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Retrofitting of a weaker building by coupling it to an adjacent stronger building using MR dampers

Mahdi Abdeddaim[*1], Abdelhafid Ounis[1a], Mahendra K. Shrimali[2b] and Tushar K. Datta[2c]

[1]*LARGHYDE Laboratory, Department of Civil Engineering and Hydraulics, Faculty of Sciences and Technology, Mohamed Khider University, BP 145 RP, 07000 Biskra, Algeria*
[2]*Center of Disaster Mitigation and Management, Malaviya National Institute of Technology Jaipur, Rajasthan 302017, India*

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Abstract. Among various retrofitting strategies, use of semi-active control for retrofitting a building structure has gained momentum in recent years. One of the techniques for such retrofitting is to connect a weaker building to an adjacent stronger building by semi-active devices, so that performances of a weaker building are significantly improved for seismic forces. In this paper, a ten storey weaker building is connected to an adjacent stronger building using magneto-rheological (MR) dampers, for primarily improving the performance of the weaker building in terms of displacement, drift and base shear. For this, a fuzzy logic controller is specifically developed by fuzzyfying the responses of the coupled system. The performance of the control strategy is compared with the passive-on and passive-off controls. Pounding Mitigation between the two buildings is also investigated using all three control strategies. The results show that there exists a fundamental frequency ratio between the two buildings for which maximum control of the weaker building response takes place with no penalty on the stronger building. There exists also a fundamental frequency ratio where control of the weaker building response is achieved at the expense of the amplification of the stronger building. However, coupling strategy always improves the possibility of pounding mitigation.

Keywords: seismic retrofitting; weaker building; coupled buildings; magneto-rheological (MR) damper; noise contamination; pounding

1. Introduction

There are many types of building which require retrofitting, rehabilitation and enhancement of their performances. Retrofitting and rehabilitation are required usually for buildings which are damaged due to previous earthquakes or due to some accidental events (Zhang *et al.* 2015, Mosleh *et al.* 2016). Retrofitting may also be required for structures which are inadequately designed or whose performance levels have to be increased, or whose strength has deteriorated with the passage of time. These structures are termed as weaker structures compared to well-designed relatively new structures. The possibility of pounding between the weaker structure and an adjacent structure during earthquake also has to be checked (Kasai *et al.* 1992, Cole *et al.* 2012, Zhai *et al.* 2015).

A lot of seismic retrofitting technics were introduced during recent years including the traditional retrofitting methods that try to increase the stiffness of the frames (Amiri *et al.* 2013); the use of control devices is one of the most widespread methods for seismic retrofitting. They are basically three types of control devices, which are active, passive and semi-active (Fisco and Adeli 2011). Any combination between those three types will be named as hybrid control (Fisco and Adeli 2011). The principal aim of those retrofitting technics is to upgrade the behaviour of existing buildings to satisfy new seismic code requirements. Passive devices were introduced for seismic retrofitting in the early 1990s (Constantinou and Symans 1992). Passive devices do not need external energy to develop the control force and it never destabilise the structure. This motivated researchers to give more importance to this type of retrofitting devices (Zhang and Soong 1992, Wu *et al.* 1997, Lopez Garcia and Soong 2002, Bayramoglu *et al.* 2014, Lavan and Amir 2014, Kaveh *et al.* 2015, Lavan 2015). However, they have a low adaptability to the change of external loading conditions or usage patterns. Active control devices are very adaptive to different load cases and usage patterns (Adeli and Saleh 1997, Kim and Adeli 2004, Hochrainer 2015). But, the external energy consumption is still one of the major concerns for this kind of devices. This led to the development of semi-active devices that have the advantage of combining passive and active characteristics. The devices use a small source of energy that can be supplied by a battery, avoiding any problem in the case of a power cut (Symans and Constantinou 1999). Magneto-rheological (MR) dampers are considered as one of the effective semi-active devices and are widely used in structural vibration control in both civil and mechanical

∗Corresponding author, Research Scholar
E-mail: abdeddaim_mms@yahoo.fr
[a]Professor
E-mail: ounisafi@gmail.com
[b]Professor
E-mail: shrimali_mk@yahoo.co.uk
[c]Emeritus Professor
E-mail: tushar_k_datta@yahoo.com

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engineering fields (Dyke *et al.* 1998, Yang *et al.* 2002, Choi *et al.* 2004, Wilson 2012, Kim *et al.* 2014).

For enhancing the performance of the weaker building, the coupling strategy may be adopted if there exists an adjacent stronger building (Yang and Lam 2015). The coupling strategy involves installation of a control device between the two buildings such that the performances of both buildings are improved against environmental loadings such as wind and earthquakes (Farghaly 2015). The control device may be passive, active and semi-active. The use of semi-active devices as connectors is a new strategy introduced during recent years. The main idea behind this strategy is to couple two or more adjacent buildings using a number of semi-active magneto-rheological (MR) dampers to reduce the response of the coupled system. Qu and Xu (2001) 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 right control algorithm is used. Xu *et al.* (2005) examined the effectiveness of MR damper through a scaled model of a twelve-floor building adjacent to a three-floor building which was connected by 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 structures. Bharti *et al.* (2010) 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 *et al.* (2011) 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 shorter building. An LQR-RNN control strategy was proposed to control the voltage induced in the MR damper. Shahidzade *et al.* (2011) examined the effect of coupling building of different heights with a MR damper, and the use of MR damper in the tallest building. Two types of damper were used a 20 T and 100 T. The results obtained demonstrate an important reduction regarding displacement and acceleration of the coupled buildings. Palacios-Quinonero *et al.* (2012) studied the seismic protection of multi-structure systems that combines inter-structure passive/semi-active damping elements. Two strategies were applied to two adjacent buildings, either coupled with passive devices or equipped separately with semi-actives devices. Kim and Kang (2012) examined the coupling of two adjacent buildings with different characteristics for the displacement, and acceleration reduction. Uz and Hadi (2014) studied the effect of coupling two adjacent buildings using a multitude of MR dampers on the response. They also used a multi-objective genetic algorithm to optimise the damper number, location and force. Abdeddaim *et al.* (2016) used the coupling strategy to reduce the pounding between adjacent buildings using a single damper at the top floor controller by fuzzy logic controller.

The published work on the coupled buildings using semi-active devices mostly focused on response reduction of the coupled buildings, not with the objective of retrofitting a weaker building by coupling it to an adjacent stronger building. In this paper, the efficiency of coupling strategy using MR damper is investigated specially for retrofitting a weaker building connected to a stronger building. For this purpose, a fuzzy rule based control algorithm is developed. The performance of the coupled system is investigated for the different control strategies namely, passive-off, passive-on, and fuzzy logic controller and for different number of MR dampers. Besides the retrofitting of the weaker building, the effect of coupling on the pounding between the two buildings is also investigated.

