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REDUCTION OF POUNDING BETWEEN BUILDINGS USING FUZZY CONTROLLER

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ABSTRACT

In this study, a fuzzy logic controller is employed to synchronize the response of two adjacent buildings coupled with a magneto-rheological (MR) damper and also, to reduce the minimum separation gap required, thus avoiding pounding hazard between adjacent buildings. Adopting a coupling strategy allows us to transform two separated structures into one system coupled by a damping device, which results in a synchronised vibrating mode between the coupled structures. A number of 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 and maximum drift. The use of fuzzy logic controller results in optimization of the damper force. In addition, it has been also observed that the use of a single damper at the top floor reduces responses and avoids pounding of adjacent buildings.

Keywords: Pounding; coupled buildings; seismic gap; fuzzy logic controller; on-off controller; magneto-rheological (MR) damper.

1. INTRODUCTION

During the past, major earthquakes have caused a multitude of damages in civil engineering structures, around the world. In most of the major devastating earthquakes, the primary causes of destruction were not the earthquakes themselves, but the second order effects. One of the major second order effects of an earthquake is pounding or hammering of two adjacent structures. This phenomenon was observed during Mexico City earthquake, 1985, Loma Prieta earthquake, 1989, Kobe earthquake, 1995, and recently Christchurch earthquake, 2011.

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Many structures, especially those located in urban areas, were damaged due to mutual pounding; this can be attributed to difference in the dynamic properties of the structures along with a very small seismic gap between the structures [1]. When subjected to earthquake ground motion urban structures, located at a very short distance apart, undergo asynchronous vibrations and, thus, pound against each other. After the 1985 Mexico City earthquake, many cases of pounding between adjacent structures were reported. In a report published in 1987, Bertero [2] pointed out a number of arrangements of adjacent buildings, having a high risk of pounding. More than 15% of the buildings, which collapsed during Mexico City earthquake, were subjected to significant mutual impact. Anagnostopoulos [3] 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. During the Loma Prieta earthquake, more than 200 cases of pounding were observed by Kasai and Jeng [4]. After Kobe earthquake, Comartin [5] 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 and Dhakal [6] during the recent Christchurch earthquake in 2011.

Jeng and Tzeng [7] determined six possible situations reliable to pounding hazard, after observing the recent mutual impact during the last earthquakes and they recommended avoiding those situations if it is possible. Dogan and Gunaydin [8] investigated the pounding causes and concluded that the unsynchronized vibrations between adjacent buildings is the main reason for mutual impact occurrences. The unsynchronized vibrations can be caused by the difference in dynamics' characteristics between two adjacent buildings, which are closely related to the mass, rigidity and stiffness of every building. Naserkhaki and Aziz [9] examined the occurrence of pounding between adjacent buildings under based fixed condition and soil-structures interaction condition. In both cases, the seismic response was amplified after the pounding. Efraimiadou and Hatzigeorgiou [10] [11] studied the pounding between adjacent building under different structural arrangement and configuration, they also studied the effect of multiple earthquakes on pounding occurrence. Mate and Bakre [12] investigated the pounding between adjacent buildings and proposed a various pounding mechanisms.

Many solutions have been proposed to reduce the response of adjacent buildings. Coupling adjacent buildings with damping devices is a convenient and effective means to reduce building response. Significant research has been conducted on this area in recent years, and various approaches have been proposed by different researchers for coupling adjacent buildings. For example Kobori and Yamada [13] proposed bell-shaped hollow connectors to link two adjacent buildings to reduce the pounding hazard. Westermo [14] has suggested an articulated link to connect two adjacent buildings to avoid pounding. In addition Seto [15] has shown that coupling adjacent structure is a viable alternative for the protection of adjacent flexible structures. Zhang and Xu [16] have demonstrated the effectiveness of discrete viscoelastic dampers as a coupling device connecting adjacent buildings. Zhu and Xu [17] have determined the 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. Christenson and Spencer Jr [18] have examined the effectiveness of coupling adjacent building with different devices for low-rise and high-rise buildings. Bigdeli and Hare [19] 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 [20] investigated the pounding reduction between adjacent buildings connected with passive-dampers. The buildings studied were having different mass distributions.

In the previous studies, it was noticed that the proposed coupling devices were either passive or active. The passive coupling can be limited to a specific range of vibration modes. The active device needs an important external energy source and will be useless in case of power cut. This observation has motivated other researchers to use semi-active devices that have the advantage of combining passive and active characteristics. Those devices use a small energy source that can be supplied by a battery in order to avoid any problem of power cut. Bharti et al [21] used a MR damper to control the response of asymmetric single degree of freedom structures. The results obtained show the effectiveness of such devices in response reduction of asymmetric structures submitted to multiple earthquakes. Qu and Xu [22] observed that a magneto-rheological damper can be used to connect two adjacent buildings which can reduce the whipping effects and the response of connected buildings if the appropriate control algorithm is used. Xu and Chen [23] examined the effectiveness of MR damper through a scaled model a twelve floor building adjacent to a three floor building are connected with MR dampers. The results show that MR dampers with a multi-level logic control algorithm can reduce the seismic whipping effect and the seismic response of both the structures. Bharti et al [24] studied the performance of a coupling strategy using MR dampers between two adjacent buildings with different heights. They demonstrated that coupling two structures with MR damper can reduce the response significantly; they also studied the influence of the voltage induced in the damper and the damper location on the performance of the device. Motra and Mallik [25] demonstrated the efficiency of a coupling strategy between adjacent buildings in the response reduction. They coupled two buildings with different heights, five and three floors with MR damper on the top floor of the shortest building. A LQR-RNN control strategy was proposed to control the voltage induced in the MR damper. Shahidzade and Tarzi [26] highlighted the effect of coupling building of different heights with MR dampers. The results obtained demonstrate an important reduction regarding displacement and acceleration of the coupled buildings. Palacios et al [27] studied the seismic protection of multi-structure systems that combines inter-structure passive/semi-active damping elements. Two strategies were applied for two adjacent buildings, either coupled with passive devices or equipped separately with semi-actives devices; the pounding reduction was not discussed in this work. Kim and Kang [28] examined the coupling of two adjacent buildings with different frequencies. They reduced the displacement and acceleration. The pounding occurrence and evolution of the seismic gap or the synchronisation of response between the adjacent buildings were not investigated in the study.

