TUNED MASS DAMPER ON BASE-ISOLATED BUILDING UNDER NEAR-FAULT EARTHQUAKES

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ABSTRACT

The effectiveness of a tuned mass damper provided at the top floor level of a base-isolated building subjected to near-fault earthquake ground motions is investigated. Since the near-fault earthquake ground motion consists of limited number of large acceleration pulses, it can be represented as sine-pulse. The buildings are modelled as shear-type structures considering four cases such as: conventional fixed-base building (FB), base-isolated building (BIS), building installed only with a tuned mass damper (STMD), and base-isolated building installed with a tuned mass damper (BI+TMD) referred to as the hybrid-passive structure. The investigation involved modelling of the buildings of varying heights ranging from five storeys to twenty storeys subjected to real near-fault earthquake ground motions. Time history analyses are carried out to study the variation of the top floor acceleration, top floor displacement and base-shear. A parametric study is also conducted to investigate the effects of isolation time period and isolation damping. It is concluded that, base isolation technique is quite effective in reducing the seismic response in terms of top floor acceleration up to eight storey buildings. However, response reduction reduces as the number of storeys increases, especially when time periods of the non-isolated building and that of the base-isolated building are nearly the same. On the other hand, considerable seismic response reduction is achieved for the buildings greater than sixteen storeys when a tuned mass damper is installed. The hybrid-passive system results in higher response reduction than the other two passive control systems for the eight to sixteen storey buildings. With increase in isolation time period, the structural response in terms of peak top floor acceleration and peak normalised base shear does not show as much variation as it does in case of the peak top floor displacement, which increases substantially. With increase in damping of the isolator, the response quantities namely, peak bearing displacement, peak top floor acceleration, and peak normalized base shear reduce. It is observed that, the dynamic response obtained for the near-fault ground motions and short duration pulses are quite similar.

INTRODUCTION

Base isolation works on the principle of decoupling of superstructure from earthquake ground motion. Further, the flexibility in lateral direction introduced by the base isolation shifts the fundamental time period of the structure to a larger value than the time period of fixed-base (FB, i.e. non-isolated) structure. Fundamental frequency of a base-isolated structure (BIS) is much lower than that of the FB [1]. Owing to the reduced stiffness, floor accelerations are controlled while top floor displacements and base displacements increase.

Tuned mass damper (TMD) is a device consisting of a mass attached to the structure via a spring-dashpot system, such that it oscillates at the same frequency as the main structure (resonance), however with 180° phase shift. The system dissipates energy due to the relative motion developed between the mass of the TMD and the structure.

The aim of using base isolation and TMD together in a structure, called hybrid-passive system (BI+TMD) is to effectively control both, the acceleration response and excessive displacement. Basic dynamic properties of the BI+TMD are mass ratio (μ_t) and tuning of the TMD; sensitivity of and interaction between isolator and TMD needs to be accounted for. The TMD parameters such as μ_t and tuning ratio are adjusted to ensure effectiveness. Resulting from the three sub-systems i.e. the structure, the TMD and the isolators, the hybrid-passive structure is non-classically damped.

The common feature of earthquake ground motions in the near-fault region is the presence of a limited number of large acceleration pulses occurring in the form of a shock, rather than a gradual build-up and a velocity pulse with a long period component as well as a large displacement [2]. The BIS is considered vulnerable to near-fault ground motions owing to possible matching of major frequency contents [3, 4]. Dynamic behaviour of both the

BIS and the FB under the near-fault motion has already been extensively studied [5, 6]. However, very few studies are reported for dynamic response of the hybrid-passive structure such as the BI+TMD [7, 8]. Therefore, it is important to study the effects of such pulse-type ground motions on long time period structures such as the BI+TMD.

