Salvi, J., Rizzi, E., Gavazzeni, M. (2014),
"Analysis on the optimum performance of Tuned Mass Damper devices in the context of earthquake engineering",
Proceedings of the *9th International Conference on Structural Dynamics (EURODYN 2014)*,
Editors: A. Cunha, E. Caetano, P. Ribeiro, G. Müller
Porto, Portugal, 30 June–2 July 2014;
Book of Abstracts, ISBN: 978-972-752-166-1, p. 85;
CD-ROM Proceedings, ISSN: 2311-9020, ISBN: 978-972-752-165-4,
Paper ID 1872, p. 1729-1736 (8 pages).

Proceedings of the 9th International Conference on Structural Dynamics, EURODYN 2014
Porto, Portugal, 30 June - 2 July 2014
A. Cunha, E. Caetano, P. Ribeiro, G. Müller (eds.)
ISSN: 2311-9020; ISBN: 978-972-752-165-4

Analysis on the optimum performance of Tuned Mass Damper devices in the context of earthquake engineering

Jonathan SALVI[1], Egidio RIZZI[1,*], Michele GAVAZZENI[1]
[1]Dipartimento di Ingegneria, Università di Bergamo, viale G. Marconi 5, I-24044 Dalmine (BG), Italy
email: jonathan.salvi@unibg.it, egidio.rizzi@unibg.it*

ABSTRACT: The mitigation of the dynamic response of buildings and structures to earthquakes is one of the fundamental aims within the design of vibration control devices. In this sense, Tuned Mass Damper (TMD) devices are generally conceived as useful and efficient means for the control of the dynamic response of structures and constructions, especially when considering ideal dynamic excitations. However, their optimum tuning and relevant performance in effectively reducing the seismic response of civil structures is currently an open topic, mostly due to the intrinsic nature of the (passive) device and the uncertainty and unpredictability of the earthquake event. The present paper deals with the concept of optimisation of the TMD at given seismic input, to assess the optimum TMD parameters for each seismic event. In this study, the optimisation of TMDs is firstly carried out within a range of earthquakes and primary frame structures, in order to achieve the ideal optimum setting for each considered case. Then, the outcomes of the investigation are gathered and analysed all together, to outline general trends and characteristics, towards possible effective design of TMDs in the seismic context. The output of this paper should enrich the current knowledge on this topic towards potential extensive applications of TMDs in the field of earthquake engineering.

KEY WORDS: Tuned Mass Damper (TMD); Optimum Seismic Tuning; Seismic Input Signal; Shear-Type Frame Structure.

1 INTRODUCTION

This paper presents an investigation on the effectiveness of optimum Tuned Mass Dampers in the context of earthquake engineering, by considering a range of different frame structures and earthquakes. The values of the optimum TMD parameters are obtained for each case and the performance of the control device in reducing the seismic response of the primary structure is assessed. The TMD parameters are optimised through a previously proposed seismic-tuning procedure [1–3], which allows to obtain the optimum TMD parameters for a specific earthquake event. This study lays within a wider research project on TMD tuning under development at the University of Bergamo [1–8].

From their first introduction, which may likely be represented by the patent of Frahm [9], TMDs have been one of the most investigated control devices. First studies have established firm theoretical bases on the tuning of TMDs for harmonic loading and undamped primary structure [10–12], and afterwards many works focused on the optimum tuning in the presence of inherent structural damping and ideal excitations, such as harmonic or white noise loadings [13–15]. In this sense, the mainstream research on TMD tuning dealt with the numerical optimisation of the control device, since the analytical tuning appears to become quite complex in the presence of inherent damping and general loading [14]. This wide group of studies established a considerable knowledge on the basic tuning of TMDs and enforced the opinion that such control devices shall basically be effective in reducing different types of structural vibrations.

An important effectiveness issue is represented by the potential validity of TMDs in the context of seismic engineering, in order to mitigate the earthquake response of civil structures and possibly prevent structural failure under seismic excitation. First, important works tried to study the level of benefit of a TMD optimised for ideal excitations added to different structures, subjected to seismic events. In this sense, the work of Kaynia et al. [16] analysed the performance of a TMD added to elastic and inelastic single-degree-of-freedom (SDOF) primary structures subjected to several earthquake signals, concluding that small differences are recorded when the seismic excitation is modeled as a white noise and that TMDs are less effective than expected towards the reduction of the earthquake response. Further similar indications were provided by the study of Sladek and Klingner [17], where the TMD was found to be not significantly effective in reducing the seismic response of a multi-degree-of-freedom (MDOF) prototype frame building. Another research front concerned the TMD tuning for seismic applications through a complex modal analysis [18–22], therefore leading to a tuning independent of the dynamic excitation, which affirmed instead that a heavily damped TMD could induce remarkable benefits in terms of structural seismic behaviour.

Recently, many works concerned the investigation, with different approaches, on the actual efficiency of passive TMDs in earthquake engineering. A first group of studies considered the earthquake signal within validation tests on previously tuned TMDs, such as those of Paredes et al. [23], where the TMD tuning took advantage from Villaverde's formulas [18, 19], Miranda [21], where the proposed tuning procedure was based on an energy-based model and whose obtained results confirmed those positive obtained by Sadek et al. [20]. Another group of studies embedded the seismic signal into the tuning procedure by means of specific models. In this sense, remarkable works where the seismic signal was modeled in the frequency domain through the Kanai-Tajimi formula were those of Hoang et al. [24], where the TMD tuning was carried-out within a numerical optimization based on the Davidon-Fletcher-Powell algorithm and that of Leung et al. [25], where the seismic input was modeled as a non-stationary process and TMD tuning was carried-out within a Particle Swarm Optimization algorithm.

Despite this large number of studies, the potential effectiveness of TMDs in the realm of earthquake engineering is still debated, essentially due to the intrinsic nature and inertia of the passive TMD device, random and unique nature of the seismic input and large variety of structural characteristics [26–28]. Furthermore, such features recently encouraged the introduction of different numerical optimisation methods with the task of improving and shortening the tuning process [25, 29–32].