All the research published on coupled buildings using semi-active devices focuses on response reduction of each building separately. None of the studies previously discussed examined the behaviour of the entire coupled system in terms of synchronized/unsynchronized vibrations or in terms of the evolution of the minimum separation gap, which is required to avoid mutual impact between the adjacent buildings. Also, none of the works investigated a probable case of pounding and its possible mitigation. In this paper, the efficiency of coupling strategy using only one MR damper 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. Different study cases with different structural configurations presenting a high risk of pounding are investigated. The results of a coupled system are compared with those of the uncoupled one. The performance of the coupled system is compared under four different control strategies namely: passive-off, passive on, semi-active on-off controller and fuzzy logic controller. It is important to note that the efficiency of fuzzy control using a semi-active MR damper has not been tested for reducing the pounding between two adjacent buildings. Besides the pounding hazard mitigation a response reduction is obtained regarding the displacement and maximum drift for the coupled buildings investigated in this study.

2. DYNAMIC MODELING OF COUPLED 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.

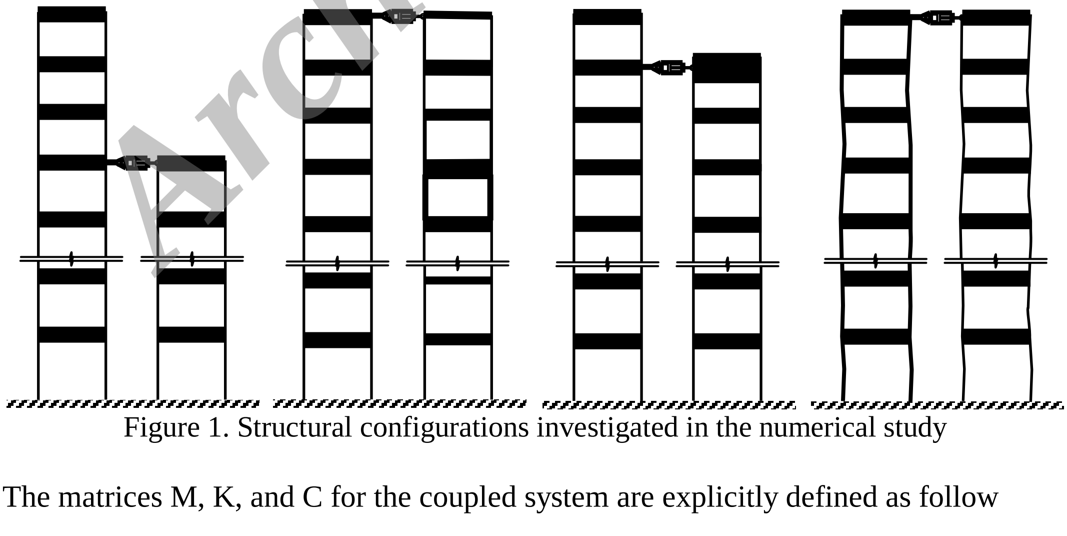


Figure 1. Structural configurations investigated in the numerical study

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

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

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

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

$[M_1]$ 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, the phenomenological model proposed by Spencer Jr et al [29] is used to simulate the dynamic behaviour of the 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 [29].

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.

2.2 Semi-active on-off controller

The voltage inputted to the damper is determined using an on-off control low proposed by Wu and Griffin [30]. As described below, the first purpose of this controller is to synchronize the response of two adjacent buildings. Thus, if the top floor displacement of the first building ($x_{n,1}$) and top floor displacement of the second building ($x_{n,2}$) are of the same sign, it means that they are moving in the same direction (no pounding risk) then the voltage will be turned Off (v_{zero}), if the displacements are of opposite sign (high risk of pounding) the voltage will be turned On at it maximum value (v_{max}).

$$v \begin{cases} v_{zero}\,, |x_{n,1}| \; and \; |x_{n,2}| > 0 \\ v_{max}\,, \qquad \quad if \; else \end{cases} \tag{20}$$

This strategy tries the voltage applied on the MR damper from zero to maximum value, which gives a sub-optimal control force. Moreover, the sudden change in voltage induces a sudden change in the outputted force that increases the system response sometimes. This is what motivated the development of better control algorithms that can change the voltage induced in the MR damper softly and slowly, such that all voltages between a maximum and zero voltage can be covered based on the feedback from the structure using the proposed fuzzy logic algorithm.

3. DESIGN OF FUZZY LOGIC CONTROLLER

In civil engineering, the fuzzy set theory was applied by many researchers. For example, Battaini, Casciati [31] used a fuzzy logic to control an active tuned mass damper. Choi, Cho [32] used a fuzzy logic controller to determine the appropriate voltage induced to MR damper in three floor scaled structures. Bhardwaj and Datta [33] used fuzzy logic to drive a hydraulic damper used for seismic response reduction. Pătraşcu and Dumitrache [34] examined and compared a fuzzy logic control strategy with other control strategies. Das, Datta [35] used fuzzy logic to model the behavior of MR damper for a semi-active control of a frame under seismic excitations. Shah and Choi [36] proposed a new adaptive fuzzy logic controller and used it to control the damping force in a MR damper. Amini, Mohajeri [37] used a semi-active damper driven by a fuzzy controller to mitigate the seismic damages in an isolated structure.