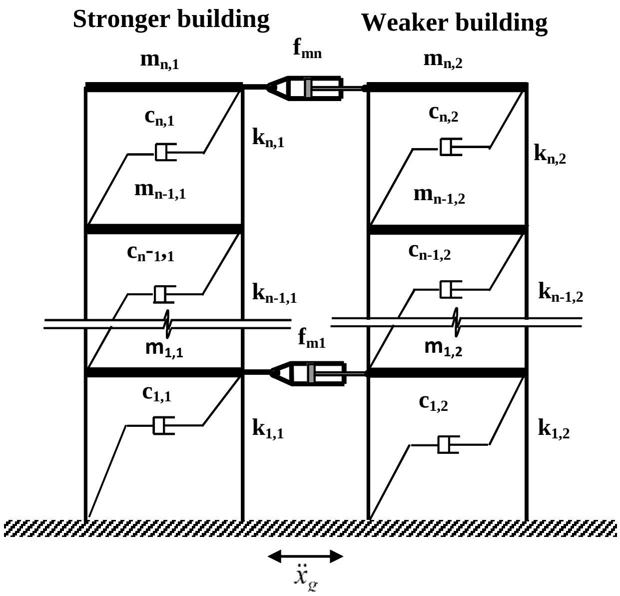

Fig. 1 Structural model of buildings connected with MR damper

2. Dynamic modeling of coupled system

It is assumed that the controlled responses of both structures remain in the elastic range. The governing equation of motion 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_d, are mass, stiffness and damping matrices of the coupled system; f_m is the vector of the input force produced by the MR damper; Γ is the damper location matrix which duly takes into account the control force applied to the buildings; 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.

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

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

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

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

Where $[M_1]$ and $[M_2]$ are the mass matrices for buildings 1 and 2, respectively. Similarly $[K_1]$, $[K_1]$ and $[c_1]$, $[c_1]$ are the stiffness and damping matrices, $[O]$ is the null matrix.

The governing Equation Eq. (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.* (1997) is used to simulate the dynamic behaviour of MR damper based on the modified Bouc-Wen model. The equations governing the force predicted by this model are

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

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

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

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

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

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

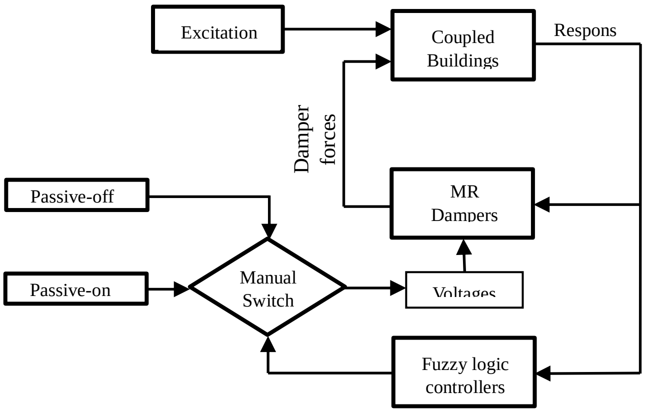

Fig. 2 Diagram of the solution procedure

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}]

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

In Eqs. (13)-(19), 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. Eq. (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 Eqs. (16)-(18).

The 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

MR damper equations were reproduced in a MATLAB Simulink model to simulate the behaviour of this device, based on the equations given above (13-19).

The solution procedure for the coupled system with the MR damper model is described with the help of the diagram in Fig. 2.

3. Control algorithms

3.1 Fuzzy logic controller

In civil engineering, the fuzzy set theory was applied by

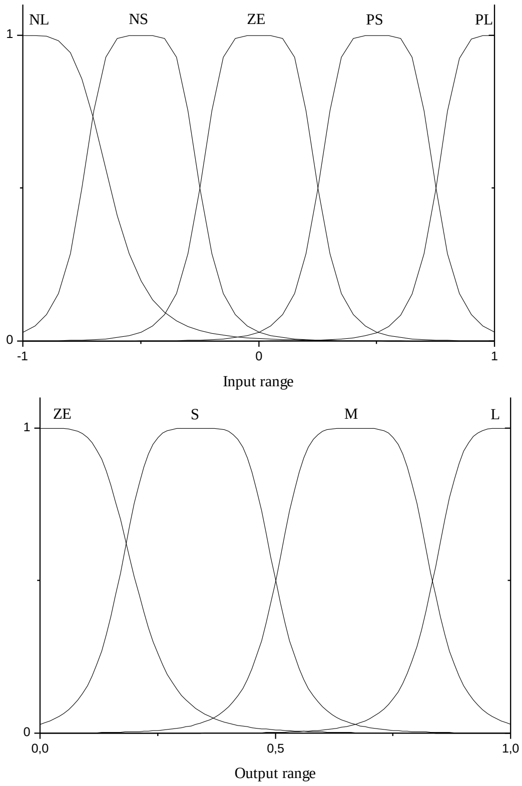

Fig. 3 fuzzy logic membership functions

many researchers. For example, Battaini *et al.* (1998) used a fuzzy logic to control an active tuned mass damper. Choi *et al.* (2004) used a fuzzy logic controller to determine the appropriate voltage induced to MR damper in three floor scaled structures. Bhardwaj and Datta (2006) used fuzzy logic to drive a hydraulic damper used for seismic response reduction. Pătraşcu *et al.* (2012) examined and compared a fuzzy logic control strategy with other control strategies. Das *et al.* (2012) used fuzzy logic to model the behaviour of MR damper for a semi-active control of a frame under seismic excitations. The novelty of controller here is that it is developed with the objective of finding the optimum reduction in response of the weaker building. The fuzzy logic is designed to reduce the response of the weaker building by applying a high voltage to the damper, whenever the weaker building displacement is large. The controller design is based on two inputs i.e., the top floor displacements of the two buildings. 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 four membership functions namely: zero (ZE), small (S), medium (M) and large (L). The range of the voltage used is (V_{zero}-V_{max}). Generalized bell-shaped membership functions are used as shown in the Fig. 3

The fuzzy rules inferences are based on the top floor displacements of the two building, by specifying a set of "*If-Then*" consequent statements. With five membership functions for each input, the relationship between the two inputs (top floor displacement of the stronger and weaker building, respectively) will result in a fuzzy rules base consisting of 25 fuzzy rules

