ASPS Conference Proceedings 1: 843-847 (2022)

Alwaha Sci. Publ. Services

Proceedings of

12th Structural Engineering Convention-An International Event (SEC 2022)

Available at https://asps-journals.com/index.php/acp

Seismic Response Analysis of Vertically Irregular RC Building with MR Dampers

Shivaji M. Dumne[1, *], M.K. Shrimali[2]

[1] Department of Applied Mechanics, Lecturer, Government Polytechnic, Nanded 431602, India
[2] Department of Civil Engineering, Professor, Malviya National Institute of Technology, Jaipur 302017, India

Paper ID - 060396

Abstract

Seismic hazard mitigation has become one of the emerging problems in structural engineering therefore; many researchers have been studied on seismic performance of reinforced concrete structures having vertically regular and irregular. It is noted that vertically irregular structures are more prone to hazards due to earthquake. The recent emerging trend is to use active, passive, semi-active controls that aid in keeping the responses of structures in permissible. The most dynamically varied semi-active damper is a Magneto-Rheological (MR) damper which is used in this study to control the seismic responses. In the present study, four different models with and without MR dampers of which three models are vertically irregular in height are subjected to four realistic ground motions. The governing equation of motion for various building models is solved numerically by New mark's step-by-step integration method. The dynamic behaviour of semiactive MR damper has been predicted by modified Bouc-Wen model. This study employed the Lyapunov direct approach as a control algorithm for stability analysis and design of MR controller. The responses of various building models are simulated through MATLAB®computing software. The study observed that considerable reduction in seismic responses of models with MR dampers is obtained as compared to respective building models without control. It is also observed that responses of building models are influenced by the vertical irregularities in mass and stiffness of building models.

Keywords: Seismichazard, Building models, vertically irregular, MR Damper, MATLAB software, Response analysis, Response mitigation,

1. Introduction

From the recent past decades, significant damages of civil structures have been caused by seismic hazards which have been underscored to rethink about traditional seismic design philosophy, Therefore, structural community pursued towards earthquake resistant of structures through concept of aseismic design approach which becomes an obvious option. The aseismic design approach involves installation of additional devices to reduce the effect of natural hazards. This approach is supplemented by control devices through various control systems such as passive, active and semiactive or combination of them. The same has been pursued effectively by researchers and being implemented to large scale in practices to ensure the structures to be safe. Large amount of energy is released at the instance of occurrence then reaches in structures and produces seismic force on structure [1]. The responses of different types are depends on factors like plan symmetry and non-symmetry. The non-symmetrical plans produce torsion in the structure [2]. The detailed study of structures symmetric in plan but having irregularity in mass and stiffness along the height has studied by the various researchers and reported exhaustively [3]. The effect of vertical irregularities on seismic response has studied and stated that it produces enough counteracting force to resist the earthquake force [4]. Traditionally the responses of vertically symmetric and non-symmetric structures are also controlled by increasing the strength and stiffness of horizontal force resisting members like columns and shear walls [5]. The response control in full scale irregular building using MR damper has been studied and observed that an effective reduction in structural response has obtained [6]. The modern trend is to use different controls that is, active control, passive control, semi-active control or its combination i.e. hybrid control. A semiactive control involves the controllable fluid and hasattracted a great deal of attention in recent years as it operates with few watts of power and continues to work as a passive device when the control algorithm fails [7]. The detail study of MR dampers and its working mechanism in different capacity along with its performance in wide range under variety of ground motion[8]. The semiactive MR damper is preffered over ER damper for its robust working in variety of operational conditionsand dynamic variation [9]. A model has proposed to predict the dynamic behaviour of MR damper, referred as phenomenological model that can effectively predicts the response over wide range of operating conditions [10]. The specific objectives are (1) Seismic response analysis of considered building models without MR control/damper (2) Seismic response analysis of same models with MR control (3) Observe the functioning of MR damper under different stiffness and mass variations. (4) Comparative study of peak responses of various building models without and with semiactive MR damper or control.

*Corresponding author. Tel: +919422873345; E-mail address: smdumne@gmail.com

Proceedings of the 12th Structural Engineering Convention (SEC 2022), NCDMM, MNIT Jaipur, India| 19-22 December, 2022

© 2022 The authors. Published by Alwaha Scientific Publishing Services, ASPS. This is an open access article under the CC BY license.

