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TUNED MASS DAMPERS TO CONTROL THE BASE-ISOLATED BENCHMARK BUILDING MODEL

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SUMMARY

Base isolation has been widely considered as an effective strategy to protect structures subject to seismic excitations. However, it has been shown that, in the case of seismic excitations with high energy content at low frequencies, i.e. a near-fault event or a seismic wave propagating itself through alluvial soil, isolation bearings may undergo gross deformations. By increasing the isolation layer damping, base displacements can be reduced. However, high damping in the isolation layer affects unfavourably the behaviour of the superstructure due to spill-over effects.

Observing that the response of base-isolated (BI) systems is dominated by the first-modal contribution and that Tuned Mass Damping (TMD) is able to reduce the fundamental vibration mode, a new idea of combining both properties into a unique system (BI&TMD) was proposed and investigated by Palazzo and Petti in 1994.

In this paper, a numerical investigation of BI&TMD combined control strategy applied to a base-isolated benchmark structure is presented. The benchmark base-isolated building model has been developed by Nagarajaiah and Narasimhan (2004), to investigate the performance of various passive, semi-active and active control methodologies.

The aim is to test, in a comparable way, the effectiveness of the BI&TMD passive strategy by evaluating several seismic performance indexes under selected seismic excitations. Design criteria of the mass damping control system based on the transfer function norm relating the seismic input to the isolators drift are carried out. Results show a mean reduction in the seismic response, for all seismic inputs, of 30% in terms of base displacements, and of 10% of superstructure absolute accelerations thus highlighting the efficiency of the proposed strategy.

1. INTRODUCTION

Since the beginning of the 90s, research on Base Isolation systems (BI) has increased exponentially (Kelly 1990). A great number of buildings have been constructed over this period using Base Isolation technique in many countries throughout the world. As is well-known, the effectiveness of Base Isolated Systems (BIS) depends on the low-pass filtering capacity of the range of frequencies where the earthquake energy is strongest and closest to the superstructure's fundamental natural vibration frequency. The filtering effect mainly influences the superstructure's inter-storey drifts by concentrating large deformations onto the isolation bearings. Therefore, the central problem of the base isolation strategy is that, under certain excitations, system may suffer from excessive displacements at the base.

The tuned mass damper (TMD), considered as a modern version of the dynamic vibration absorber (DVA) concept (Frham 1909), is a passive control device consisting in a mass, a linear spring and a viscous damper, attached to a primary mechanical system (main structure) in order to control passively its dynamic response.

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Through an optimal design of the absorber parameters, the TMD's dynamic reaction force applied on the main structure causes that part of the energy in the main structure being transferred to the TMD and dissipated by the viscous damper. Therefore, the auxiliary Tuned Mass Dampers system TMD is capable of reducing the main system response near the tuned frequency (Den Hartog 1956) while the higher modes are only marginally influenced.
By observing that well isolated system responses are dominated by the first-modal contribution and that Tuned Mass Dampers are able to reduce the fundamental vibration mode, a new idea of combining both properties into a unique system was proposed and investigated by Palazzo and Petti (Palazzo and Petti 1994).
Considering the BI structure as a single-degree-of-freedom equipped with a TMD, and subsequently by applying the Laplace transform to the motion equations, it's possible to prove that the TMD works as a closed loop control on the isolation layer, figure 1 (Palazzo and Petti 1997).

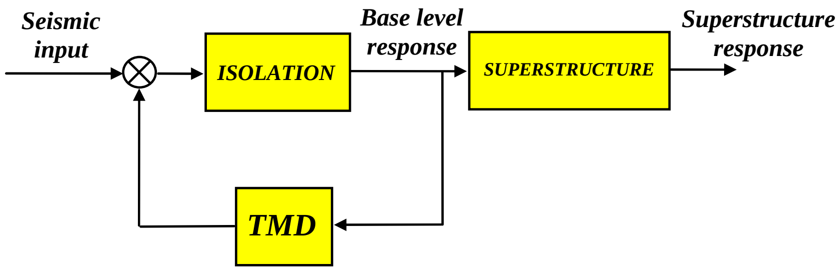

Figure 1: BI&TMD control system's diagram block scheme (Palazzo and Petti, 1997)

