Control of Base Isolated Benchmark using Combined Control Strategy with Fuzzy Algorithm Subjected to Near-Field Earthquakes

H. Shariatmadar[1], Mozhgansadat Momtazdargahi[2]

1- Associated Professor, Department of Civil Engineering, Faculty of Engineering, Ferdowsi University of Mashhad, Iran

2- Master Student, Department of Civil Engineering, Faculty of Engineering, Ferdowsi University of Mashhad, Iran

Shariatmadar@um.ac.ir
momtazdargahi.1991@stu.um.ac.ir

Abstract

The Purpose of control structure against earthquake is to dissipate earthquake input energy to the structure and reduce the plastic deformation of structural members. There are different methods for control structure against earthquake to reduce the structure response that they are active, semi-active, inactive and hybrid.
In this paper two different combined control systems are used first system comprises base isolator and multi tuned mass dampers (BI & MTMD) and another combination is hybrid base isolator and multi tuned mass dampers (HBI & MTMD) for controlling an eight story isolated benchmark steel structure. Active control force of hybrid isolator is estimated by fuzzy logic algorithms. The influences of the combined systems on the responses of the benchmark structure under the two near field earthquake (Newhall & Elcentro) are evaluated by nonlinear dynamic time history analysis.

Applications of combined control systems consisting of passive or active systems installed in parallel to base-isolation bearings have the capability of reducing response quantities of base-isolated (relative and absolute displacement) structures significantly. Therefore in design and control of irregular isolated structures using the proposed control systems, structural demands (relative and absolute displacement and ect) in each direction must be considered separately.

Keywords: Base Isolated benchmark structure, Multi Tuned Mass Dampers, Hybrid Isolators, Nearfield Earthquake, Fuzzy Algorithm

1. INTRODUCTION

The response reduction of structures to dynamic loadings like earthquake and wind loads has been a subject of study for many decades. Therefor there is a need to use structural control method for decreasing response and damage in structures. Structural control methods are divided into several categories including passive, active, semi-active and hybrid control systems [1]. Passive systems have been extensively used because of easy application, high reliability and low cost. One of these inactive systems is base isolator Although the response quantities of a fixed-base building are reduced substantially through base isolation, the base displacement may be excessive, particularly during near-field ground motions [2]. So using other complementary system to improve the seismic behavior of asymmetric base isolated structure is required

Tuned mass damper (TMD) is one of the oldest passive control devises which was first used by Frahm [3]. Following him, many studies were done for determining optimum parameters of TMD and also MTMD for decreasing the structural response. However, passive systems have some deficiencies like limited control.

Active control force in a hybrid base isolator can be generated by different control algorithms. In the last few years, application of smart control algorithms like fuzzy has been increased. Because of its ability to handle nonlinearities, independency on mathematical model and its inherent robustness. Structural control with hybrid base isolator through FLC has attracted the extensive attention of researchers during the recent years Tsai [4] Investigated effect of mass dampers to reduce lateral displacement of 5-story base isolated structure. He noticed that mass dampers have very little effectiveness in reducing the structural response during the initial seconds. Kareem [5] focused on the dynamic analysis of isolated structures under the effect of the wind. The results show that locating mass dampers ,Whether in high or the lowest level of structure lead to a reduction in the structural response. However, placing TMD in lowest level is more effective. Taniguchi ,Kiureghian and Melkumyan [6] researched on the effect of the mass damper set on isolated structures and determined the optimal parameters of TMD's. They showed that adding TMD to the structure causes, 15 to 25 percent reduction in structure response. However in near field earthquake this number decreases to 10 percent.