The present paper attempts a first investigation on the potential role of TMDs in earthquake engineering. The actual values of optimum TMD parameters are sought, intended as tuned specifically on a given seismic input signal, and the relevant level of effectiveness of the so-conceived control device is measured in the abatement of the primary structure response to an earthquake. Moreover, the study focuses on the possible relationships between the obtained structural dynamic behaviour and the characteristics of the considered strong motion signals.

The paper is organised as follows. First, the structural and dynamic context is presented, composed of a range of SDOF and MDOF shear-type frame buildings, characterised by five typologies and numbers of storeys and two values of floor masses, i.e. ten buildings in total. A TMD is added on top of them. The primary structure characteristics have been chosen in order to suitably cover the entire seismic response spectrum, and therefore to represent adequate scenarios of real buildings. Such structural systems are subjected to five selected real earthquake base accelerations, referring to strong motion data with different characteristics. Hence, fifty different instances are considered in the present optimisation study. The TMD mechanical parameters are tuned on each specific seismic input, by an implemented seismic-tuning method [1–3]. The main features of the proposed tuning procedure are explained in detail, with focus on the numerical method and on the optimisation variables. The outcomes of this ensemble of numerical optimisation processes have been gathered in the form of tables and bar charts, so as to represent the main features of the obtained results. Such output is then briefly discussed, in order to tracing first possible indications towards potential seismic engineering applications.

2 STRUCTURAL AND DYNAMIC CONTEXT

A linear structural system, composed of a shear-type frame building as primary structure and a TMD added on top, has been assumed as benchmark model for this study, supposed to be subjected to a generic seismic base acceleration $\ddot{x}_g(t)$.

The primary structure is characterised by a diagonal mass matrix $\mathbf{M}_S$, a tridiagonal stiffness matrix $\mathbf{K}_S$ and a tridiagonal viscous damping matrix $\mathbf{C}_S$ [33]. However, the latter has been modeled through classical Rayleigh damping as simply proportional to the stiffness matrix [18, 19]:

$$\mathbf{C}_S = \beta \mathbf{K}_S \,, \qquad \beta = \frac{2\zeta_{S,I}}{\omega_{S,I}} \tag{1}$$

where $\zeta_{S,I}$ and $\omega_{S,I}$ are respectively the given structural damping ratio and the angular frequency of the primary structure, referred to its first mode of vibration. In particular, the first mode damping ratio has been assumed here as $\zeta_{S,I} = 0.05$, which is a suitable (relatively high) value for real structures, and thus quite challenging in the present TMD effectiveness context (TMD vibration reduction expected to increase at lowering inherent damping ratio).

The TMD mechanical parameters are the mass m_T, the constant stiffness k_T and the viscous damping coefficient c_T. The TMD angular frequency and damping ratio are classically defined as follows:

$$\omega_T = \sqrt{\frac{k_T}{m_T}}, \qquad \zeta_T = \frac{c_T}{2\sqrt{k_T m_T}} \tag{2}$$

Besides the TMD damping ratio ζ_T, the other free parameters useful for the optimum tuning process of the control device are the mass ratio μ and the frequency ratio f, defined as follows [20]:

$$\mu = \frac{m_T}{\boldsymbol{\Phi}_{S,I}^T \mathbf{M}_S \boldsymbol{\Phi}_{S,I}}, \qquad f = \frac{\omega_T}{\omega_{S,I}} \tag{3}$$

where $\Phi_{S,I}$ is the first mode shape of the primary structure, normalised so as to exhibit a unit value at the top storey.

The different primary structures are characterised by common structural parameters [5]. Indeed, for the present study the following data have been assumed:

- Elastic modulus: E = 30000 MPa;
- Square column dimension: l_c = 0.3 m;
- Number of columns: n_c = 20;
- Column height: h_c = 3 m;
- Number of storeys: n_s = 1, 2, 5, 10, 20;
- Floor mass: $m_{S,i}$ = 50000 kg = 50 t or $m_{S,i}$ = 100000 kg = 100 t.

Such parametric choice allows for a wide range of modal frequencies, with periods varying from about 0.1 s to 2 s, so as to investigate at the same time short, medium and long period structures. In this sense, the modal analysis of such structures provided data reported in Tables 1–3 (where the subscript j denotes the j-th mode of vibration).

The five considered seismic input signals (with features listed in Table 4) are the following: Imperial Valley 1940 (I1940, El Centro station, S00E component [18, 20]), Loma Prieta 1989 (L1989, Corralitos station, 0 component [20]), Kobe 1995 (K1995, Takarazuka station, 90 component [23]), L'Aquila 2009 (A2009, Valle Aterno station, WE component [3]), Tohoku 2011 (T2011, Sendai station, NS component [3]). Such earthquake events are often quoted in the literature and exhibit different characteristics, magnitude and duration, in order to exploit possible consequences in the tuning process.

Table 1. Modal periods $T_{S,j}$ [s], $m_{S,i}$ = 50 t.

Mode	1 storey (m_{tot} = 50 t)	2 st. (m_{tot} = 100 t)	5 st. (m_{tot} = 250 t)	10 st. (m_{tot} = 500 t)	20 st. (m_{tot} = 1000 t)
I	0.10472	0.16944	0.36791	0.70065	1.3670
II		0.064720	0.12604	0.23530	0.45656
III			0.079955	0.14331	0.27501
IV			0.062240	0.10471	0.19759
V			0.054570	0.083978	0.15490
VI				0.071427	0.12799
VII				0.063371	0.10960
VIII				0.058115	0.096326
IX				0.054794	0.086370
X				0.052951	0.078698
XI					0.072669
XII					0.067868
XII					0.064015
XIV					0.060914
XV					0.058426
XVI					0.056452
XVII					0.054919
XVIII					0.053774
XIX					0.052980
XX					0.052513

Table 2. Modal periods $T_{S,j}$ [s], $m_{S,i}$ = 100 t.