Published online: December 19, 2022
doi:10.38208/acp.v1.592

2. Structural Model of Building Model

For the present study, four building model are considered. Each of the models is ten storey shear building with symmetry in plan but specific modifications to each model in vertical. Total mass at each floor level is 325.51 MT while total stiffness of each floor is 8203125.00 KN and modal damping ratio for each mode is 0.05. Each of models is subjected to four realistic time histories such as Imperial Valley, 1940, Loma Prieta, 1989, Kobe, 1995 and Northridge, 1994. First of four models is regular with mass and stiffness distribution on each floor is similar. Second model has reduced mass, to 60% of corresponding mass on fifth floor of first model. Model 3 has reduced to 80% of corresponding stiffness of fifth floor (weak storey) of first model and Model 4 has reduced to 80% of corresponding stiffness of first floor (bottom soft storey) of first model. Two types of analysis performed i.e. one uncontrolled response analysis where these models vibrate freely under influence of four seismic excitations. Second, controlled response analysis where MR dampers are placed on all floors of three models and top nine floors (no damper on bottom soft storey) of model 4. These four models are also excited by the same four ground motions. The models of building are idealized as linear shear type building with lateral degrees-of-freedom at their floor levels. This model is assumed to remain in linear elastic state therefore does not yield under unidirectional earthquake. Further, it is assumed that there is no spatial variation of ground motion and any effect due to soil-structure interaction is neglected.
The governing equation of motion for multi degrees-of-freedom building with damper is expressed in matrix form as,

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]\{r\}\ddot{u}_g + [D_p]\{f_d\} \qquad (1)$$

where, $[M]$, $[C]$ and $[K]$ are the matrices of mass, damping and stiffness of damper connected building respectively, $\{u\} = \{u_1, u_2, u_3, \ldots, u_n\}$,$\{\dot{u}\}and\{\ddot{u}\}$are the vectors of floor displacement, velocity and acceleration respectively with respect to the ground, $\{r\}$is the vector of influence coefficient consisting all elements equal to one, $\ddot{u}_g$ is the ground acceleration due to earthquake, $[D_p]$ is the matrix of damper position, $\{f_d\}$ is the vectors of damper force.

2.1. Computation of MR Damper Force

The MR dampers are similar to regular hydraulic damper except MR fluid. The MR fluids in which suspensions of micron-sized, magnetisable particles in an appropriate carrier liquid. Normally, MR fluid is free flowing liquid having a consistency similar to that of motor oil. However, in the presence of an applied magnetic field, these particles acquire a dipole moment, aligned with the external field that causes particle forming linear chains parallel to the field as shown in figure 1. This phenomenon can solidify the suspension and restrict the fluid movement as a result yield strength is developed. The degree of change is related to the magnitude of applied magnetic field and control law which control the external power supply to MR damper. The phenomenological model that describes the actual working of MR damper, herein modified Bouc-Wen model has been used. The damper force predicted by Modified Bouc-Wen Model [10] is

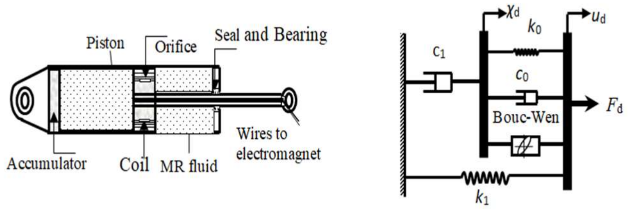

Fig. 1 (a) Schematic view of MR damper (b) Modified Bouc-Wen Model

The equation of damper force predicted by this model is

$$f_d = c_1\dot{x} + k_1(u_d - x_0) \qquad (2)$$

$$\dot{z} = -\gamma\left|\dot{u}_d - \dot{x}\right|(z)\left|z\right|^{(n-1)} - \beta(\dot{u}_d - \dot{x})\left|z\right|^{n} + A_d(\dot{u}_d - \dot{x}) \qquad (3)$$

$$\dot{x} = \left\{\frac{1}{(c_0 + c_1)}\right\}\{\alpha_0 z + c_0\dot{u}_d + k_0(u_d - x) \qquad (4)$$