Although the combined systems have been successfully applied in many engineering problems , But Review of past researches showed that less attention has been paid to the combination of hybrid base isolators with multiple mass dampers. In this paper, two versions of a combined control systems are developed and applied to a benchmark base-isolated building model. The first system comprises base isolator and multi tuned mass dampers and another combination is hybrid base isolator and multi tuned mass dampers. The tuned mass dampers are distributed in this order that once 50% of TMD placed on roof level (story -8) and next 50% on base level (TB), in second distribution 25% of TMD placed on roof level (story-8), 25% is on story 7 and 50% placed on base level (B78), in both x and y directions. Mass dampers are set to first mode of superstructure. Active control force of hybrid isolator is estimated by fuzzy logic algorithms. Performance of the proposed controllers, for seismic attenuation, is evaluated by by nonlinear dynamic time history analysis simulations using the smart base-isolated benchmark building [7-9]

Finally, the influences of the combined systems on the responses of the benchmark structure included relative and total displacement, of structure under the 2 near field earthquake (Newhall, Elcentro) are evaluated. Results show that multi inactive control systems (BI & MTMD) control the relative displacement of structure well in most of the cases, although it is difficult to conclude a general result for absolute displacement responses. Additionally multi active control systems (HBI & MTMD) are capable to fulfil some structural needs like absolute displacement, however their affection degree for decreasing relative displacement is variable. Therefore in design and control of irregular isolated structures using the proposed control systems, structural demands (acceleration, displacement and …) in each direction must be considered separately.

2. STRUCTURAL MODEL

The benchmark structure is a base-isolated eight-story, steel-braced framed building, 82.4-m long and 54.3-m wide, The floor plan is L-shaped as shown in Fig.1. The superstructure is modeled as a three dimensional linear elastic system. The superstructure members, such as beam, column, bracing, and floor slab are modeled in detail. Floor slabs and the base are assumed to be rigid in plane. The superstructure and the base are modeled using three master degrees of freedom (DOF) per floor at the center of mass. The combined model of the superstructure (24 DOF) and isolation system (3DOF) consists of 27 degrees of freedom. All twenty four modes in the fixed base case are used in modeling the superstructure. The superstructure damping ratio is assumed to be 5% in all fixed base modes. The nominal isolation system consists of 61 nonlinear isolation bearings (friction pendulum or (LRB) and 31 linear elastomeric bearings.

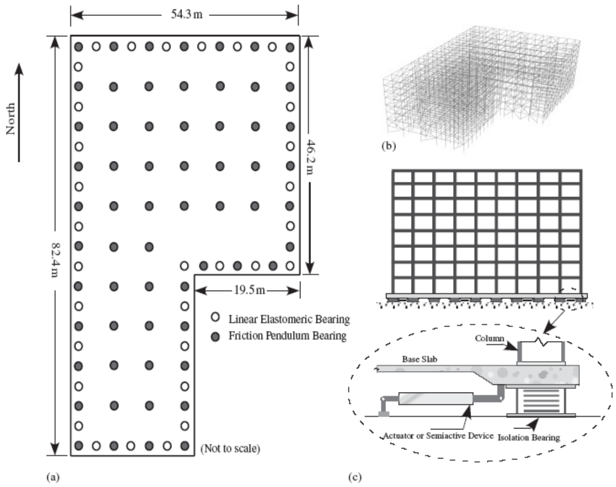


Figure 1. Base isolated benchmark

In this paper, the drivers are assumed to be fully active. They are placed in six specific locations, including the corners and center of mass of the base. At each location, there are two controllers—one in the x-direction and the other in the y-direction.

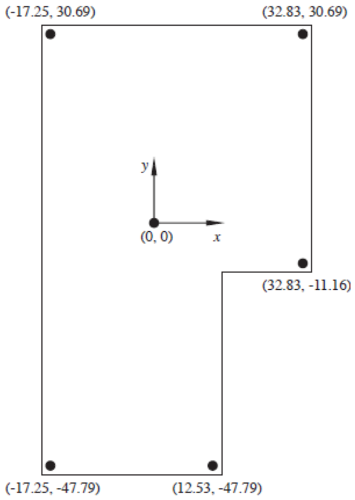


Figure 4. Location of actuators in benchmark structure.