Mode	1 storey (m_{tot} = 100 t)	2 st. (m_{tot} = 200 t)	5 st. (m_{tot} = 500 t)	10 st. (m_{tot} = 1000 t)	20 st. (m_{tot} = 2000 t)
I	0.14809	0.23962	0.52031	0.99087	1.9332
II		0.091528	0.17825	0.33276	0.64567
III			0.11307	0.20268	0.38892
IV			0.088021	0.14809	0.27944
V			0.077174	0.11876	0.21906
VI				0.10101	0.18101
VII				0.089620	0.15500
VIII				0.082187	0.13622
IX				0.077490	0.12214
X				0.074884	0.11129
XI					0.10277
XII					0.095980
XII					0.090531
XIV					0.086145
XV					0.082627
XVI					0.079835
XVII					0.077667
XVIII					0.076048
XIX					0.074926
XX					0.074265

Table 3. Effective modal masses $M_{eff,j}$ [%].

Mode	1 storey	2 st.	5 st.	10 st.	20 st.
I	100.00	94.72	87.95	84.79	83.00
II		5.27	8.71	9.14	9.15
III			2.42	3.09	3.24
IV			0.75	1.42	1.61
V			0.15	0.74	0.94
VI				0.40	0.60
VII				0.22	0.41
VIII				0.11	0.29
IX				0.04	0.20
X				0.01	0.15
XI					0.11
XII					0.08
XII					0.06
XIV					0.04
XV					0.02
XVI					0.01
XVII					0.01
XVIII					0.00
XIX					0.00
XX					0.00

3 TMD SEISMIC-TUNING METHOD

The tuning process adopted in this study is obtained through a specific procedure, which has been presented in previous works [1–3]. It consists of the optimisation of the TMD for a specific seismic input, by involving the earthquake signal within the optimisation routine. The main task of such operating way is the achievement of the optimum TMD for each selected seismic event. In particular, such a method has been developed in the time domain, i.e. the optimisation process is looped with a time solver based on classical Newmark's average acceleration method. A complete flowchart and further details on the related features of the tuning procedure are reported in [1–3].

Table 4. Seismic input signals main data.

Name	M	Duration [s]	PGA [g]	PSa^{max} [g]	$T(PSa^{max})$ [s]
I1940	6.9	40	0.359	0.907	0.253
L1989	7.0	25	0.801	2.693	0.329
K1995	7.0	48	0.694	2.506	0.471
A2009	5.8	50	0.676	1.803	0.111
T2011	9.0	300	1.547	2.562	0.655

In general, the tuning of the TMDs can be easily stated and managed as a classical optimisation problem, where the free parameters of the control device play the role of optimisation variables:

$$\min_{\mathbf{p}} \mathbf{J}(\mathbf{p}), \qquad \mathbf{l}_b \leq \mathbf{p} \leq \mathbf{u}_b \tag{4}$$

where $\mathbf{p}$, $\mathbf{J}(\mathbf{p})$, $\mathbf{l}_b$ and $\mathbf{u}_b$ represent the optimisation variables, the objective function, the lower and upper bounds on the optimisation variables, respectively.

In the present context, the usual approach adopted in the literature will be considered, where the frequency ratio f and the TMD damping ratio ζ_T are taken as optimisation variables, namely $\mathbf{p} = [f, \zeta_T]$, while the mass ratio μ is assumed to be given from scratch. Here, it is taken equal to $\mu = 0.02$, which is a value that may be representative of real application cases. Since the main goal is the reduction of the structural seismic response, the displacement of the primary structure has been taken here as objective function, assumed as a Root Mean Square (RMS) estimation. Motivations of this choice have been widely explored in [1–3, 5].

The solution of the optimisation problem through a numerical optimisation method is basically due to the large dimension of the problem and to the random nature of the seismic excitation. In particular, the numerical optimisation takes advantage of a classical nonlinear gradient-based optimisation algorithm available within MATLAB [34], based on Sequential Quadratic Programming (SQP), which guarantees fast and reliable tuning. Indeed, the values assumed for the tolerances and the maximum value of iterations and function evaluations were able to ensure both fast convergence and high level of accuracy [1, 2].

In order to start the optimisation process, an initial evaluation of the tuning variables must be computed. This is obtained here through the well-known Den Hartog's tuning formulas [12], depending on the assumed mass ratio μ:

$$f^0 = \frac{1}{1+\mu}, \qquad \zeta_T^0 = \sqrt{\frac{3\mu}{8(1+\mu)}} \tag{5}$$

which shall provide a good starting approximation for the tuning process [3]. In particular, for the adopted value of $\mu = 0.02$ one obtains:

$$f^0(\mu = 0.02) = 0.980392, \quad \zeta_T^0(\mu = 0.02) = 0.0857493 \tag{6}$$

which configures a TMD quite close to the resonance condition with respect to the first mode of vibration and lightly damped.

However, the assumption of different possible tuning formulas (e.g. those proposed in [6], or others) for the initialisation guess would not change the final estimation of the optimum TMD parameters.

4 ANALYSIS OF SEISMIC-TUNING RESULTS

The outcomes of the proposed tuning process on the selected cases of primary structures and earthquake events are represented in Tables 5–6 and Figs. 1–8, in terms of optimum TMD parameters and percentage response reduction, respectively.

4.1 *Optimum TMD parameters*

The optimum frequency ratio f^{opt} (Table 5) takes values mainly from about 0.9 to 1, i.e. close to resonance conditions on the first mode, but it appears that no specific trend could be outlined. The average values confirm somehow the classical results, which establish an exactly resonant TMD for a virtual mass ratio μ close to zero ($f^{opt} = 1$) and a decreasing frequency ratio at increasing mass ratio.

Table 5. Optimum frequency ratio f^{opt} (Den Hartog's ref. value [12], Eqs. (5)–(6): $f_{DH}(\mu = 0.02) = 0.980392$).

Structure		I1940	L1989	K1995	A2009	T2011
50 t	1 st.	0.957932	0.840197	1.04629	0.932728	0.961677
	2 st.	1.01663	0.890821	0.975869	0.967520	0.918909
	5 st.	0.937887	1.03015	0.967220	0.926385	0.972470
	10 st.	1.02345	0.804186	0.997930	0.967308	0.943341
	20 st.	0.995848	1.01890	0.987987	0.970454	0.955676
100 t	1 st.	0.902234	0.945464	0.935821	0.979243	0.947657
	2 st.	0.906119	1.00737	0.889979	0.905931	0.998331
	5 st.	0.938291	0.882076	0.955918	0.957847	0.962374
	10 st.	0.986089	0.992377	0.979035	0.921196	0.975995
	20 st.	0.968208	0.998243	1.00224	0.954614	0.997559

A first group of values not belonging to the main range described above is that of values slightly higher than 1, which is something not recognised by various tuning formulas, since $f^{opt} = 1$ is typically indicated as a sort of upper threshold. These values look to be randomly distributed within the results. A second case out of the average trend, is represented by the value of f^{opt} near to 0.8 for the 10-storey structure with $m_{S,i}$ = 50 t, subjected to the Loma Prieta earthquake.