The objective of the proposed combined system is to control the system response by only reducing the fundamental modal contribution which is dominant in such systems. This positive behavior is due to the appropriate combination of three fundamental properties of the original systems: the reduction in the ground motion transmission to the superstructure, the vibration mode modification due to the BI and the first vibration mode reduction by means of the TMD at this frequency.
Combined system BI&TMD has been positively tested when applied to plane frame systems, both in the case of recorded seismic events and of synthetic excitations produced through stochastic approaches (De Ligio M., Palazzo B., Petti L. 1997). In three-dimensional systems, structural eccentricity between centers of mass and stiffness may produce dynamic latero-torsional coupling, necessitating the use of additional forces to control the other modal contributions.
The existing technical literature underlines how using of a TMDs system to control such structures represents nowadays a very important issue for scientific community. Among the original contributions, the study by Jangid and Datta (Jangid R.S., Datta T.K., 1997) has to be cited. They study the control response of a two degrees of freedom torsional system through a cluster of multiple tuned mass dampers. The input to the main system was white noise excitation. The optimum frequency bandwidth value corresponding to the maximum reduction in the root mean square value of the main system response, was obtained by a parametric variation study. A noteworthy contribution to control system design has been provided by Lin et al. (Lin C.C., Ueng J.M., Huang T.C., 1999), studying a multi-story torsional building system either one or two tuned mass dampers. They propose a method to identify the dominant modes and critical orientation of the damper track. The optimal parameters are obtained by minimization of the root mean square response of displacement of the dominant mode for a random input. Recently, Singh et al. (Singh M.P., Singh S., Moreschi L.M., 2002) presented an experimental investigation in which four tuned mass dampers, placed along two orthogonal directions in pairs, are considered to control the coupled lateral and torsional response of a multistory building structures subjected to bi-directional earthquake induced ground motions.
Together with passive mass damping effectiveness studies, the scientific literature concerning active and semiactive devices has grown over the last fifteen years. Such a research issue has found renewed interest within the "early warning system" applications (Kanda et al. 1994) (Occhiuzzi et al. 2004). Nowadays, it's possible to identify the intensity and the frequency content of the upcoming earthquake with some seconds in advance and this knowledge may be used for setting the most appropriate control algorithm to modify the mechanical characteristics of the mass damping, e.g. by using magnetoreologic systems, in order to maximize its effectiveness in terms of seismic response reduction. Nevertheless, possible interaction between Early Warning System and Structural Control is a quite recent subject which still needs to be fully investigated. present authors expect to study such topic in the future with reference to a hybrid mass damping system applied to a benchmark structure.
The present paper aims to give an initial contribution to this field of research by testing BI&TMD control strategy effectiveness through the use of a tri-dimensional isolated benchmark structure. A design procedure is

proposed for a TMD system's parameters based on the frequency response of the isolated structure to a white noise input signal. In particular, an iterative algorithm to minimize the transfer function norm relating the seismic input to isolator drift is carried out. Numerical results are carried out in terms of performance indexes allowing for a comparative analysis between the proposed control strategy and those arising from other studies concerning active and semi-active control strategies on the same structure model.

2. THE BENCHMARK STRUCTURE MODEL

The benchmark structure is a base-isolated eight-storey, steel-braced frame building, 82.4 meters long and 54.3 meters wide, similar to existing buildings in Los Angeles, California [Narasimhan et al. 2002]. The floor plan is L-shaped as shown in Figure 2. The superstructure bracing is located at the building's perimeter. Metal decking and a grid of steel beams support all concrete floor slabs. The steel superstructure is supported on a reinforced concrete base slab, which is integral with concrete beams below with drop panels below each column location. The isolators are connected between these drop panels and the footings below as is shown in figure 2. The superstructure is modelled as a three-dimensional linear elastic system. The superstructure components, such as beam, column, bracing, and floor slab are modelled in detail. The floor slabs and the base are assumed to be rigid in plane. The superstructure and the base are modelled by using three master degrees of freedom (DOF) per floor at the centre of the mass. The combined model of the superstructure (24 DOF) and isolation system (3 DOF) consists of 27 degrees of freedom. All twenty four modes in the fixed base case are used in modelling the superstructure. The superstructure damping ratio is assumed to be 5% in all fixed base modes.
The base isolation system for the aforementioned superstructure is not strictly assigned as it can be modified depending on the dynamic response analysis to be carried out. Generally, it is possible to arrange three device types into 92 default positions: the linear elastometric isolation system with low damping, the non-linear friction isolation system representing a friction pendulum system, and the bilinear elastometric isolation system representing a lead-rubber system. In terms of modelling, the isolation system can also be regarded as a linear isolation system consisting of 92 linear elastometric bearings and passive friction dampers in numbers equal to the friction pendulum devices; that is why the friction pendulum bearings consist of a linear elastic part due to the curvature of the sliding surface and friction. In this study, numerical analyses refer to the isolator configuration in which all the devices are linear elastometric. This solution is the most widespread in applications on full-scale isolation systems.