Table 2 Fuzzy inference rules for retrofitting weaker structures

Weaker building	Strong building				
	NL	NS	ZE	PS	PL
NL	L	M	L	L	L
NS	M	M	M	L	M
ZE	ZE	S	ZE	S	ZE
PS	M	L	M	M	M
PL	L	L	L	M	L

Table 3 Structural parameters of the stronger and weaker buildings used in numerical study

Floor	Stronger				Weaker					
	Flexible		Rigid		40% Weaker		30% Weaker		20% Weaker	
	m_i [t]	$k_i\times10^3$ [kN/m]	m_i [t]	$k_i\times10^3$ [kN/m]	m_i [t]	$k_i\times10^3$ [kN/m]	m_i [t]	$k_i\times10^3$ [kN/m]	m_i [t]	$k_i\times10^3$ [kN/m]
1	100	161	55	161	100	0.6×161	100	0.7×161	100	0.8×161
2	100	161	55	161	100	0.6×161	100	0.7×161	100	0.8×161
3	100	161	55	161	100	0.6×161	100	0.7×161	100	0.8×161
4	100	161	55	161	100	0.6×161	100	0.7×161	100	0.8×161
5	100	161	55	161	100	0.6×161	100	0.7×161	100	0.8×161
6	100	161	55	161	100	0.6×161	100	0.7×161	100	0.8×161
7	100	161	55	161	100	0.6×161	100	0.7×161	100	0.8×161
8	100	161	55	161	100	0.6×161	100	0.7×161	100	0.8×161
9	100	161	55	161	100	0.6×161	100	0.7×161	100	0.8×161
10	50	161	27.5	161	50	0.6×161	50	0.7×161	50	0.8×161

A five-by-five table with each cell to hold the corresponding outputs can be categorized for these rules as shown in Table 2.

3.2 Other control algorithms

Apart from the fuzzy logic controller, passive-off and passive-on controllers are used. In passive-off, the voltage applied to the MR damper is zero and the MR damper behaves purely as a passive device. In passive-on, maximum voltage is applied to the MR damper. Note that actuation of the damper is governed by the inter-storeys relative displacement and velocity.

4. Numerical study

A system of two adjacent buildings is considered, each building has ten storeys and considered as a shear building. One building is stronger and the other is assumed to be weaker, reduced stiffness of the weaker building is uniform along the height. Both structures remain in the elastic range during the vibrations. For this study, two cases of the stronger building are considered, one is flexible and the second one is rigid. For both cases, stiffness remains the same but masses vary as shown in Table 3. Three cases of the weaker building are considered. The weaker buildings have reduced stiffness compared to the strong building.

Table 4 The natural frequencies of the stronger and weaker buildings.

Frequency [Hz]	Stronger building		Weaker building		
	Flexible	Rigid	40% Weaker	30% Weaker	20%Weaker
f_1	1.00	1.35	0.77	0.83	0.89
f_2	2.98	4.02	2.30	2.49	2.66
f_3	4.88	6.59	3.78	4.08	4.37
f_4	6.67	8.99	5.16	5.58	5.96
f_5	8.29	11.1	6.42	6.93	7.41

Three reductions in stiffness for the weaker building are considered namely, 40%, 30% and 20%. A stiffness proportional damping is assumed for both buildings with the damping ratio equal to 5%. Tables 3 and 4 show the structural parameters of the stronger and weaker buildings, respectively.

The two buildings were coupled using MR dampers installed on different locations (Fig. 1). Three damper locations are investigated as (*i*) one damper used at the top floor, (*ii*) three dampers used, at the first, middle and top floors and (*iii*) five dampers used, at the first, third, fifth, seventh and top floors.

The MR dampers are driven by three different control strategies namely Passive-off, Passive-on and fuzzy logic controller as described before.

The two buildings were subjected to Northridge earthquake record, 1994 and Kocaeli earthquake record, 1999, with the maximum ground acceleration scaled to 0.2 g for both Northridge and Kocaeli earthquakes. Six study cases are considered in order to create different ratios of fundamental periods (stronger/weaker defined by δ):

- Case I: weaker building (40% stiffness loss) coupled with stronger flexible building (δ =1.29),
- Case II: weaker building (40% stiffness loss) coupled with stronger rigid building (δ =1.75),
- Case III: weaker building (30% stiffness loss) coupled with stronger flexible building (δ =1.20),
- Case IV: weaker building (30% stiffness loss) coupled with stronger rigid building (δ =1.62),
- Case V: weaker building (20% stiffness loss) coupled with stronger flexible building (δ =1.12),
- Case VI: weaker building (20% stiffness loss) coupled with stronger rigid building (δ =1.51).

The responses investigated are the maximum top floor displacement ($\Delta_{\max}$), the maximum base shear (V_{base}) and the maximum drift ($D_{\max}$). The percentage variations in responses quantities of interest with the frequency ratio for different cases of study for the two earthquakes are shown in Figs. 4-9.

From the Figs. 4-9, it is observed that the maximum response reduction of the weaker building can be achieved for a particular response quantity of interest at a particular frequency ratio. However, higher reductions in responses are obtained at relatively higher frequency ratios. Further, it is observed that for certain frequency ratios, the reduction in response of the weaker building is obtained at the expense of response amplification in the stronger building. . It is also worth noting that, for frequency ratios at which optimum

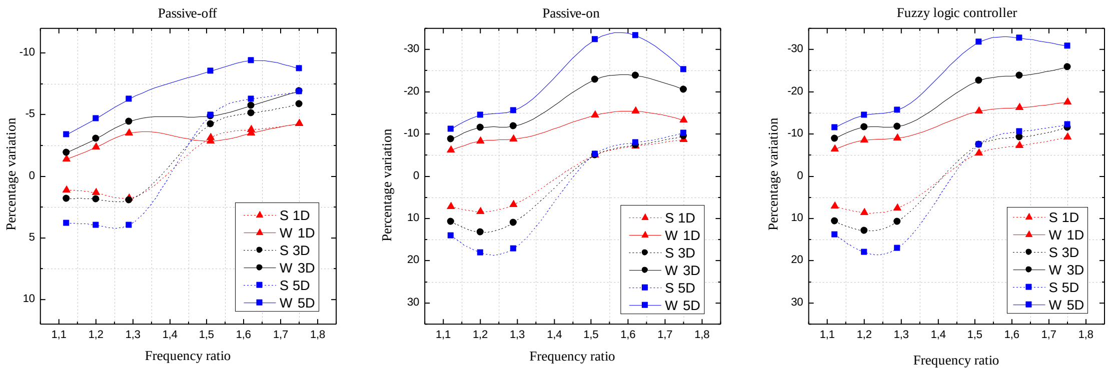

Fig. 4 Percentage variation in ($\Delta_{\max}$) with respect to frequency ratio under Northridge earthquake, 1994

