure or the two adjacent structures under white noise ground excitation. This technique has been proven once with evidence of experimental results for the coupled buildings. For example: the Kajima Intelligent (KI) Building complex in Tokyo, Japan. This complex coupled the five- and nine-story structures in a low-rise office complex with passive yielding elements connected at the 5th floor. The Triton Square office complex, the complex is a cluster of three buildings, 155, 175, and 195 m tall. The 155 and 175 m tall buildings are coupled at a height of

136 m. The 175 and 195 m tall buildings are coupled at a height of 160 m. The three buildings are coupled with two 35 t active control actuators for wind and seismic protection [16]. Bigdeli et al. [17] studied the optimal passive damper location between adjacent building using genetic algorithm, many parameters were investigated, but no pounding occurrence or reduction was mentioned or studied. Naserkhaki et al. [18] investigated the pounding reduction between adjacent buildings connected with passive-dampers. The buildings studied were having different mass distributions.

In this study, the efficiency of coupling strategy using only a single MR damper as passive device at the top floor is examined for pounding reduction between adjacent buildings. The principal aim of this work is to avoid pounding between adjacent buildings, including ten floors each but having different dynamics characteristics. Two structural dispositions will be investigated. The performance of the coupled system is compared under two control strategies, passive-off where a 'zero' voltage will be applied to the damper and passive-on where different finite voltages will be applied to the damper. Besides the pounding hazard mitigation, a response reduction is obtained regarding the displacement, inter-storey drift and acceleration for the coupled buildings investigated in this study.

2. Dynamic modeling of connected system

The governing motion equation of the coupled system shown in Fig.1 is expressed as:

$$[M]\{\ddot{x}\}+[C_d]\{\dot{x}\}+[K]\{x\}=[\Gamma]\{f_m\}-[M][r]\{\ddot{x}_g\} \tag{1}$$

where, M, K, C, are mass, stiffness and damping matrix of the coupled system, f_m is the vector of the input force produced by the MR damper; Γ is the damper location matrix; r is an influence coefficient vector which contains elements equal to unity; $\ddot{x}_g$ is the ground acceleration and $\ddot{x}, \dot{x}$ and x are respectively the system acceleration, velocity and displacement vectors.

