# COST-EFFECTIVENESS OF TUNED MASS DAMPER AND BASE ISOLATION

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**ABSTRACT :**

This study is focused on the statistical assessment of peak responses of structures with tuned mass dampers (TMD) or base isolation devices (BID) under seismic excitations and on the lifecycle cost of a structure with an option of installing these devices. For the assessment, a structure is modeled as a two-degree-of-freedom system; one degree-of-freedom represents a main structure and the other represents an auxiliary system (i.e., TMD or BID). The hysteretic behavior of the main structure and auxiliary system is approximated by the Bouc-Wen model. A parametric study of linear and nonlinear responses of the system is carried out by using 381 ground motion records, and the ratios of the maximum displacement and ductility demand of the system with auxiliary devices to those without are considered as a measure of effectiveness of TMD/BID. The linear and nonlinear responses are also incorporated for assessing possible damage states and damage costs in the lifecycle cost analysis. The latter is employed as the basis for evaluating the cost-effectiveness of applying TMD and BID in reducing seismic risk.

**KEYWORDS:** Tuned mass damper, Base isolation, Inelastic response, Lifecycle cost

## 1. INTRODUCTION

Strong earthquakes cause damage to structures and infrastructure. The losses could be mitigated by increasing a seismic design level or by installing additional energy dissipation devices, such as tuned mass dampers (TMD) and base isolation devices (BID). These mitigation strategies are effective as long as their use can reduce the expected lifecycle cost. TMD and BID are widely applied for engineered facilities to reduce vibration. Many studies have investigated the performance of TMD/BID; most of them were focused on linear elastic responses of main structures (e.g., Soong and Dargush, 1997; Naeim and Kelly, 1999), while some studied nonlinear responses of inelastic systems (e.g., Soto-Brito and Ruiz, 1999; Lukkunaprasit and Wanitkorkul, 2001; Kikuchi et al., 2008), and several recommendations for selecting optimal TMD/BID were proposed (e.g., Sadek et al., 1997; Jangid, 2007). Since inelastic structural responses are associated with structural damage and collapse, and the use of auxiliary devices is expected to reduce vibration and damage in main structures, a statistical assessment of peak inelastic responses of structures with TMD/BID under seismic excitations are of direct interest. Further, it is noted that parametric studies focusing on the cost-effectiveness of TMD/BID, which is lacking, could be valuable for engineers in designing or retrofitting structures with TMD/BID.

The main objectives of this study are to assess the statistics of peak elastic and inelastic responses of structures with TMD/BID under seismic excitations, and to assess the cost-effectiveness of structures with an option of installing these devices in mitigating seismic risk. For the assessment, a simplified structural model is considered and its nonlinear behavior is approximated by the Bouc-Wen model (Wen, 1976; Foliente, 1995). Numerical analysis of linear and nonlinear responses of the system is carried out by using 381 ground motion records, and the ratios of the maximum displacement and ductility demand of the system with auxiliary devices to those without are considered as a measure of effectiveness of the auxiliary devices. Moreover, the linear and nonlinear responses are incorporated for assessing possible damage states and damage costs in the lifecycle cost analysis. The latter is employed as the basis for evaluating the cost-effectiveness of TMD/BID in reducing seismic risk.

## 2. MODELING STRUCTURAL SYSTEM WITH TUNED MASS DAMPER/BASE ISOLATION

### *2.1 Mathematical Model*

To simplify analysis and to consider nonlinear structural behavior and the effects of TMD/BID, a main structural system as well as TMD/BID is approximated by an inelastic single-degree-of-freedom (SDOF) system. Based on this simplification, the overall system is represented by a two-degree-of-freedom system, which is illustrated in Figure 1a. If a TMD system is considered, Subsystems I and II shown in the figure represent a main structure and TMD, respectively, while if a BID system is of interest, Subsystems I and II represent BID and a main structure, respectively.

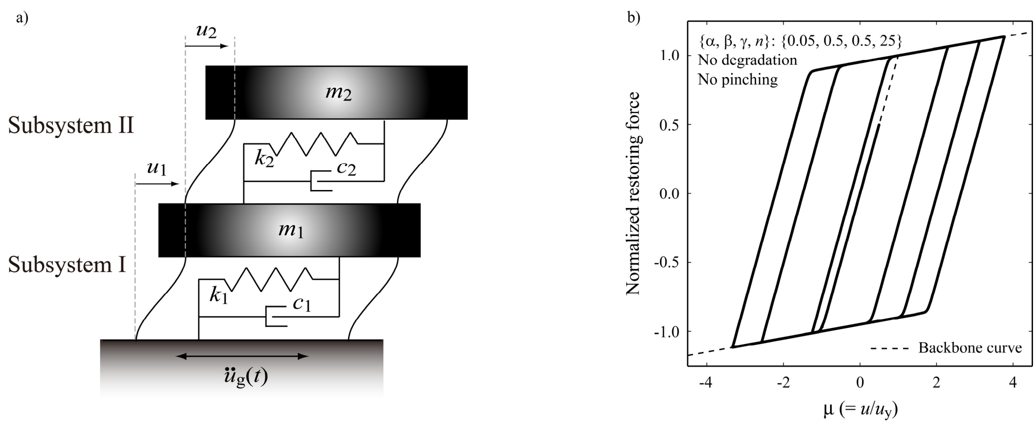


Figure 1 Two-degree-of-freedom structural model: a) Idealized system and b) Force-deformation curve under cyclic loading.