where, u_d is the damper displacement with respect to ground; x is an internal pseudo-displacement of damper; z is the hysteretic displacement of damper that accounts for history dependence of response; k_1 is the accumulator stiffness; c_0 is introduced to control the viscous damping of damper at large velocities, c_1 is the viscous damping used to produce non-linear roll-off in the force-velocity loop at low velocities; $k_0$is introduced to control the stiffness of damper at large velocities; x_0 is the initial displacement of linear spring k_1; $\alpha_0$is the evolutionary coefficient and γ, β, n and A_d are the damper parameters that controls the shape of hysteresis loop and dot (·) represents the differentiation with respect to time. The model parameters are depends on command voltage, c_0, c_1, α_0 are expressed respectively as

$$c_0 = c_{0a} + c_{0b}U \quad (5)$$

$$c_1 = c_{1a} + c_{1b}U \qquad (6)$$

$$\alpha_0 = \alpha_{oa} + \alpha_{ob}U \quad (7)$$

Where, U is the output of first order filter and is given by the following equation

$$\dot{U} = -\eta(U - V) \qquad (8)$$

An Eq. (8) is necessary to model the dynamics in reaching rheological equilibrium and in driving the electromagnet in the MR damper. A small time lag exists between the command signals and damper force due to inductance in coil of electromagnet. This time lag is modeled by first-order filter equation between the maximum commands voltage applied (V_{max}) and output of first-order filter *(U)* using time constant ($1/\eta$) of first order filter.

For the solution of differential equation of motion, we transform the time variant equation to state space by using the derivative of state space variable parameter$\dot{z}$.

$$\{\dot{z}(t)\} = [A]\{z(t)\} + [B_d]\{f_d(t)\} + [E]\ddot{u}_g(t) \quad (9)$$

Where, z is the state variable, A is the system matrix composed of mass, stiffness and damping, B_d is the damper distribution matrix and E is the matrix of excitation force and are explicitly given as

$$\dot{z} = \begin{bmatrix} \dot{u} \\ \ddot{u} \end{bmatrix};\quad z = \begin{bmatrix} u \\ \dot{u} \end{bmatrix};\quad A = \begin{bmatrix} O & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix};$$

$$B_d = \begin{bmatrix} O \\ M^{-1}D_p \end{bmatrix},\quad E = \begin{bmatrix} O \\ -r \end{bmatrix}$$

Where, $[I]$ and $[O]$ are the identity and null matrices, respectively; vector $\dot{z}$ (t) is the state variable of structural system which contains relative velocity and acceleration response with respect to ground.

In this analysis, the Lyapunov direct theory is employed as control algorithm for stability analysis and design of semiactive controller. The fundamental philosophy of Lyapunov direct approach is "if total energy of the system is continuously dissipated, then system must eventually settle down to equilibrium". This approach requires the use of Lyapunov function L ({Z}) which must be a positive definite function of the state of system {Z}. According to this theory, if the rate of change of function $\dot{L}(\{Z\})$ is negative, semi-definite function, then system is stable in the sense of Lyapunov. Thus, the goal, in determining the appropriate control law, is that to choose input that will make $\dot{L}$ as much negative as possible. An infinite no of Lyapunov functions could be selected, resulting in variety of control laws. In this approach, a Lyapunov function is chosen in the form as below for present problem as

$$(\{Z\}) = \frac{1}{2}\|Z\|^2{}_P \quad (10)$$

The term $\frac{1}{2}\|Z\|^2{}_P$is the p-norm of state as defined by $\|Z\| = [\{ZT\}[PL]\{Z\}]^{1/2}$where [PL] is real, symmetric, positive definite matrix and in case of linear system, to ensure $\dot{L}$as negative definite term found $[P_L]$ is found out from the Lyapunov equation as below

$$[A^T][P_L] + [P_L][\,A\,] = -[\,Q_P\,] \quad (11)$$

For a positive definite matrix, $[Q_P]$ is considered as a unit matrix for the present problem. The derivative of Lyapunov function for the solution of state space is

$$\dot{L} = -\frac{1}{2}\{Z^T\}[Q_P]\{Z\}+\{Z^T\}[P_L][B_d]\{f_d\}+\{Z^T\}[P_L][E]\ddot{u}(12)$$

For stability, the equation (9) need to be minimised (made as negative), the only term which can directly be affected by change in control voltage is the middle term containing $\{f_d\}$. The control voltage from control law supplied to MR driver is restricted either to ' 0 ' or ' 1 ' max corresponding to a fixed set of states. Thus for min of (9), the control law is given by

$$V=V_{max}H(\{-Z^T\}[P_L][B_d]\{f_d\}) \quad (13)$$

Where H (.) is the heavy side step function and when has non zero value, full command voltage ($V=V_{max}$) is supplied, else voltage is 'zero'(V = 0).

