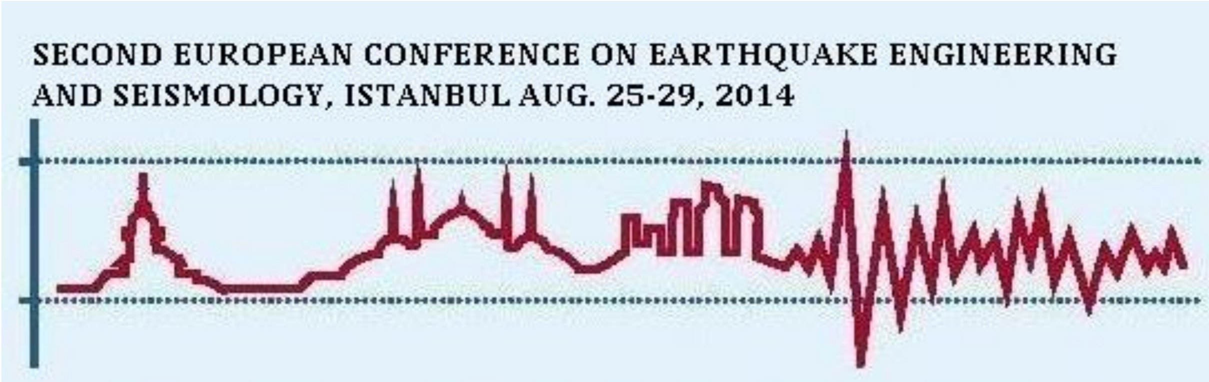

PROPOSAL FOR EQUIVALENT DAMPING RATIO TO ACCOUNT FOR LEAD CORE HEATING EFFECT IN LRBs

Gökhan OZDEMİR[1]

ABSTRACT

In this paper, a new formulation to estimate the equivalent damping ratio, which is a function of the area under the hysteretic force-deformation relation, used in equivalent linear analysis is proposed for structures isolated with lead rubber bearings (LRBs). Proposed formulation is capable of incorporating the variation in hysteretic behavior of LRBs due to reduction in strength of bearing as a function of lead core heating. The proposed equation considers the change in energy dissipation capacity of an LRB when a non-deteriorating hysteretic representation is used in modeling rather than the actual deteriorating representation. Thus, a series of NTHA, where LRBs are represented by both deteriorating and non-deteriorating hysteretic force-deformation relations, are performed to obtain the differentiation in dissipated energies. The accuracy of the proposed equation to estimate the maximum isolator displacements (MIDs) is tested by comparing the MIDs obtained from a number of nonlinear response history analyses (NRHA) with the predicted ones. NRHA are conducted with near field ground motions that constitute similar characteristics in terms of magnitude, closest distance to fault rupture, and local soil condition. In the analyses, effects of isolator properties namely, isolation period and characteristic strength and seismicity level on the efficiency of proposed formulation are also investigated. It is found that the proposed equation results in highly accurate estimations for MIDs, regardless of isolator characteristics and seismicity level.

INTRODUCTION

The main design parameter for seismic base isolated structures is the displacement over the isolation level. Because, isolator displacements dictates: i) the space around the isolated superstructure to facilitate unrestricted movement of the superstructure, ii) forces transmitted to bridge substructure or foundation of the structures, iii) geometrical features of the isolators. As a consequence, prediction of maximum isolator displacements (MIDs) is of vital importance in design of seismic isolated structures (SISs). Although, the most reliable way to predict the isolator displacements is to perform nonlinear response history analyses (NRHA), due to its simplicity in calculation, one of the most common ways to determine the MID of a SIS is a simplified method based on the use of elastic response spectrum. This method enables the prediction of maximum elastic deformations of a system with a representative period and damping ratio. However, since the behavior of isolators is nonlinear, there is a need to identify an equivalent linear system which is able to represent the nonlinear characteristic of seismic isolation systems. Such linearization requires the definition of equivalent linear elastic terms namely, effective stiffness, k_{eff}, and equivalent damping ratio, ξ_{eq}. Since, it is an approximate solution, the accuracy of the simplified method of analysis in determining the response quantities of SIS has been tested by numerous studies in literature (Kwan and Billington, 2003; Jara and Casas, 2006; Dicleli and Buddaram, 2007; Ozdemir and Constantinou, 2010; Jara et al., 2012). In these studies, accuracy of