When a control method based on fuzzy set theory is used for vibration control of a damping device, it has an inherent robustness, it also makes it easier to treat the uncertainties of input data from the ground motion and structural vibration sensors, and the ability to interact with the non-linear behavior of the structure because there is no longer the need for an exact mathematical model of the structure. The main idea of a fuzzy control inference is based on three basic parts: fuzzyfication, were continuous inputs are transformed into linguistic variables, fuzzy rule inference consisting of fuzzy 'IF-THEN' rules, and defuzzyfication that ensures exact and physically interpretable values for control output.

The design of fuzzy control includes: the definition of input and output variables; the membership function design; and the rule base design. Using fuzzy rules and membership functions, fuzzy control converts linguistic variables into numerical values required in most applications. The fuzzy inference rule is completely based on the selected input variables.

3.1 Fuzzy logic controller for pounding reduction

In this study, the first objective behind the introduction of a fuzzy logic controller is the pounding reduction. The main reason for pounding between adjacent buildings is the unsynchronized vibrations which occur during earthquakes. The fuzzy logic is this case is designed to synchronize the response of the coupled adjacent buildings by making them move in the same direction at the same time. This eliminates any probable unsynchronized vibrations that will result in pounding situations. The controller design is based on two inputs that are based on the top floor displacements of buildings (1) and (2) respectively. Each input has five membership functions namely: negative large (NL), negative small (NS), zero (ZE) and positive small (PS) and positive large (PL). The output, in this case, is the voltage applied on the damper. The output function has three membership functions namely: zero (ZE), small (S), medium (M) and large (L). The range of the voltage used is (0V-9V). Generalized bell-shaped membership functions were used in this case as shown in Fig. 2.

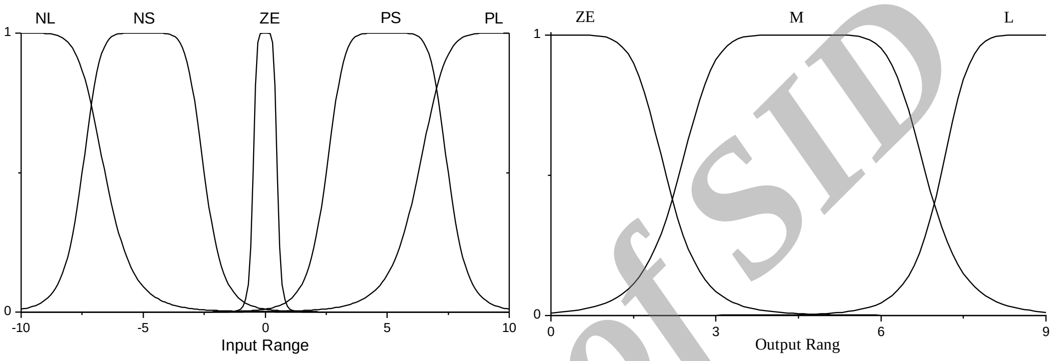


Figure 2. Input and output member ship functions

The fuzzy rules inference is based on the top floor displacement of building (1) and (2), by specifying a set of IF-THEN consequent statements. With five membership functions for each input, the relation between those two inputs will result in a fuzzy rules base consisting of 25 fuzzy rules. A five-by-five table with each cell to hold the corresponding outputs can be categorized for these rules (Table 2).

There are three choices for the voltage output corresponding to each rule. For example, if the building (1) top floor displacement is positive large (PL) and the building (2) top floor displacement is negative large (NL), which involves an unsynchronized vibration and a high risk of pounding. The voltage in this case, will be large (L), to produce a higher force in the damper. The fuzzy inference rules are shown in Table 2.

Table 2: Fuzzy inference rules for avoiding pounding between adjacent structures

	NL	NS	ZE	PS	PL
NL	ZE	S	M	L	L
NS	S	S	M	M	L
ZE	M	M	ZE	M	M
PS	L	M	M	S	S
PL	L	L	M	S	ZE

The solution procedure for the coupled system with the MR damper model driven by the fuzzy logic controller is described with the help of the diagram in Fig. 3.

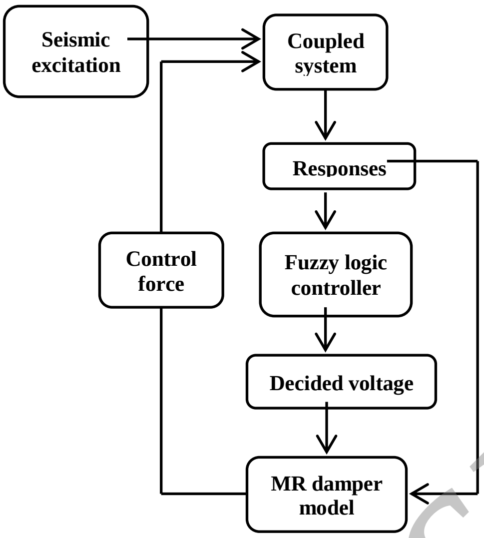


Figure 3. Diagram of the solution procedure using fuzzy logic controller

4. 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 I: Two buildings of unequal heights.
- Case II: Two buildings of same heights with one building having irregularities in mass and stiffness.
- Case III: Two buildings of nearly same heights with one building having a heavy mass on top floor.
- Case IV: Two damaged buildings of equal height.

Tables 3-6 describes the structural parameters for different cases.