To take nonlinear hysteretic behavior of the subsystems into account, it is considered that the hysteretic displacement is governed by the Bouc-Wen model (Wen, 1976; Foliente, 1995). The use of this popular hysteretic model is justified, since it can cope with degrading, deteriorating, and pinching behavior. In such a case, the governing equation is given by,

$$
\begin{aligned}
&\ddot{\mu}_1 + 2\xi_1\omega_{n1}\dot{\mu}_1 + \alpha_1\omega_{n1}^2\mu_1 + (1-\alpha_1)\omega_{n1}^2\mu_{z1} - 2\rho\Delta\xi_2\omega_{n2}\dot{\mu}_2 - \alpha_2\rho\Delta\omega_{n2}^2\mu_2 - (1-\alpha_2)\rho\Delta\omega_{n2}^2\mu_{z2} = \frac{-\ddot{u}_g}{(\phi_1 u_{01})} \\
&\ddot{\mu}_2 + 2(1+\rho)\xi_2\omega_{n2}\dot{\mu}_2 + \alpha_2(1+\rho)\omega_{n2}^2\mu_2 + (1-\alpha_2)(1+\rho)\omega_{n2}^2\mu_{z2} = \frac{2\xi_1\omega_{n1}\dot{\mu}_1}{\Delta} + \frac{\alpha_1\omega_{n1}^2\mu_1}{\Delta} + \frac{(1-\alpha_1)\omega_{n1}^2\mu_{z1}}{\Delta} \\
&\dot{\mu}_{zi} = \frac{h(\mu_{zi},\varepsilon_{Ni})}{1+\delta_{\eta i}\varepsilon_{Ni}}\left[\dot{\mu}_i - (1+\delta_{\nu i}\varepsilon_{Ni})\left(\beta_i|\dot{\mu}_i||\mu_{zi}|^{n_i-1}\mu_{zi} + \gamma_i\dot{\mu}_i|\mu_{zi}|^{n_i}\right)\right], \quad i=1,2 \\
&h(\mu_{zi},\varepsilon_{Ni}) = 1-\zeta_{si}(1-\exp(-p_i\varepsilon_{Ni}))\exp\left(-\left(\frac{\mu_{zi}\,\mathrm{sgn}(\dot{\mu}_i) - q_i/((1+\delta_{\nu i}\varepsilon_{Ni})(\beta_i+\gamma_i))^{1/n}}{(\lambda_i+\zeta_{si}(1-\exp(-p_i\varepsilon_{Ni})))(\psi_i+\delta_{\psi i}\varepsilon_{Ni})}\right)^2\right), \quad i=1,2 \\
&\varepsilon_{Ni} = (1-\alpha_i)\int_0^t \dot{\mu}_i\mu_{zi}\,d\tau, \quad i=1,2
\end{aligned}
\qquad (2.1)
$$

where for the $i$-th subsystem ($i$ = 1,2), $\mu_i$ (= $u_i/u_{yi}$) is the normalized displacement, $u_i$ is the translational displacement relative to the base of the subsystem, and $u_{yi}$ is the yield displacement; $\xi_i$ (= $c_i/(2m_i\omega_{ni})$) is the damping ratio, $c_i$ is the damping coefficient, $m_i$ is the mass, $\omega_{ni}$ (= $(k_i/m_i)^{0.5}$) is the natural vibration frequency, and $k_i$ is the stiffness; $\rho$ (= $m_2/m_1$) is the mass ratio; $\Delta$ is the ratio of $u_{y2}$ to $u_{y1}$ (i.e., $\Delta = (\phi_2 u_{02})/(\phi_1 u_{01})$), $\phi_i$ (= $u_{yi}/u_{0i} = f_{yi}/f_{0i}$) is the normalized strength, $f_{yi}$ denotes the yield force of the $i$-th subsystem, $u_{0i}$ and $f_{0i}$ denote the peak values of the earthquake-induced displacement and resisting force of the $i$-th (linear elastic) subsystem subjected to a considered ground motion record $\ddot{u}_g$; $\alpha_i$ is the ratio of post-yield stiffness to initial stiffness; $\mu_{zi}$ (= $z_i/u_{yi}$) is the normalized hysteretic displacement; and $h(z_i,\varepsilon_{Ni})$ is the pinching function, sgn(•) is the signum function and $\varepsilon_{Ni}$ is the dissipated energy through hysteresis per mass normalized with respect to $f_{yi}u_{yi}$. For each subsystem, there are 12 Bouc-Wen model parameters: $\alpha_i$, $\beta_i$, $\gamma_i$, and $n_i$ are the shape parameters, $\delta_{\nu i}$ and $\delta_{\eta i}$ are the degradation parameters, and $\zeta_{si}$, $p_i$, $q_i$, $\psi_i$, $\delta_{\psi i}$, and $\lambda_i$ are the pinching parameters.