In view of the above, the primary objective of the study is to investigate effectiveness of a tuned mass damper on the BIS in controlling the accelerations and large displacements under near-fault earthquakes. The specific objectives of the study include: (1) to investigate the number of storeys for which the BI+TMD is the most effective under near-fault earthquakes; (2) to further carryout parametric study for investigating effects of (a) variation in number of storeys, (b) variation in time period of base isolation, and (c) variation in damping of base isolation; and (3) to compare the response of base-isolated structures under near-fault earthquake with sine-pulse motion.

MATHEMATICAL MODELLING

Mathematical models of (a) FB; (b) BIS; (c) STMD; (d) BI+TMD considered in the study are shown in Fig. 1. Numerical study is carried out to find the range of number of stories for which the hybrid-passive system is comparatively the most efficient, by modelling the four types of structures from five storeys to twenty storeys. Key parameters are identified for further investigation, such as the time period of isolation and damping of base isolation. Assumptions made in the study are: (1) mass is lumped at each floor level; (2) one lateral degree of freedom at each floor level is considered; and (3) soil-structure interaction is neglected. In this study, laminated rubber bearing (LRB) is considered for base isolation, and single TMD at top floor level is considered to be attached.

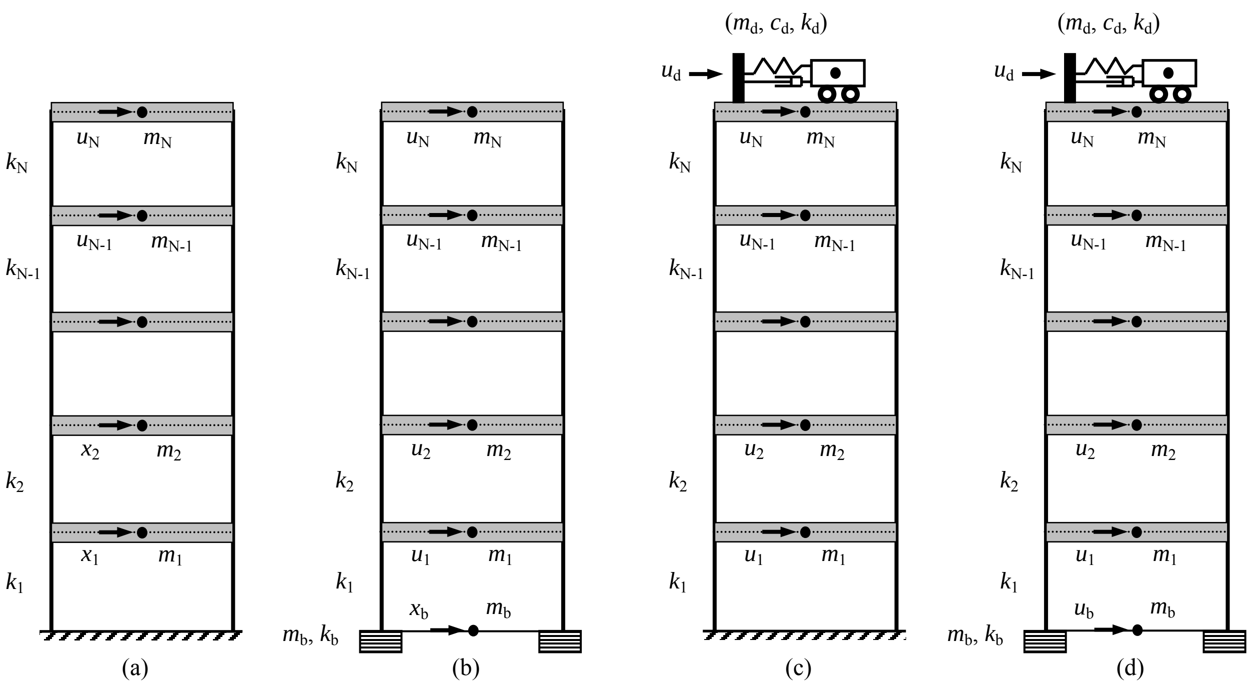

Fig. 1: Mathematical models of *N*-storey (a) fixed-base structure (FB), (b) base-isolated structure (BIS), (c) structure with a TMD (STMD), and (d) hybrid-passive structure (BI+TMD)