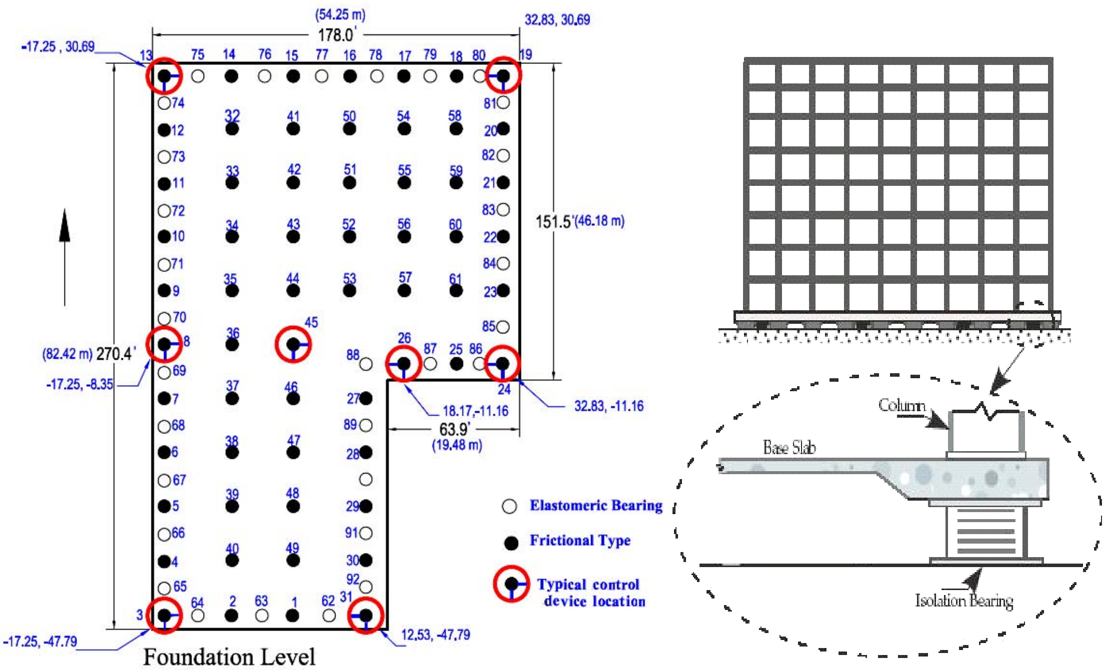

Figure 2: Nominal Isolation system plan and view of the isolation bearing (only elastomeric bearing are considered in this paper) [Narasimhan et al. 2002]

As is already known, the main effect of applying base isolation control strategy is to increase the fundamental vibration period of the system. Moreover, in the benchmark structure under examination it also produces latero-torsional effects due to the non-regular distribution of the isolation bearings (Figure 2). Apart from the seismic demand concentration at the base level, latero-torsional coupling between the rotational and north-south translational component is evident in first modal form. Such a coupling effect is not present in the fixed superstructure and it does not affect the translational component in an east-west direction.
Base isolation aseismic strategy also allows the superstructure to remain in the elastic state when rare seismic events occur, so benchmark authors use a linear model to investigate its dynamic behaviour. A non-linear Bouc-Wen model (Park Y.J.,Wen Y.K. and Ang A.HS., 1986) is used instead to consider the bi-axial hysteretic behaviour of friction and bi-linear elastometric bearings.
The numerical resolution procedure for dynamic equations has been encoded by the authors of the benchmark in Matlab code, through the use of the Simulink tool with appropriate calculation algorithms [Narasimhan et al. 2002]. The implemented code uses a non-editable input file containing structural data to assemble the dynamic matrices, these are processed by an S-function in Simulink performing the non-linear dynamic analysis (Figure 3).
As regards the BI&TMD passive control system, its implementation within the benchmark's authors framework is not straightforward. This framework, in fact, has only been conceived to foresee the application of active and semi-active devices at base level. The aim of investigating passive control strategy effectiveness on an isolated system constrains us to modify the original simulink scheme. In particular, no sensors are needed for passive control systems, so a dedicated block can be erased. Nevertheless, a new simulink block has been created to model the dynamic actions of the mass damping system (Figure 4).

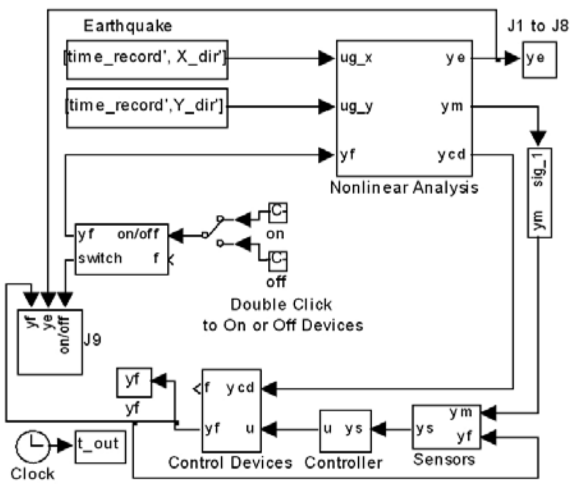

Figure 3: Original simulink control system scheme

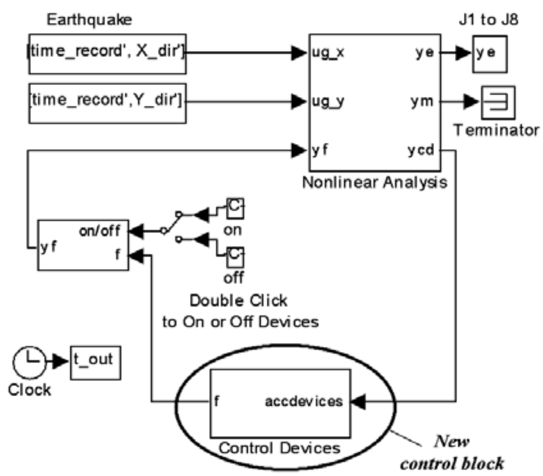

Figure 4: BI&TMD simulink control system scheme

3. MASS DAMPING ON BASE ISOLATION: DESIGN CRITERIA

Mass damping design in a three-dimensional structural system is a problem with no simple solution due to the high number of design variables to be considered. Scientific interest in this issue can be demonstrated by different studies which have been published recently [M. P. Singh, S. Singh, L. M. Moreschi, 2002].
In this paper, control of both rotational and translational motion component is needed due to the latero-torsional coupling in isolated structure. his dynamic effect conditions the design of the mass damping control system in a critical way. In particular, the TMD's optimal values of stiffness will be significantly different from those obtainable by considering the formulae in literature applied to the translation motion's damping and frequency in a distinctly equivalent model. Moreover, torsional seismic response control is improved by spreading out mass damping devices.
This work is concerned with the design of two TMD systems, each consisting of two bi-directional mass damping devices located in such a way as to maximize the devices' spread; configuration A and configuration B (Figure 5).
As is already known, the dynamic parameter that mainly influences a TMD's performance is its stiffness and the proposed design methodology concerns an evaluation of optimal stiffness for a mass damping system. A Matlab code, based on an iterative algorithm, has been written with the aim of calculating the optimal stiffness values necessary to minimize the peak value of the frequency response function for each of the base level's three