Use of the normalized displacement $\mu_i$ is advantageous, since it directly provides the ductility demand for $\mu_i > 1$. It must be noted that $u_{0i}$, which depends only on $\omega_{ni}$ and $\xi_i$ for a record, is calculated by considering that each subsystem rests on the ground and is subjected to the considered record. Eqn. 2.1 can be expressed in the form of state-vector equations and solved by using the Gear's method. Note that in particular if Subsystem II is ignored, Eqn. 2.1 describes the behavior of the main structure without TMD/BID.

For the statistical assessment of the peak responses and response ratios for the structure shown in Figure 1, a set of 381 California records, each with two horizontal components, from 31 seismic events is considered. These records are selected from the 592 records used in Hong and Goda (2007) and extracted from Next Generation Attenuation database (PEER Center, 2006), but with a more stringent criterion with regard to the low-cut filter corner frequency in processing raw data. That is, the low-cut filter corner frequency of 0.2 Hz instead of 0.5 is considered.

### *2.2. Some Considerations for TMD and BID*

If TMD is considered, Subsystems I and II represent a main structure and TMD, respectively, and Eqn. 2.1 can be used to carry out parametric investigations of the effects of TMD on linear and nonlinear responses of the main structure. If the main structure is considered to be linear elastic, one only needs to set $\alpha_1 = 1.0$ and ignore $\mu_{z1}$ and $\varepsilon_{N1}$ in Eqn. 2.1. For a given structure, the optimal design of a TMD system is often focused on selecting combinations of the mass ratio $\rho$, the frequency ratio $\omega_{TR}$ (= $\omega_2/\omega_1$), and $\xi_2$ (of TMD) for a target performance criterion. For a given $\rho$, Sadek et al. (1997) suggested simple equations to select optimal values for $\omega_{TR}$ and $\xi_2$.

If BID is considered, Subsystems I and II represent BID and a main structure, respectively. There are several BID systems used in practice. In particular, the low-damping rubber bearing system is often approximated by a linear system, whereas the lead-plug bearing system is approximated by a bilinear system. These two cases are considered in this study. The important design parameters for BID systems are the isolation period $T_I$ and the isolation damping ratio $\xi_I$. By considering a rigid main structure, these parameters are often related to those of the base isolator using $T_I = T_1(1+\rho)^{0.5}$ and $\xi_I = \xi_1/(1+\rho)^{0.5}$. An index $\kappa$ (= $(T_2/T_I)^2$) which usually ranges from 0.01 to 0.1 for practical applications, can be used as a guide to select the parameters of isolation systems (Naeim and Kelly, 1999). In addition, for bilinear isolators, two more parameters need to be considered (Jangid, 2007): the yield displacement $u_{y1}$ and the yield strength normalized by the total weight of isolated structures $Q_{y1} = k_1u_{y1}/((m_1+m_2)g)$, where $g$ is the gravitational acceleration. Based on several studies (Naeim and Kelly, 1999; Jangid, 2007; Kikuchi et al., 2008), typical ranges of the model parameters for isolation systems are: 3 s to 4 s for $T_I$, 2% to 5% for $\xi_1$, 1 to 10 for $\rho$, 0.025 m to 0.1 m for $u_{y1}$, and 0.05 to 0.15 for $Q_{y1}$. Note that $\rho$ depends on $T_2$, which is related to the number of stories of a main structure.

## 3. PROBABILISTIC CHARACTERISTICS OF PEAK STRUCTURAL RESPONSES

### *3.1 Response Ratios for TMD*

Consider that a structure is treated as a linear elastic SDOF system with $T_1$ and $\xi_1 = 0.05$ and could be designed or retrofitted using TMD for a specified $\rho$. One is interested in assessing whether such a design or retrofit with TMD can reduce peak structural responses. For the numerical analysis, it is considered that TMD is modeled as a linear elastic SDOF system, $\rho$ equals 0.02, 0.05, or 0.1, and TMD is (optimally) tuned based on the equations given by Sadek et al. (1997). The ratio between the peak response of the main structure with TMD and that without TMD, $r_{E\text{-}T}$, is evaluated by using the considered 381 records, and the statistics of $r_{E\text{-}T}$ are shown in Figures 2a and 2b.