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simplified method of analysis was investigated by comparing the estimated response quantities with the ones obtained from NRHA. In their studies, researchers considered several parameters that highly affect both the equivalent linearization and the hysteretic behavior of the employed isolators such as ground motion characteristics (duration, intensity and frequency content) and isolator characteristics (characteristic strength to weight ratio, isolation period, type of hysteretic representations). Nevertheless, none of the previous studies considered the deterioration in force-deformation relation of isolators by assuming a non-deteriorating (steady-state) force-deformation relation for investigated isolators. However, Robinson (1982) revealed that there occurs a strength deterioration in hysteretic force-deformation behavior of an LRB, which is among the most widely used isolators, under cyclic motion. Recently published two companion papers showed that the deterioration in strength of LRBs is basically due to heat generated at the lead core (Kalpakidis and Constantinou, 2009a, b). Furthermore, it has been revealed that in terms of MIDs, there may be severe differentiation in cases where LRBs are represented by deteriorating and non-deteriorating force-deformation relations (Kalpakidis et al., 2010; Ozdemir et al, 2011; Ozdemir and Dicleli, 2012). Results of Ozdemir et al. (2011) also showed that such differentiation in MIDs is a function of isolator characteristics (characteristic strength to weight ratio and isolation period). Thus, there is a need to investigate the adequacy of the existing approximate methods to predict the response of LRBs when the effect of lead core heating is taken into account.

RESEARCH OBJECTIVES AND OUTLINE

The objectives of the present study are (i) to assess the accuracy of the existing formulations for simplified analysis of SISs; (ii) to determine the relations between the dissipated energies of LRBs represented by both non-deteriorating and deteriorating hysteretic representations; (iii) to improve the accuracy of existing simplified methods by translating these energy relations into a set of proposed equations to be used in preliminary design of, specifically, structures isolated with LRBs where lead core heating effect is of concern; (iv) to test the validity of the proposed formulation at different seismicity levels. To achieve the purpose of the study presented herein, several NRHA and simplified analyses are conducted. In NRHA, the temperature dependent behavior of LRBs is employed by means of a deteriorating force-deformation relation that is capable of representing the instantaneous reduction in the strength of bearing as a function of rise in lead core temperature under cyclic motion. In the analyses, significance of several parameters such as isolation period, characteristic strength of isolators, and seismicity level are investigated.

The assessment of the existing simplified analysis methods is conducted by comparing the MIDs of the considered isolated structures obtained from both equivalent linear systems employed in simplified analyses and NRHA in which lead core heating is incorporated. Such a comparison enables to acquire best form of approximation used in simplified analyses which is then used as a basis for the proposed formulations by considering the relations between dissipated energies in deteriorating ($E_{deteriorating}$) and non-deteriorating ($E_{non\text{-}deteriorating}$) representations of LRBs. $E_{deteriorating}/E_{non\text{-}deteriorating}$ ratios are used to propose a new empirical relationship for approximation of effective damping ratios and to improve the accuracy in predictions of simplified analysis methods. Finally, the equation proposed to calculate the effective damping ratio of the equivalent linear representation of LRB is also tested at low- and medium-seismicity conditions.

STRUCTURAL MODEL

In this study, several parametric analyses with various isolation systems were performed with a 3-story seismic isolated steel frame structure. The investigated seismic isolated structure was adopted from the hypothetical emergency operation center designed by Dr. Charles A. Kircher for National Earthquake Hazards Reduction Program (NEHRP) (2006). The structure has a total height of 9m with 3m story height at each floor and is symmetric in plan where the dimensions are 36mx54m. There are four and six bays in short and long directions with equal bay lengths of 9m, respectively. Total weight of the superstructure is 73000 kN. Weight of the floor at roof level is taken as 75% of the weight of the other floors and weight at the isolation level is assumed to be equal to the first and second floor weights. The idealized analytical model of the investigated seismic isolated structure is given in Fig. 1. The superstructure shown in Fig. 1 was modeled with elastic elements. Floor masses were equally distributed to joints with rigid diaphragm assumption at each floor. Nonlinear zero-length link elements of OpenSees (2009) were utilized to model bilinear force-deformation relations of isolators.

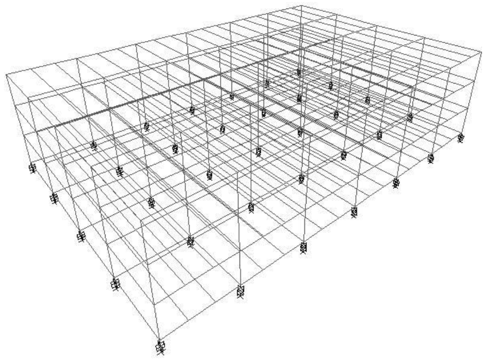


Figure 1. Idealized analytical model of the investigated seismic isolated structure.

SELECTED GROUND MOTIONS

The ground motions used in this study are composed of 40 near-field records with a closest distance (*R*) to the fault rupture less than 20 km (Somerville et al., 1997) and taken from the study of Gunay and Sucuoglu (2009). The average shear wave velocities of the records at the uppermost 30 m (V_{s30}) soil profile are ranging between 180 m/sec and 360 m/sec. Selected ground motions were compiled from the PEER (available at peer.berkeley.edu/smcat/search.html) database. The corresponding moment magnitudes (M_w) of the selected records range from 6.2 to 7.5. Fig. 2 presents the 5% damped acceleration spectra of the selected ground motions. The black solid line shown in Fig. 2 represents the mean spectra of each set of motions.