The optimum TMD damping ratio ζ_T^{opt} values are presented in Table 6. As previously obtained for f^{opt}, it appears that no apparent trend could be outlined from the point of view of either the number of floors, the floor mass or the earthquake event. The majority of the values states a lightly damped TMD, since the average value is placed as $\zeta_T^{opt} < 0.1$, except for three cases, localised for the 5-, 10- and 20-storey buildings, with $m_{S,i}$ = 100 t, where the parameters reach values $\zeta_T^{opt} > 0.1$.

However, these latter values are just slightly higher than the average values. In general, within the optimisation process a limited sensitivity has been recovered on ζ_T^{opt} with respect to the choice of the building and, most important, of the given seismic input, especially if compared to f^{opt}. Actually, ζ_T may be set *a priori* even to higher values, also in order to reduce the TMD stroke [26, 27], and this may lead to a similar single variable optimisation process based only on f. This approach is not further pursued here.

Table 6. Optimum TMD damping ratio ζ_T^{opt} (Den Hartog's ref. value [12], Eqs. (5)–(6): $\zeta_{T,DH}(\mu = 0.02) = 0.0857493$).

Structure		I1940	L1989	K1995	A2009	T2011
50 t	1 st.	0.0833859	0.0672752	0.0399561	0.0691284	0.0600775
	2 st.	0.0488832	0.0610556	0.0734991	0.0648160	0.0840450
	5 st.	0.0579924	0.0296280	0.0664836	0.0308040	0.0574330
	10 st.	0.0330782	0.0200000	0.0259262	0.0591488	0.0652691
	20 st.	0.0777593	0.0234133	0.0589682	0.0656034	0.0722782
100 t	1 st.	0.0675043	0.0824066	0.0559911	0.0424983	0.0590355
	2 st.	0.0623518	0.0548905	0.0400777	0.0732743	0.0995966
	5 st.	0.0587246	0.0229060	0.0390583	0.128111	0.0839710
	10 st.	0.110842	0.0709814	0.0406915	0.0569847	0.0334780
	20 st.	0.0720089	0.116005	0.0517711	0.0601580	0.0655906

4.2 *RMS response reduction*

Figs. 1–2, respectively for $m_{S,i}$ = 50 t and $m_{S,i}$ = 100 t, display the percentage response reduction in terms of RMS displacement of the top storey, which represents the response index assumed as objective function within the optimisation process.

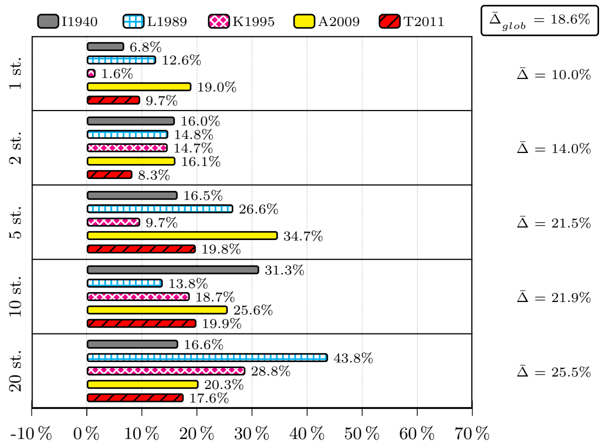

Figure 1. Percentage reduction of $x_{S,n}^{RMS}$ with $m_{S,i}$ = 50 t.

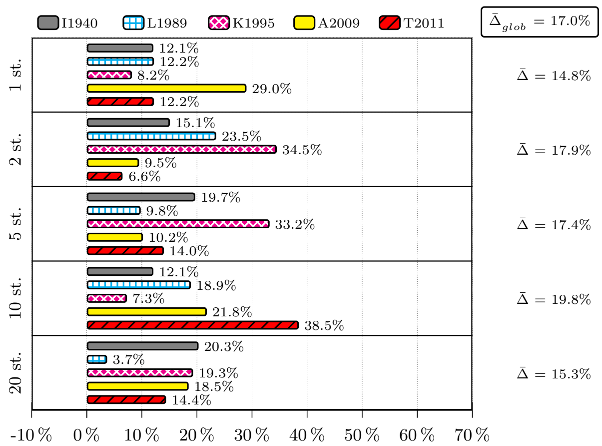

Figure 2. Percentage reduction of $x_{S,n}^{RMS}$ with $m_{S,i}$ = 100 t.

First, for all the cases the remarkable result of an always positive response reduction has been recovered, which should denote, in principle, a beneficial effect of the TMD in these terms. In general, an average reduction from 10% to 25% has been obtained, with noticeable peaks of performance at about 40%. Just a small group of cases exhibits a very small response reduction, i.e. less than 5%. In this sense, noticeable cases are represented by 1- and 20-storey buildings, when subjected to the Kobe and Loma Prieta earthquakes, respectively. Notice that the present gains in earthquake vibration response reduction are obtained for a quite high value of inherent structural damping ($\zeta_{S,I}$ = 0.05); larger response abatements could be achieved at lower values of $\zeta_{S,I}$.

The achieved percentage reduction of the RMS seismic kinetic energy of the primary structure (not an objective function) is depicted in Figs. 3–4. It leads to the following considerations.