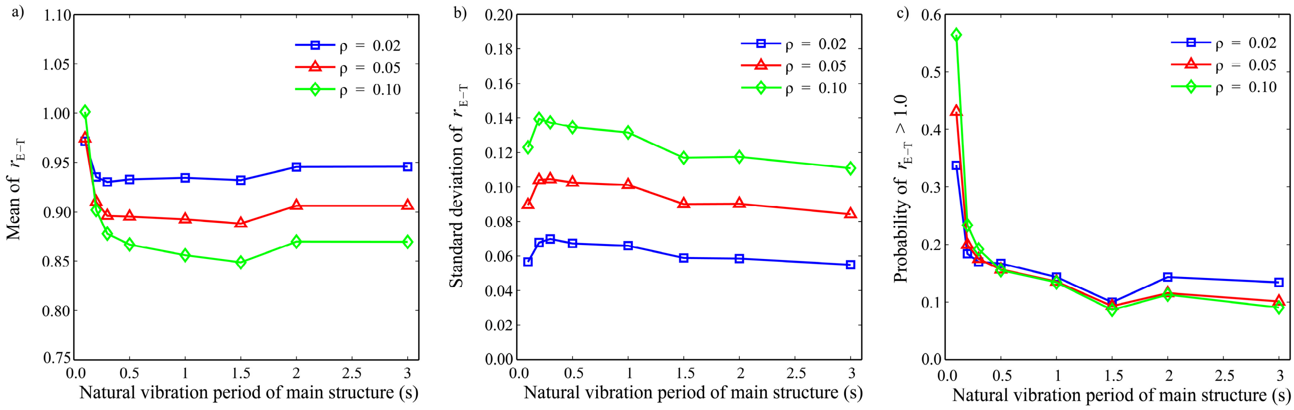


Figure 2 Effects of TMD on the peak response ratio $r_{E-T}$: a) Mean of $r_{E-T}$, b) Standard deviation of $r_{E-T}$, and c) Probability of $r_{E-T}$ greater than one $P(r_{E-T}>1)$.

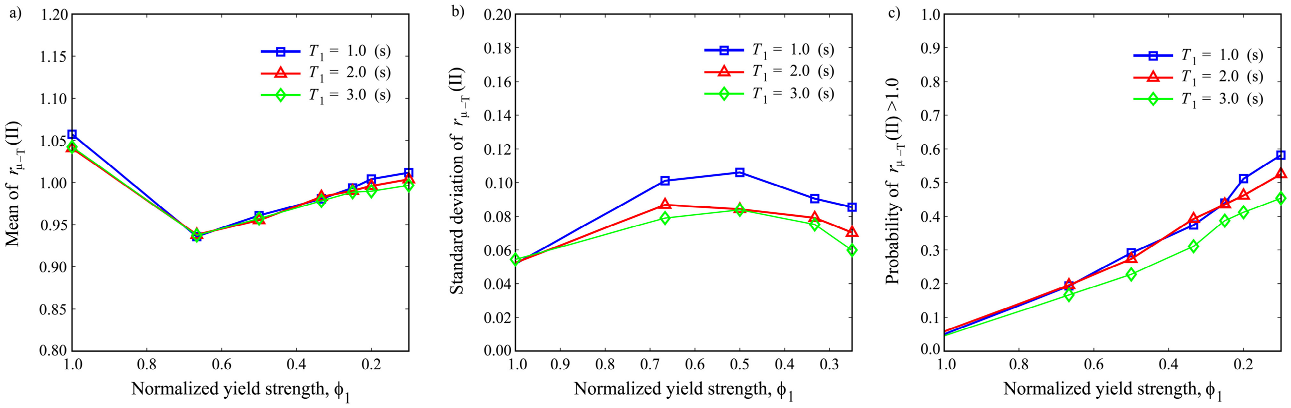


Figure 3 Effects of TMD on the ductility demand ratio $r_{\mu-T}$(II) considering $\rho$ = 0.05 and $[\alpha, \beta, \gamma, n]$ = [0.05, 0.5, 0.5, 25]: a) Mean of $r_{\mu-T}$(II), b) Standard deviation of $r_{\mu-T}$(II), and c) Probability of $r_{\mu-T}$(II) greater than one $P(r_{\mu-T}(II)>1)$.