3. Numerical Study

For numerical study, four RCC building models are considered as described earlier. These models are excited under same four realistic ground motions. The mass of each story of building models is considered as 325.51 MT while l stiffness of each floor is 8203125.00 KN/m and modal damping ratio for each mode is 0.05. This model is subjected to four unidirectional excitation due to a real Imperial Valley, 1940, Loma Prieta, 1989, Kobe, 1995 and Northridge, 1994. The maximum command voltage supplied to the current driver of MR damper is 6V and base shear (B_{sy}) is normalized by weight of respective building. The building models are assumed to be in linear elastic state therefore does not yield during excitation. The peak response parameters of interest are, top floor displacement (u_f), top floor acceleration (a_f), normalized storey shear (S_{sy}/W), and storey drift (u_r).

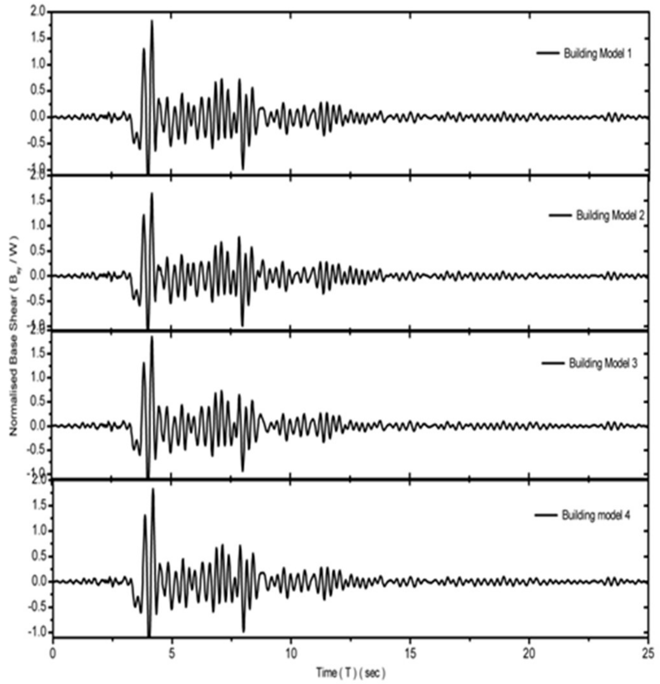

Fig.2 Time varying uncontrolled base shear response for building models under North Ridge-1994Earthquake

Table 1 Comparative study of peak uncontrolled peak responses for buildings models under various EQs

Earthquake	Model	Peak Accl^n (g)	Percentage change	Peak Displ. (cm)	Percentage change	Peak Storey shear (kN)	Percentage change
Imperial valley	1	1.0658	0	1.916	0	0.761	0
	2	1.1298	-6.005	1.917	-0.020	0.7402	2.734
	3	1.0494	1.539	1.91	0.339	0.7447	2.142
	4	1.075	-0.864	1.925	-0.459	0.7592	0.237
Loma - Prieta	1	1.5912	0	3.041	0	1.2867	0
	2	1.6453	-3.399	2.907	4.416	1.2134	5.697
	3	1.5915	-0.019	3.088	-1.542	1.2727	1.088
	4	1.5899	0.082	3.056	-0.483	1.283	0.288
Kobe	1	2.2454	0	4.037	0	1.6242	0
	2	2.167	3.492	3.692	8.557	1.4551	10.42
	3	2.2418	0.161	4.134	-2.402	1.6082	0.985
	4	2.2567	-0.504	4.061	-0.587	1.6239	0.019
Northridge	1	2.3408	0	4.259	0	1.8317	0
	2	2.2029	5.892	3.809	10.57	1.6472	10.08
	3	2.4257	-3.63	4.501	-5.694	1.8726	-2.233
	4	2.3738	-1.409	4.288	-0.695	1.8305	0.066

The time varying response analysis is performed for responses of storey displacement, storey acceleration and normalised base shear that is base shear divided by weight of regular model. Figure 2 shows a typical plot of time varying uncontrolled response of normalised base shear using Origin software for all the models excited by North Ridge earthquake (EQ) only.

The uncontrolled peak responses of each model are observed. Further, peak responses of model 2, 3 and 4 are compared with the peak responses of model 1 in terms of percentage change are shown in Table 1.