motion components. Four design cases have been investigated, each damper's configuration is studied by considering two values of mass ratio: $\mu = 0.05$ and $\mu = 0.1$ .Optimal damping is simply estimated by using Ioi-Ikeda formulae [Ioi T., Ikeda K., 1978].
The code procedure processes the results of dynamic analysis concerning the benchmark system's response to 50 different white noise input signals while mean and standard deviation response values over a wide frequency range are evaluated. These results allow for an iteractive correction of the stiffness parameters until the two peaks in the mean frequency response for the translation component have the same amplitude. The optimal stiffness values obtained for the cases investigated are summarized in table 1.
This technique is very general aiming to minimize the controlled system transfer function peak, which evaluation is a no trivial task in the case of non-linear response of the isolation devices.

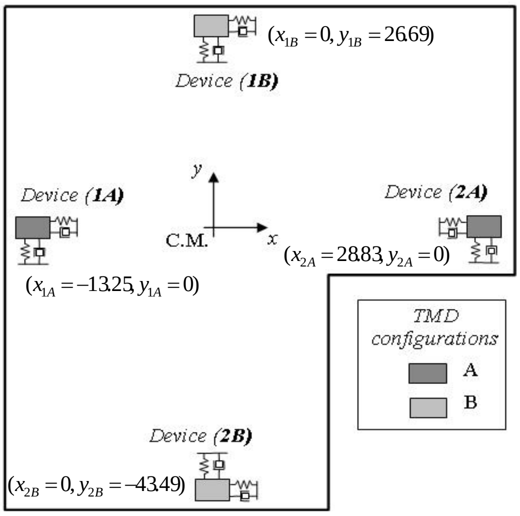

Figure 5: Design configurations for mass damping system

In figures 6-7, "optimal" frequency response for x-translation component with dampers located at configuration A, are plotted. More specific design considerations are possible by considering figure 8-10, where a comparison between the frequency response of a Base Isolated system and Base Isolated with TMDs system is represented. Generally, effectiveness in reducing peak amplitude is improved in the case of TMD having a larger mass (figure 8-10) while differing damper configuration has a negligible effect on the x-direction frequency response (figure 8), otherwise this parameter affects both y-direction and rotational dynamic responses. This is because of the coupling effect between two such components, whilst x-direction displacement in isolation bearings only concerns the second modal form contribution.
Therefore, mass damper location should be considered as a variable in a comprehensive design methodology. Nevertheless, recent studies have shown that designing TMD parameters on translating fundamental frequencies is an effective way of controlling a system's translation of seismic responses, whilst torsional motion, coupled with them and therefore having their same frequency, can be reduced by simply spreading out the mass dampers. In this paper, the translational component of the motion is controlled by means of TMD's design and torsional response by spreading out the mass dampers according to the plan configuration of the isolated level.
Finally, it is important to underline that the isolation system design has been effected with no additional weight due to mass dampers, so devices located at TMD positions should be verified under new service conditions.

Table 1: Optimal mass damper parameters

Mass ratio	Optimal frequency ad damping	Configuration A	Configuration B
$\mu = 0.05$	$(\omega^x_{TMD}, \xi^x_{TMD})$	**(1.84 rad/s, 0.132)**	**(1.86 rad/s, 0.132)**
	$(\omega^y_{TMD}, \xi^y_{TMD})$	**(1.78 rad/s, 0.131)**	**(1.76 rad/s, 0.131)**
$\mu = 0.10$	$(\omega^x_{TMD}, \xi^x_{TMD})$	**(1.77 rad/s, 0.181)**	**(1.77 rad/s, 0.181)**
	$(\omega^y_{TMD}, \xi^y_{TMD})$	**(1.72 rad/s, 0.181)**	**(1.67 rad/s, 0.181)**

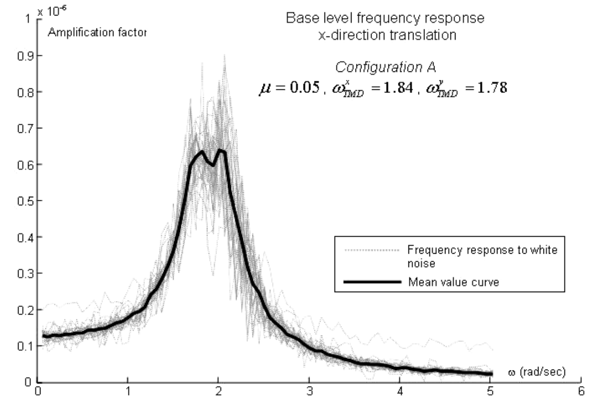

Figure 6: Base level frequency response for optimal design parameters

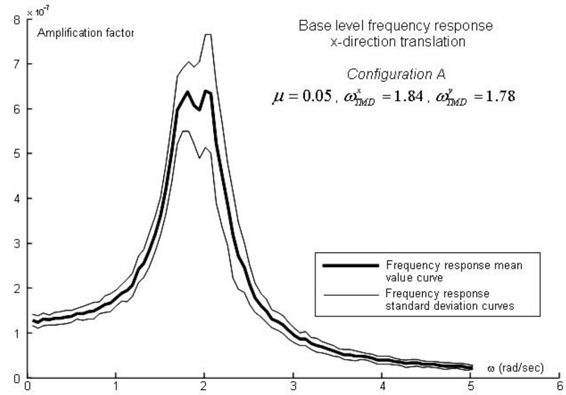

Figure 7: Mean and standard deviation frequency response for optimal design parameters