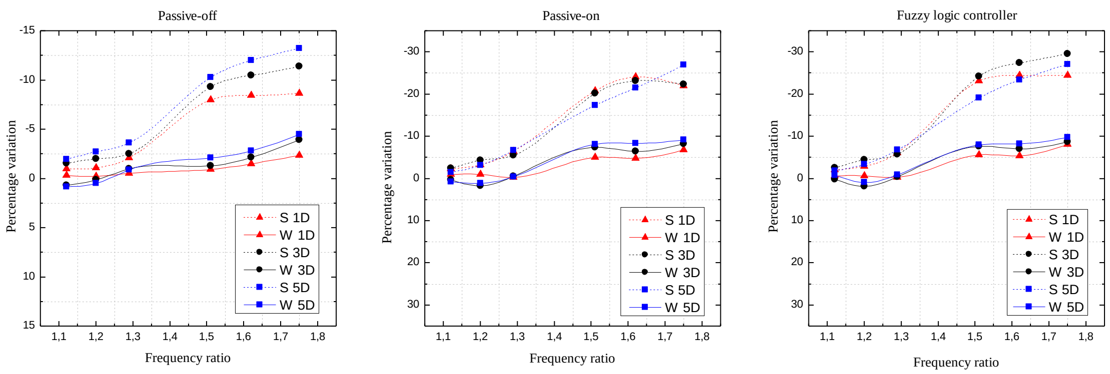

Fig. 5 Percentage variation (V_{base}) with respect to frequency ration under Northridge earthquake, 1994

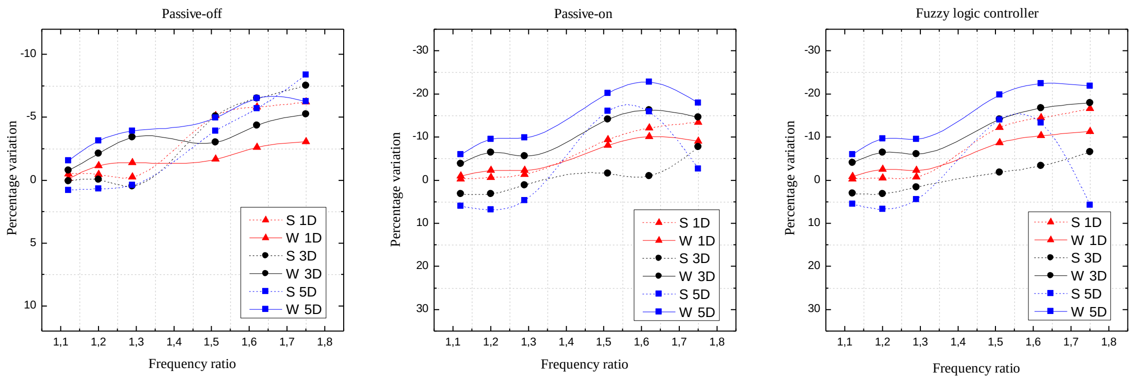

Fig. 6 Percentage variation in ($D_{\max}$) with respect to frequency ratio under Northridge earthquake, 1994

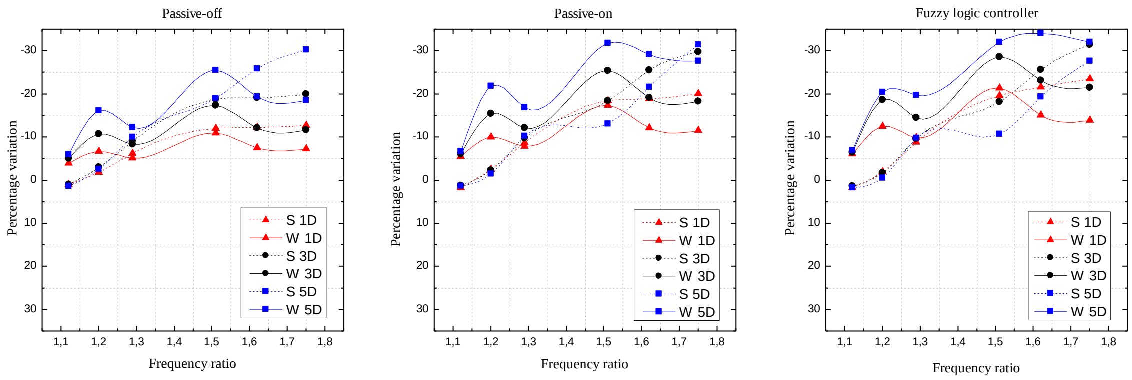

Fig. 7 Percentage variation in ($\Delta_{\max}$) with respect to frequency ratio under Kocaeli earthquake, 1999

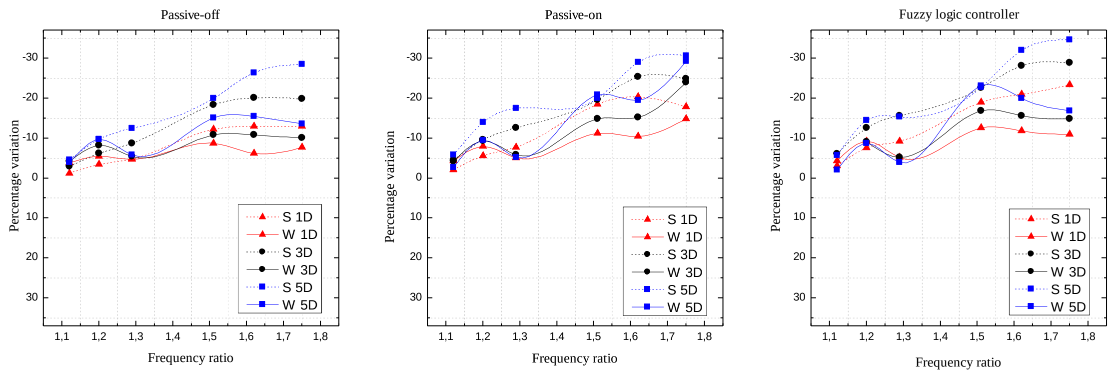

Fig. 8 Percentage variation in (V_{base}) with respect to frequency ratio under Kocaeli earthquake, 1994