Consider a nonlinear base-isolated building structure as shown in Figure 1. For the control design and because the mathematical model of the benchmark structure is very complicated and cannot be used directly for control purposes [9], a dynamic model composed of two coupled subsystems, namely, the main structure or superstructure (Sr) and the base isolation (Sc), is employed. The equations of motion for the elastic superstructure are expressed in the following form:

$$\mathbf{M}_{n\times n}\ddot{\mathbf{U}}_{n\times 1}+\mathbf{C}_{n\times n}\dot{\mathbf{U}}_{n\times 1}+\mathbf{K}_{n\times n}\mathbf{U}_{n\times 1}=-\mathbf{M}_{n\times n}\mathbf{R}_{n\times 3}(\ddot{\mathbf{U}}_{\mathrm{g}}+\ddot{\mathbf{U}}_{\mathrm{b}})_{3\times 1} \tag{1}$$

In which, n is three times the number of floors (excluding base), M is the superstructure mass matrix, C is the superstructure damping matrix in the fixed base case, K is the superstructure stiffness matrix in the fixed base case and R is the matrix of earthquake influence coefficients, i.e. the matrix of displacements and rotation at the center of mass of the floors resulting from a unit translation in the X and Y directions and unit rotation at the center of mass of the base. Furthermore, Ü, Ú and U represent the floor acceleration velocity and displacement vectors relative to the base, $\ddot{\upsilon}_b$ is the vector of base acceleration relative to the ground and $\ddot{\upsilon}g$ is the vector of ground acceleration. The equations of motion for the base are as follows:

$$\mathbf{R}^{\mathrm{T}}_{3\times n}\mathbf{M}_{n\times n}[(\ddot{\mathbf{U}})_{n\times 1}+\mathbf{R}_{n\times 3}(\ddot{\mathbf{U}}_{\mathrm{g}}+\ddot{\mathbf{U}}_{\mathrm{b}})_{3\times 1}]_{n\times 1}+\mathbf{M}_{\mathrm{b}_{3\times 3}}(\ddot{\mathbf{U}}_{\mathrm{g}}+\ddot{\mathbf{U}}_{\mathrm{b}})_{3\times 1}+\mathbf{C}_{\mathrm{b}_{3\times 3}}\dot{\mathbf{U}}_{\mathrm{b}_{3\times}}+\mathbf{K}_{\mathrm{b}_{3\times 3}}\mathbf{U}_{\mathrm{b}_{3\times 1}}+\mathbf{f}_{\mathrm{B}_{3\times 1}}+\mathbf{f}_{\mathrm{c}_{3\times 1}}=0 \tag{2}$$

in which, Mb is the diagonal mass matrix of the rigid base, Cb is the resultant damping matrix of viscous isolation elements, Kb is the resultant stiffness matrix of elastic isolation elements and f is the vector containing the nonlinear bearing and device forces, and control forces. Eqn. (2) can be reformulated in the modal domain and the fixed base frequencies, damping ratios, and modes can be used for modeling the superstructure, the state space equations can be formulated as:

$$\dot{\mathrm{X}}(t)=\mathbf{A}\mathrm{X}(t)+\mathrm{Bu}(t)+\mathrm{E}\ddot{\mathrm{U}}_g(t)=\mathrm{g}(\mathbf{X},\mathrm{u},\ddot{\mathrm{U}}_g) \tag{3}$$

$$\mathrm{A}=\begin{bmatrix} 0 & \mathrm{I} \\ -\overline{\mathrm{M}}^{-1}\overline{\mathrm{K}} & -\overline{\mathrm{M}}^{-1}\overline{\mathrm{C}} \end{bmatrix},\ \mathrm{B}=\begin{bmatrix} 0 \\ \mathrm{I} \end{bmatrix},\ \mathrm{E}=\begin{bmatrix} 0 \\ -\left\{ \begin{matrix} \mathrm{MR} \\ \mathrm{R}^T\mathrm{MR}+\mathrm{M}_b \end{matrix} \right\} \end{bmatrix}. \tag{4}$$

$$\overline{\mathrm{M}}=\begin{bmatrix} \mathrm{M} & \mathrm{MR} \\ \mathrm{R}^T\mathrm{M} & \mathrm{R}^T\mathrm{MR}+\mathrm{M}_b \end{bmatrix},\ \overline{\mathrm{C}}=\begin{bmatrix} \mathrm{C} & 0 \\ 0 & \mathrm{C}_b \end{bmatrix}, \tag{5}$$

$$\overline{\mathrm{K}}=\begin{bmatrix} \mathrm{K} & 0 \\ 0 & \mathrm{K}_b \end{bmatrix},\ \mathrm{u}=\begin{bmatrix} 0 \\ \mathrm{f} \end{bmatrix} \tag{6}$$

In the present study, FLC has been designed using two input variables each one having three upper and three lower membership functions (MFs), and one output variable with seven upper and seven lower MFs. The upper and lower MFs chosen for the input and output variables are triangular shaped and have been defined on the common interval [-1,1]. These MFs are shown in Figures 2 and 3, respectively. The fuzzy variables used to describe the fuzzy space are defined in table 1.