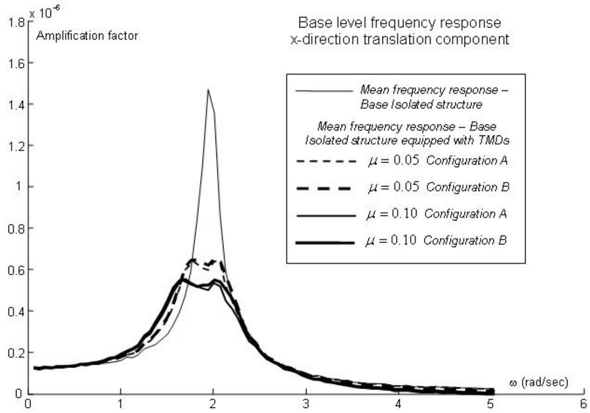

Figure 8: Frequency response comparison: BI system vs BI&TMD systems

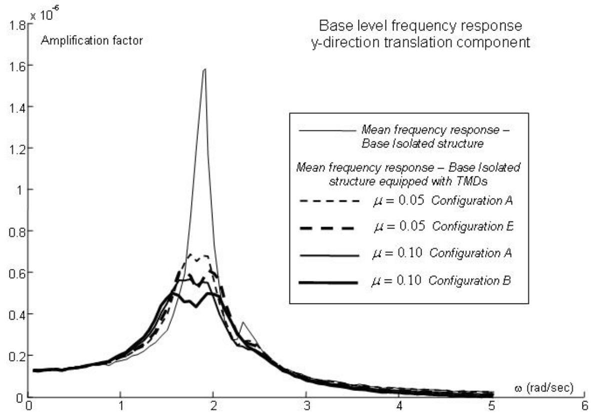

Figure 9: Frequency response comparison: BI system vs BI&TMD systems

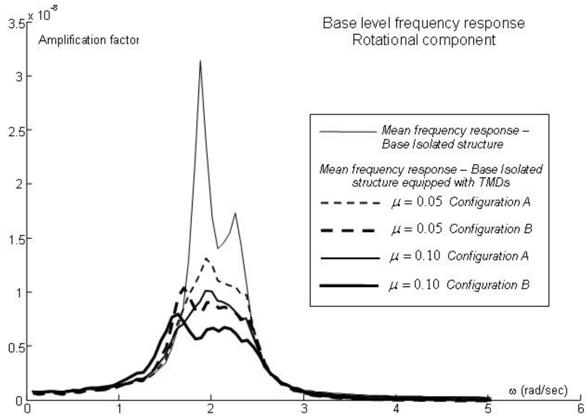

Figure 10: Frequency response comparison: BI system vs BI&TMD systems

4. BI&TMD CONTROL SYSTEM EFFECTIVENESS

Wide-ranging numerical experimentation on the dynamic response of base-isolated benchmark structures equipped with Tuned Mass Dampers, whose parameters are listed in table 1, has been carried out in order to verify the effectiveness of the proposed control strategy. The benchmark's authors suggest both a set of bi-directional recorded seismic inputs [Nagarajaiah and Narasimhan, 2004], table 2, to study the spatial dynamic behaviour of the structure, and a set of performance indexes to describe the effect of the control system on the isolated benchmark. In this study seven of these have been taken into consideration:

- Peak base shear (isolation-level) in the controlled structure normalized by the corresponding shear in the uncontrolled structure: $J_1(q) = \max_t \left\| V_b(q,t) \right\| / \max_t \left\| \hat{V}_b(q,t) \right\|$;

- Peak structure shear (at first-storey level) in the controlled structure normalized by the corresponding shear in the uncontrolled structure: $J_2(q) = \max_t \|V_1(q,t)\| / \max_t \|\hat{V}_1(q,t)\|$;
- Peak base displacement or isolator deformation in the controlled structure normalized by the corresponding displacement in the uncontrolled structure: $J_3(q) = \max_{t,i} \|d_i(q,t)\| / \max_{t,i} \|\hat{d}_i(q,t)\|$;
- Peak inter-storey drift in the controlled structure normalized by the corresponding inter-storey drift in the uncontrolled structure: $J_4(q) = \max_{t,f} \|d_f(q,t)\| / \max_{t,f} \|\hat{d}_f(q,t)\|$;
- Peak absolute floor acceleration in the controlled structure normalized by the corresponding acceleration in the uncontrolled structure: $J_5(q) = \max_{t,f} \|a_f(q,t)\| / \max_{t,f} \|\hat{a}_f(q,t)\|$;
- RMS base displacement in the controlled structure normalized by the corresponding RMS base displacement in the uncontrolled structure: $J_7(t) = \max_i \|\sigma(d(q,t))\| / \max_i \|\sigma(\hat{d}(q,t))\|$;
- RMS absolute floor acceleration in the controlled structure normalized by the corresponding RMS acceleration in the uncontrolled structure: $J_8(t) = \max_f \|\sigma(a(q,t))\| / \max_f \|\sigma(\hat{a}(q,t))\|$.

where $i = 1,..., N_i$ is the isolator number, $k = 1,..., N_d$ is the device number, $f = 1,..., N_f$ is the floor number, $q = 1,...,7$ is the earthquake number, t is the time. Results of numerical analysis, in terms of performance indexes, are reported in tables 3-6 for the benchmark structure having x-axis in fault parallel direction and y-axis in fault normal direction. Similar results are available for 90 degrees rotation of the structure orientation. Every table refers to one of four design cases, in which the optimal TMD parameters listed in Table 1 are considered.