Conventional fixed-base structure (FB)

The general equation of motion for a FB (non-isolated) subjected to a horizontal ground motion is described here. The displacement of the ground is denoted by u_g, the total (or absolute) displacement of the mass m_j by u_j^t, and the relative displacement between this mass and the ground by u_j. Hence, the acceleration, velocity, and displacement are the resultant of motion of ground and superstructure, due to the earthquake. At each instant of time these displacements are related by,

$$u_j^t(t) = u_j(t) + u_g(t) \tag{1}$$

The governing differential equation of motion, Eq. 2 for a FB (non-isolated) subjected to a horizontal ground motion hence can be written as,

$$[M_s]\{\ddot{u}(t)\} + [C_s]\{\dot{u}(t)\} + [K_s]\{u(t)\} = -[M]\{r\}\ddot{u}_g(t) \tag{2}$$

where, $[M_s]$, $[C_s]$, and $[K_s]$ are the mass, damping, and stiffness matrices of the superstructure, respectively; $\{\ddot{u}\}$, $\{\dot{u}\}$, and $\{u\}$ are the acceleration, velocity, and displacement vectors, respectively; $\{r\}$ is the influence coefficient vector. Total mass of the structure is, $M = \sum m_j$.

Base-isolated structure (BIS)

The displacements in the BIS are related as in Eq. 3, where, u_j is the relative floor displacement at j^{th} floor with respect to the isolator, u_b is the displacement of the isolator and m_b is the mass of the isolator.

$$u_j^t(t) = u_j(t) + u_b(t) + u_g(t) \tag{3}$$

The general governing equation of motion, Eq. 4 for the BIS is given by,

$$[M_b]\{\ddot{u}^t(t)\} + [C_b]\{\dot{u}^t(t)\} + [K_b]\{u^t(t)\} = -\{\overline{M}_b\}\ddot{u}_g(t) \tag{4}$$

where,

$$[M_b] = \begin{bmatrix} m_N & \cdots & 0 & 0 & m_N \\ \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & \cdots & m_2 & 0 & m_2 \\ 0 & \cdots & 0 & m_1 & m_1 \\ 0 & \cdots & 0 & 0 & m_b \end{bmatrix} \tag{5}$$

$$[K_b] = \begin{bmatrix} k_N & -k_N & \cdots & 0 & 0 \\ -k_N & k_N + k_{N-1} & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & k_2 + k_1 & 0 \\ 0 & 0 & \cdots & -k_1 & k_1 + k_b \end{bmatrix} \tag{6}$$

$$\{\overline{M_b}\} = [M_b]\{r\} = \{2m_N \quad 2m_{N-1} \quad \cdots \quad 2m_2 \quad 2m_1 \quad m_b\}^T \tag{7}$$

Structure with tuned mass damper (STMD)

Consider a FB having a TMD of mass m_d , damping c_d and stiffness k_d attached at the top floor. The mass, damping, and stiffness of the superstructure are same as described earlier. The equation of motion, Eq. 8 for the STMD is,

$$[M_t]\{\ddot{u}(t)\} + [C_t]\{\dot{u}(t)\} + [K_t]\{u(t)\} = -\{\overline{M}_t\}\ddot{u}_g(t) \tag{8}$$

where, $\{\ddot{u}\}$, $\{\dot{u}\}$, and $\{u\}$ are vectors of horizontal acceleration, velocity, and displacement, respectively, relative to the ground, with components for the TMD and the superstructure. The mass and stiffness matrices for the system can thus be written as,

$$[M_t] = \begin{bmatrix} m_d & 0 & \cdots & 0 & 0 \\ 0 & m_5 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & m_2 & 0 \\ 0 & 0 & \cdots & 0 & m_1 \end{bmatrix} \tag{9}$$

$$[K_t] = \begin{bmatrix} k_d & -k_d & \cdots & 0 & 0 \\ -k_d & k_d + k_5 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & k_3 + k_2 & -k_2 \\ 0 & 0 & \cdots & -k_2 & k_2 + k_1 \end{bmatrix} \tag{10}$$

The damping matrix of the superstructure is not known explicitly. It is constructed by assuming the modal damping ratio in each mode of vibration for superstructure, which is kept constant. Ratio of mass of TMD to that of the superstructure is called mass ratio (μ_t).