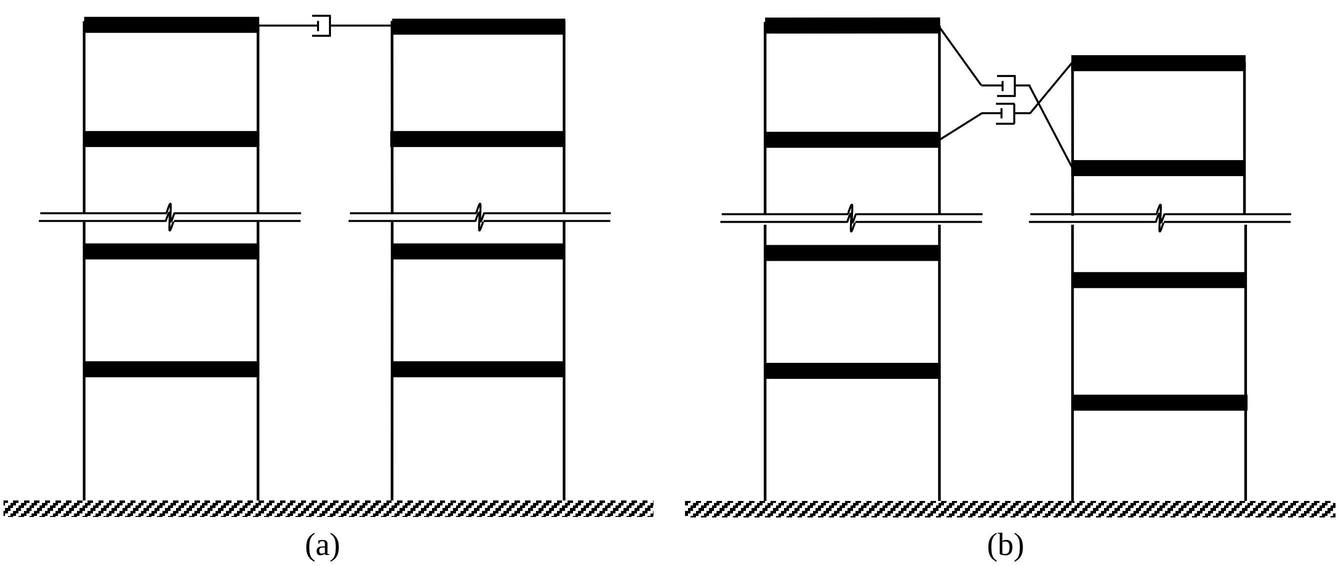

Fig.1 - Structural disposition studied (a) adjacent buildings with same floor level (b) adjacent building with different floor level.

The matrices M, K, and C for the coupled system are explicitly defined as follow.

$$M=\begin{bmatrix}[M_1] & [O_1]\\ [O_2] & [M_2]\end{bmatrix} \tag{2}$$

$$K = \begin{bmatrix} [K_1] & [O_1] \\ [O_2] & [K_2] \end{bmatrix} \tag{3}$$

$$C_d = \begin{bmatrix} [C_1] & [O_1] \\ [O_2] & [C_2] \end{bmatrix} \tag{4}$$

where $[M_1]$ and $[M_2]$ are the separated mass matrices for building 1 and 2, respectively. Similarly $[K_1]$, $[K_2]$ and $[C_1]$, $[C_2]$ are the stiffness and damping matrices, $[O_1]$ and $[O_2]$ are the null matrices of the buildings 1 and 2 respectively.

The governing Equation (1) can be written in state-space form as:

$$\{\dot{z}\} = [A]\{z\} + [B]\{u\} \tag{5}$$

$$\{y\} = [C]\{z\} + [D]\{u\} \tag{6}$$

where:

$$A = \begin{bmatrix} -M^{-1}C_d & -M^{-1}K \\ E & 0 \end{bmatrix} \tag{7}$$

$$B = \begin{bmatrix} M^{-1}\Gamma & -E \\ 0 & 0 \end{bmatrix} \tag{8}$$

$$C = [E] \tag{9}$$

$$D = [0] \tag{10}$$

where, [E] and [0] are, respectively, identity and zeros matrices of convenient sizes. The vectors z and u in this case are:

$$z = \begin{bmatrix} \dot{x} \\ x \end{bmatrix} \tag{11}$$

$$u = \begin{bmatrix} f \\ \ddot{x}_g \end{bmatrix} \tag{12}$$

2.1. Dynamic model of MR damper

In this study, phenomenological model proposed by Jr et al. [19] is used to simulate the dynamic behaviour of MR damper based on the Bouc-Wen modified model, the equations governing the force predicted by this model are:

$$f = c_1\dot{y} + k_1(x - x_0) \tag{13}$$

$$\dot{y} = \frac{1}{(c_1 + c_0)} + (\alpha z + c_0\dot{x} + k_0(x - y)) \tag{14}$$

$$\dot{z} = -\gamma|\dot{x} - \dot{y}|z|z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}) \tag{15}$$

$$\alpha = \alpha_a + \alpha_b u \tag{16}$$

$$c_1 = c_{1a} + c_{1b}u \tag{17}$$

$$c_0 = c_{0a} + c_{0b}u \tag{18}$$

$$\dot{u} = -\eta(u - v) \tag{19}$$

In equations (13-18), the accumulator stiffness is represented by k_1; the viscous damping observed at large and low velocities is represented by c_0 and c_1, respectively; k_0 is present to control the stiffness at large velocities; and x_0 is the initial displacement of spring k_1 associated with the nominal damper force due to the accumulator; γ ; β and A are hysteresis parameters for the yield element; α is the evolutionary coefficient. Equation (19) represents a first order filter used to simulate rheological equilibrium and driving the electromagnet in the MR damper, where the force is dependent on the voltage applied to the current driver in equations (16-18).

A total of 14 model parameters are obtained to characterize the prototype MR damper using experimental data and a constrained nonlinear optimization algorithm. The resulting parameters are given in Table 1 Spencer Jr et al. [20].