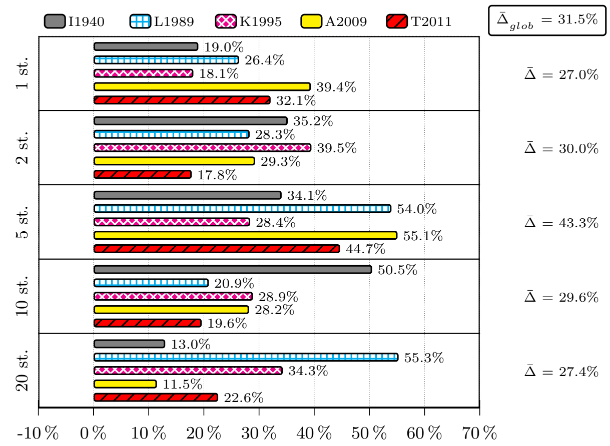

Figure 3. Percentage reduction of T_S^{RMS} with $m_{S,i}$ = 50 t.

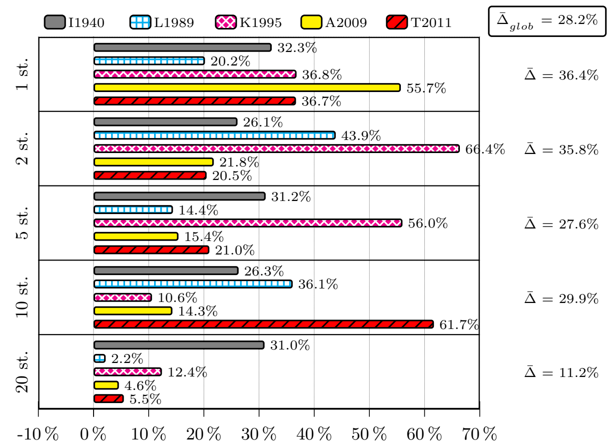

Figure 4. Percentage reduction of T_S^{RMS} with $m_{S,i}$ = 100 t.

Again, for the overall sample of buildings and earthquakes, positive reduction values have been obtained. The general level of reduction is quite remarkable, from 11% to 43% on average of overall kinetic energy loss. Such a fact underlines the benefit coming from the addition of the TMD. Moreover, many cases display values of about 50%–60% reduction, which represent outstanding results, especially if considering that $\zeta_{S,I}$ = 0.05 has been assumed. A case that exhibits an almost negligible effectiveness of the control device in terms of kinetic energy is represented by the 20-storey building, $m_{S,i}$ = 100 t, when subjected to the Loma Prieta earthquake, which confirms the low TMD efficiency already detected previously for the RMS displacement reduction; low reductions are also obtained for the L'Aquila and Tohoku earthquakes.

4.3 *Peak response reduction*

Within the evaluation of the TMD global effectiveness, it is worth considering also the peak response indexes, even if not being assumed as objective function, and therefore not optimised. The percentage reduction of the primary structure top storey peak displacement $x_{S,n}^{max}$ (Figs. 5–6) displays an average value of about 12%, but the distribution of the values appears to be quite random, and different cases display very small reduction, or even negative values (though of quite small magnitude). These irregularities could be due to the absence of correlation between the optimised response quantity and the peak response. Indeed, it is somehow expected that, within the overall response, also the peak displacement could be reduced, but this expectation is not guaranteed by the present tuning process, which is focused on the primary structure RMS displacement as objective function.

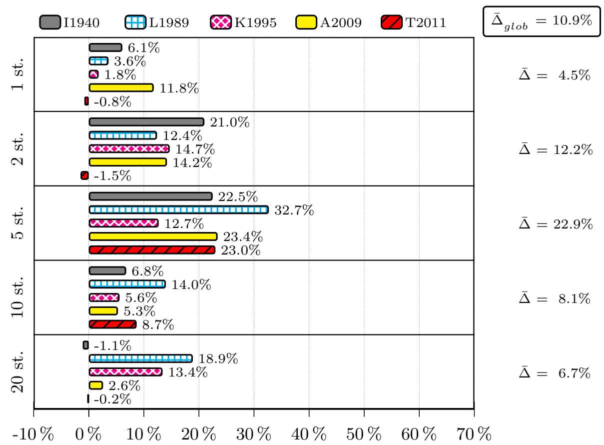

Figure 5. Percentage reduction of $x_{S,n}^{max}$ with $m_{S,i}$ = 50 t.

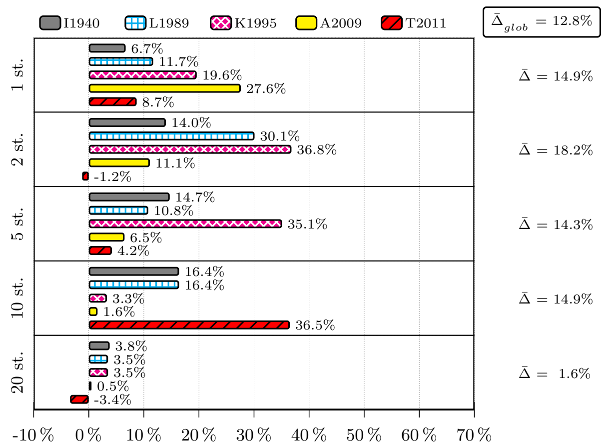

Figure 6. Percentage reduction of $x_{S,n}^{max}$ with $m_{S,i}$ = 100 t.

The considerations reported above hold true also by further observation of Figs. 7–8, where the performance in reducing the peak kinetic energy is depicted. Also for such peak response one may observe that the kinetic energy is in general much reduced than the displacement, with an average value of about 22% and the highest value even at 60%.

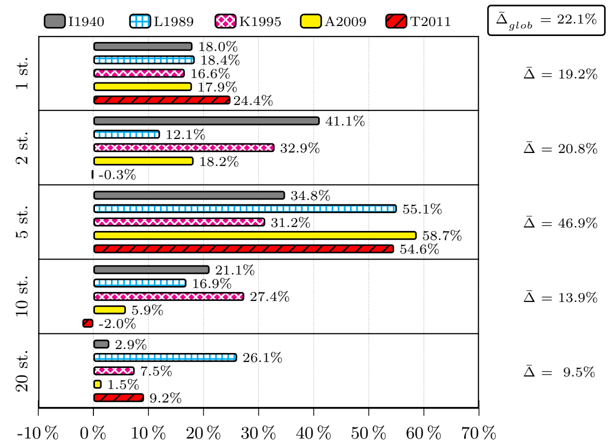

Figure 7. Percentage reduction of T_S^{max} with $m_{S,i}$ = 50 t.