Table 1: Fuzzy variables

Membership function	Variable	Definition
Input	P	Positive
	Z	Zero
	N	Negative
Output	PB	Positive Big
	PM	Positive Medium
	PS	Positive Small
	Z	Zero
	NS	Negative Small
	NM	Negative Medium
	NB	Negative Big

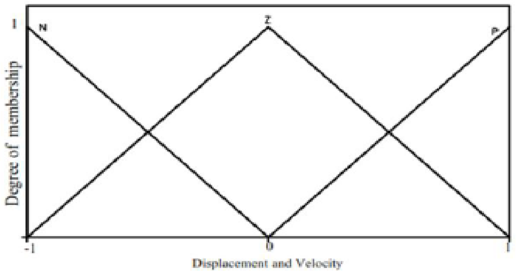


Figure 2. MFs of input variables (displacement and velocity)

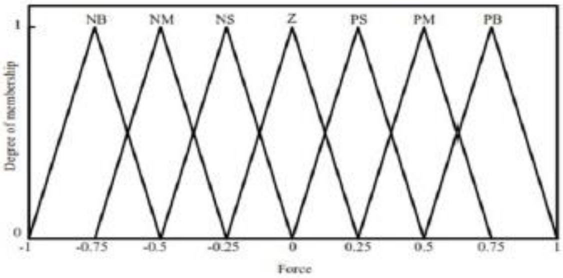


Figure 3. MFs of output variable (active control force)

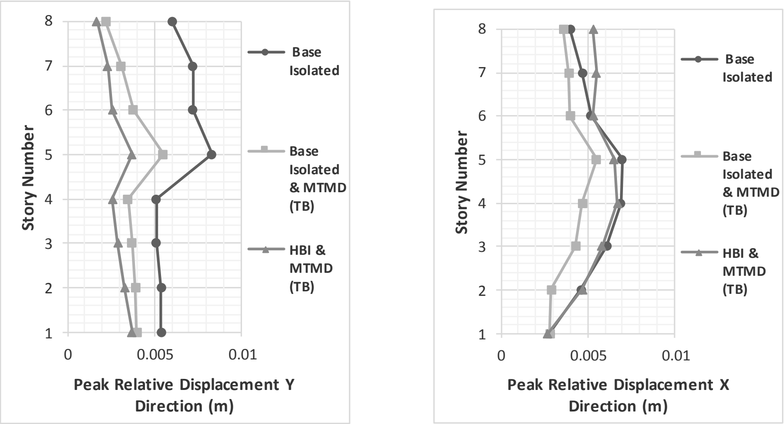
Displacement and velocity of the drivers chosen as input variables of controller for the FLC design. These input variables help in generating the inference rule base. In this study, the inference rules have been developed by expert's knowledge and are shown in Table 2

Table 2: Inference rules for the FLC

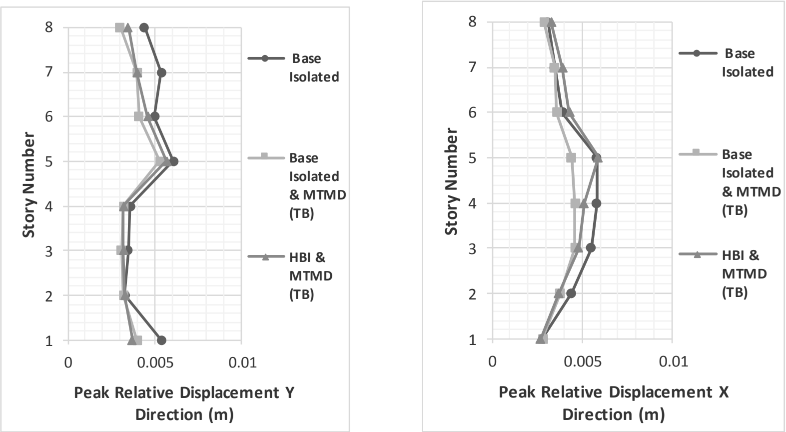
	Velocity		
Displacement	N	Z	P
N	PB	PM	PS
Z	PS	Z	NS
P	NS	NM	NB