Table 1 - Characterisation parameters for the MR damper

Parameter	Value [Unit]	Parameter	Value [Unit]
c_{0a}	50.30 [kN.sec/m]	α_a	8.70 [kN/m]
c_{0b}	48.70 [kN.sec/m.V]	α_b	6.40 [kN/m.V]
k_0	0.0054 [kN/m]	γ	496 [m^{-2}]
c_{1a}	8106.2 [kN.sec/m]	β	496 [m^{-2}]
c_{1b}	7807.9 [kN.sec/m.V]	A	810.50
k_1	0.0087 [kN/m]	n	2
x_0	0.18 [m]	η	190 [sec^{-1}]

In this study the MR damper equations where reproduced in a MATLAB Simulink model to simulate the behaviour of this device, based on the equations given above. Note that the control forces generated by the damper are similar to passive system with either applied zero voltage or a finite voltage.

3. Numerical study

For the purpose of this study, two shear buildings are modelled adjacent to each other. The structural configurations of the buildings modelled are so selected, that they present a high risk of pounding (Fig. 1). The different cases modelled are:

- Case (a): Two buildings of same height with different structural parameters.
- Case (b): Two buildings with different floor heights having different structural parameters.

Tables 2-3 describe the structural parameters for different cases (mass, stiffness and first naturel frequency).

Table 2 - Structural parameters for Case (a).

Building (1)			Building (2)		
m [t]	k [kN/m]	1st ω_n [Hz]	m [t]	k [kN/m]	1st ω_n [Hz]
100	161×10^3	0.95	25	80.5×10^3	1.34

Table 3 - Structural parameters for Case (b).

Building (1)			Building (2)		
m [t]	k [kN/m]	1st ω_n [Hz]	m [t]	k [kN/m]	1st ω_n [Hz]
100	161×10^3	0.95	25	112.7×10^3	1.59

The mass and stiffness are equally distributed to all the floor for both buildings in both studied cases, a 5% damping is considered and calculated using Rayleigh damping [21].

Buildings are subjected to El Centro, 1940 and Kocaeli, 1999 earthquakes, with a maximum acceleration of 0.3*g* and 0.6*g*, respectively. Top floor displacements of building (1) and building (2) are compared by superposition, to determine the possibility of pounding. After that, a damping system is placed between the two adjacent buildings. A single MR damper is placed on the top floor of the adjacent buildings for case (a) as shown in Fig.1.a. For the case (b) a cross fram damping configuration is adopted since the adjacent building are having different floor heights is the particular case two MR dampers will be used as shown in Fig.1.b. The results of coupling strategy are obtained for passive control strategies, and are compared. For passive control two conditions are analysed. The passive off condition is one in which the voltage is fixed to ‘zero’ volts, while in case of a passive-on condition, a fixed voltage is applied at all times. In passive-on condition, three cases are studied, having different values of constant voltage of 3V, 6V and 9V.

3.1 Pounding hazard localisation

Different buildings built adjacent to each other may pound against each other in case of earthquakes. The possibility of pounding depends upon two factors namely unsynchronized vibrations of two adjacent buildings and evolution of the gap provided between them. A minimum gap is required in order to avoid pounding between two adjacent buildings. Under strong earthquakes, the original gap provided between adjacent buildings could become insufficient for avoiding pounding.