Table 3: Structural parameters for case I

	Building (1)			Building (2)		
	$m_{i\ [t]}$	$k_{i\ [kN/m]}$	$c_{i\ [kN\ sec/m]}$	$m_{i\ [t]}$	$k_{i\ [kN/m]}$	$c_{i\ [kN\ sec/m]}$
1	50	200×10^3	359.2	100	160×10^3	330.8
2	50	200×10^3	359.2	100	160×10^3	330.8
3	50	200×10^3	359.2	100	160×10^3	330.8
4	50	200×10^3	359.2	100	160×10^3	330.8
5	50	200×10^3	359.2	100	160×10^3	330.8
6	50	200×10^3	359.2	100	160×10^3	330.8
7	50	200×10^3	359.2	100	160×10^3	330.8
8	50	200×10^3	359.2	-	-	-
9	50	200×10^3	359.2	-	-	-
10	50	200×10^3	359.2	-	-	-

Table 4: Structural parameters for case II

	Building (1)			Building (2)		
	m_i [t]	k_i [kN/m]	c_i [kN sec/m]	m_i [t]	k_i [kN/m]	c_i [kN sec/m]
1	50	200×10^3	359.2	120	160×10^3	459.1
2	50	200×10^3	359.2	130	120×10^3	370.1
3	50	200×10^3	359.2	170	150×10^3	462.7
4	50	200×10^3	359.2	140	130×10^3	401.0
5	50	200×10^3	359.2	100	200×10^3	616.9
6	50	200×10^3	359.2	110	160×10^3	493.5
7	50	200×10^3	359.2	135	180×10^3	555.2
8	50	200×10^3	359.2	100	160×10^3	493.5
9	50	200×10^3	359.2	105	190×10^3	586.1
10	50	200×10^3	359.2	090	150×10^3	462.7

Table 5: Structural parameters for Case III

	Building (1)			Building (2)		
	m_i [t]	k_i [kN/m]	c_i [kN sec/m]	m_i [t]	k_i [kN/m]	c_i [kN sec/m]
1	70	160×10^3	380.2	100	160×10^3	459.5
2	70	160×10^3	380.2	100	160×10^3	459.5
3	70	160×10^3	380.2	100	160×10^3	459.5
4	70	160×10^3	380.2	100	160×10^3	459.5
5	70	160×10^3	380.2	100	160×10^3	459.5
6	70	160×10^3	380.2	100	160×10^3	459.5
7	70	160×10^3	380.2	100	160×10^3	459.5
8	70	160×10^3	380.2	100	160×10^3	459.5
9	70	160×10^3	380.2	300	160×10^3	598.5
10	70	160×10^3	380.2	-	-	-

Table 6: Structural parameters for Case IV

	Building (1)			Building (2)		
	m_i [t]	k_i [kN/m]	c_i [kN sec/m]	m_i [t]	k_i [kN/m]	c_i [kN sec/m]
1	100	$0.8 \times 200 \times 10^3$	454.4	100	$0.7 \times 160 \times 10^3$	380.2
2	100	$0.8 \times 200 \times 10^3$	454.4	100	$0.7 \times 160 \times 10^3$	380.2
3	100	$0.8 \times 200 \times 10^3$	454.4	100	$0.7 \times 160 \times 10^3$	380.2
4	100	$0.8 \times 200 \times 10^3$	454.4	100	$0.7 \times 160 \times 10^3$	380.2
5	100	$0.8 \times 200 \times 10^3$	454.4	100	$0.7 \times 160 \times 10^3$	380.2
6	100	$0.8 \times 200 \times 10^3$	454.4	100	$0.7 \times 160 \times 10^3$	380.2
7	100	$0.8 \times 200 \times 10^3$	454.4	100	$0.7 \times 160 \times 10^3$	380.2
8	100	$0.8 \times 200 \times 10^3$	454.4	100	$0.7 \times 160 \times 10^3$	380.2
9	100	$0.8 \times 200 \times 10^3$	454.4	100	$0.7 \times 160 \times 10^3$	380.2
10	100	$0.8 \times 200 \times 10^3$	454.4	100	$0.7 \times 160 \times 10^3$	380.2

Note: the factors 0.8 and 0.7 represent the damage in the buildings.

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. An MR damper is placed between the two adjacent buildings, on the top floor of shorter building. The results of coupling strategy are obtained for passive as well as semi-active 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. The two semi-active control strategies considered are on-off controller and fuzzy logic based controller.

4.1 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.

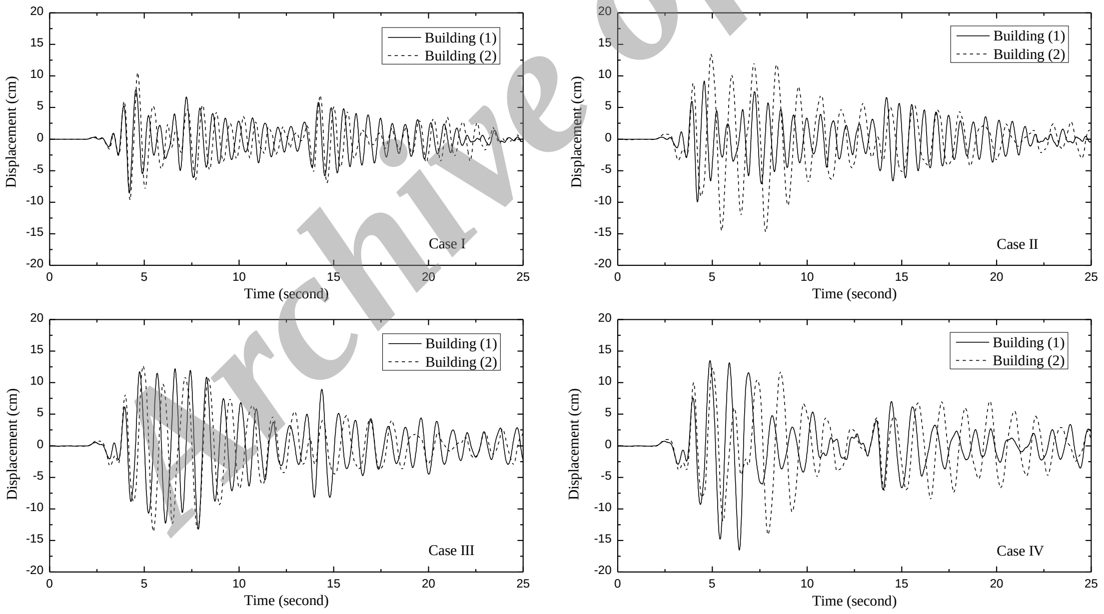


Figure 4. Top floor displacements of buildings (1) and (2) under El Centro earthquake