The figures suggest that the effectiveness of TMD in reducing the peak displacement for stiff structures is not very significant, whereas it can be beneficial for $T_1 \geq 0.5$ (s). These observations are in agreement with those made by Sadek et al. (1997). The figures also show that as $\rho$ increases, the effectiveness of TMD increases, whereas the standard deviation of $r_{E-T}$ increases. In all cases, uncertainty associated with $r_{E-T}$ can be important. To see the implication of this, the probability of $r_{E-T}$ greater than one, $P(r_{E-T}>1)$, is estimated from the samples for the considered cases, and the obtained values are shown in Figure 2c. The results indicate that $P(r_{E-T}>1)$ is not very sensitive to $\rho$ and $T_1$ (except for $T_1 < 0.3$ (s)), and that the probability of the performance of the structure with TMD being worse than the original structure is about less than 20%. Probability distribution fitting results, not shown herein, suggest that $r_{E-T}$ can be modeled as a lognormal variate.

Instead of considering linear elastic structures with/without TMD, a more realistic scenario is to consider that main structures behave inelastically under severe seismic excitations. In such a case, for a given $\phi_1$, one can evaluate the ratio $r_{\mu-T}$, $r_{\mu-T} = \mu_{1-T}/\mu_1$, where $\mu_{1-T}$ is the ductility demand of the main structure with TMD, and $\mu_1$ denotes the ductility demand of the main structure without TMD. Given $\phi_1$ and a record, one needs to consider three cases ($\mu_1>1$, $\mu_{1-T}\geq1$), ($\mu_1>1$, $\mu_{1-T}<1$), and ($\mu_1\leq1$, $\mu_{1-T}\geq1$) (the case ($\mu_1<1$, $\mu_{1-T}<1$) was assessed using $r_{E-T}$). To distinguish these three combinations, $r_{\mu-T}$(II), $r_{\mu-T}$(IE) and $r_{\mu-T}$(EI) are used for ($\mu_1>1$, $\mu_{1-T}\geq1$), ($\mu_1>1$, $\mu_{1-T}<1$), and ($\mu_1\leq1$, $\mu_{1-T}\geq1$), respectively instead of $r_{E-T}$. Note that $r_{\mu-T}$(II) represents the ductility demand ratio and is focused on in the following, while the cases $r_{\mu-T}$(IE) and $r_{\mu-T}$(EI) indicate that the installation of TMD improves and worsens performance, respectively.

For evaluating these ratios, consider that the degradation and pinching effect can be ignored, and the remaining

Bouc-Wen model parameters [$\alpha$, $\beta$, $\gamma$, $n$] equal [0.05, 0.5, 0.5, 25] for the main structure (see Figure 1b). Given $\phi_1$ and $T_1$ of the main structure, one first evaluates $\mu_1$ for a record, and then one estimates $\mu_{1\text{-T}}$ for the structure with TMD using the same record. Based on the obtained samples of $\mu_1$, $\mu_{1\text{-T}}$, and $r_{\mu\text{-T}}$, the statistics of $r_{\mu\text{-T}}$(II) are presented in Figures 3a and 3b, and the probability of $r_{\mu\text{-T}}$(II) greater than one, denoted by $P(r_{\mu\text{-T}}(\text{II})>1)$, is shown in Figure 3c. The results presented in Figure 3a suggest that the mean of $r_{\mu\text{-T}}$(II) is less than unity in almost all considered cases. This indicates that on average the use of TMD effectively reduces inelastic responses of the structure. However, the installation of TMD is not necessarily beneficial, since this effectiveness is associated with uncertainty (i.e., large standard deviation of $r_{\mu\text{-T}}$(II); see Figure 3b) and the value of $P(r_{\mu\text{-T}}(\text{II})>1)$ is significant (see Figure 3c). Furthermore, the probability distribution fitting is carried out for $r_{\mu\text{-T}}$(II) and the results indicate that $r_{\mu\text{-T}}$(II) can be modeled as a Frechet or lognormal variate depending on structural characteristics.

To further investigate the effectiveness of TMD for structures with different hysteretic shape, stiffness/strength degradation, and pinching behavior, the above analysis is repeated for selected sets of Bouc-Wen model parameters. Results suggest that in such cases the aforementioned observations are equally applicable. In general, the installation of TMD can be beneficial for longer natural vibration periods and larger normalized yield strength values, although there is some chance of worsen performance due to variability of ground motions. Therefore, the benefit of installing TMD must be assessed in terms of cost-effectiveness, including damage costs, which will be discussed shortly.

### *3.2 Response Ratios for BID*

To evaluate the effectiveness of BID in reducing peak responses, samples of the ratio of the maximum displacement ductility demand of isolated structures to that of fixed structures, $r_{\mu\text{-B}}$, are evaluated by using the considered records. For non-degrading and non-pinching structures with linear isolators ($T_I$ = 3 (s), $\xi_I$ = 0.05, and $\rho = 10T_2$), the mean of $r_{\mu\text{-B}}$ is shown in Figure 4a for a range of $T_2$ and $\phi_2$ values. The results show that for $T_2 \le 0.5$ (s) and $\phi_2 \ge 1$, the mean is about 0.15-0.2, the mean for $T_2 = 1.0$ (s) is greater than that for $T_2 \le 0.5$ (s), and the mean tends to increase as $\phi_2$ decreases. Therefore, the use of BID mitigates seismic demand significantly. The increase in the mean of $r_{\mu\text{-B}}$ as $\phi_2$ decreases is expected, since the vibration period of inelastic structures tends to be longer as the excitation level increases.