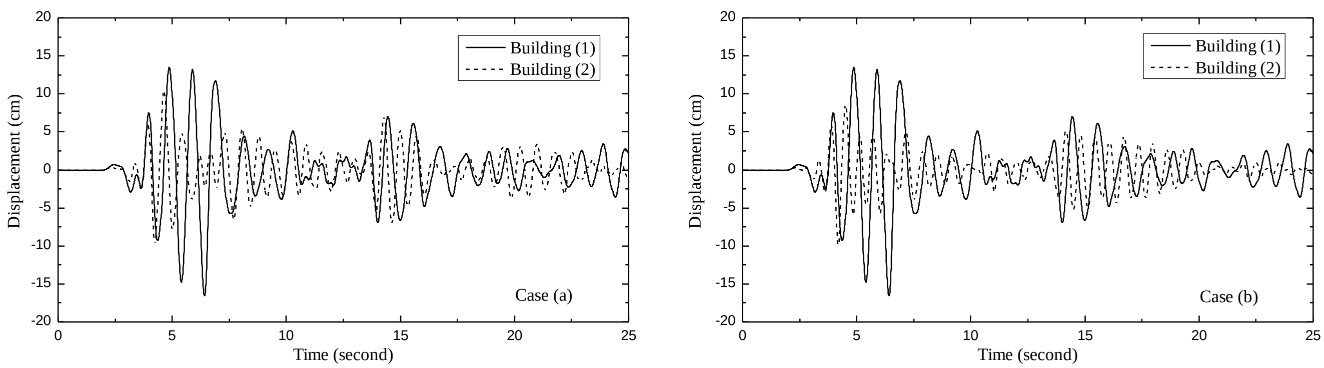

Fig. 2 - top floor displacement of building (1) and (2) under El Centro earthquake.

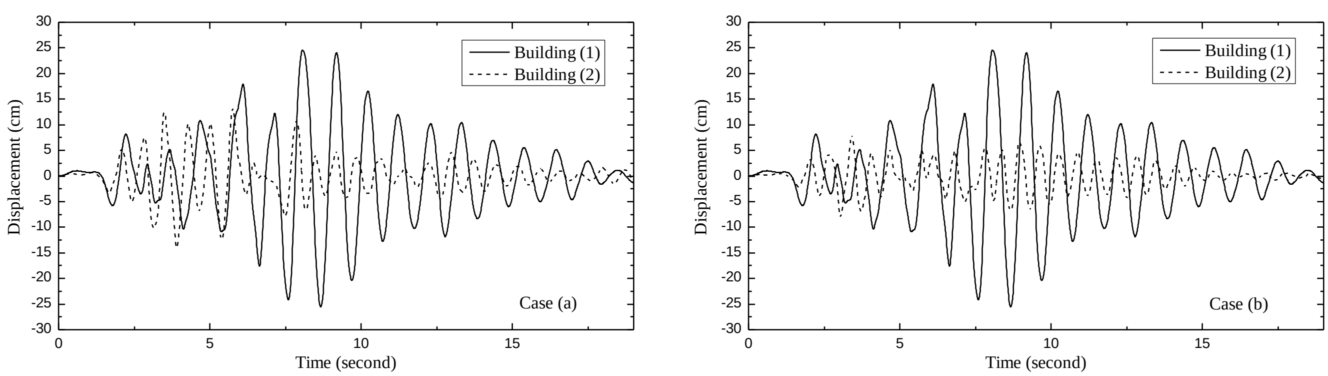

Fig. 3 – top floor displacement of building (1) and (2) under Kocaeli earthquake.

Figures 2 and 3, shows the time histories of top floor displacement of uncoupled buildings (1) and (2) under El Centro and Kocaeli earthquakes, respectively. It can be clearly seen in the figures that vibrations of the uncoupled buildings are non-synchronous for both studied cases. As a consequence the two buildings can pound against each other if the minimum gap provided is less than that required. It can also be observed that unsynchronized vibrations can be observed at large or small displacements.

3.2 Pounding hazard control

The adjacent buildings were coupled at the top floor using MR dampers. One of the advantages of MR damper is its capacity to adopt multiple damping values. The top floor location of the damper is motivated by the fact the larger displacements occur at this level, thus high risk of pounding is expected at this level. The primary aim of coupling buildings in this study is to reduce the pounding. That includes the elimination of unsynchronized vibrations (Figs. 4 and 5) and the minimum gap reduction (Tables 4 and 5).