3. NUMERICAL RESULTS

The controlled benchmark structure is simulated for four earthquake ground accelerations defined in the benchmark problem (Newhall, El Centro, Rinaldi, Kobe). All the excitations are used at the full intensity. In this paper, only the simulation results of two earthquakes (Newhall and Elcentro) are considered ,this is due to the similarity of the results of the other two ground accelerations.The peak displacement response of relative and absolute displacement of the floors with proposed control systems were compared in different cases including: base isolated, base isolated with MTMD and hybrid base isolated with MTMD through type-1 FLC .These results along with peak response reductions (Response reduction $=\left\{\frac{(\text{Uncontrolled response} - \text{Controlled response})}{\text{Uncontrolled response}} * 100\right\}$) are also presented in Tables 3 for different control systems only for newhall record, in x and y direction respectively

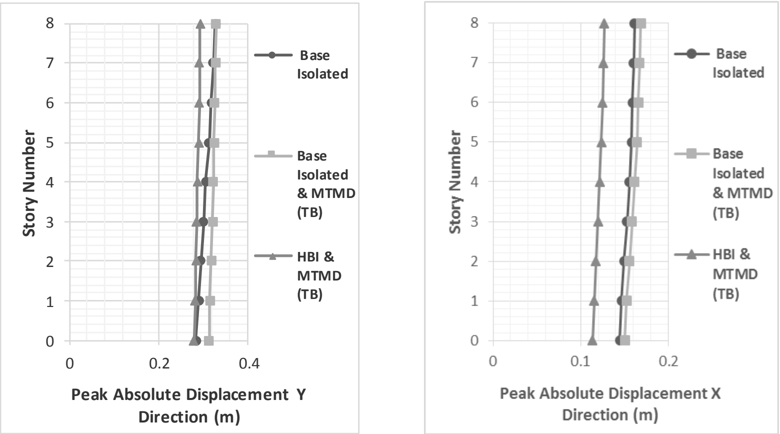


Newhall earthquake

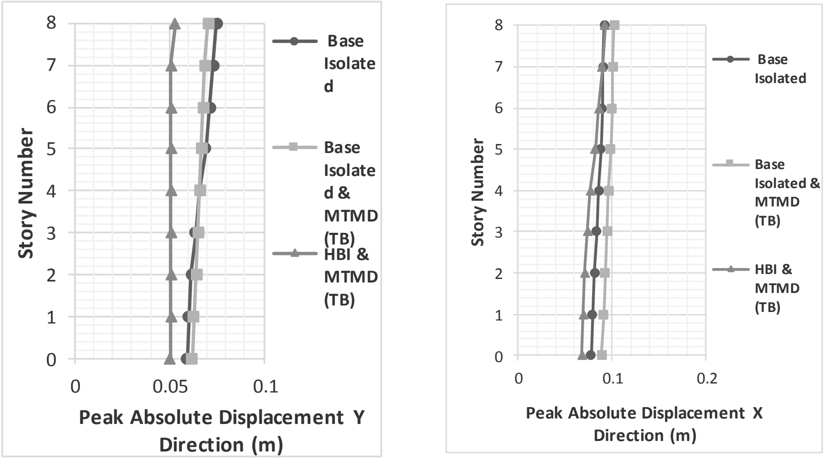


Elcentro earthquake

Figure 4. peak relative displacement responses of floors



Newhall earthquake



Elcentro earthquake

Figure 5. peak absolute displacement responses of floors

Table 3: Peak response and peak response reduction of absolute displacement using different control systems (Newhall X and Y direction)