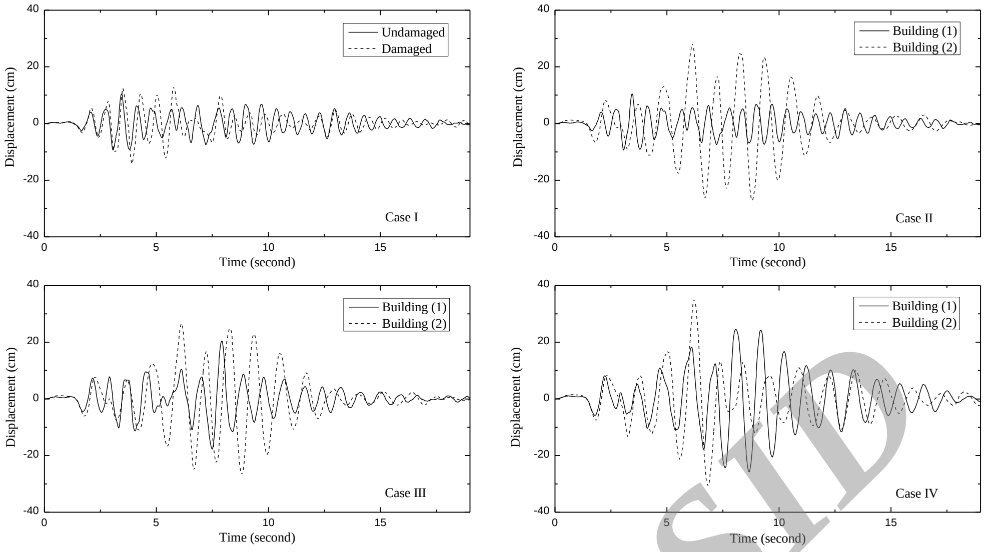


Figure 5. Top floor displacements of buildings (1) and (2) under Kocaeli earthquake

Figs. 4 and 5, 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. 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.

4.2 Pounding hazard reduction

The adjacent buildings were coupled at the top floor using an MR damper. One of the advantages of MR damper is its capacity to adopt multiple damping values.

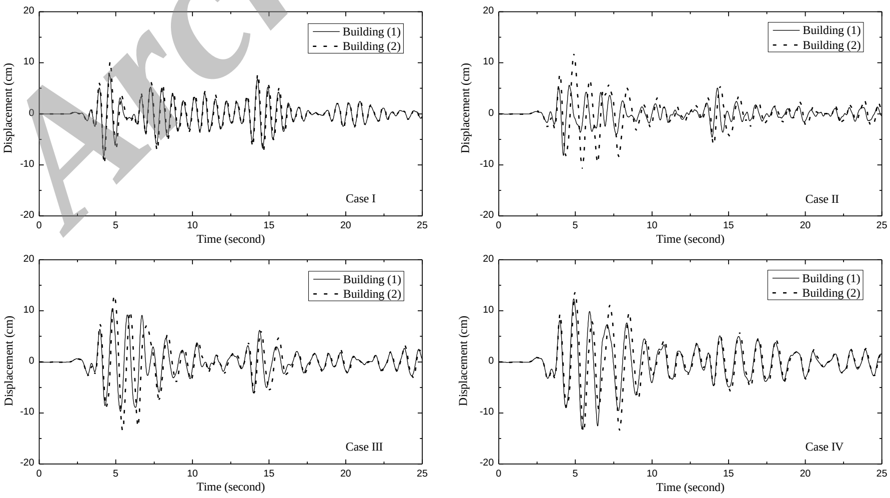


Figure 6. Top floor displacements of buildings (1) and (2) coupled with MR damper under El Centro earthquake

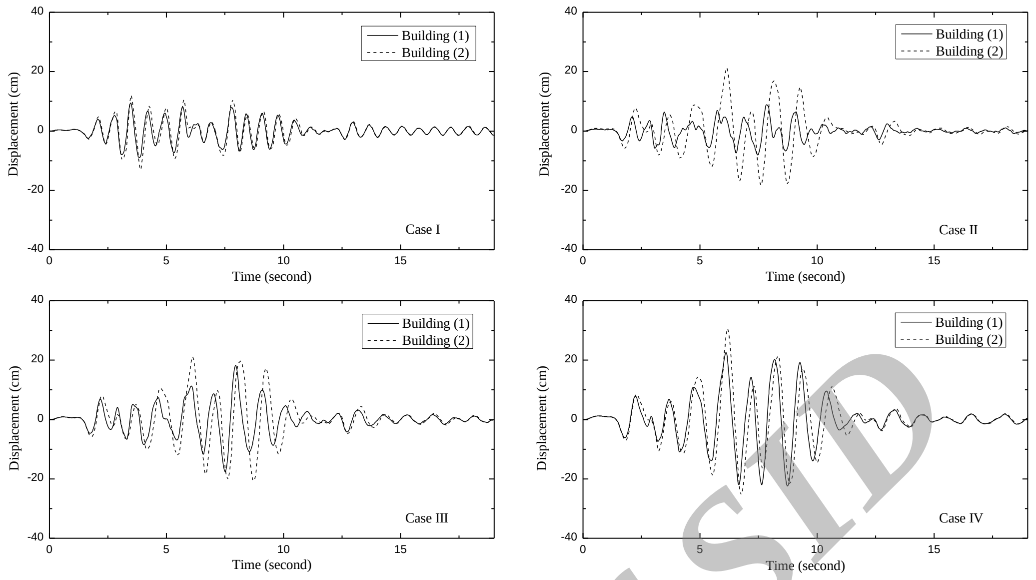


Figure 7 Top floor displacements of buildings (1) and (2) coupled with MR damper under Kocaeli earthquake

The damper force can be controlled by varying the voltage applied to the MR damper. The primary aim of coupling buildings in this study is to reduce the pounding. That includes the elimination of unsynchronized vibrations (Fig. 6 and 7) and the minimum gap reduction (Tables 7 and 8).