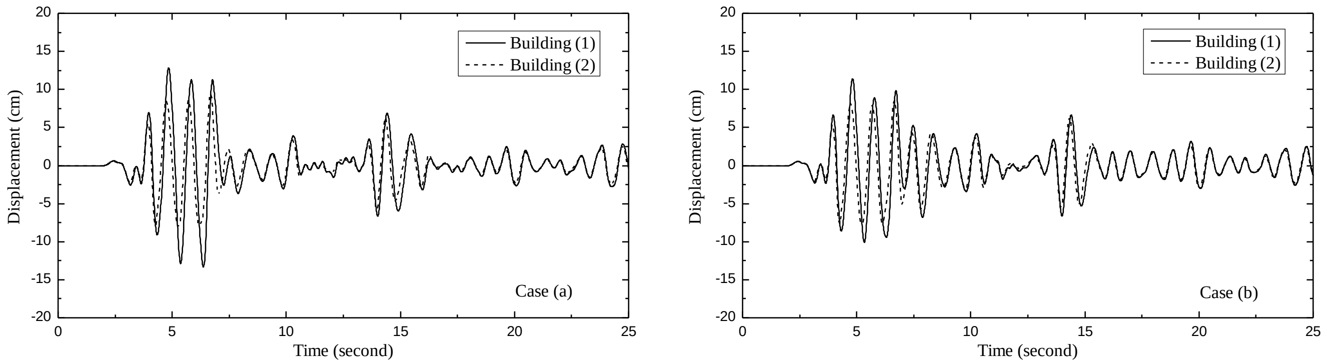

Fig. 4 – Top floor displacement of building (1) and (2) coupled with MR damper under El Centro earthquake

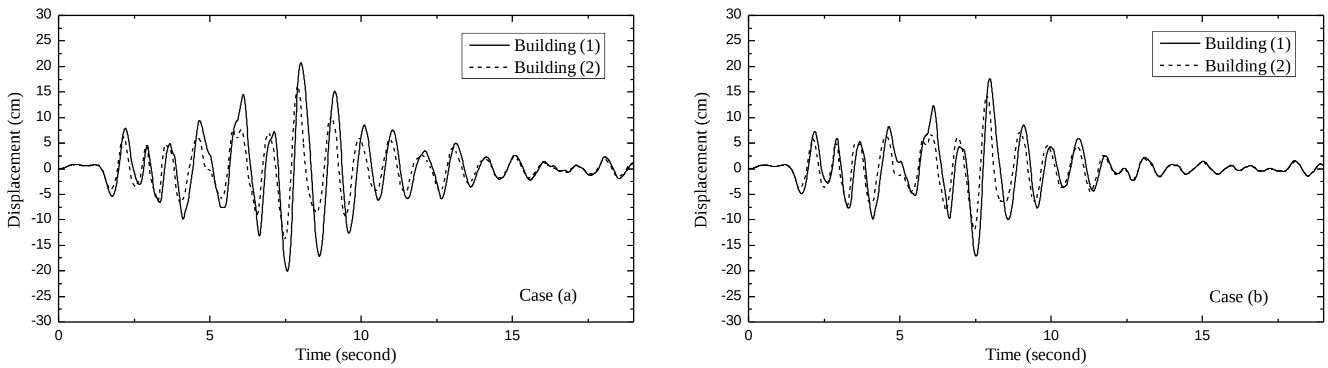

Fig. 5 – Top floor displacement of building (1) and (2) coupled with MR damper under Kocaeli earthquake

It can be clearly observed from Figures. 4 and 5, that the performance of the coupling strategy regarding the unsynchronized vibrations reduction is effective, for both El Centro and Kocaeli earthquakes. It can be seen that the top floor displacement of building (1) and building (2) are totally synchronized, thus avoiding pounding hazard between adjacent buildings. The results presented are obtained using passive-on controller with a 9V applied voltage and they demonstrate the effectiveness of the coupling strategy for pounding mitigation.

Table 4 - The minimum gap (cm) required to avoid pounding under El Centro earthquake.

Earthquake	Case	Uncoupled	Passive-Off	Passive-on		
				3V	6V	9V
El Centro, 1940	(a)	19.50	16.85	12.17	10.45	09.14
	(b)	17.83	13.86	09.16	07.23	05.75

Table 5 - The minimum gap (cm) required to avoid pounding under Kocaeli earthquake.