Table 2: Recorded seismic events for numerical analysis

Earthquake event	Magnitude	Station
Northridge (14 January 1994)	6.7 Mw	Newhall
Northridge (14 January 1994)	6.7 Mw	Sylmar
Imperial Valley (15 October 1979)	6.6 Mw	El Centro
Northridge (14 January 1994)	6.7 Mw	Rinaldi
Kobe (17 January 1995)	6.9 Mw	JMA station
Jiji (21 September 1999)	7.3 Mw	Shikhkang
Erzinkan (13 March 1992)	7.1 Mw	Erzinkan

Table 3: Performance indexes values - $\mu = 0.05$ - Configuration A (FP-X, FN-Y)

Seismic event / *Performance indexes*	*Newhall*	*Sylmar*	*El Centro*	*Rinaldi*	*Kobe*	*Jiji*	*Erzinkan*
J_1	0.8809	0.8885	0.9602	0.9833	0.7979	0.9319	0.9348
J_2	0.8846	0.9131	0.9426	0.9836	0.8007	0.9314	0.9542
J_3	0.8056	0.9076	0.7213	0.8859	0.7740	0.8733	0.7533
J_4	0.8938	0.9366	0.8283	0.9690	0.8103	0.9323	0.7990
J_5	0.9261	0.9736	0.8465	0.9864	0.9406	0.9428	0.9184
J_7	0.6142	0.6571	0.6502	0.6473	0.6828	0.6875	0.6901
J_8	0.7883	0.7824	0.6234	0.7051	0.6710	0.8203	0.7152

Table 4: Performance indexes values - $\mu = 0.10$ - Configuration A (FP-X, FN-Y)

Seismic event / *Performance indexes*	*Newhall*	*Sylmar*	*El Centro*	*Rinaldi*	*Kobe*	*Jiji*	*Erzinkan*
J_1	0.8515	0.8564	0.9256	0.9662	0.7711	0.9167	0.8928
J_2	0.8700	0.8826	0.9085	0.9670	0.7704	0.9160	0.9118
J_3	0.8026	0.8517	0.5902	0.8016	0.6456	0.8831	0.6556
J_4	0.8489	0.8846	0.7996	0.9539	0.7530	0.9159	0.7588
J_5	0.8848	0.9445	0.8179	0.9723	0.9244	0.9260	0.8712
J_7	0.5513	0.5789	0.5420	0.5417	0.5755	0.6240	0.5696
J_8	0.7164	0.7109	0.5447	0.6308	0.5791	0.7489	0.6282

Table 5: Performance indexes values - $\mu = 0.05$ - Configuration B (FP-X, FN-Y)

Seismic event / *Performance indexes*	*Newhall*	*Sylmar*	*El Centro*	*Rinaldi*	*Kobe*	*Jiji*	*Erzinkan*
J_1	0.8834	0.9036	0.9615	0.9843	0.8048	0.9262	0.9412
J_2	0.8848	0.9157	0.9435	0.9846	0.8041	0.9257	0.9608
J_3	0.7702	0.8939	0.5917	0.8657	0.6652	0.8804	0.7265
J_4	0.8972	0.9279	0.8272	0.9700	0.8113	0.9263	0.8046
J_5	0.9292	0.9759	0.8461	0.9873	0.9391	0.9368	0.9250
J_7	0.5413	0.6435	0.5366	0.6124	0.5846	0.6539	0.6492
J_8	0.7396	0.7956	0.5871	0.7215	0.6551	0.8050	0.7148

Table 6: Performance indexes values - $\mu = 0.10$ - Configuration B (FP-X, FN-Y)

Seismic event / *Performance indexes*	*Newhall*	*Sylmar*	*El Centro*	*Rinaldi*	*Kobe*	*Jiji*	*Erzinkan*
J_1	0.8524	0.8624	0.9289	0.9685	0.7832	0.9072	0.9051
J_2	0.8708	0.8884	0.9108	0.9692	0.7822	0.9064	0.9244
J_3	0.7448	0.8303	0.5140	0.7749	0.5493	0.8917	0.6360
J_4	0.8556	0.8748	0.7982	0.9559	0.7572	0.9062	0.7694
J_5	0.8908	0.9498	0.8177	0.9742	0.9220	0.9162	0.8838
J_7	0.4761	0.5704	0.4387	0.5147	0.4757	0.6128	0.5396
J_8	0.6751	0.7340	0.5223	0.6491	0.5687	0.7514	0.6422

Results analysis allows for the following consideration on the proposed control strategy effectiveness:

- TMD on BI designed according to the proposed methodology improves the seismic behaviour of the benchmark isolated structure in respect to all considered performance indexes and recorded seismic events;
- Indexes J_3 (peak base displacement) and J_7 (RMS base displacement), concerning the control of the base level motion, presents lower values when compared to the others. This is consistent with the design target to minimize the isolation bearings displacements. Moreover, the superstructure absolute acceleration, in terms of root mean square (J_8 index), is also strongly reduced;
- The proposed strategy to reduce isolators displacement presents different effectiveness levels on varying the dynamic characteristics of the seismic event. High performance are obtained for the El-Centro earthquake, more than 50% reduction in J_7 index (table 6), whilst for the Jiji earthquake slightly less than 10% reduction has been observed (table 6).
- TMD on BI appears to be very effective in reducing the RMS seismic response of the isolators. Its effectiveness is reduced if referred to the isolators peak displacement control;

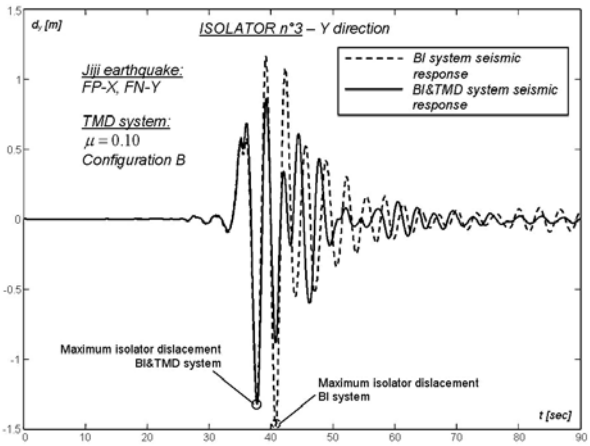

Figure 11: Seismic response of an isolation bearing – BI vs BI&TMD system

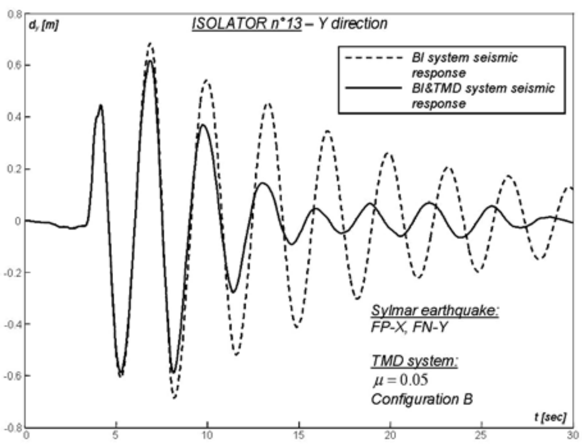

Figure 12: Seismic response of an isolation bearing – BI vs BI&TMD system

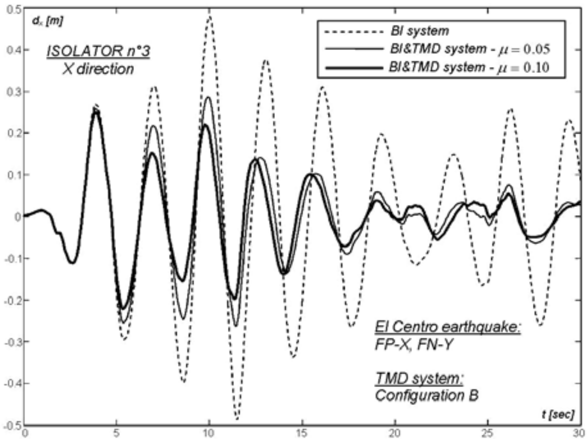

Figure 13: Seismic response of an isolation bearing – BI vs BI&TMD system

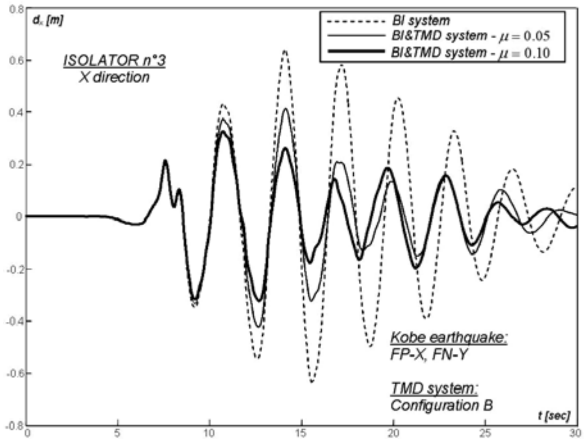

Figure 14: Seismic response of an isolation bearing – BI vs BI&TMD system

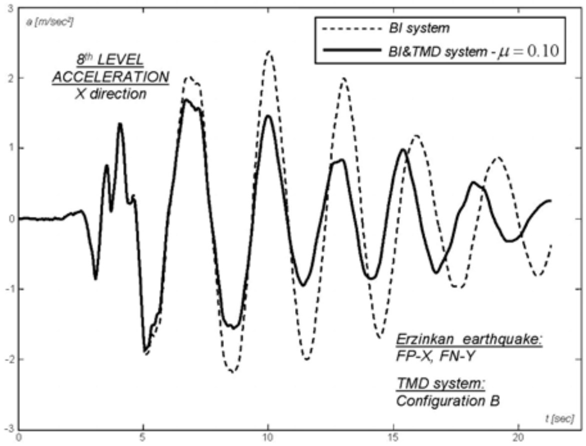

Figure 15: Seismic response of superstructure – BI vs BI&TMD system

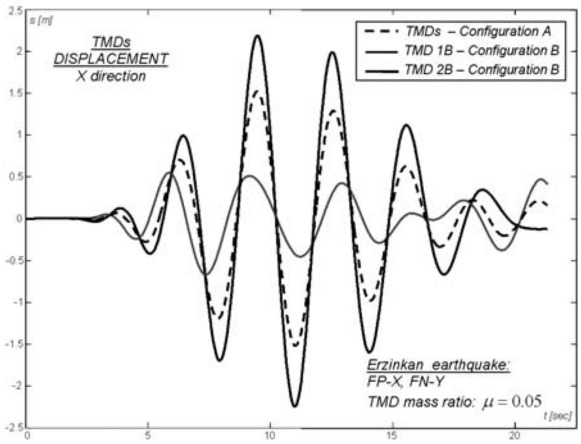

Figure 16: Seismic response of Tuned Mass Dampers

Final considerations are due to the proper dynamic features of mass damping devices. The inertia of TMDs does not allow devices to be effective in the application of the control actions at once. Therefore, in the case of "near fault" seismic events, characterized by a sort of input energy impulse during the first few seconds of the earthquake, mass damping shows itself to be an ineffective system to control seismic response peak values. Figures 11-12 represent the comparison between base isolation displacement for BI and BI&TMD systems to the Jiji and Sylmar earthquakes and peak displacement reduction is not so great in these cases.

Otherwise, high effectiveness in reducing both base level peak displacement and RMS is observed for "far fault" seismic events. In figures 13 and 14 the seismic response of an isolation bearing to the El-Centro and Kobe earthquakes is plotted.

A similar consideration should be carried out for superstructure absolute acceleration (tables 3-6). In figure 15, x-direction absolute acceleration of the roof is plotted for Erzinkan seismic events. Another design factor to be considered concerns with the TMD's dynamic, in figure 16 x-direction TMDs displacement are plotted for Erzinkan seismic events. Finally, in tables 7-8 maximum TMD displacement are listed.