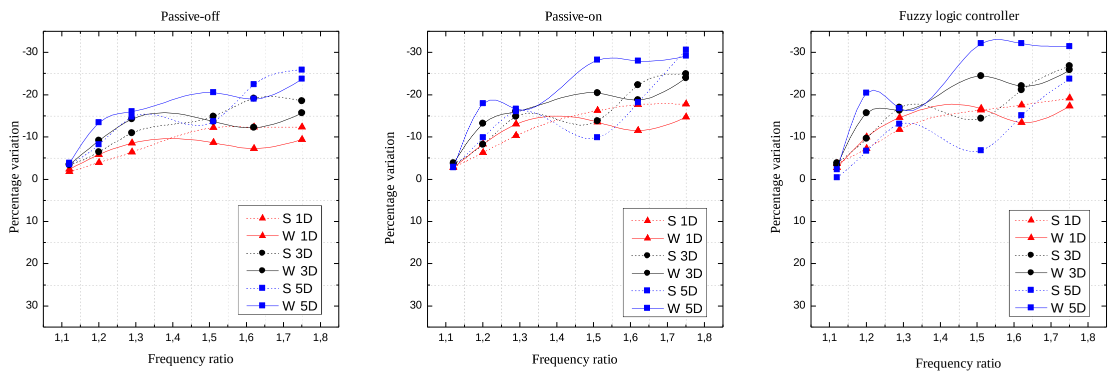

Fig. 9 Percentage variation in ($D_{\max}$) with respect to frequency ratio under Kocaeli earthquake, 1999

response reduction for weaker building takes place, a reduction in response of stronger building is also attained, nonetheless small it may be.

It is observed from the figures that out of the three

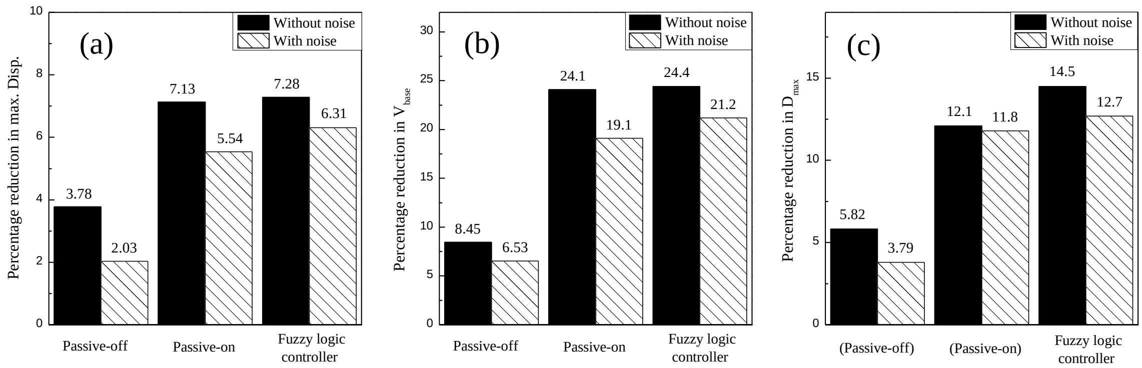

Fig. 10 Percentage reduction in (a) $\Delta_{\max}$, (b) V_{base}, and (c) $D_{\max}$ for the stronger building with and without noise (ψ=20)

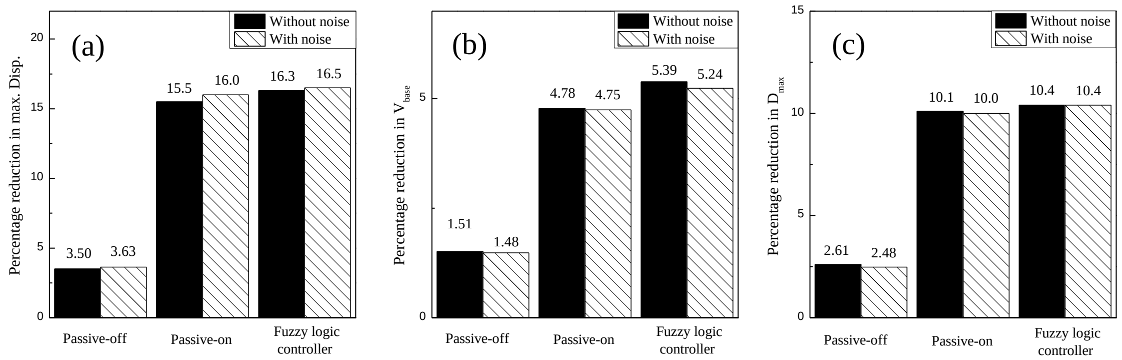

Fig. 11 Percentage reduction in (a) $\Delta_{\max}$, (b) V_{base}, and (c) $D_{\max}$ for the weaker building with and without noise (ψ=20)

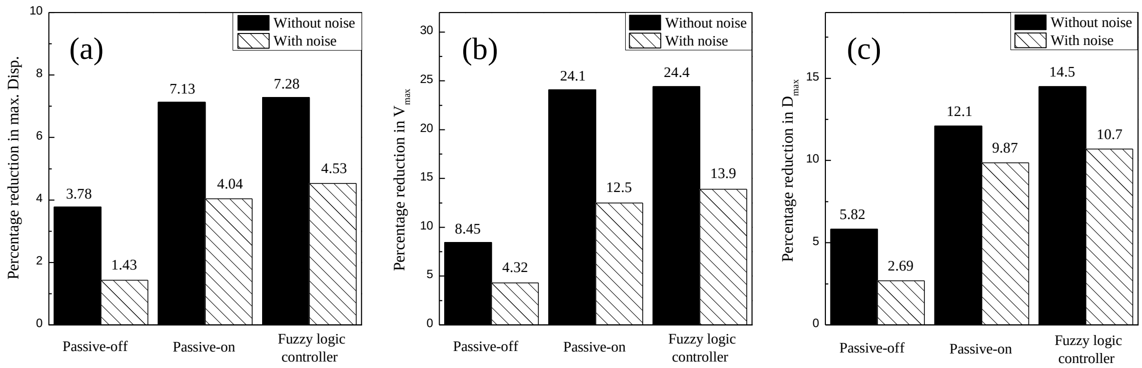

Fig. 12 Percentage reduction in (a) $\Delta_{\max}$, (b) V_{base}, and (c) $D_{\max}$ for the stronger building with and without noise (ψ=10)