It can be clearly observed from Figs. 6 and 7, 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, except for case II were it is observed the synchronization is not completely perfect for both studied earthquakes. The synchronization in rest of the cases is implicit, thus avoiding pounding hazard between adjacent buildings. The results presented are obtained using a fuzzy logic controller and they demonstrate the effectiveness of the coupling strategy for pounding mitigation.

Table 7: The minimum gap (cm) required to avoid pounding under El Centro earthquake

Earthquake	Case	Uncoupled	Passive-Off	Passive-on			On-off controller	Fuzzy logic controller
				3V	6V	9V		
El Centro, 1940	I	07.72	06.77	05.46	04.49	03.68	06.78	04.07
	II	19.50	18.73	15.97	13.94	12.41	14.82	12.45
	III	20.42	18.73	14.96	12.25	10.23	15.41	10.86
	IV	15.20	13.49	10.25	7.99	06.39	12.18	07.31

Table 8: The minimum gap (cm) required to avoid pounding under Kocaeli earthquake

Earthquake	Case	Uncoupled	Passive-Off	Passive-on			On-off controller	Fuzzy logic controller
				3V	6V	9V		
Kocaeli, 1999	I	12.00	10.37	07.63	05.73	04.40	08.91	04.90
	II	30.65	28.16	22.73	20.02	18.62	22.27	19.16
	III	35.31	32.28	25.74	21.38	18.40	27.72	18.84
	IV	29.53	27.10	21.97	18.46	15.67	25.26	15.84

Tables 7 and 8 show the minimum gap required between adjacent buildings to avoid pounding. The results are obtained using four control strategies. It can be observed from the tables that coupling two adjacent buildings with only one damper 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) and a fuzzy logic controller, which are nearly equally effective. The performances of passive-off and on-off controller are limited and the reductions obtained are not significant. For El Centro earthquake maximum reductions are 52.3%, 36.3%, 49.9% and 58.0% for cases I, II, III and IV, respectively. For Kocaeli earthquake maximum reductions are 63.33%, 39.2%, 47.8% and 46.9% for cases I, II, III and IV, respectively.

4.3 Dynamic performance of the coupled system

After the investigation of the performance of coupling strategy in reducing the pounding hazard, dynamic performances of coupled buildings are observed in terms of top floor displacement and maximum drift reduction. Tables 9-12 show the top floor displacement of building (1) and (2) under different control strategies for all the cases considered.

Table 9: Top floor displacement (cm) of buildings (1) and (2) for case I

Earthquake	Buildings	Uncoupled	Passive-Off	Passive-on			On-off controller	Fuzzy logic controller
				3V	6V	9V		
El Centro, 1940	1	09.96	09.83	09.59	09.52	09.55	09.79	09.59
	2	10.56	10.54	10.44	10.31	10.10	10.61	10.21
Kocaeli, 1999	1	10.47	10.56	10.76	10.95	11.16	11.08	11.15
	2	14.30	14.00	13.50	13.14	12.92	13.47	12.99

Table 10: Top floor displacement (cm) of buildings (1) and (2) for case II

Earthquake	Buildings	Uncoupled	Passive-Off	Passive-on			On-off controller	Fuzzy logic controller
				3V	6V	9V		
El Centro, 1940	1	09.96	09.73	09.12	08.50	08:00	09.35	08.15
	2	14.75	13.97	12.77	12.00	11.80	12.35	11.92
Kocaeli, 1999	1	10.47	09.94	08.58	07.92	08.63	08.75	08.84
	2	28.31	27.32	24.84	22.82	21.12	25.12	21.17

Table 11: Top floor displacement (cm) of buildings (1) and (2) for case III

Earthquake	Buildings	Uncoupled	Passive-Off	Passive-on			On-off controller	Fuzzy logic controller
				3V	6V	9V		
El Centro, 1940	1	13.55	12.11	11.44	11.06	10.81	11.69	10.72
	2	13.59	13.47	13.38	13.36	13.41	13.29	13.45
Kocaeli, 1999	1	20.44	19.97	18.91	18.57	18.62	20.36	18.56
	2	26.77	25.77	23.56	22.03	20.82	24.15	21.09

Table 12: Top floor displacement (cm) of buildings (1) and (2) for case IV

Earthquake	Buildings	Uncoupled	Passive-Off	Passive-on			On-off controller	Fuzzy logic controller
				3V	6V	9V		
El Centro, 1940	1	16.52	15.66	13.91	13.37	13.09	14.52	13.16
	2	14.09	14.10	13.94	13.71	13.78	13.75	13.70
Kocaeli, 1999	1	25.76	24.46	22.55	22.11	22.33	23.50	22.37
	2	35.09	34.07	32.27	31.28	30.54	32.56	30.52

From Tables 9-12, 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 damper. In the overall analysis, the performances of the fuzzy logic controller and passive-on (9V) controller are nearly close. The performances of passive-off and on-off controller are limited, and in some cases this leads to enhanced responses (Table 9-12).

Figs. 8-11 show the maximum drift for all the floors of buildings (1) and (2) for the cases considered, under El Centro and Kocaeli earthquakes, respectively.