To assess probabilistic characteristics of $\mu_2$, probability distribution fitting is carried out using samples of $\mu_2$ for different values of $T_2$ and $\phi_2$ by considering commonly employed probability distributions including the lognormal, Weibull, Gumbel, Frechet, and gamma distributions. The results suggest that $\mu_2$-1 (> 0) can be considered as a gamma variate, for which the quantile-quantile (Q-Q) plot is illustrated in Figure 4b. Moreover, preliminary results suggest that simple empirical equations as functions of structural characteristics (including $\phi_2$) and isolator's characteristics can be developed to estimate the mean and standard deviation of $\mu_2$.

It must be emphasized that the probability distribution of $\mu_2$ conditioned on $\mu_2 > 1$ alone is insufficient to evaluate probability that the ductility demand is greater than a ductility capacity value $\mu_C$. For this, one needs an estimate of probability of $\mu_2 > 1$, $P(\mu_2>1)$; the assessed values of $P(\mu_2>1)$ are shown in Figure 4c, indicating that they depend on $T_2$ and $\phi_2$. It is considered that this probability can be approximated by $P(\mu_2>1) = \Phi((\ln(1/\phi_2)-\theta_1)/\theta_2)$, where $\Phi(\bullet)$ represents the standard normal distribution function, and the parameters $\theta_1$ and $\theta_2$ are determined based on the least squares fitting. The fitted relation for $P(\mu_2>1)$ is also shown in Figure 4c.

The analysis for the results shown in Figure 4a is repeated by considering bilinear base isolators, and the results are shown in Figure 5a for a few values of $Q_{y1}$ and $u_{y1}$. It can be observed from the figure that higher effectiveness of BID is achieved by selecting lower values of $Q_{y1}$ or higher values of $u_{y1}$. Note that a steeper pre-yield force-displacement slope of the base isolator decreases the effectiveness of BID but it has a desirable effect of reducing the displacement demand in base isolators. Thus, an optimum design of BID must consider seismic demands on both structure and base isolator. Statistical analysis of the samples of $\mu_2$ shown in Figures 5b and 5c indicates that observations made concerning the probability distribution of $\mu_2$-1 conditioned on $\mu_2 > 1$

and $P(\mu_2>1)$ for the linear base isolator is equally applicable for the bilinear base isolator. It is noted that parametric studies considering structures with different hysteretic behavior and different combinations of $T_I$, $\xi_I$, and $\rho$ are also carried out and the obtained results, in general, exhibit similar trends as discussed above.

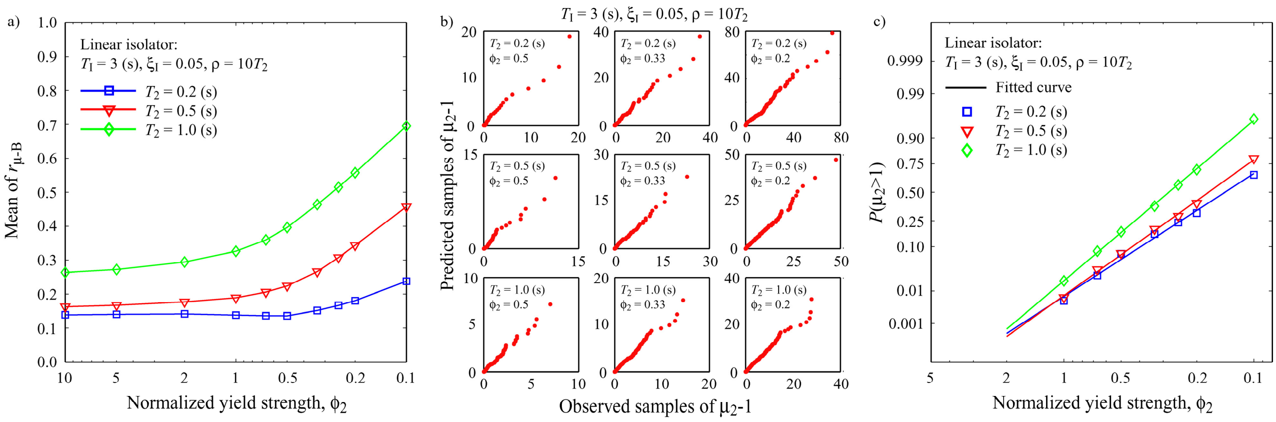


Figure 4 Statistics of peak responses of structures with linear isolators: a) Mean of the ductility demand ratio $r_{\mu\text{-B}}$, b) Q-Q plot of $\mu_2$-1 for the gamma distribution, and c) Probability of $\mu_2$ greater than one $P(\mu_2>1)$.