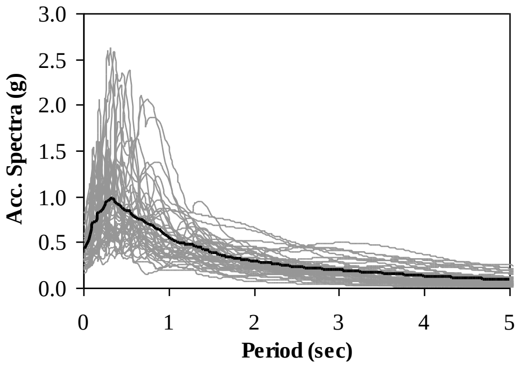


Figure 2. 5% damped acceleration spectra of ground motions.

SCALING OF GROUND MOTIONS

The scaling methodology used in this study is composed of two complimentary steps and in accordance with the specifications of American Society of Civil Engineering (ASCE) (2005). ASCE (2005) assures that the selected ground motions should be scaled such that for the period range under interest, the average of the 5% damped spectral ordinates from all ground motions does not fall below 1.3 times the corresponding 5% damped target spectrum by more than 10%. In the first step, 5% damped acceleration spectrum of each ground motion record becomes compatible with the target spectrum. The second step of the scaling was performed to assure the requirements of ASCE (2005). For detailed information about the procedure, see Ozdemir and Constantinou (2010). Fig. 3 shows the scaled average spectrum of those ground motions together with the 5% damped design spectra. The minimum, maximum, and average of scale factors used in this study are, respectively, 0.8, 4.3, and 2.6.

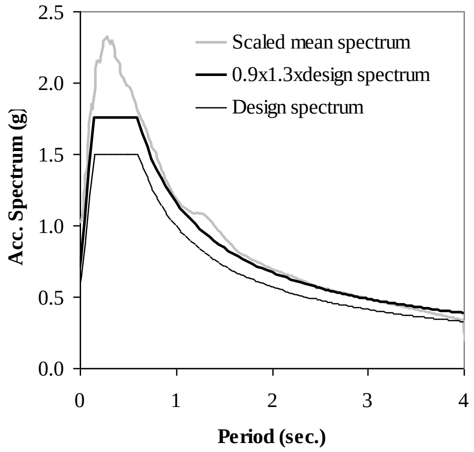


Figure 3. Design spectrum and mean spectrum of ground motions after scaling.

DETERIORATING HYSTERETIC BEHAVIOR OF LRBs

The nonlinear force-deformation relation of LRBs is generally represented by a generic non-deteriorating bilinear hysteretic model. However, experimental studies showed that hysteretic behavior of LRBs deteriorates under cyclic motion (Robinson, 1982). Basis of such variation in strength of isolators has been identified so far by the effects of loading history, aging, contamination and heating. On the other hand, Kalpakidis and Constantinou (2009a, b) revealed that most of the reduction in strength of LRBs occurs due to heating of lead core. Authors also proposed a mathematical model that is capable of simulating the deterioration in strength of LRBs as a function of the lead core temperature. Their model considers the instantaneous temperature rise in the lead core due to cyclic motion of LRBs and allows calculating the reduction in strength of isolator by reducing the initial yield stress of the lead, instantly. According to that model, the temperature rise, $\dot{T}_L$, in the lead core is calculated by the following set of equations:

$$\dot{T}_L = \frac{\sigma_{YL}(T_L)\cdot\left|Z\cdot\dot{D}\right|}{\rho_L\cdot c_L\cdot h_L} - \frac{k_s\cdot T_L}{r\cdot\rho_L\cdot c_L\cdot h_L}\cdot\left(\frac{1}{F}+1.274\cdot\left(\frac{t_s}{r}\right)\cdot\left(t^+\right)^{-1/3}\right) \tag{1}$$

$$F = \begin{cases} 2\cdot\left(\dfrac{t^+}{\pi}\right)^{1/2} - \dfrac{t^+}{\pi}\cdot\left[2-\left(\dfrac{t^+}{4}\right)-\left(\dfrac{t^+}{4}\right)^2-\dfrac{15}{4}\cdot\left(\dfrac{t^+}{4}\right)^3\right], & t^+ < 0.6 \\ \dfrac{8}{3\cdot\pi} - \dfrac{1}{2\cdot\left(\pi\cdot t^+\right)^{1/2}}\cdot\left[1-\dfrac{1}{3\cdot\left(4\cdot t^+\right)}+\dfrac{1}{6\cdot\left(4\cdot t^+\right)^2}-\dfrac{1}{12\cdot\left(4\cdot t^+\right)^3}\right], & t^+ \geq 0.6 \end{cases} \tag{2}$$

$$t^+ = \frac{\alpha_s\cdot t}{r^2} \tag{3}$$

$$\sigma_{YL}\left(T_L\right) = \sigma_{YL0}\cdot\exp\left(-E_2\cdot T_L\right) \tag{4}$$

where, h_L, r, ρ_L, c_L and σ_{YL0} are the height, radius, density, specific heat and initial yield stress of the lead core, respectively; t_s is the total shim plate thickness, α_s is the thermal diffusivity of steel, k_s is the thermal conductivity of steel, t^+ is the dimensionless time, t is the time since the beginning of the motion, and E_2 is a constant that relates the temperature and yield stress. In Equation (1), Z is the hysteretic dimensionless quantity that varies between ±1, and $\dot{D}$ is the relative velocity of the bearing.