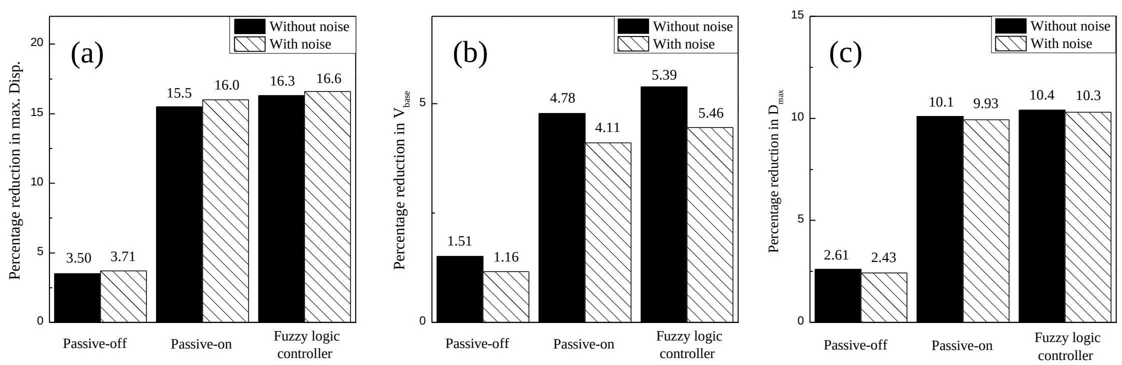

Fig. 13 Percentage reduction in (a) $\Delta_{\max}$, (b) V_{base}, and (c) $D_{\max}$ for the weaker building with and without noise (ψ=10)

responses quantities of interest, the maximum reduction in base shear response is minimal for the weaker building. The corresponding reduction in the base shear of the stronger building is always more than, the weaker building. For the reduction in maximum drift, the pattern of variation remains the same as that of the displacement; the maximum

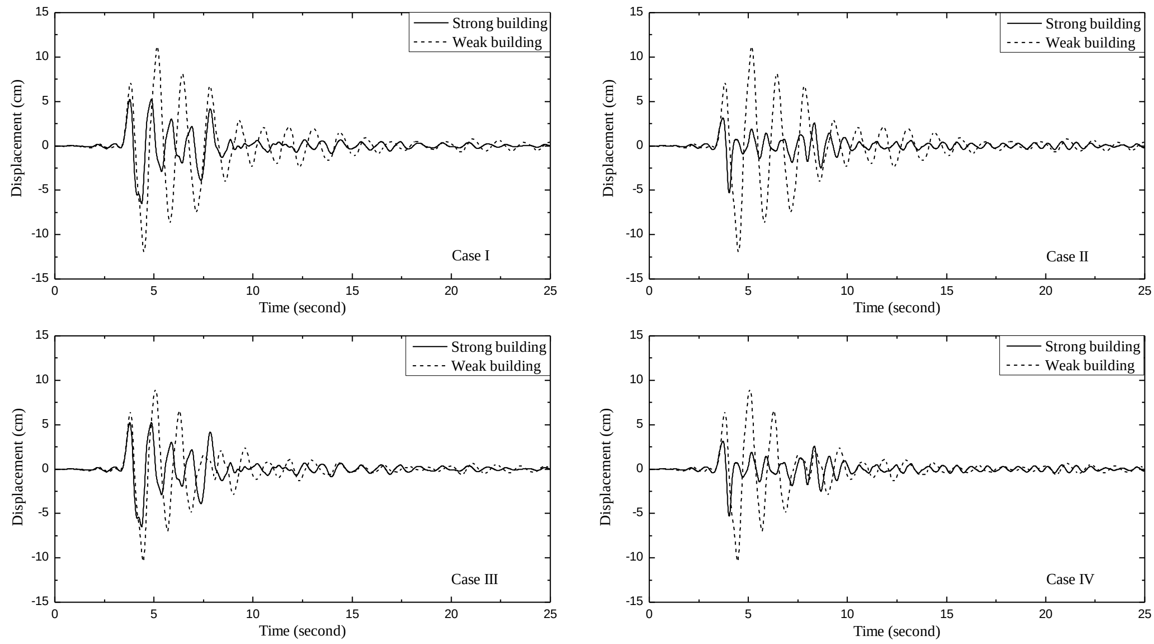

Fig. 14 Top floor displacements of stronger and weaker buildings under Northridge earthquake, 1994

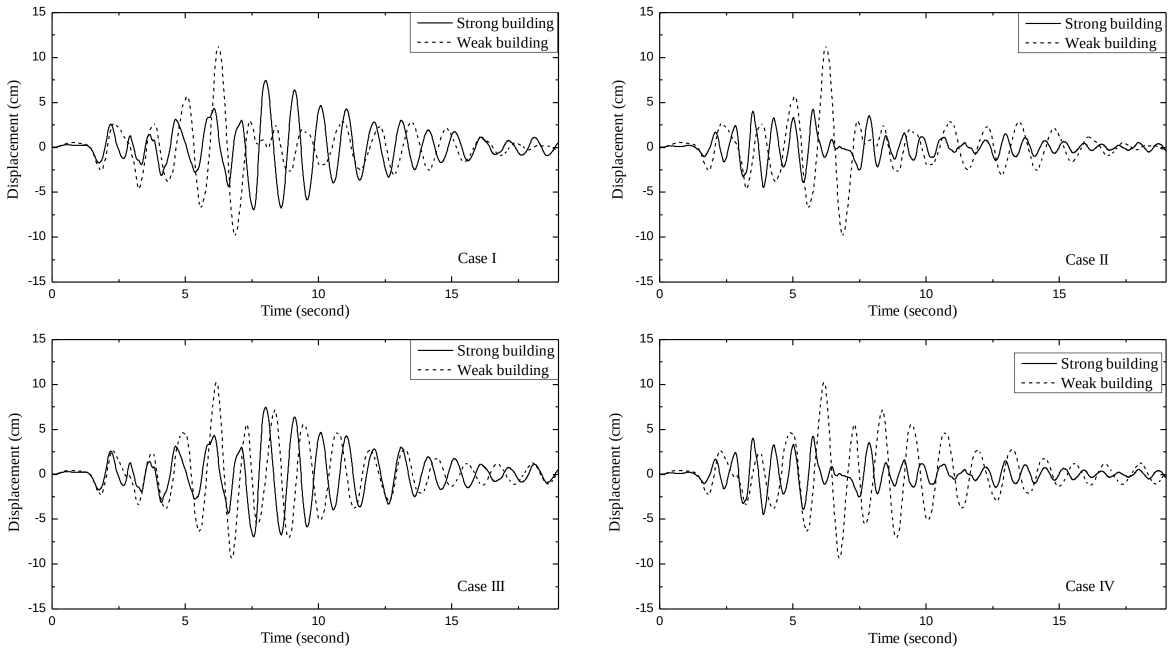

Fig. 15 Top floor displacements of stronger and weaker buildings under Kocaeli earthquake, 1990

reduction in response in the weaker building is always more, compared to that of the stronger building.