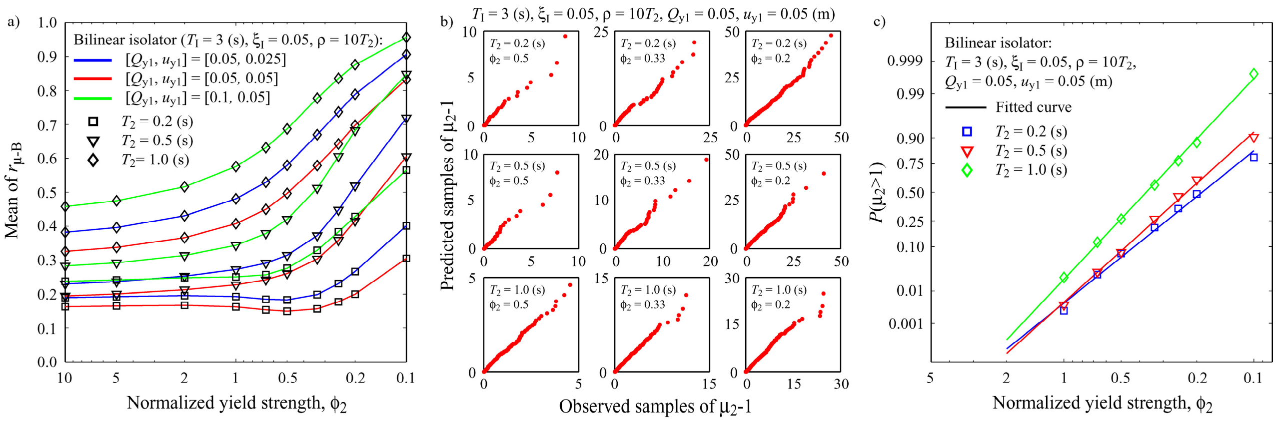


Figure 5 Statistics of peak responses of structures with bilinear isolators: a) Mean of the ductility demand ratio $r_{\mu\text{-B}}$, b) Q-Q plot of $\mu_2$-1 for the gamma distribution, and c) Probability of $\mu_2$ greater than one $P(\mu_2>1)$.

## 4. COST-EFFECTIVENESS OF TUNED MASS DAMPERS AND BASE ISOLATION

To investigate the cost-effectiveness of TMD/BID for design and retrofit, a lifecycle cost model of a building considered by Goda and Hong (2006) is adopted. Based on their formulation, information given in CSA (1981) and some simplification, the lifecycle cost that is normalized by the reference structural component cost $C_{ST,ref}$, $LC_N(A,t)$, during its service period of $t$ years and with a seismic design level $A$ (representing the design spectral acceleration) is expressed as,

$$LC_N(A,t) = (A/A_{ref})^{a_1} + a_2 + \sum_{i=1}^{N(t)} \left( [(A/A_{ref})^{a_1} + a_2]\delta_i^{a_3} + a_4\delta_i^{a_5} \right) e^{-\gamma\tau_i}, \quad (4.1)$$

where $a_i$, ($i$ = 1,…,5), is the model parameters; $C_0(A)$ (= $((A/A_{ref})^{a_1}+a_2)C_{ST,ref}$) represents the initial construction cost of a building, $A_{ref}$ is the reference seismic design level that corresponds to $C_{ST,ref}$; $C_0(A)\delta^{a_3}$ and $C_{ST,ref}\times a_4\delta^{a_5}$

represent the repair/reconstruction cost and damage cost excluding costs due to injury and fatality for a given damage factor $\delta$; $\delta = \max(\min((\mu_D-1)/((\mu_C-1),1),0)$, in which $\mu_C$ is the inelastic ductility capacity of a building; $N(t)$ is the number of seismic events that affect the structure in $t$ years; $\tau_i$ is the occurrence time of the $i$-th seismic event; and $\gamma$ is the discount rate.

It is considered that $\mu_C$ is a lognormal variate with the mean depending on structural characteristics (i.e., materials and lateral load resisting systems) and the coefficient of variation (cov) equal to 0.5, and that the annual maximum pseudo-spectral acceleration at a site (i.e., elastic seismic demand) is lognormally distributed with the mean and cov given in Goda and Hong (2006). The probabilistic characteristics of ductility demand $\mu_D$ for structures with/without TMD/BID (i.e., $\mu_1$ for a TMD system and $\mu_2$ for a BID system) were discussed previously as a function of the normalized yield strength $\phi$ (i.e., ratio of the yield strength of a building to the elastic seismic demand due to a randomly occurring seismic event), noting that $\phi$ can be related to the seismic hazard and seismic design coefficients (Hong and Hong, 2007). The cost model parameters used for the analyses are selected based on available information (CSA, 1981; Goda and Hong, 2006) by taking the 1000-year return period level as a reference: $[a_1, a_2, a_3, a_4, a_5] = [0.1, 3, 0.9, 3, 0.9]$.