Once the yield stress of lead is defined as a function of instantaneous lead core temperature, the force carried by LRB, F_b, can be calculated as described in Equation (5).

$$F_b = k_d D_y + \sigma_{YL}(T_L) A_L Z \quad (5)$$

where A_L is the cross-sectional area of the lead core, k_d and D_y are the post-yield stiffness and yield displacement of the bilinear force-deformation relation, respectively (see Fig. 5a). In Eqn. (5), Z satisfies the first-order differential equation given below:

$$D_y \dot{Z} = \left(A - |Z|^2 B\left(1 + \mathrm{sgn}\left(\dot{D}Z\right)\right)\right)\dot{D} \quad (6)$$

where A and B are dimensionless quantities that control the shape and size of the hysteresis loops of the bearing. To provide that Z varies in between ±1, the relation between A and B is selected as A=2B. Hence, A and B are equal to 1.0 and 0.5, respectively.

DESIGN OF ANALYZED LRBs

The current practice when performing NRHA of isolated structures is to conduct bounding analysis. In bounding analysis, two non-deteriorating force-deformation relations are used to define the properties for upper and lower bound cases. Results from upper bound analysis are generally used to calculate maximum shear force acting on the isolator whereas results from lower bound analysis are generally used to obtain maximum isolator displacement. Definitions of upper and lower bound properties of LRBs used in the analyses are as follows: (i) the effective yield stress of lead used in the upper bound analyses is obtained from the first cycle of bilinear hysteretic behavior, (ii) the effective yield stress of lead used in the lower bound analyses is obtained by taking the average of effective yield stresses of lead obtained from the first three cycles. Since, the research objective of this study is to predict the maximum isolator displacements more accurately rather than isolator forces, when the term "non-deteriorating" is used to define the hysteretic behavior of LRBs, the force-deformation relation that corresponds to lower bound characteristics is referred. It should also be noted that the only differentiation between deteriorating and non-deteriorating curves is not the effect of temperature rise in the lead core. The second distinction between deteriorating and non-deteriorating cases is that the initial yield strength of deteriorating force-deformation relation is 1.35 (Constantinou et al., 2007) times that of the non-deteriorating one. This ratio comes from the correlation between upper and lower bound characteristics of the bearing. In this study, the effective yield stress value of the lead for lower bound analysis was selected as 10 MPa (Robinson, 1982). Since, the relation between the yield stresses of the lead in the upper (σ_u) and lower (σ_l) bound cases was stated as σ_u=1.35σ_l (Constantinou et al., 2007) based on several experimental results, the effective yield stress of the lead for the upper bound case was selected as 13.5 MPa. This value basically stands for the initial yield stress, σ_{YL0}, of the lead core which was used in the construction of deteriorating bilinear hysteresis.

In order to assess the effect of isolator characteristics on the accuracy of simplified method of analysis to estimate MIDs, 16 LRBs were designed. These bearings have various isolation periods and characteristic strength to weight ratios to be able to perform parametric analyses. Each of these isolators was designed following an iterative procedure that fulfills the requirements for stability and strength of bearings. Analyzed LRBs were designed in accordance with the design spectrum given in Fig. 3. Isolators were designed with post-yield isolation periods, T_d, of 2.25s, 2.50s, 2.75s, 3.00s. The characteristic strength to weight ratios of the designed LRBs are 0.075, 0.090, 0.105, 0.120. Table 1 presents characteristics of the considered LRBs. It is to be noted that the design properties given in

Tables 1 are based on the lower bound properties (σ_l=10 MPa) and used to define the corresponding non-deteriorating force deformation relationships. On the other hand, although their deteriorating counterparts have the same geometrical features, their initial yield strength, F_y (see Fig. 4.a), is different in accordance with Eqn. (6). Inserting 13.5 MPa for the initial value of $\sigma_{YL}(T_L)$ rather than 10 MPa gives the initial yield strength, F_y, of the deteriorating force-deformation relation of the considered LRBs.