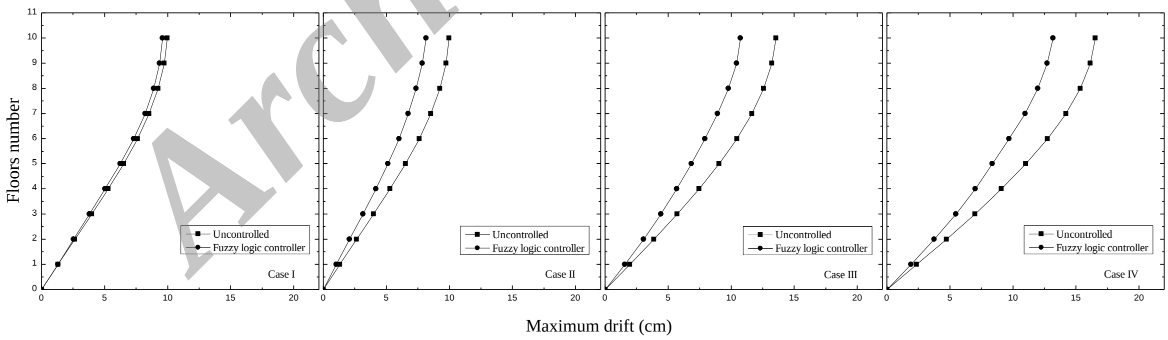


Figure 8. Maximum drift of building (1) under El Centro earthquake

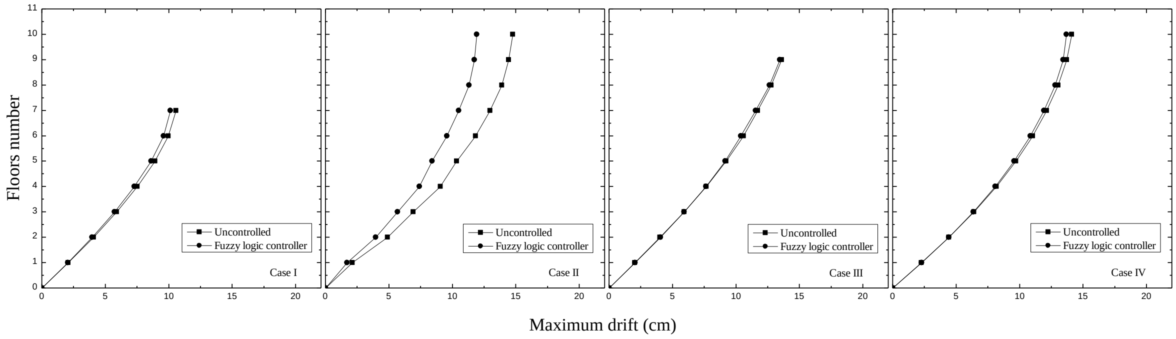


Figure 9. Maximum drift of building (2) under El Centro earthquake

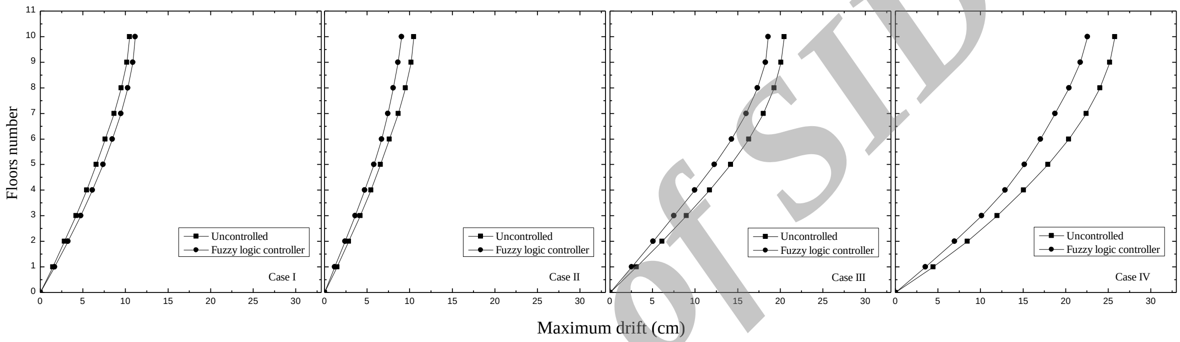


Figure 10. Maximum drift of building (1) under Kocaeli earthquake

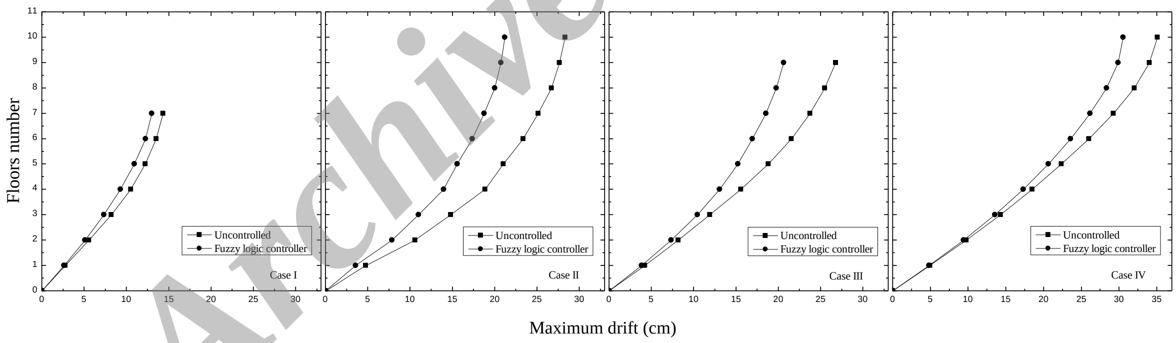
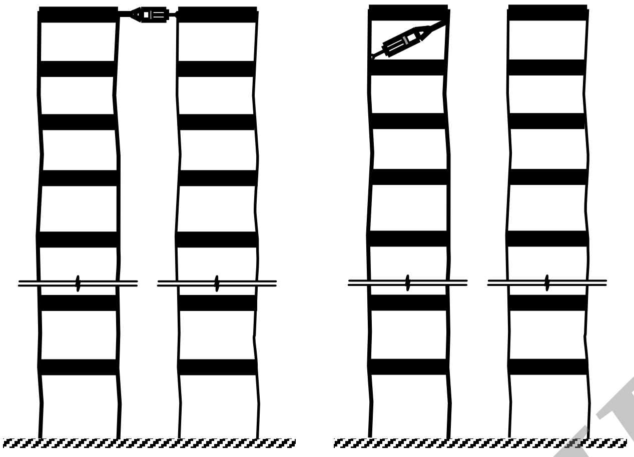


Figure 11. Maximum drift of building (2) under Kocaeli

A reduction in the maximum drift in all the floors can be observed. As the response of uncoupled floors has also changed, it can be said that the coupling strategy affects the response of unconnected floors. Moreover it can also be observed that the damper driven by the fuzzy logic controller does not adversely affect the behaviour of coupled structures.