Hybrid-passive structure (BI+TMD)

With all mathematical notations same as mentioned in the preceding paragraphs, the governing differential equation of motion, Eq. 11 for the BI+TMD can be written as,

$$[M_h]\{\ddot{u}^t(t)\} + [C_h]\{\dot{u}^t(t)\} + [K_h]\{u^t(t)\} = -\{\overline{M}_h\}\ddot{u}_g \tag{11}$$

where,

$$[M_h] = \begin{bmatrix} m_d & 0 & \cdots & 0 & m_d \\ 0 & m_N & \cdots & 0 & m_N \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & m_1 & m_1 \\ 0 & 0 & \cdots & 0 & m_b \end{bmatrix} \tag{12}$$

$$[K_h] = \begin{bmatrix} k_d & -k_d & \cdots & 0 & 0 \\ -k_d & k_d + k_5 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & k_2 + k_1 & 0 \\ 0 & 0 & \cdots & -k_1 & k_1 + k_b \end{bmatrix} \tag{13}$$

$$\{\overline{M}_h\} = \{2m_d \quad 2m_N \quad 2m_{N-1} \quad \cdots \quad 2m_2 \quad 2m_1 \quad m_b\}^T \tag{14}$$

where, $[M_h]$ is a diagonal matrix with diagonal element $m_{jj} = m_j$, mass lumped at the j^{th} floor.

NUMERICAL STUDY

Seismic response of (a) FB; (b) BIS; (c) STMD; and (d) BI+TMD for 5, 8, 12, and 20 storeys is investigated under real near-fault earthquake ground motions. Earthquake motions selected for the study are Imperial Valley, 1979 recorded at Array#5; normal component of 1992 Landers earthquake recorded at Lucerne Valley; normal component of 1992 Northridge earthquake recorded at Rinaldi station; and normal component of 1992 Northridge earthquake recorded at Sylmar station. The peak ground accelerations (PGA) of Imperial Valley, Landers, Northridge (Rinaldi), and Northridge (Sylmar) earthquake motions are 0.36, 0.71, 0.87, and 0.71 *g*, respectively; where, *g* is the acceleration due to gravity. Structural damping is 5% (kept constant in all modes) for all structures except for the BIS and the BI+TMD, where 10% damping is assumed in the first mode owing to isolation damping governing the first mode of vibration. Time period (T_b) and damping ratio (ξ_b) characterise the isolation system. The mass and stiffness properties are assumed uniform over the height of the structure. Time periods for the first and second mode are shown in Table 1.

Table 1: Modal time periods of different structures considered.

Description of Structure	Mode	Time Period (sec)			
		5 Storey	8 Storey	12 Storey	20 Storey
Conventional fixed-base building (FB)	1	0.50	0.77	1.13	1.85
	2	0.11	0.26	0.38	0.62
Base-isolated building (BIS)	1	2.01	2.30	2.51	2.50
	2	0.27	0.40	0.55	0.78
Building installed only with a tuned mass damper (STMD)	1	0.64	0.81	1.14	1.86
	2	0.40	0.43	0.44	0.65
Base-isolated building installed with a tuned mass damper (BI+TMD)	1	2.02	2.31	2.51	2.51
	2	0.50	0.46	0.62	0.80

Effect of number of storeys

The isolation system considered for the study is laminated rubber bearing (LRB). Peak bearing displacement, peak top floor acceleration, and peak normalised base shear for the four structures with varying number of storeys under different earthquakes are shown in Table 2. The base shear is normalised with weight of structure$\left(W = \sum m_j \times g\right)$. The considered response parameters are compared with response under sine-pulse motion and it is concluded that, the dynamic response obtained for the near-fault ground motions and the short duration pulses are quite similar.