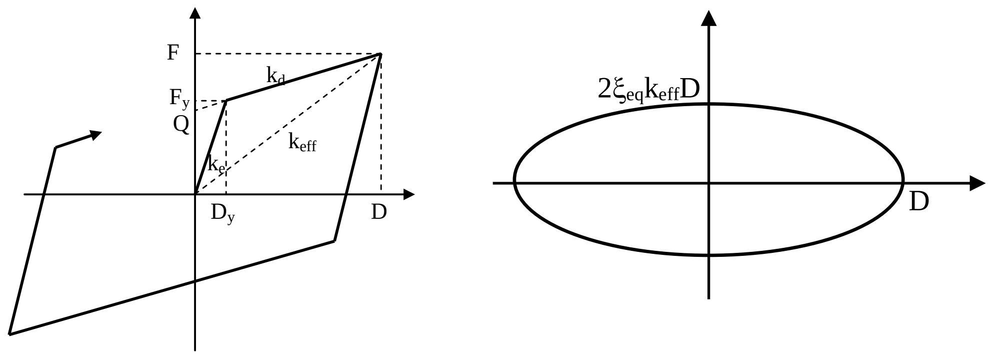
Table 1. Properties of the analyzed LRBs.

n	k_d (post-yield stiffness) (N/mm)	T_d (post-yield period) (sec.)	*D* (design displacement) (mm)
Q/W=0.075; *d*=142mm; *D*=848mm; *Q*=156.8kN			
23	1665.8	2.25	498
29	1353.5	2.50	542
34	1110.6	2.75	583
41	941.6	3.00	622
Q/W=0.090; *d*=155mm; *D*=848mm; *Q*=188.2kN			
23	1665.8	2.25	456
29	1353.5	2.50	492
34	1110.6	2.75	525
41	941.6	3.00	555
Q/W=0.105; *d*=167mm; *D*=848mm; *Q*=219.5kN			
23	1665.8	2.25	417
29	1353.5	2.50	446
34	1110.6	2.75	472
41	941.6	3.00	495
Q/W=0.120; *d*=179mm; *D*=848mm; *Q*=250.9kN			
23	1665.8	2.25	381
29	1353.5	2.50	404
34	1110.6	2.75	427
41	941.6	3.00	452

In Table 1, *n* is the number of rubber layers (the number of steel plates along the height of the bearing equals *n*-1); T_d is the post-yield period; *U* is the maximum design displacement of the isolator; *d* is the diameter of the lead core; *D* is the diameter of the bearing. The thicknesses of each rubber layer and steel plate were selected as 7.1mm (0.28in) and 3mm (0.118in), respectively.

EQUIVALENT LINEARIZATION OF BILENAR HYSTERETIC BEHAVIOR

The isolation systems considered in this study are composed of LRBs and are typically represented by a generic bilinear hysteretic curve (Fig. 4.a). Such a representation is steady-state and does not consider any deterioration in strength of isolator under cyclic motion. In Fig. 4.a, k_e is the initial elastic stiffness; k_d is the post yield stiffness; *Q* is the characteristic strength of the bearing; F_y and U_y are yield strength and yield displacement of the bearing, respectively; *F* and *U* are maximum force acting on the bearing and maximum isolator displacement, respectively; k_{eff} is the effective stiffness.



(a) (b)

Figure 4. (a) Idealized non-deteriorating hysteresis of a typical LRB (b) Hysteresis of a viscous damper.

Equivalent linearization is an attempt to simplify the nonlinear behavior (Fig. 4.a) of systems by assuming a representative linear system so that the maximum displacement response of both equivalent linear and nonlinear systems matches. This is achieved by defining effective stiffness, k_{eff}, and equivalent damping ratio, ξ_{eq}. Although there are several methods in literature to define equivalent linear parameters, secant stiffness method is the most commonly used analytical method. According to secant stiffness method, k_{eff} is defined as the slope of the dashed line that connects the origin to the point of maximum displacement and force as shown in Fig. 4.a and simply calculated by maximum force, F, divided by maximum displacement, U. The corresponding equivalent damping ratio, ξ_{eq}, is determined based on the assumption that the hysteretic energy dissipated at one cycle of isolator motion is equal to the viscous energy dissipation of the equivalent linear system. This implies that the area under the bilinear force-deformation relation given in Fig. 4.a is equal to the area under the curve shown in Fig. 4.b (Naeim and Kelly, 1999). As a result, ξ_{eq} is derived as:

$$\xi_{eq} = \frac{4Q(D - D_y)}{2\pi k_{eff} D^2} \quad where \quad k_{eff} = \frac{F}{D} = \frac{Q}{D} + k_d \tag{7}$$

ASSESSED SIMPLIFIED METHODS

In the literature, there exists several methodologies, both analytical and empirical, to determine equivalent linear parameters k_{eff} and ξ_{eq} to be used in simplified method of analysis. The secant stiffness method, which is discussed in the previous section, is the most commonly used method to idealize the nonlinear hysteretic behavior of isolators by an equivalent linear system. It is even described as the “standard” method to be used in such idealization (Kwan and Billington, 2003). However, due to the assumptions involved in secant stiffness method, there have been numerous researches that investigate its accuracy to predict the maximum response quantities of the corresponding nonlinear isolation system. For instance, two of the assumptions involved in secant stiffness method emerge in the definition of ξ_{eq}. The derivation of Equation (7) assumes that the excitation frequency of the nonlinear system is identical to that of idealized system and the nonlinear system has a non-deteriorating (steady-state) response. Furthermore, such idealization does not consider the effects of ground motion characteristics such as duration, intensity and frequency content. Thus, existing methods attempt to cover the effects of these factors by developing empirical formulations. In the following subsections, previously proposed formulations developed to increase the accuracy of the simplified method of analysis are discussed briefly.