X Direction

Story Number	Base Isolated	Base Isolated & MTMD (TB)	HBI & MTMD (TB)	Base Isolated & MTMD (TB) (%)	HBI & MTMD (TB) (%)
8	0.1614	0.1684	0.127	-4.337%	21.314%
7	0.1604	0.1672	0.1259	-4.239%	21.509%
6	0.1592	0.1658	0.1248	-4.146%	21.608%
5	0.1578	0.1642	0.1236	-4.056%	21.673%
4	0.1554	0.1614	0.1217	-3.861%	21.686%
3	0.1527	0.1586	0.1196	-3.864%	21.676%
2	0.1496	0.1554	0.1173	-3.877%	21.591%
1	0.1467	0.1525	0.1152	-3.954%	21.472%
Base	0.1445	0.1502	0.1135	-3.945%	21.453%
TMD Top	-	0.2203	0.2282		
TMD Bottom	-	0.1762	0.1772		

Y Direction

Story Number	Base Isolated	Base Isolated & MTMD (TB)	HBI & MTMD (TB)	Base Isolated & MTMD (TB) (%)	HBI & MTMD (TB) (%)
8	0.3273	0.3286	0.2928	-0.397%	10.541%
7	0.3236	0.328	0.2924	-1.360%	9.642%
6	0.3188	0.3268	0.2915	-2.509%	8.563%
5	0.3134	0.3252	0.2902	-3.765%	7.403%
4	0.3056	0.3226	0.2878	-5.563%	5.825%
3	0.3005	0.3206	0.286	-6.689%	4.825%
2	0.2954	0.3183	0.284	-7.752%	3.859%
1	0.29	0.3158	0.2817	-8.897%	2.862%
Base	0.2846	0.3129	0.2791	-9.944%	1.933%
TMD Top	-	0.3538	0.3098		
TMD Bottom	-	0.362	0.3253		

It is seen from the Table 3 that actuators reduce the base isolated peak displacement response of the floors and base about 21% in x direction (for the Newhall earthquake) and and 10% maximum in y direction (for the Newhall earthquake. But MTMD does not reduce the peak absolute displacement and in some cases increases it up to 20% (for Elcentro earthquake) .This feature of hybrid base isolators in reducing the peake displacement of floors is revealed in the time history responses. Comparison of displacement time history responses of the top floor for different control systems compared to uncontrolled response when subjected to Newhall earthquake is presented in Figure 8. As shown in Figure 8, the controlled time response of displacement can be significantly decrease in HBI controller compared to the history responses obtained by MTMDs.

Time-history plots

Figures 5–7 show the time-history plots of various response quantities for the uncontrolled building, and the building with robust active controllers. Figure 4 shows the ground acceleration for this earthquake. It is observed from these figures that the absolute displacement of combined system with actuators in base can be effectively reduced compared with the uncontrolled case and MTMDs.

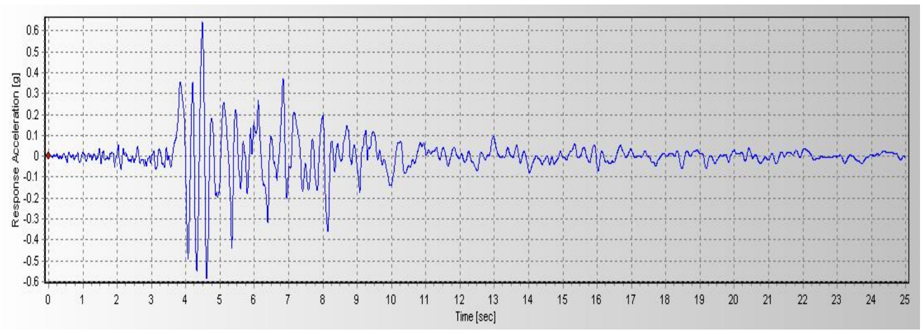


Figure 6. 1994 Newhall earthquake, ground acceleration.