Earthquake	Case	Uncoupled	Passive-Off	Passive-on		
				3V	6V	9V
Kocaeli, 1999	(a)	25.32	22.27	18.84	15.70	13.30
	(b)	25.75	21.20	15.94	12.65	10.61

Tables 4 and 5 show the minimum gap required between adjacent buildings to avoid pounding. The results are obtained two passive control strategies. It can be observed from the tables that coupling two adjacent buildings with damping devices at the top floor can be effective in reducing the minimum gap. The maximum reduction in the gap is obtained using a passive-on (9V). For El Centro earthquake maximum reductions are 53.1% and 67.7% for cases (a) and (b), respectively. For Kocaeli earthquake maximum reductions are 47.7% and 58.7% for cases (a) and (b), respectively.

3.3 Dynamic performance of the coupled structures

After the investigation of performance of coupling strategy in reducing the pounding hazard, dynamic performances of coupled buildings are observed in terms of top floor displacement. Tables 6-7 show the top floor displacement of building (1) and (2) under different control strategies for both cases considered.

Table 6 - Top floor displacement (cm) of buildings (1) and (2) under El Centrol earthquake.

Earthquake	Case	Buildings	Uncoupled	Passive-Off	Passive-on		
					3V	6V	9V
El Centro, 1940	(a)	(1)	16.54	15.59	14.05	13.44	13.31
		(2)	10.43	09.73	08.65	08.17	09.42
	(b)	(1)	16.54	14.36	11.56	11.35	11.38
		(2)	09.89	06.94	05.96	07.65	08.59

Table 6 - Top floor displacement (cm) of buildings (1) and (2) under Kocaeli earthquake.

Earthquake	Case	Buildings	Uncoupled	Passive-Off	Passive-on		
					3V	6V	9V
Kocaeli, 1999	(a)	(1)	25.54	23.81	21.66	20.90	20.76
		(2)	13.99	11.93	13.26	14.83	16.20
	(b)	(1)	25.54	21.90	18.24	17.52	17.11
		(2)	08.16	07.43	10.72	12.72	14.41

From Tables 6 and 7, it can be noted that, in most of the cases, response reduction can be obtained. However, the percentage reduction is not significant. This may be attributed to the use of only one damping system at the top floor level. In the overall analysis, applying a high voltage may induce a response increase in the coupled system. This underscore the importance of semi-active controllers, which can provide variable stiffness and force at each time step, thus avoiding the response increase of the connected building, a reactive control system is very important in such cases.

3.4 Performance of MR damper as a passive device

The performance of the MR damper will be examined under two strategies (passive-on, passive-off). Table 7 and 8 show the peak damper force under different control strategies for El Centro and Kocaeli earthquakes, respictevely. As expected more the voltage is raised more the peak damper force is high.

Table 7 - Peak damper force (kN) under different control strategies under El Centro earthquake.

Earthquake	Case	Damper number	Passive-Off	Passive-on		
				3V	6V	9V
El Centro, 1940	Case (a)	(1)	68.17	194.02	285.79	363.48
	Case (b)	(1)	67.12	167.62	228.29	280.77
		(2)	68.71	176.24	235.86	288.70

Table 8 - Peak damper force (kN) under different control strategies under Kocaeli earthquake.

Earthquake	Case	Damper number	Passive-Off	Passive-on		
				3V	6V	9V
Kocaeli, 1999	Case (a)	(1)	98.75	304.17	440.68	540.04
	Case (b)	(1)	94.62	278.90	385.40	454.98
		(2)	96.97	285.23	394.82	467.86

Figures 5 and 6 show the hysteretic behaviour of the MR damper while driven by different control strategies for the studied case (a), and this under El Centro and Kocaeli earthquakes, respectively. Case (a) was used to generate the hysteresis graphs of the MR damper.