Hwang and Sheng, 1993 (*herein termed as Hwang 1993*)

Hwang and Sheng (1993) focused on the linearized system parameters, effective stiffness and equivalent damping ratio, especially, for LRBs. Authors proposed a set of formulation for both k_{eff} and ξ_{eq} as given below. In Eqns. (8) and (9), k_e is the initial elastic stiffness, k_{eff} is the effective stiffness, ξ_{eq} is the equivalent damping ratio, and μ is the ductility ratio defined as maximum isolator displacement, D, over yield deformation, D_y (see Fig. 5.a).

$$k_{eff} = \left[1 + \ln\left[1 + 0.13(\mu - 1)^{1.137}\right]\right]^{-2} \cdot k_e \tag{8}$$

$$\xi_{eq} = 0.0587(\mu - 1)^{0.371} \tag{9}$$

Hwang et al., 1995 (*herein termed as Hwang 1995*)

Hwang et al. (1995) proposed a similar formulation to increase the accuracy of the simplified method of analysis to predict the MID of LRB isolated bridges. The empirical formulations proposed by Hwang et al. (1995) for effective stiffness and equivalent damping ratio are given through Eqns. (10) and (11), respectively. In these equations, α is the ratio between post-yield stiffness, k_d, and initial stiffness, k_e, and μ stands for the ductility ratio of the bilinear force-deformation relation which is calculated by maximum isolator displacement, D, over yield deformation, D_y (see Fig. 5.a).

$$k_{eff} = \frac{1+\alpha(\mu-1)}{\mu}\left[1-0.737\frac{\mu-1}{\mu^2}\right]^{-2} \cdot k_e \tag{10}$$

$$\xi_{eq} = \frac{2(1-\alpha)\left(1-\frac{1}{\mu}\right)}{\pi[1+\alpha(\mu-1)]} \cdot \frac{\mu^{0.58}}{6-10\alpha} \tag{11}$$

Jara and Casas, 2006 (*herein termed as Jara 2006*)

Jara and Casas (2006) attempt to predict the MIDs of bridges supported on LRBs by proposing an empirical relation to determine equivalent damping ratio of linearized system. Authors used the secant stiffness method to obtain effective stiffness, k_{eff}, and calculate the equivalent damping ratio, ξ_{eq}, by equating the nonlinear displacement response spectrum for a given earthquake to the linear displacement response spectrum. The expression proposed by Jara and Casas (2006) to predict the equivalent damping ratio is:

$$\xi_{eq} = 0.05 + 0.05\ln(\mu) \tag{12}$$

Jara et al., 2012 (*herein termed as Jara 2012*)

Jara et al. (2012) improved the formulation proposed by Jara and Casas (2006) to predict the equivalent damping ratio of linearized systems by incorporating the term, η, which accounts for the effect of the soil deposit where ground motions are recorded. Authors stated that η is 0.065 for earthquakes recorded at firm soils and 0.085 for earthquakes recorded at soft soils.

$$\xi_{eq} = 0.05 + \eta\ln(\mu) \tag{13}$$

Dicleli and Buddaram, 2007 (*herein termed as Dicleli 2007*)

Dicleli and Buddaram (2007) evaluated the equivalent linear analysis of SDOF systems as a function of both ground motion characteristics (intensity and frequency characteristics) and isolator properties. Dicleli and Buddaram (2007) demonstrated that the effective period of the structure should be incorporated into the formulations used to predict equivalent damping ratio. Authors proposed an empirical formulation for equivalent damping ratio, ξ_{eq}, as given in Eqn. (14), where T_e is the initial period of the bilinear hysteretic force-deformation relation based on initial stiffness, k_e (see Fig. 5.a). Authors obtained effective stiffness, k_{eff}, using the secant stiffness method.

$$\xi_{eq} = \frac{4Q(D-D_y)}{2\pi k_{eff} D^2}\sqrt{0.41\left(\frac{T_{eff}}{T_e}-1\right)} \tag{14}$$

ASCE, 2005

To encourage the use of seismic isolation technique, existing codes tend to support the use of simplified method of analysis in design of SIS, at least at the preliminary design stage. Being one of the most commonly used code for seismic isolated structures, ASCE (2005) defines the secant stiffness method to calculate both k_{eff} and ξ_{eq} as described in Eqn. (7).

EVALUATION OF CONSIDERED SIMPLIFIED METHODS

In this section, the accuracy of the simplified formulations, discussed in previous section, to estimate the MIDs of structures isolated with LRBs is tested when lead core heating is of concern. This is achieved by comparing the MID estimated by simplified method of analysis (D_{SMA}) with the one obtained from nonlinear response history analysis (D_{NRHA}) in which deteriorating force-deformation relations were used to idealize hysteretic behavior of LRBs. Comparisons are done as a function of the isolator characteristics namely, characteristic strength to weight ratio, Q/W, and isolation period, T_d. Results are presented in Fig. 5 in terms of D_{SMA}/D_{NRHA}.