Table 2: Peak response of different structures with varying storeys under different earthquakes.

Earthquake	Storey	Peak Bearing Displacement (cm)		Peak Top Floor Acceleration (g)				Peak Normalized Base Shear (W)			
		BIS	BI+TMD	FB	BIS	STMD	BI+TMD	FB	BIS	STMD	BI+TMD
1979 Imperial Valley (Array#5)	5	30.19	30.10	1.32	0.34	0.91	0.33	0.91	0.31	0.65	0.31
	8	45.61	45.51	0.70	0.42	0.63	0.34	0.45	0.38	0.43	0.38
	12	50.89	50.51	0.68	0.42	0.65	0.46	0.48	0.39	0.47	0.39
	20	27.93	27.60	0.50	0.58	0.56	0.55	0.28	0.36	0.27	0.36
1992 Landers (Lucerne Valley)	5	33.07	32.58	2.70	0.38	1.62	0.36	1.72	0.35	1.40	0.34
	8	29.11	28.79	2.27	0.33	1.97	0.25	1.59	0.25	1.25	0.25
	12	26.32	26.06	2.00	0.32	1.89	0.28	1.08	0.20	1.01	0.20
	20	14.03	13.97	1.11	0.60	1.05	0.59	0.38	0.18	0.40	0.18
1992 Northridge (Rinaldi)	5	51.26	50.66	2.03	0.59	1.66	0.56	1.71	0.54	1.34	0.52
	8	45.73	45.51	2.51	0.45	2.34	0.43	1.89	0.38	1.66	0.38
	12	39.99	39.99	2.19	0.46	2.26	0.45	1.40	0.32	1.34	0.32
	20	24.32	24.80	1.52	1.98	1.59	0.97	0.59	1.80	0.53	0.31
1992 Northridge (Sylmar)	5	48.93	48.42	1.35	0.56	1.28	0.54	0.93	0.51	0.81	0.50
	8	55.76	55.51	1.32	0.53	0.95	0.53	0.70	0.46	0.59	0.46
	12	58.11	58.13	1.66	0.53	1.23	0.50	0.89	0.44	0.82	0.44
	20	33.90	34.07	1.25	0.61	1.04	0.58	0.54	0.43	0.54	0.43
Sine-Pulse Motion	5	29.94	29.29	2.97	0.32	2.38	0.32	0.24	0.31	0.20	0.31
	8	43.02	43.02	0.29	0.38	0.23	0.38	0.22	0.36	0.21	0.36
	12	46.71	46.63	0.28	0.41	0.26	0.41	0.20	0.36	0.20	0.35
	20	26.58	26.45	0.39	0.44	0.42	0.44	0.31	0.34	0.31	0.34