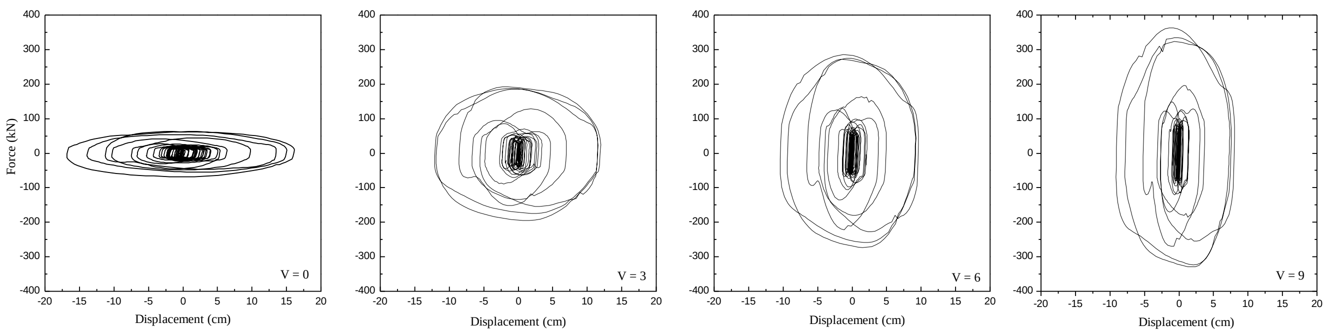

Fig.5 – Hysteresis behaviour of the damper under El Centro earthquake, for case (a).

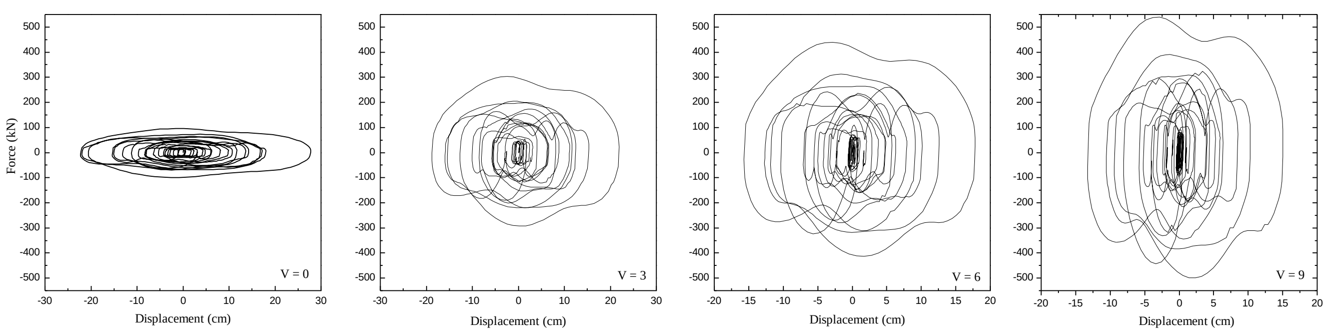

Fig.6 – Hysteresis behaviour of the damper under Kocaeli earthquake, for case (a).

Form fig. 5 and 6, it is clear that more energy is dissipated by the damper when high voltage is applied to it. Higher voltage induces more force and less relative displacement which results in a reduction of the separation gap between the two connected structures. The large damper force can be obtained by manipulating the applied voltage and the damper proprieties.

The maximum order of force to be transferred by MR damper is 567.86 kN (Table 8) for the maximum voltage applied in case (b). This force can be transmitted to the structure through proper fastening and anchorage, designed to carry the demand forces.

4. Conclusion

The effectiveness of coupling two adjacent buildings for pounding hazard mitigation using a single damping system was investigated for two different cases. Two control strategies were used. It can be observed that the coupling strategy is very effective regarding responses synchronization of coupled systems and reduction of the minimum gap required, thus, avoiding pounding between adjacent buildings; especially. Results of the numerical study lead to the following conclusions:

1. The coupling strategy is effective in pounding hazard mitigation. This can be observed in terms of minimum gap reduction and response synchronization between adjacent buildings for almost all studied cases.

2. Using only one damping system on the top floor of adjacent buildings can result in total response synchronizations between adjacent buildings, avoiding any potential pounding situations.

3. Coupling two adjacent buildings on the top floor with only one damper can results in a response reduction in terms of displacement if the appropriate voltage is applied to the damper.

4. A comparison between two control strategies namely, passive-off, passive-on, indicates that in overall analysis passive-on strategy is the most effective option.