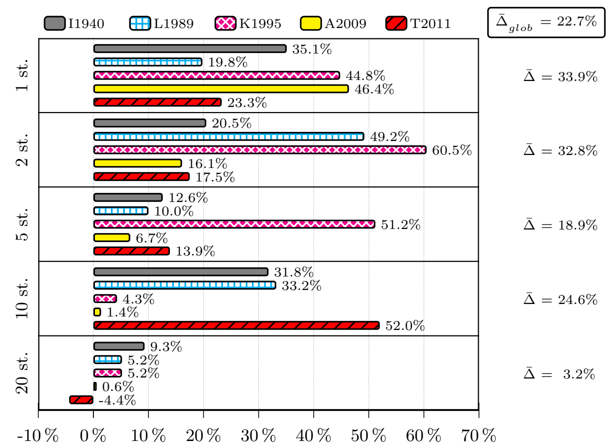

Figure 8. Percentage reduction of T_S^{max} with $m_{S,i}$ = 100 t.

An interesting issue is represented by the similarity, for both floor masses, between the values of the displacement and the kinetic energy bar charts, for both RMS and max values, which could suggest possible connections between these quantities, at least from the point of view of the performance of the control device. Notice again that the reduction gains reached here are obtained for a quite high value of assumed inherent damping ratio, namely $\zeta_{S,I}$ = 0.05. Even better outcomes could be obtained for lower values of damping. Also, results are derived here for a mass ratio μ = 0.02 and possible effects of TMD mass increase may also lead to better performances [5].

4.4 Resumé on average performances

As a further investigation, the average performance values of vibration reduction in terms of all the considered indexes (RMS and max measures, displacement and kinetic energy) have been gathered in Figs. 9–10, at assumed building (number of storeys), and in Figs. 11–12, at considered earthquake.

As expected, the reduction of the RMS response is higher than that of the peak response, for all the considered cases. However, in general, a good effectiveness of the TMD in the abatement also of the peak response is recovered. A deeper look at the reduction values point out an overall better performance obtained for the kinetic energy indexes with respect to the displacement indexes, many times with outstanding values, especially for the RMS index. This feature is confirmed here as a noticeable effect of the TMD addition, as also obtained from previous studies [1–3].

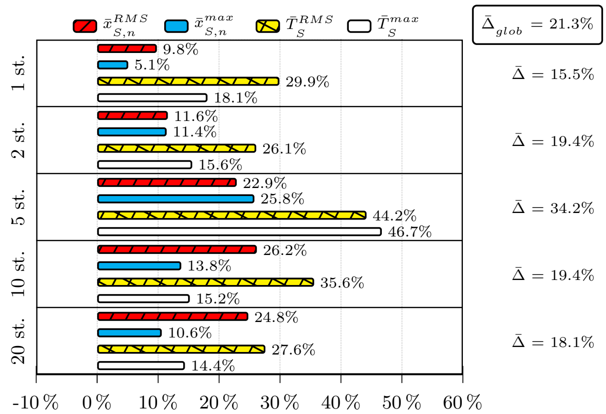

Figure 9. Average percentage response reduction at assigned building (number of storeys), $m_{S,i}$ = 50 t.

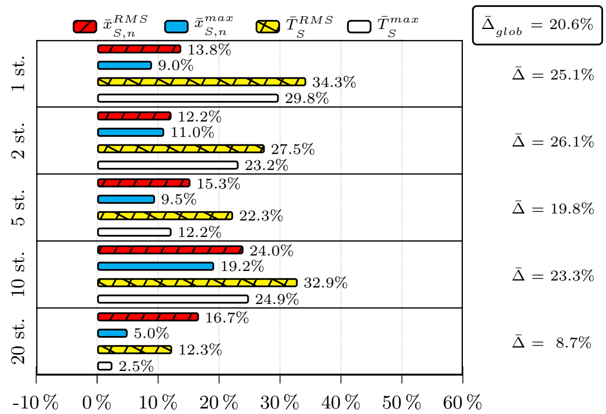

Figure 10. Average percentage response reduction at assigned building (number of storeys), $m_{S,i}$ = 100 t.

The best case is likely represented by the 5-storey building, with $m_{S,i}$ = 50 t, as especially noted in Fig. 9, while from the point of view of the assigned seismic event, quite different results are recovered. It is interesting to note that the global performance is almost the same for the different assumed floor masses, i.e. of about 20%, with a slightly better results for lighter floor masses, in the present setting. Such information would likely be confirmed through the possible relationships between the modal values of the building and the characteristics of the seismic signal, topic that is not discussed in the present study.

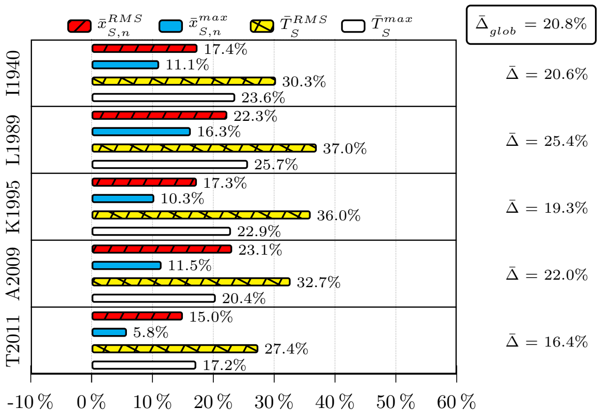

Figure 11. Average percentage response reduction at assigned earthquake, $m_{S,i}$ = 50 t.

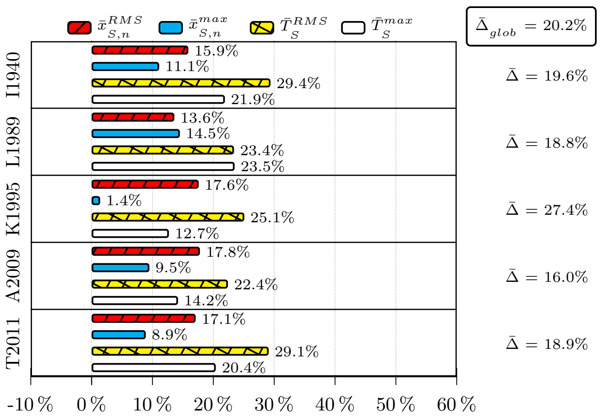

Figure 12. Average percentage response reduction at assigned earthquake, $m_{S,i}$ = 100 t.