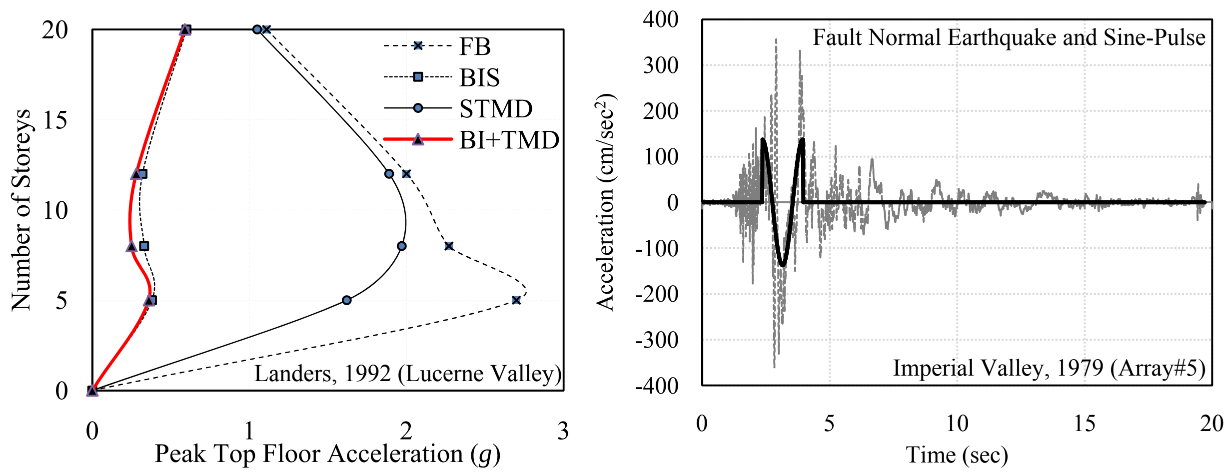

Fig. 2: (a) Peak top floor acceleration for four types of structures with 5, 8, 12, and 20 storeys (b) Time plot of near-fault ground acceleration and the modelled sine-pulse

Peak top floor acceleration for four types of structures with 5, 8, 12, and 20 storeys under Landers, 1992 (Lucerne Valley) is shown in Fig. 2(a) and a sine-pulse motion modelled for Imperial Valley, 1979 (Array#5) is shown in Fig. 2(b). It is observed that, in comparison, the BI+TMD shows the least top floor acceleration. Effectiveness of the BI+TMD is observed to be the maximum for 8 to 16 storeys. The resulting hybrid-passive system reduces the bearing displacement (resulting due to increase in flexibility) along with acceleration and base shear. Time history for bearing displacement and top floor acceleration of 8 storey structures under Northridge, 1992 (Rinaldi) is shown in Fig. 3. Mass ratio (μ_t) is taken as 1.98%. It is observed that, the BI+TMD results in the maximum seismic response reduction.