The number of dampers used to couple the two buildings also has a significant effect on the reduction of response for the weaker building; better response reduction for the weaker building is obtained with a greater number of dampers. Further, the reduction in response for the two earthquakes considered, are observed to be of same order.

The response reduction also varies according to the control algorithm adopted. The fuzzy logic controller is observed to be effective, as it provides maximum response reduction for both the buildings, at the optimum frequency ratio. Nevertheless, for certain cases, Passive-on control strategy also provides a similar reduction in responses.

The reason for relatively less reduction, even amplification, of response of the stronger building for certain frequency ratios is that it is stiffer than the weaker one. As a result, the weaker building shares some stiffness of the stronger building due to the coupling effect and thereby, undergoes less vibration compared to the uncoupled state of vibration. Moreover, the MR dampers as connectors between the two buildings dissipate seismic energy leading to less energy input due to the excitation and hence, less vibration of the buildings takes pace. Consequently, the weaker building always has a reduction in the response quantities. On the other hand, there is a loss

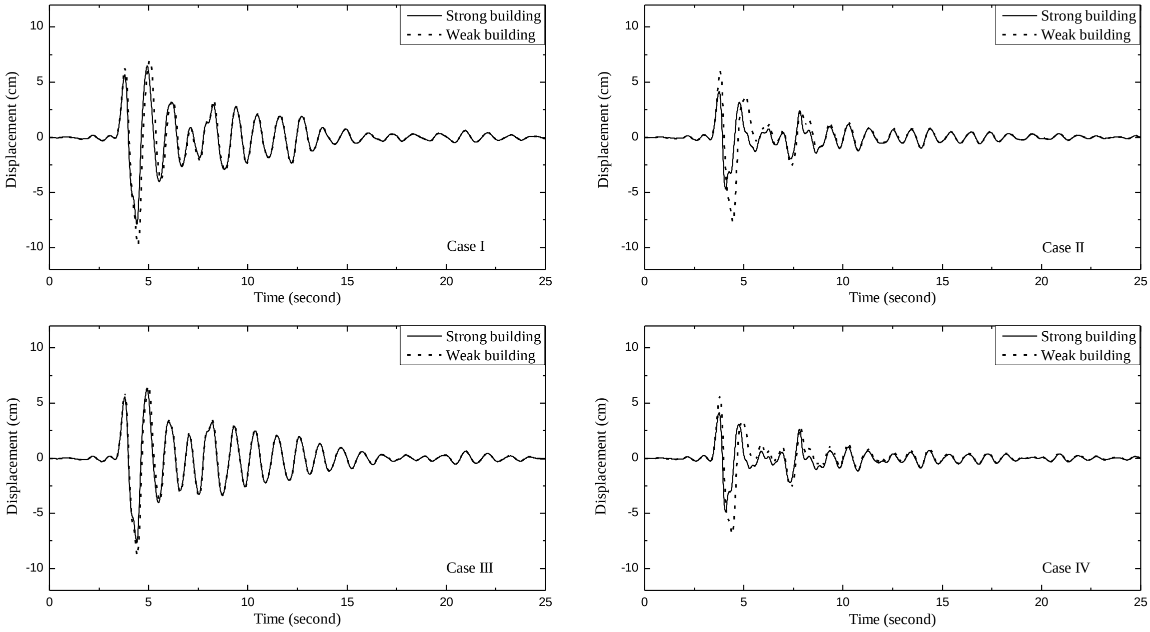

Fig. 16 Top floor displacements of stronger and weaker building coupled with MR dampers under Northridge earthquake, 1994

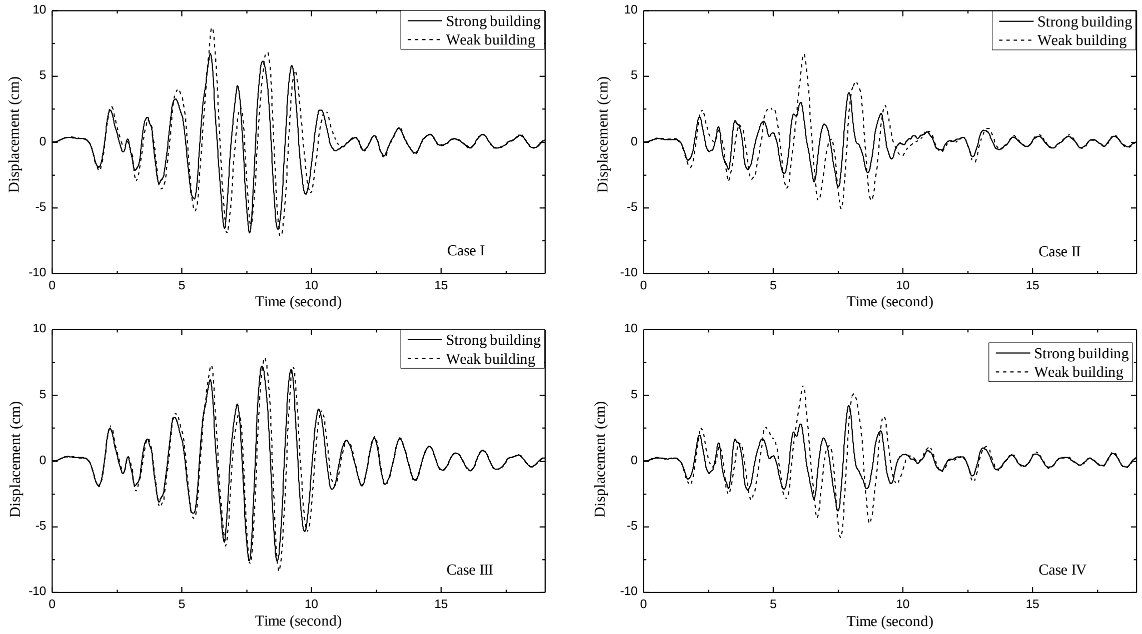

Fig. 17 Top floor displacements of stronger and weaker building coupled with MR dampers under Kocaeli earthquake, 1999

of stiffness in the stronger building due to sharing effect making it more flexible and therefore, it's response increases compared to the uncoupled state of vibration. However, there is a counteracting effect because of the dissipation of energy in the MR dampers. The net result is to decrease the reduction of response and if the stronger building is flexible, this may even amplify the response rather than controlling it.