5. A semi-active control applied on the MR damper will result in a better optimisation of damper force used, thus, avoiding the response increase of the coupled system due to high forces transferred to the structures.

References

[1] Bertero VV (1987): Observations on structural pounding. In: *The Mexico Earthquakes—1985 Factors Involved and Lessons Learned*. ASCE, pp 264-278

[2] Anagnostopoulos SA (1988): Pounding of buildings in series during earthquakes. *Earthquake Engineering & Structural Dynamics*, **16** (3):443-456

[3] Kasai K, Jeng V, Patel P, Munshi J, Maison B (1992): Seismic pounding effects-survey and analysis. In: *Proc. Earthquake Engrg. 10th World Conf*. pp 19-24

[4] Comartin CD, Greene, M. and Tubbesing, S.K (1995): The Hyogo-Ken Nanbu Earthquake. *Earthque Engineering Research Institute,*

[5] Cole GL, Dhakal RP, Turner FM (2012): Building pounding damage observed in the 2011 Christchurch earthquake. *Earthquake Engineering & Structural Dynamics*, **41** (5):893-913

[6] Naserkhaki S, Aziz FNA, Pourmohammad H (2012): Earthquake induced pounding between adjacent buildings considering soil-structure interaction. *Earthquake Engineering and Engineering Vibration,* **11** (3):343-358

[7] Zhai C, Jiang S, Li S, Xie L (2015): Dimensional analysis of earthquake-induced pounding between adjacent inelastic MDOF buildings. *Earthquake Engineering and Engineering Vibration,* **14** (2):295-313

[8] Jeng V, Tzeng W (2000): Assessment of seismic pounding hazard for Taipei City. *Engineering Structures*, **22** (5):459-471

[9] Dogan M, Gunaydin A (2009): Pounding of adjacent RC buildings during seismic loads. *Journal of Engineering and Architecture Faculty of Eskişehir Osmangazi University,* **22** (1),

[10] Mate NU, Bakre S, Jaiswal O (2015): Seismic pounding of adjacent linear elastic buildings with various contact mechanisms for impact simulation. *Asian Journal of Civil Engineering (BHRC),* **16** (3):383-415

[11] Kobori T, Yamada T, Takenaka Y, Maeda Y, Nishimura I (1988): Effect of dynamic tuned connector on reduction of seismic response-application to adjacent office buildings. In: *Proceedings of the 9th world conference on earthquake engineering*. pp 773-778

[12] Westermo BD (1989): The dynamics of interstructural connection to prevent pounding. *Earthquake Engineering & Structural Dynamics*, **18** (5):687-699

[13] Seto K (1994): Vibration control method for flexible structures arranged in parallel. In: *Proc. First World Conference on Structural Control*.

[14] Zhang W, Xu Y (1999): Dynamic characteristics and seismic response of adjacent buildings linked by discrete dampers. *Earthquake Engineering & Structural Dynamics*, **28** (10):1163-1185

[15] Zhu H, Xu Y (2005): Optimum parameters of Maxwell model-defined dampers used to link adjacent structures. *Journal of Sound and Vibration,* **279** (1):253-274

[16] Christenson RE, Spencer Jr B, Johnson EA, Seto K (2006): Coupled building control considering the effects of building/connector configuration. *Journal of Structural Engineering*, **132** (6):853-863

[17] Bigdeli K, Hare W, Tesfamariam S (2012): Configuration optimization of dampers for adjacent buildings under seismic excitations. *Engineering Optimization*, **44** (12):1491-1509

[18] Naserkhaki S, Daneshvar-Ghorbani S, Tayyebi-Tolloei D (2013): Heavier adjacent building pounding due to earthquake excitation. *Asian Journal of Civil Engineering (BHRC),* (2):14

[19] Jr BS, Dyke S, Sain M, Carlson J (1997): Phenomenological model for magnetorheological dampers. *Journal of engineering mechanics*, **123** (3):230-238

[20] Spencer Jr B, Dyke S, Sain M, Carlson J (1997): Phenomenological model for magnetorheological dampers. *Journal of engineering mechanics*,

[21] Hart GC, Wong KKF (2000): *Structural dynamics for structural engineers*. Wiley.