5 CONCLUSIONS

The present paper dealt with the optimum tuning of passive Tuned Mass Damper devices at given seismic input signals. In particular, the investigation involved five earthquake events and five shear-type frame structures, for two values of floor masses, for a total of fifty cases, with a (relatively high) fixed value of the primary structure damping ratio ($\zeta_{S,I} = 0.05$, for the first mode of vibration) and of a selected value of the mass ratio ($\mu = 0.02$), consistently with possible engineering applications.

The proposed optimum tuning has considered the primary structure RMS displacement of the top storey as objective function, since it concerns the whole time history, also in the seismic engineering context, and allows for a good level of robustness of the optimisation process. At the same time this leads to improve also other kinematic and energy response indexes.

The outcomes of the so-conceived research framework have been presented in the form of tables and bar charts, where the optimum TMD parameters and the percentage response reduction have been reported, respectively, by providing the following indications:

- The obtained optimum TMD parameters exhibit values that globally reflect the possible classical tuning for generic ideal excitations (either harmonic or white noise loading), with a frequency ratio f^{opt} of about unity and a TMD damping ratio ζ_T^{opt} lower that 0.10. However, some particular cases report more unusual results, such as frequency ratios higher than 1 and TMD damping ratios close to 0.15.

- The percentage reduction of the RMS response globally displayed positive values, thus proving that a general benefit coming from the addition of the control device is always achieved. In particular, an average reduction of about 18% for $x_{S,n}^{RMS}$ and 30% for T_S^{RMS} has been obtained, with lower peaks of performance of about 5% and higher peaks larger than 50%. A general better performance has been recorded for T_S^{RMS} with respect to the targeted $x_{S,n}^{RMS}$. Such a fact somehow confirms the ability of the TMD device in the abatement of the main structure kinetic energy, in the seismic context [16].

- A further analysis on the overall average TMD performance, developed at assumed buildings (number of storeys) and at given earthquake, revealed that a mean abatement of about 20% is obtained. A slightly better effectiveness is recovered for lighter buildings, even if confined to the considered combination of buildings and earthquakes.

- Overall, the effect of a seismic-tuned TMD on a 2×(5×5) matrix array significant ensemble of regular frame structures and earthquakes has been analysed, by providing important indications especially on the main expected behaviour of the so designed structural system and seismic performance of the control device.

- Mostly, at this stage the TMD can be considered, in principle, a healthy solution in view of seismic retrofitting or design for normal buildings, since it produces a global visible abatement of the seismic response, in terms of the main response quantities.

The present work rather analyses agnostically the theoretical possibility of performing an optimum tuning of the TMD device at a given seismic input; the consequent reduction of the structural response to earthquake excitation is quantified all along, in terms of different kinematic and energy response indexes, on both mean (RMS) and max values.

First, it appears that the optimum tuning has been achieved consistently for all the considered cases and specifically for all the adopted seismic input signals, referring to strong motion data. Second, it is found that the added TMD is always effective in reducing the seismic response of the structure, with a level of vibration reduction that looks rather uncorrelated to the type of building, number of storeys, floor masses and input earthquake excitation.

Additional correlation and explanation attempts may address: wider databases of buildings and earthquakes; mutual collocation of the structural mode spectrum with respect to the earthquake response spectrum. This shall lead to further more definite conclusions on the potential effectiveness of TMD devices in reducing the earthquake response of civil engineering structures.

ACKNOWLEDGEMENTS

The Authors would like to acknowledge public research funding from "Fondi di Ricerca d'Ateneo ex 60%" and a ministerial doctoral grant at the University of Bergamo, Dept. of Engineering (Dalmine).

REFERENCES

[1] J. Salvi, E. Rizzi, *Minimax optimization of Tuned Mass Dampers under seismic excitation*, Proc. of 8th Int. Conf. on Structural Dynamics (EURODYN 2011), Leuven, Belgium, 4–7 July 2011, G. De Roeck, G. Degrande, G. Lombaert, G. Müller (Eds.), Book of Abstracts, ISBN: 978-90-760-1931-4, p. 68; CD-ROM Proceedings, p. 1892–1899, 8 pages, 2011.

[2] J. Salvi, E. Rizzi, *Numerical tuning of Tuned Mass Dampers under earthquake loading*, Technical Report, Università di Bergamo, Dipartimento di Ingegneria (Dalmine), Italy, ISBN: 978-88-905817-4-8, 35 pages, 2011.

[3] J. Salvi, E. Rizzi, *Optimum tuning of Tuned Mass Dampers for frame structures under earthquake excitation*, submitted for publication, 2014.

[4] E. Rizzi, D. Brescianini, M. Scotti, *On the optimal tuning of Tuned Mass Dampers in structural systems*, Proc. of ECCOMAS Thematic Conference - 2nd Int. Conf. on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2009), Rhodes, Greece, 22–24 June 2009, M. Papadrakakis, N.D. Lagaros, M. Fragiadakis (Eds.), 24 pages, 2009.

[5] M. Gavazzeni, *Sul controllo ottimale della risposta sismica mediante dispositivi Tuned Mass Damper (On the optimal control of the seismic response through Tuned Mass Damper devices)*, Laurea Thesis in Building Engineering, Università di Bergamo, Facoltà di Ingegneria, Advisor: E. Rizzi, Co-Advisor: J. Salvi, 271 pages, December 2011.

[6] J. Salvi, E. Rizzi, *A numerical approach towards best tuning of Tuned Mass Dampers*, Proc. of 25th Int. Conf. on Noise and Vibration Engineering (ISMA 2012), Leuven, Belgium, 17–19 September 2012, P. Sas, D. Moens, S. Jonckheere (Eds.), Book of Abstracts, ISBN: 978-90-738-0289-6, p. 141; CD-ROM Proceedings, p. 2419-2434, 16 pages, 2012.