4.1 Effect of noise on the response reduction

Measurement noise contamination may deteriorate the efficiency of the control algorithm in all feedback control strategies Therefore, the robustness of the algorithm and the damper efficiency should be tested for noise contamination. The noise contamination is assumed to be a white noise random process (Chen and Xu 2008).

$$\text{RMS (noise intensity)} = \frac{1}{\psi}\ \text{RMS (building response)} \tag{20}$$

The noise time histories will be added to the displacement and velocity time histories which are sent to the damper model and the fuzzy logic in the feedback loop. Results are shown for case IV of the study i.e., 30% weaker building connected to the stronger rigid building under Northridge earthquake. The case study is conducted with a single damper with ψ=20 and 10. Results are shown in Figs.

10-13.

From Figs. 10-13 it can be seen that the noise contamination does not affect the percentage reduction in response significantly. Compared to the weaker building, the stronger building is more affected by the noise contamination. In general, the MR damper performances as a coupling device were not affected significantly by the noise contamination.

4.2 Pounding control

Uncoupled weaker building response could be large during an earthquake. As a result, weaker building can pound against an adjacent building. The possibility of pounding depends upon two factors namely, unsynchronized vibrations of the two adjacent buildings and the gap provided between them. A minimum gap is required in order to avoid the pounding between the two buildings. Original building which becomes weaker was provided with a gap that could become insufficient for avoiding pounding. When the same weaker building is coupled with a stronger building with MR dampers, the possibility of pounding could be reduced due to (*i*) synchronous vibrations of the two buildings and (*ii*) the reduction of response of the weaker building. This is shown with the results of the numerical study. For this purpose, cases I-IV were investigated for unsynchronized/synchronous vibrations and minimum gap requirement

Figs 14 and 15 show the top floor displacement time histories of uncoupled weaker and stronger buildings under Northridge and Kocaeli earthquakes, respectively. It is seen from the figures that the vibrations of the uncoupled buildings are non-synchronous. As a consequence the two buildings can pound with each other if the minimum gap is less than the required one.

Figs. 16 and 17 show superposed graphs of the top floor displacements of stronger and weaker buildings coupled with MR damper under Northridge and Kocaeli earthquakes, respectively for all the four cases. The responses of the weaker and stronger buildings are totally synchronized, thereby reducing the possibility of pounding.

Tables 5-8 show the minimum required gap between the adjacent buildings to avoid pounding for the four cases. It is observed from the tables that coupling a weaker building with a stronger one can be very effective in reducing the minimum gap required to avoid pounding for all the four cases. The maximum reduction in the gap is obtained while using five dampers with an input voltage induced by the fuzzy logic controller. The percentage reductions of the minimum gap under Northridge earthquake are 71.20, 56.74, 76.84 and 69.74 for cases I, II, III and IV respectively. For Kocaeli earthquake, the percentage reductions of the minimum gap are 43.90, 52.62, 52.62 and, 50.57 for cases I, II, III and IV respectively.

5. Conclusions

The effectiveness of coupling weaker building with a stronger building is investigated for retrofitting the weaker building. The two buildings are coupled using different numbers of MR dampers. It is observed that the coupling strategy is very effective in retrofitting weaker building in terms of displacement, base shear, and drift responses. The coupling strategy is also effective in reducing the possibility of pounding between two adjacent buildings. Results of the numerical study lead to the following conclusions:

• Coupling a stronger building with a weaker building

Table 5 The minimum gap (cm) required to avoid pounding for case I

Earthquakes	Number of damper	Uncoupled	Passive-off V_{zero}	Passive-on V_{max}	Fuzzy logic controller
Northridge, 1994	1	12.78	11.54	07.82	07.80
	3	12.78	10.89	05.98	05.96
	5	12.78	09.80	03.71	03.68
Kocaeli, 1999	1	10.85	09.65	08.98	08.41
	3	10.85	08.41	08.06	07.31
	5	10.85	08.02	06.74	05.78

Table 6 The minimum gap (cm) required to avoid pounding for case II

Earthquakes	Number of damper	Uncoupled	Passive-off V_{zero}	Passive-on V_{max}	Fuzzy logic controller
Northridge, 1994	1	09.34	08.77	06.72	06.61
	3	09.34	08.41	05.19	05.16
	5	09.34	07.78	04.07	04.04
Kocaeli, 1999	1	12.30	10.97	10.22	09.76
	3	12.30	10.25	09.19	08.60
	5	12.30	09.15	07.71	06.90

Table 7 The minimum gap (cm) required to avoid pounding for case III

Earthquakes	Number of damper	Uncoupled	Passive-off V_{zero}	Passive-on V_{max}	Fuzzy logic controller
Northridge, 1994.	1	09.46	08.49	05.47	05.45
	3	09.46	07.96	03.99	03.96
	5	09.46	07.04	02.23	02.19
Kocaeli, 1999.	1	10.85	09.26	08.40	07.65
	3	10.85	08.51	07.35	06.38
	5	10.85	07.34	05.28	05.14

Table 8 The minimum gap (cm) required to avoid pounding for case IV

Earthquakes	Number of damper	Uncoupled	Passive-off V_{zero}	Passive-on V_{max}	Fuzzy logic controller
Northridge, 1994.	1	07.90	07.51	05.86	05.74
	3	07.90	07.27	04.62	04.57
	5	07.90	06.80	03.31	03.29
Kocaeli, 1999.	1	11.35	09.94	09.12	08.57
	3	11.35	09.14	07.99	07.29
	5	11.35	07.94	06.44	05.61

can be very effective for retrofitting the weaker building; knowing the ratio of the fundamental frequency between the two buildings, a rational decision can be made whether coupling strategy would be effective.

• In general, it is found that coupling a weaker building with a rigid stronger building decrease the response of both the weaker and stronger buildings, while coupling a weaker building with a flexible stronger building decrease the response of the weaker building at the expense of the increase in response of the stronger building; there exists a fundamental frequency ratio between the two buildings that provides the optimal results.

• A comparison between three control strategies namely, passive-off, passive-on and fuzzy logic controller, indicates that fuzzy logic controller is more effective.

• Except for passive-off controller, control of response improves with the increase in the number of dampers.

• Noise contamination doesn't significantly affect control of responses; however, the effect of noise contamination is comparatively more for the stronger building.

• The coupling strategy is effective in pounding hazard mitigation; this can be observed in the minimum gap reduction and the response synchronisation between the weaker and stronger buildings.

• As a perspective, experimental tests can be conducted on scaled or real models using shaking tables to complete the theoretical work accomplished in this study.

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