4.4 Efficiency of coupling strategy using one damper

To prove the efficiency of the coupling strategy in pounding reduction, one of the studied cases will be used as a benchmark model. In this part of the numerical study, the damper will be placed in only one of the structures (Fig. 12).



(a) (b)

Figure 12. Structural configuration used for the comparative study

The damper will be driven using the same control strategies. A comparison between a coupled system and a single controlled building system will be presented. The parameters examined are response synchronization, evolution of the minimum gap, under El Centro earthquake. The case IV will be retained in this part.

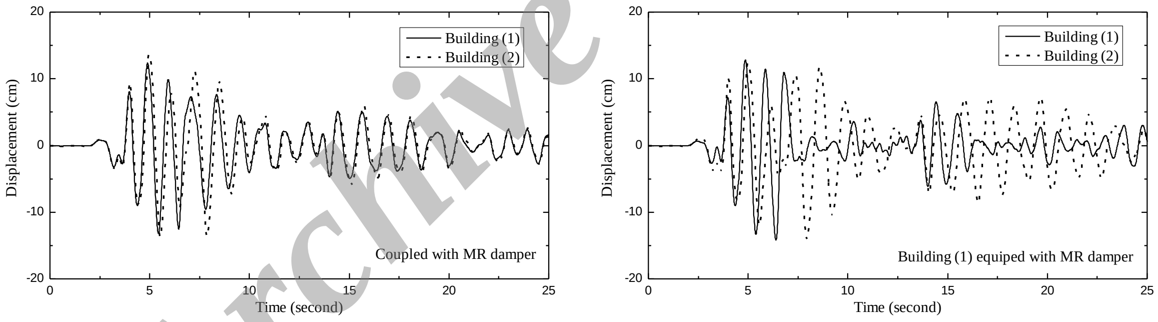


Figure 13 Top floor displacements of building (1) and (2) under El Centro, 1940

From Fig. 13, it can be seen that equipping only one building with a MR damper will not synchronize the vibrations between the adjacent buildings, meaning that the pounding will not be reduced. As compared to the coupling strategy the single controlled building strategy is not effective regarding pounding reductions.

Table 13: The minimum gap (cm) required to avoid pounding under El Centro earthquake.

Earthquake	Case	Uncoupled	Passive -Off	Passive-on			On-off controller	Fuzzy logic controller
				3V	6V	9V		
El Centro, 1940	IV (a)	15.20	13.49	10.25	7.99	06.39	12.18	07.31
	IV (b)	15.20	14.86	14.65	14.52	14.48	14.54	14.44

Table 13 show the minimum gap required between adjacent buildings to avoid pounding. The results are obtained using four control strategies. Comparison between the coupling strategy and the single controlled building strategy show that the coupling strategy is more effective regarding minimum gap reduction, and, therefore, pounding reduction. The minimum gap reduction under the single controlled building strategy is not significant and dose not exceeds 5% in the best scenario.

4.5 Performance of the MR damper

The performance of the MR damper will be examined under four control strategies. Case IV will be retained for this purpose. The fuzzy logic benefits can be observed in the optimization of the peak damper force produced by the damper. Table 14 shows the peak damper force under different control strategies. As expected more the voltage is raised more the peak damper force is high. Using the proposed fuzzy logic controller we can optimize the peak damper force under both El Centro and Kocaeli earthquakes, respectively.

Table 14: Peak damper force (kN) under different control strategies

Earthquake	Passive-Off	Passive-on			On-off controller	Fuzzy logic controller
		3V	6V	9V		
El Centro, 1940	54.71	171.56	250.88	304.96	382.82	291.36
Kocaeli, 1999	101.48	314.12	472.58	597.20	709.92	515.41

Table 15: Total absolute damper force (kN) under different control strategies

Earthquake	Passive-Off	Passive-on			On-off controller	Fuzzy logic controller
		3V	6V	9V		
El Centro, 1940	1.62×10^5	4.45×10^5	6.16×10^5	7.18×10^5	6.58×10^5	5.51×10^5
Kocaeli, 1999	1.69×10^5	4.52×10^5	6.09×10^5	7.02×10^5	6.42×10^5	5.58×10^5

Table 15 shows the total absolute force of the damper, which was generated during the earthquake excitations. It is clear that the proposed fuzzy logic algorithm can optimize the total damper force produced by the damper during the earthquake excitation compared to other control strategies.

5. CONCLUSION

The effectiveness of coupling two adjacent buildings for pounding hazard mitigation using a single MR damper was investigated for different cases. Multiple 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, if an appropriate control algorithm is associated to the MR damper. 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 damper 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 and maximum drift event in the uncoupled floors.
4. A comparison between four control strategies namely, passive-off, passive-on, On-off controller and fuzzy logic controller indicates that in overall analysis fuzzy logic controller strategy is the most effective option.
5. A comparison between the coupling strategy and a single semi-active control strategy shows that the coupling strategy is more effective it terms of response synchronization and minimum gap reduction.
6. The fuzzy logic controller can optimize the damper force in terms of peak damper force and total force produced by the damper as compared to other control strategies.

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