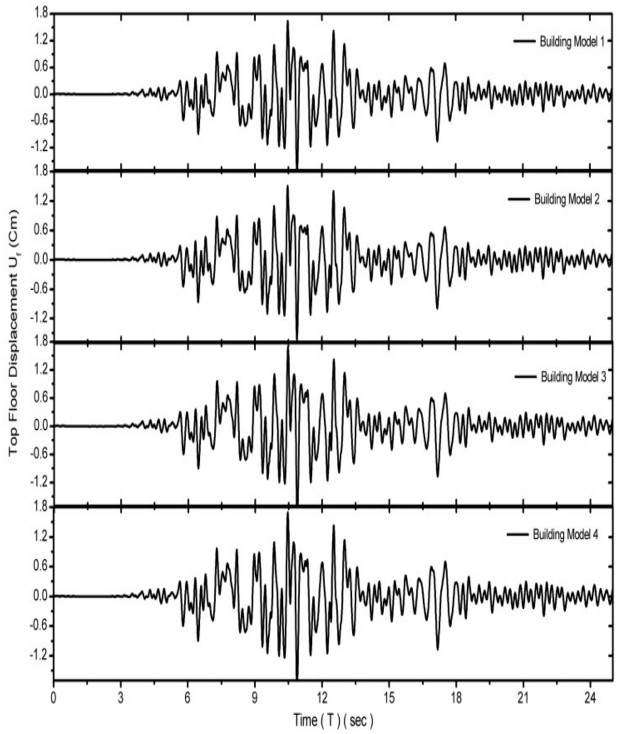

Fig.3 Time varying controlled top floor displacement response of building models with MR damper under Loma Prieta-1989 EQs

Table 2 Comparative study of peak responses of building models with and without MR dampers under various EQs

Earthquake	Model	Peak Accl^n (g)	Percentage change	Peak Displ. (cm)	Percentage change	Peak Storey shear (kN)	Percentage change
Imperial Valley	1	1.048	0	1.245	0	0.554	0
	2	1.078	-2.901	1.173	5.721	0.515	7.025
	3	1.008	3.760	1.262	-1.374	0.545	1.6780
	4	1.046	0.191	1.281	-2.885	0.558	-0.723
Loma - Prieta	1	1.524	0	1.763	0	0.887	0
	2	1.379	9.517	1.633	7.413	0.824	7.117
	3	1.555	-2.035	1.844	-4.572	0.893	-0.699
	4	1.624	-6.583	1.821	-3.278	0.890	-0.429
Kobe	1	1.474	0	2.137	0	1.059	0
	2	1.392	5.584	1.926	9.861	0.967	8.680
	3	1.496	-1.493	2.216	-3.716	1.063	-0.369
	4	1.526	-3.555	2.19	-2.495	1.062	-0.303
Northridge	1	1.773	0	2.957	0	1.499	0
	2	1.725	2.696	2.663	9.956	1.372	8.496
	3	1.812	-2.160	3.073	-3.937	1.52	-0.834
	4	1.819	-2.639	3.032	-2.533	1.506	-0.447

This study also performed the same building models with control using MR dampers as described in the problem are excited under same realistic earthquakes. The peak responses i.e. peak acceleration, peak displacement and peak storey shear of each building models are analysed and results are tabulated in the Table 2. From the results, it is observed that the peak values of responses for model 3 and4has better response reduction whereas model 2 as comparative to other building models. Further, it is concluded that model 2 works effectively during excitation due to four earthquakes.

The time varying response analysis is carried out for controlled top floor displacement response of building models with MR damper under Loma Prieta-1989. The figure 3 shows a typical accelerogram using Origin software of time varying top storey displacement response for all the models excited under Loma Prieta time history.

Typical plot using Origin software for normalised damper force, that is, damper force/weight of building against the displacement of damper of top floor for all the four models under Kobe earthquake is shown in figure 4. The closed loop is also referred as energy loop and area enclosed under the energy loop signifies the amount of energy dissipated. From the shape of energy loop, one can conclude that shape of all the loops almost is similar; it means that damper is functioning well and stable under different stiffness and mass variations. The force and displacement characteristics denote that area under loop is max for building model 4 while least for building model 2.