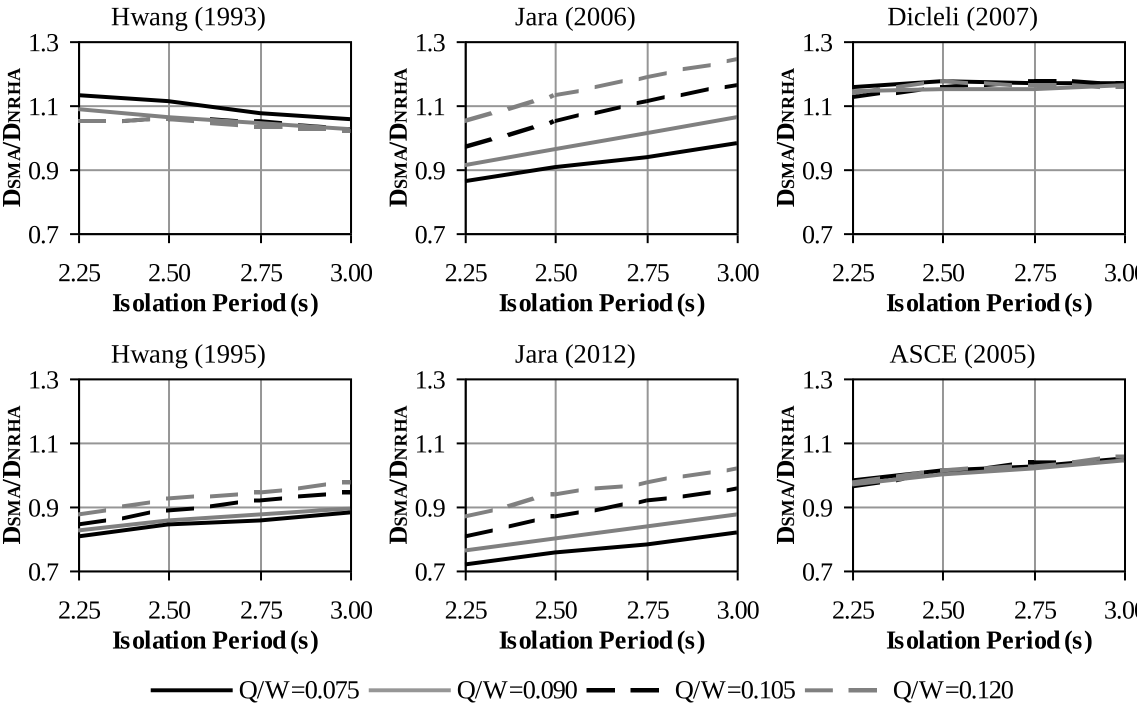


Figure 5. Evaluation of existing formulations to estimate the MIDs.

The motivation for evaluation of the existing simplified methods to estimate the nonlinear response of LRB isolated structures is to seek the “best” set of equation that may be adopted to consider the lead core heating effect, accordingly. The term “best” is used to define the case where D_{SMA}/D_{NRHA} results are independent of the isolator characteristics, Q/W ratio and T_d, as much as possible.

In Fig. 5, it is clear that D_{SMA}/D_{NRHA} ratios obtained by equations proposed by Hwang (1993), Hwang (1995), Jara (2006), and Jara (2012) depends highly on the isolator characteristics. Especially, employing the equations of Jara (2006) and Jara (2012) result in high amplitude variations in D_{SMA}/D_{NRHA} as a function of Q/W ratio (D_{SMA}/D_{NRHA} ratio increases with increasing Q/W ratio). Moreover, accuracy of formulations proposed by Hwang (1993), Hwang (1995), Jara (2006), and Jara (2012) to estimate D_{NRHA} differentiates due to change in isolation period (D_{SMA}/D_{NRHA} ratios have either decreasing or increasing trends with an increase in isolation period for all of the considered Q/W ratios). Although the secant stiffness method employed in ASCE (2005) gives close D_{SMA}/D_{NRHA} values for different Q/W ratios, again, D_{SMA}/D_{NRHA} ratios of ASCE (2005) depends on isolation period (D_{SMA}/D_{NRHA} ratios increase with increasing isolation period). The only empirical formulation that has almost the same D_{SMA}/D_{NRHA} ratios for all of the considered isolation characteristics is the one proposed by Dicleli (2007). Thus, the form of the empirical formulation developed by Dicleli (2007) is used as a basis to propose an improved equation to estimate the MIDs.