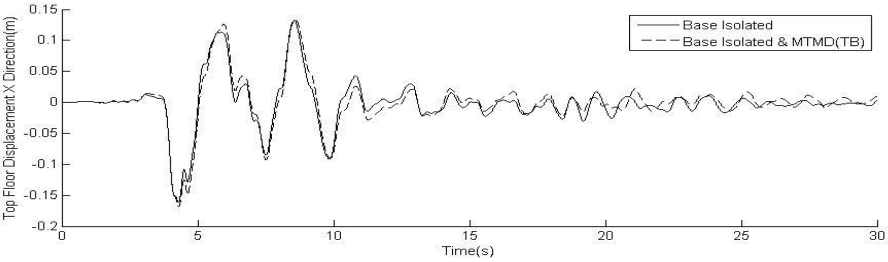


Figure 7. Time history of the base isolated building and base isolated with MTMD under Newhall excitation. Absolute displacement of top storey in the x-direction

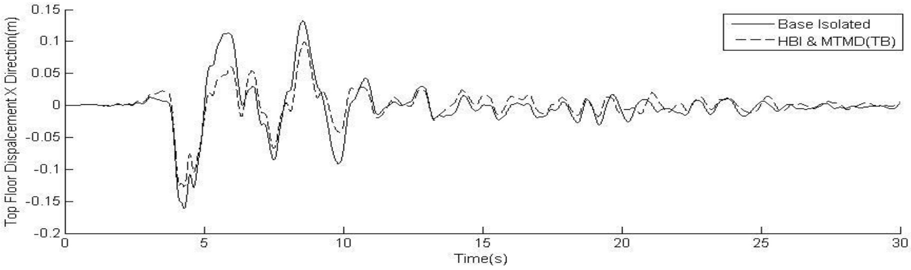


Figure 8. Time history of the base isolated building and Hybrid base isolated with MTMD under Newhall excitation. Absolute displacement of top storey in the x-direction

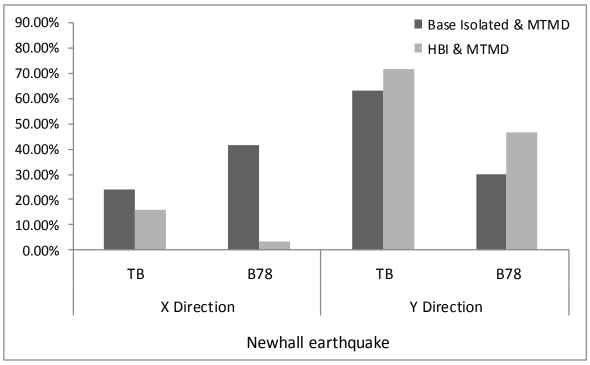


Figure 8.Maximum reduction percentage of relative displacement of floors

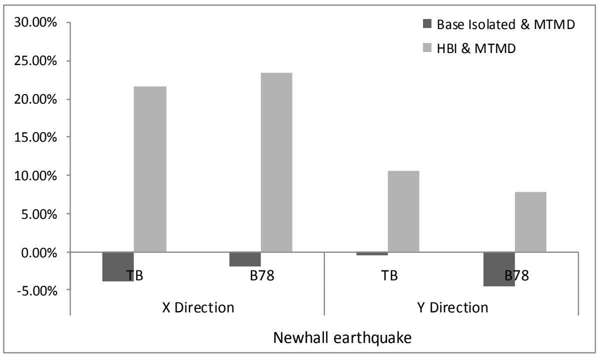


Figure 8.Maximum reduction percentage of absolute displacement of floors

It is seen that inactive multi controllers (BI & MTMD) significantly decrease the relative displacement , but their performance in reduction of absolute displacement is limited. The benefit of the active control strategy is the reduction in base displacements of up to 21% without an increase in drift..For the base-isolated buildings, superstructure drifts are reduced significantly (up to 70%) using MTMDs compared with the corresponding uncontrolled structure.

4. CONCLUDING REMARKS

Combined control systems are proposed for the benchmark problem that utilizes the complimentary behavior of MTMD and active actuators elements. This control strategy arrangement has been shown to be effective in mitigation of seismic loads on civil engineering structures. Results show that multi inactive control systems (BI & MTMD) control the relative displacement of structure well in most of the cases, although it is difficult to conclude a general result for absolute displacement responses. Additionally multi active control systems (HBI & MTMD) are capable to fulfil some structural needs like absolute displacement, however their affection degree for decreasing relative displacement is variable. Therefore in design and control of irregular isolated structures using the proposed control systems, structural demands (acceleration, displacement and ect) in each direction must be considered separately.

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