By following the analysis procedure outlined in Goda and Hong (2006), the expected values of $LC_N(A,t)$, $E(LC_N(A,t))$, for non-degrading and non-pinching structures with/without TMD and BID located in Vancouver are calculated and shown in Figure 6a and Figure 6b, respectively. For a TMD system, three cases with different mass ratios ($\rho$ = 0.02, 0.05, and 0.1) for $T_1$ = 2.0 (s) are considered, while for a BID system, two cases with linear and bilinear base isolators ($T_I$ = 3 (s), $\xi_I$ = 0.05, $\rho$ = 5, $Q_{y1}$ = 0.05, $u_{y1}$ = 0.05 (m)) for $T_2$ = 0.5 (s) are considered. As expected, in all cases $E(LC_N(A,t))$ without TMD/BID is greater than $E(LC_N(A,t))$ with TMD/BID, since additional design, construction, and installation costs associated with TMD/BID are not included in this calculation. This difference expressed in terms of the percentage of the initial construction cost $C_0(A)$, ranges from 0.2% to 2.5% for the TMD system, and from 2% to 16% for the BID system around the return periods of practical interest (e.g., 250 to 2500 years). Therefore, if the cost associated with TMD/BID is less than the percentage of $C_0(A)$, the installation of auxiliary devices is cost-effective.

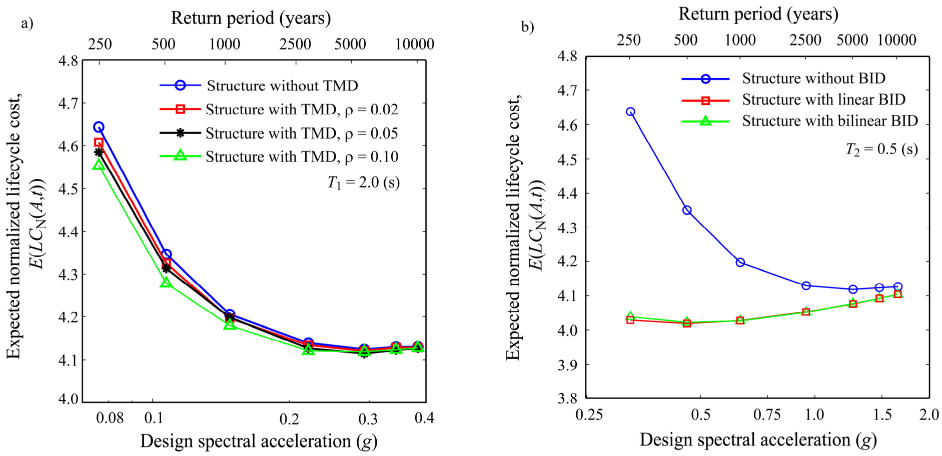


Figure 6 Expected normalized lifecycle cost for a range of seismic design levels: a) Three TMD systems with different mass ratios and b) Two BID systems with linear and bilinear base isolators.

## 5. CONCLUSIONS

The present study investigates the statistics of peak elastic and inelastic responses of structures with TMD/BID under seismic excitations, and assesses the cost-effectiveness of structures with an option of installing these devices in mitigating seismic risk. The analysis results indicate that TMD reduces peak structural responses by as much as 10-15%, depending on the mass ratio, and is effective for structures with longer vibration periods.

The effectiveness of TMD decreases as the seismic excitation level increases and its installation could have a negative impact on the structure. The results for BID systems show that BID significantly reduces peak structural responses by as much as 70-80% and is particularly beneficial for structures with shorter vibration periods. This effectiveness decreases as the seismic excitation level increases, since the degradation of structures leads to the elongation of the vibration period. It is also indicated that bilinear base isolators, although slightly less effective than linear ones, can be useful for practical applications, since peak displacement demands in isolators are reduced. Furthermore, the lifecycle cost analysis results illustrate that TMD reduces the expected lifecycle cost by about up to 2.5% in terms of the initial construction cost, whereas BID reduces it by about up to 16%. If design/construction/installation costs of TMD/BID are less than the indicated costs, TMD/BID is cost-effective for seismic retrofitting and should be considered as a viable option in achieving enhanced seismic protection. Such information is especially valuable to make optimal decisions for managing seismic risk efficiently.

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