Table 7: Maximum x-direction TMD displacement [m]

Seismic events			Newhall	Sylmar	El Centro	Northridge	Kobe	Jiji	Erzinkan
$\mu = 0.05$	*Conf.* ***A***	*FPX-FNY*	0.6172	1.0707	0.4433	1.1013	0.9094	***1.6686***	1.5125
		FPY-FNX	1.2604	1.5395	0.3783	1.3928	0.4911	***3.0677***	1.4371
	Conf. ***B***	*FPX-FNY*	1.0516	1.5598	0.8044	1.4547	1.2339	***2.5552***	2.2362
		FPY-FNX	1.4702	1.6652	0.6234	1.6407	1.1257	***3.4037***	1.9969
$\mu = 0.10$	*Conf.* ***A***	*FPX-FNY*	0.4405	0.7742	0.3502	0.7647	0.6115	1.1056	***1.1421***
		FPY-FNX	0.9694	1.1065	0.2524	0.9598	0.3920	***2.2898***	1.0197
	Conf. ***B***	*FPX-FNY*	0.7263	1.0120	0.4918	0.9772	0.7986	1.5697	***1.5991***
		FPY-FNX	1.1508	1.1814	0.4011	1.2075	0.7264	***2.4435***	1.3381

Table 8: Maximum y-direction TMD displacement [m]

Seismic events			Newhall	Sylmar	El Centro	Northridge	Kobe	Jiji	Erzinkan
$\mu = 0.05$	*Conf.* ***A***	*FPX-FNY*	1.3775	1.4645	0.4164	1.4853	0.8040	***3.4436***	1.5824
		FPY-FNX	0.6247	0.9282	0.5331	1.1424	1.1431	***1.7882***	1.4242
	Conf. ***B***	*FPX-FNY*	1.2176	1.3370	0.2912	1.2118	0.5147	***2.9204***	1.2804
		FPY-FNX	0.5609	0.9055	0.4373	0.8705	0.8096	***1.4116***	1.3167
$\mu = 0.10$	*Conf.* ***A***	*FPX-FNY*	1.0679	1.0724	0.2985	1.0662	0.5952	***2.5662***	1.1167
		FPY-FNX	0.4531	0.7613	0.4077	0.8671	0.7807	***1.2441***	1.0491
	Conf. ***B***	*FPX-FNY*	0.9282	1.0361	0.2178	0.8853	0.3909	***2.2062***	0.9717
		FPY-FNX	0.4001	0.7199	0.3460	0.6674	0.5530	***1.1344***	1.0209

5. CONCLUSION

In this paper numerical experimentation has been carried out in order to study the effectiveness of using a TMD system located at the base level of a seismically isolated benchmark structure to control displacement of the isolation bearings.

The control system is designed by minimizing the peak frequency response of the controlled system. Optimal stiffness parameters fo mass damping are evaluated by a Matlab algorithm which evaluates the mean frequency response of the benchmark to a set of white noise input signals and iteratively corrects the dynamic characteristic values of the mass dampers. A time-history analysis of designed BI&TMD systems for two different damper configurations and two dampers' mass ratio, confirms the effectiveness of the proposed strategy. A 40% mean reduction in RMS dynamic response of the base level, with 60% maximum reduction, is observed. TMD on BI appears to be very effective in reducing the RMS seismic response of the isolators, its effectiveness is reduced if referred to the isolators peak displacement control, for which a 30% mean reduction is obtained.

Moreover, the proposed strategy presents different effectiveness levels on varying the dynamic characteristics of the seismic event. High performances are obtained for "far-fault" earthquake, whilst effects of "near-fault" earthquakes on isolators are not effectively controllable by using mass dampers.

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