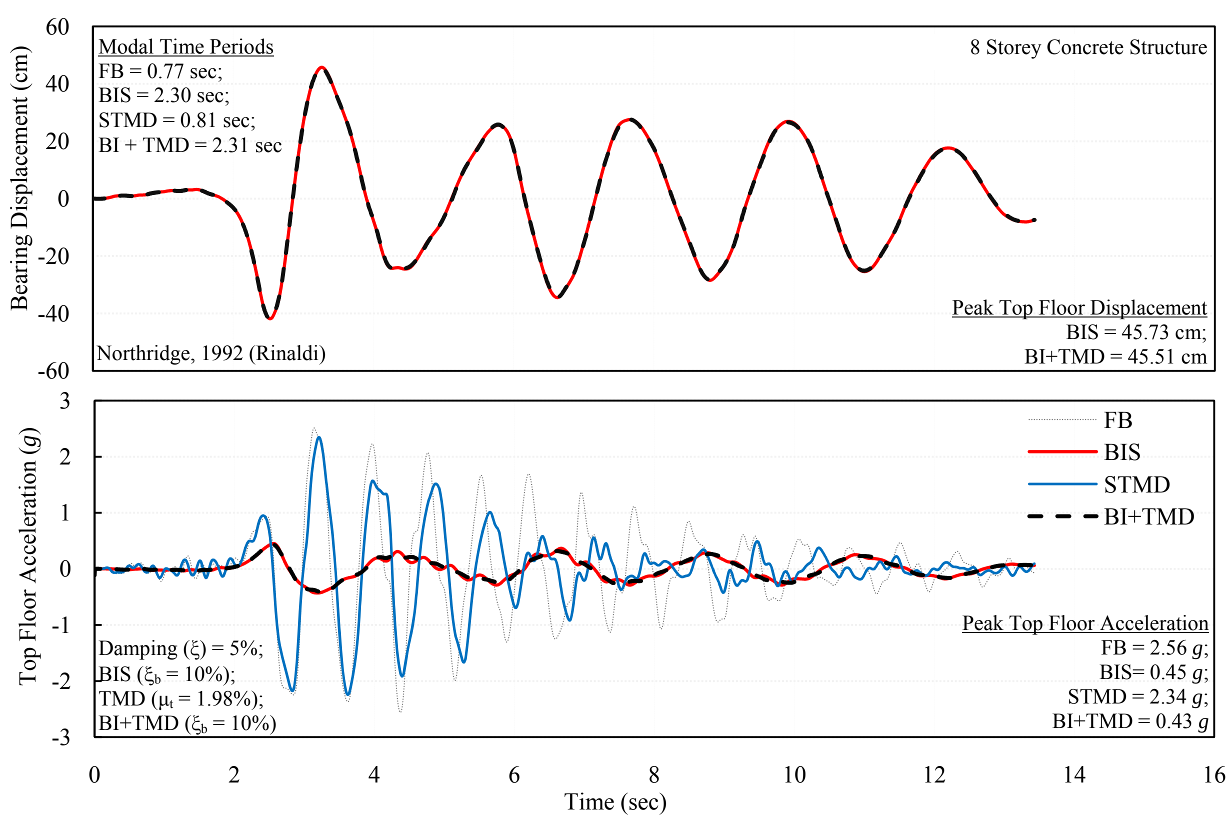

Fig. 3: Time history of bearing displacement and top floor acceleration of 8 storey structure under Northridge, 1992 (Rinaldi)

Effect of isolation time period

The isolation time periods considered for the study are: (a) 1.25 sec; (b) 1.5 sec; (c) 2.0 sec; (d) 2.2 sec; (e) 2.4 sec; and (f) 2.5 sec. For all investigations, TMD of the STMD is tuned to the fundamental frequency of the FB, and the TMD of the BI+TMD with the fundamental frequency of the BIS. Time periods of the BIS and the BI+TMD (T_t) is 2.51 sec. It is observed both for the BIS and the BI+TMD that, with increase in isolation time period, the structural response in terms of peak top floor acceleration and peak normalised base shear does not show as much variation as it does in case of the peak top floor displacement, which increases substantially. It is also observed that, effectiveness of the BI+TMD in reduction of top floor acceleration and peak normalized base shear reduces with increase in time period of isolation (Fig. 4). The BI+TMD is the most effective, in terms of peak top floor acceleration response reduction for the fundamental time period of the FB ranging from 0.8 sec to 1.8 sec. For a stiffer structure, fundamental time period is low; addition of flexible base isolation considerably reduces its seismic response. However, the BI+TMD does not help in significantly reducing peak bearing displacement with increase in isolation time period as compared to the BIS.

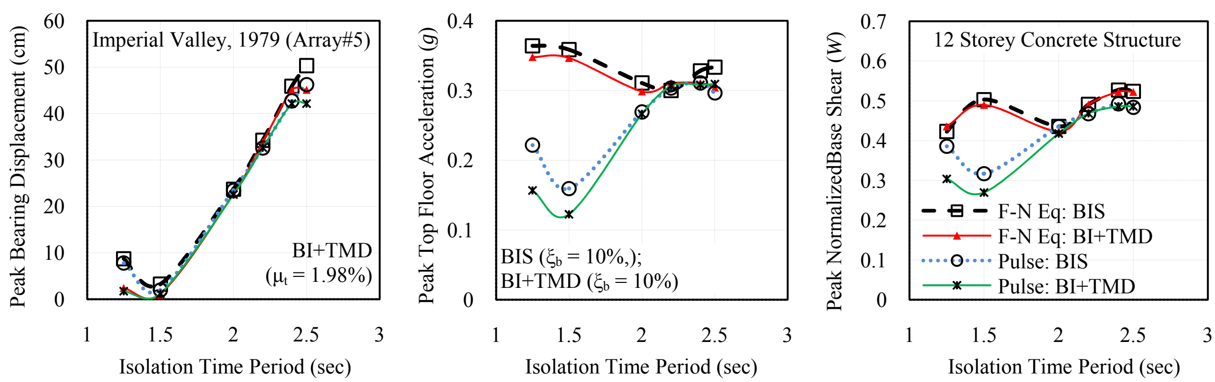

Fig. 4: Variation of peak bearing displacement, peak top floor acceleration and peak normalised base shear against varying isolation time period [F-N Eq: Fault-Normal Earthquake and Pulse: Sine-Pulse Motion]