Further, a comparative study of the peak responses at various floor levels of the uncontrolled vibration of models respectively with controlled vibration of models under influence of various seismic excitations. The percentage change in controlled response with uncontrolled responses of various building models under Imperial Valley earthquake. The responses such as peak floor displacement (P_{uf}), peak floor acceleration (P_{af}), peak storey drift (P_{ur}) and storey shear (S_{sy}) are compared and results are shown in Table 3.

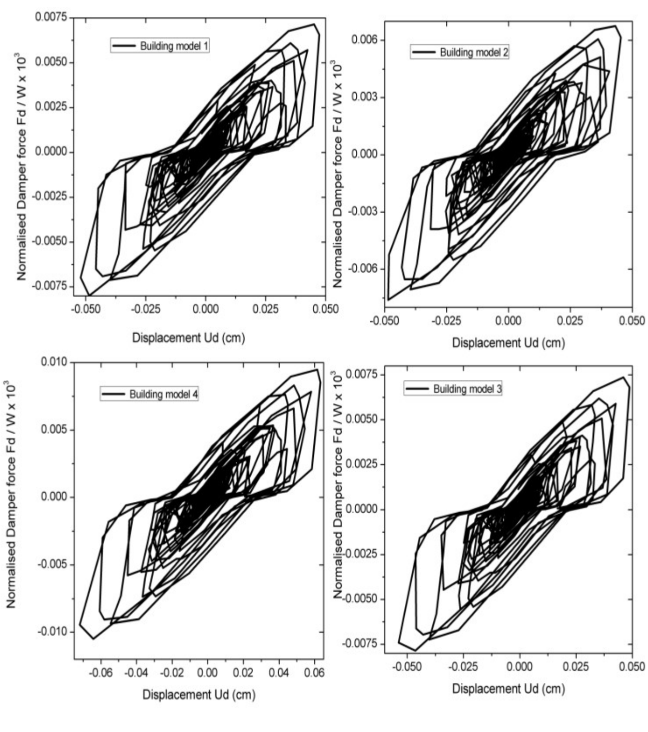

Fig.4 Force displacement diagram of top floor MR damper for various building models under Kobe-1995 Earthquake

Table 3Percentage change in controlled response with uncontrolled responses of various building models under Imperial Valley earthquake

Model-1				
Floor	P_{uf}	P_{af}	P_{ur}	S_{sy}
1	35.0	1.7	6.0	-0.9
2	35.6	3.7	11.4	1.7
3	6.6	9.9	17.6	5.6
4	38.8	20.5	23.6	10.0
5	39.8	29.0	29.4	14.1
6	41.7	36.8	33.9	17.5
7	43.6	40.8	38.2	20.9
8	45.3	29.0	42.1	24.1
9	47.0	13.0	45.7	26.2
10	48.5	-4.3	48.6	27.2

Model-2				
Floor	P_{uf}	P_{af}	P_{ur}	S_{sy}
1	38.8	4.6	10.9	6.8
2	39.3	10.2	15.0	8.2
3	40.3	17.8	20.4	11.4
4	41.8	26.0	26.5	15.5
5	43.6	33.5	31.5	18.2
6	45.6	39.7	36.9	22.5
7	47.6	37.2	41.5	25.9
8	49.4	13.9	45.4	28.4
9	51.0	13.3	48.7	30.0
10	52.3	1.2	51.3	30.4

Model-3				
Floor	P_{uf}	P_{af}	P_{ur}	S_{sy}
1	33.9	3.9	9.6	0.6
2	34.5	3.5	14.6	3.2
3	35.5	6.9	19.7	6.2
4	36.9	16.5	23.0	9.5
5	38.6	25.5	27.4	13.1
6	41.0	35.7	32.4	17.2
7	43.0	36.3	37.2	20.9
8	44.9	26.5	41.5	23.8
9	46.7	12.5	45.2	25.8
10	48.4	-6.4	48.4	26.9

Model-4				
Floor	P_{uf}	P_{af}	P_{ur}	S_{sy}
1	33.5	2.7	1.8	-0.7
2	34.3	3.8	10.9	3.5
3	35.4	11.5	17.3	7.4
4	36.9	21.8	22.9	11.0
5	38.7	28.9	28.0	14.3
6	40.6	35.6	32.7	17.2
7	42.4	38.8	37.1	20.6
8	44.2	27.5	41.1	23.5
9	45.8	11.4	44.6	25.5
10	47.4	-5.4	47.7	26.5

The comparative results for peak uncontrolled and controlled responses respectively for all the four models have been shown in table 3 and outline of study results are observed as

For Imperial Valley earthquake, it can be concluded that average percentage control in displacement response for model 1, 3, 4 is about 35% while that for model 2 is about 40%. Thus reduction in mass brings displacement response under control. Further, percentage control in displacement response for North Ridge Eq. is steady about 30%.