[7] J. Salvi, E. Rizzi, E. Rustighi, N.S. Ferguson, *Analysis and optimisation of Tuned Mass Dampers for impulsive excitation*, Proc. of the 11th Int. Conf. on Recent Advances in Structural Dynamics (RASD 2013), Pisa, Italy, July 1–3, 2013, E. Rustighi (Ed.), Book of Abstracts, p. 64, CD-ROM Proceedings, ISBN: 9780854329649, Paper ID 1002, p. 1-15, 15 pages, 2013.

[8] J. Salvi, E. Rizzi, E. Rustighi, N.S. Ferguson, *On the optimisation of a hybrid Tuned Mass Damper for impulse loading*, submitted for publication, 2013.

[9] H. Frahm, *Device for damping vibrations of bodies*, U.S. Patent No. 989958, p. 3576–3580, 1911.

[10] J. Ormondroyd, J.P. Den Hartog, *The theory of the dynamic vibration absorber*, Journal of Applied Mechanics, ASME, 50(7):9–22, 1928.

[11] J.E. Brock, *A note on the damped vibration absorber*, *Journal of Applied Mechanics*, ASME, 13(4):A–284, 1946.

[12] J.P. Den Hartog, *Mechanical Vibrations*, McGraw-Hill, 4th ed., 1956.

[13] G.B. Warburton, *Optimum absorber parameters for various combinations of response and excitation parameters*, Earthquake Engineering and Structural Dynamics, 10(3):381–401, 1982.

[14] S.V. Bakre, R.S. Jangid, *Optimum parameters of tuned mass damper for damped main system*, Structural Control and Health Monitoring, 14(3):448–470, 2006.

[15] S. Krenk, J. Høgsberg, *Tuned mass absorbers on damped structures under random load*, Probabilistic Engineering Mechanics, 23(4):408–415, 2008.

[16] A.M. Kaynia, D. Veneziano, J.M. Biggs, *Seismic effectiveness of Tuned Mass Dampers*, Journal of the Structural Division (ASCE), 107(8):1465–1484, 1981.

[17] J.R. Sladek, R.E. Klingner, *Effect of tuned mass dampers on seismic response*, Journal of the Structural Division (ASCE), 109(8):2004–2009, 1983.

[18] R. Villaverde, *Reduction in seismic response with heavily-damped vibration absorbers*, Earthquake Engineering and Structural Dynamics, 13(1):33–42, 1985.

[19] R. Villaverde, L.A. Koyama, *Damped resonant appendages to increase inherent damping in buildings*, Earthquake Engineering and Structural Dynamics, 22(6):491–507, 1993.

[20] F. Sadek, B. Mohraz, A.W. Taylor, R.M. Chung, *A method of estimating the parameters of Tuned Mass Dampers for seismic applications*, Earthquake Engineering and Structural Dynamics, 26(6):617–635, 1997.

[21] J.C. Miranda, *On tuned mass dampers for reducing the seismic response of structures*, Earthquake Engineering and Structural Dynamics, 34(7):847–865, 2005.

[22] J.C. Miranda, *System intrinsic, damping maximized, tuned mass dampers for seismic applications*, Structural Control and Health Monitoring, 19(9):405–416, 2012.

[23] M.M. Paredes, R.C. Barros, A. Cunha, *A parametric study of TMD's for regular buildings under earthquakes*, Proceedings of 2nd International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2009), Rhodes, Greece, 22–24 June 2009, M. Papadrakakis, N.D. Lagaros, M. Fragiadakis (Eds.), p. 1–15, 2009.

[24] N. Hoang, Y. Fujino, P. Warnitchai, *Optimal tuned mass damper for seismic applications and practical desing formulas*, Engineering Structures, 30(3):707–715, 2008.

[25] A.Y.T. Leung, H. Zhang, C.C. Cheng, Y.Y. Lee, *Particle Swarm Optimization of TMD by non-stationary base excitation during earthquake*, Earthquake Engineering and Structural Dynamics, 37(9):1223–1246, 2008.

[26] A. Tributsch, C. Adam, T. Fürtmuller, *Mitigation of earthquake induced vibrations by Tuned Mass Dampers*, Proceedings of 8th International Conference on Structural Dynamics (EURODYN 2011), Leuven, Belgium, 4–7 July 2011, G. De Roeck, G. Degrande, G. Lombaert, G. Müller (Eds.); CD-ROM Proceedings, p. 1742–1749, 2011.

[27] A. Tributsch, C. Adam, *Evaluation and analytical approximation of Tuned Mass Dampers performance in an earthquake environment*, Smart Structures and Systems, 10(2):155–179, 2012.

[28] G.C. Marano, R. Greco, F. Trentadue, B. Chiaia, *Constrained reliability-based optimization of linear tuned mass dampers for seismic control*, International Journal of Solids and Structures, 44(22-23):7370–7388, 2007.

[29] S. Soheili, M. Abachizadeh, A. Farshidianfar, *Tuned mass dampers for earthquake oscillations of high-rise structures using Ant Colony Optimization technique*, Proceedings of 18th Annual International Conference on Mechanical Engineering (ISME 2010), Tehran, Iran, 11–13 May 2010, p. 1–6, 2010.

[30] A. Farshidianfar, S. Soheili, *Bee Colony Optimization of Tuned Mass Dampers for vibrations of high-rise buildings including Soil Structure Interaction*, Proceedings of 6th National Congress on Civil Engineering, Semnan, Iran, 26–27 April 2011, p. 1–8, 2011.

[31] G. Bekdaş, S.M. Nigdeli, *Estimating optimum parameters of tuned mass dampers using harmony search*, Engineering Structures, 33(9):2716–2723, 2011.

[32] M. Mohebbi, A. Joghataie, *Designing optimal tuned mass dampers for nonlinear frames by Distributed Genetic Algorithms*, The Structural Design of Tall and Special Buildings, 21(1):57–76, 2012.

[33] S.S. Rao, *Mechanical Vibrations*, Pearson, 5th ed., 2011.

[34] The MathWorks Inc., *MATLAB User's Guide and Optimization Toolbox*, USA, 2011.