Effect of isolation damping

For the eight storey BIS and BI+TMD subjected to Imperial Valley, 1979 (Array#5) isolation damping considered for this study are: (a) 5%; (b) 10%; (c) 15%; and (d) 20% in the first mode and 5% damping in all other modes with other structural parameters kept constant. As the damping of the isolator increases, it is observed that, peak bearing displacement, peak top floor displacement, and peak normalised base shear are reduced both for the BI+TMD and the BIS. For an eight storey structure, increase in damping of the isolator reduces the peak top floor acceleration response of the BI+TMD more than the BIS showing its effectiveness (Fig. 5). These observations related to the improved seismic performance of the BI+TMD as compared to the BIS and the STMD are similar to those reported for high-rise structures as well [9].

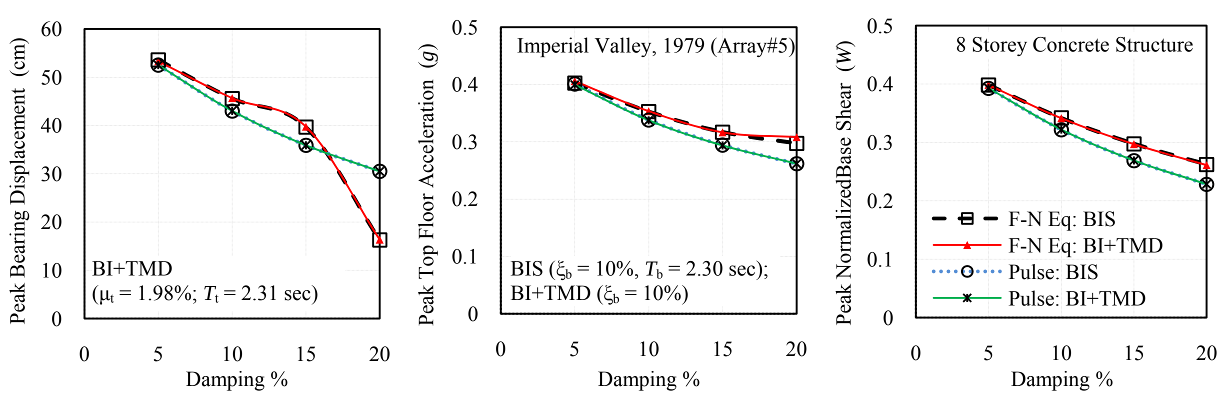

Fig. 5: Variation of peak bearing displacement, peak top floor acceleration and peak normalised base shear against isolation damping [F-N Eq: Fault-Normal Earthquake and Pulse: Sine-Pulse Motion]

CONCLUSIONS

From the study conducted herein the following conclusions are arrived at: (1) Base isolation is quite effective for seismic response reduction for structures up to eight storeys; (2) A tuned mass damper is effective for seismic response reduction for structures with more than sixteen storeys; (3) The hybrid-passive structure constituting of base isolation and a tuned mass damper is comparatively more effective in seismic response reduction for structures with number of storeys ranging from eight to sixteen; (4) For lower isolation time periods, the seismic responses for the base-isolated structure and hybrid-passive are quite different; i.e., for flexible isolated systems, effectiveness in seismic response reduction of base-isolated structure and hybrid-passive structure are almost similar; (5) With increase in damping of the isolator, the response quantities namely, peak bearing displacement, peak top floor acceleration, and peak normalized base shear reduces; and (6) The dynamic response obtained for the near-fault ground motions and short duration pulses are quite similar.

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