- For of Loma Prieta earthquake, an average percentage control in displacement response for model 1, 2, is about 43% while that for model 3, 4 is about 40%.
- For Kobe earthquake, it is observed that average percentage control in displacement response for model 1, 2, 3, 4 is about 47%, it means mass and stiffness irregularity doesn't affect response control
- The percentage response for peak storey drift, peak storey acceleration and peak storey shear vary from storey to storey. It thus concludes that percentage control is directly proportional to the distance of storey from base or ground.
- The displacement response control for both building model 3 and model 4 of building is similar, thus for displacement response control, location of the stiffness irregularity has limited effect.
- For building model 4, no controls were provided in the bottom weak storey; this also seems to have little effect on displacement response. Further, similar type of conclusions for storey shear could be drawn.
- From the results, it can be concluded that percentage response control for building model with mass irregularity (reduction in mass) is more than that of others.
- The effect of mass on displacement response is directly related that is, as floor mass reduces then responses also reduces and vice-versa.
- The reduction in stiffness at mid height of building frame affects adversely and inversely
- From this hysteresis loop one can conclude that more amount of work is required to be done by the damper in dissipating the energy.

4. Conclusion

An over view of this study in which entire study is undertaken in three parts, first part of uncontrolled response analysis, second of controlled response analysis and third of comparative study analysis of uncontrolled and controlled response is presented then the following conclusions are drawn

1. Reduction in stiffness increases the response storey drift of all the floors situated above the regular floor.
2. Presence of soft story at the ground floor is not recommended from the result of seismic response reduction consideration.
3. The use of MR dampers resulting to most effective control over the response reduction of all building models as compared to the respective uncontrolled building models.
4. For all types of building models, most effective control over the displacement response is 52.3% under the Imperial Valley earthquake.
5. It also concludes that MR damper required lesser amount of damping force to dissipate more energy in controlling theseismic responses of building; it means that it works functionally well.

Disclosures

Free Access to this article is sponsored by SARL ALPHA CRISTO INDUSTRIAL.

References

1. Housner GW, Bergman LA, Caughey TK, Chassiakos AG, Claus RO, Masri SF, Skelton RE, Soong TT, Spencer BF, Yao JTP. Structural control: past, present and future. Journal of Engineering Mechanics, ASCE, 1997; 123(9): 897-971.
2. Bharti SD, Dumne SM, Shrimali MK. Seismic response analysis of asymmetric RC building with MR dampers. Engineering Structures, 2010; 12: 2122-2133.
3. Costa AG, Oliveira CS, Duarte RT. Influence of vertical irregularities on seismic response of buildings. Tokyo - Kyoto, Japan, Proceeding Ninth World Conf. on Earthquake Engineering, 1988: 491-496.
4. Chintanapakdee C, Chopra AK. Seismic Response of Vertically Irregular Frames: Response History and Modal Pushover Analysis. Journal of Structural Engineering, ASCE: 2004.
5. Al Ali A, Krawinkler H. Effects of Vertical Irregularities on Seismic Behaviour of Building Structures. Report no. 130, Stanford USA.: The John A. Blume Earthquake Engineering Center, Department of Civil and Environmental Engineering Stanford University. 1998.
6. Yoshida O, Dyke SJ. Response Control in Full - scale Irregular Building Using MR damper. *Journal of Structural Engineering, ASCE,* 2003.
7. Symans MD, Constantinou MC. Semiactive control systems for seismic protection of structures: state-of-the-art review. Engineering Structures, 1999; 21:469-487.
8. Yang G, Spencer Jr BF, Carlson JD, Sain MK. Large-scale MR fluid dampers: modeling and dynamic performance considerations. Engineering Structures, 24: 2002:309-323.
9. Kori JG, Jangid R. Semi Active MR Dampers for Seismic control of structures. Bulletin of the NewZealand Society for Earthquake Engineering volumne, 2009:42-63 .
10. Spencer BF, Dyke SJ, Sain MK., Carlson JD. Phenomenological Model for Magneto-Rheological Damper. Smart Materials and Structures, 2005:707-714.