RELATION BETWEEN DISSIPATED ENERGIES OF DETERIORATING AND NON-DETERIORATING CASES

In this section, relation between the dissipated energies of cases, where both deteriorating and non-deteriorating force-deformation relations of LRBs are employed, is obtained. For this purpose, several NRHA were performed with considered LRB isolated structures. Variations in dissipated energies of deteriorating and non-deteriorating cases are obtained by means of energy ratios $E_{deteriorating}/E_{non-deteriorating}$ as a function of both Q/W and T_d. Here, both $E_{deteriorating}$ and $E_{non-deteriorating}$ terms are used to represent the summation of dissipated energies under all excitation cycles of corresponding hysteretic behavior. Corresponding $E_{deteriorating}/E_{non-deteriorating}$ ratios are tabulated in Table 2. Each data presented in Table 2 represents the averages of computed $E_{deteriorating}/E_{non-deteriorating}$ ratios. Based on the data given in Table 2, $E_{deteriorating}/E_{non-deteriorating}$ ratios are incorporated in the proposed equation to estimate the equivalent damping ratio as described in the following section.

Table 2. Average $E_{deteriorating}/E_{non-deteriorating}$ ratios.

Q/W ratio	**Isolation Period, T_d (sec)**			
	2.25	**2.50**	**2.75**	**3.00**
0.075	1.02	1.03	1.03	1.04
0.090	1.03	1.03	1.03	1.04
0.105	1.02	1.03	1.02	1.03
0.120	1.02	1.02	1.03	1.03

PROPOSED EMPRICAL FORMULATIONS FOR ξ_{eq}

In light of the performance of existing formulations to predict MIDs, there is a need to improve the accuracy of formulations employed by existing simplified methods to estimate the maximum nonlinear response of LRB isolated structures. In previous sections, the form of the formulation that should be considered in the calculations of equivalent linear systems is determined. The proposed form of formulation to estimate the equivalent damping ratio is as follows:

$$\xi_{eq} = E_r \cdot \frac{4Q\left(D - D_y\right)}{2\pi k_{eff} D^2} \sqrt{\varphi \cdot \left(\frac{T_{eff}}{T_e} - 1\right)} \tag{15}$$

In Eqn. (15), the change in energy dissipation capacity of LRBs due to deterioration in isolator strength as a function of lead core heating is incorporated by considering the term E_r. In Eqn. (15), E_r stands for the $E_{deteriorating}/E_{non-deteriorating}$ ratio and equals to 1.03. This value is obtained by taking the average of $E_{deteriorating}/E_{non-deteriorating}$ ratios presented in Table 2. The term φ in Eqn. (15) is calculated by means of a regression analysis that seeks the minimum least square fit and found to be 0.7.

The success of the proposed equation for equivalent damping ratio, ξ_{eq}, in estimating MIDs of LRB isolated structures under investigation, Fig. 6 is depicted. In this figure, MIDs estimated by simplified method of analyses ($D_{proposed}$), where Eqn. (15) is used to calculate ξ_{eq}, versus MIDs obtained from NRHA (D_{NRHA}) are depicted as a function of both Q/W ratio and T_d. The black solid line shown in Fig. 6 represents the cases where $D_{proposed}$ and D_{NRHA} are equal to each other.

Fig. 6 demonstrates that the proposed formulations are highly effective in estimation of MIDs of LRB isolated structures obtained from NTHA. Proposed formulation results in almost the same MIDs with those of NRHA with a slight overestimation which can be neglected. Fig. 6 also reveals that the accuracy of the estimations for MIDs performed by the proposed formulation is not sensitive to any change in isolation period, T_d, and Q/W ratio with the exception of Q/W=0.075 which is unrealistically low value for the corresponding design spectra.

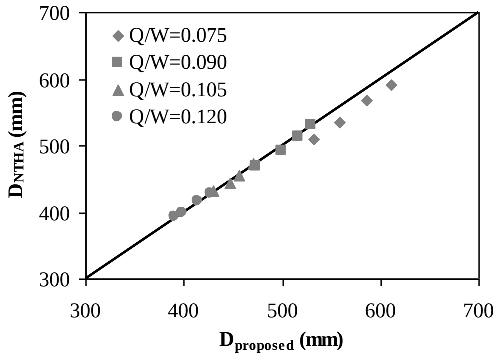


Figure 6. Comparison of MIDs obtained by simplified method of analysis, in which proposed formulations are used to calculate the equivalent damping ratio, with the ones obtained from NRHA.

EVALUATION OF PROPOSED FORMULATION IN CASE OF LOW- AND MEDIUM-SEISMICITY

In this section, the accuracy of the proposed formulation for ξ_{eq} to predict the MIDs is tested for different seismicity levels. For the corresponding NRHA, considered ground motions are scaled down to represent low- and medium-seismicity levels. Thus, the scale factors used previously are multiplied by 1/3 and 2/3 to represent low- and medium-seismicity levels, respectively. The 5% damped design spectrum is also scaled down with the same factors in order to be used in simplified calculations.

Analyses are conducted with LRBs where the isolation periods are between 2.25s and 3.0s while keeping the Q/W ratio constant and equal to 0.105. As it is depicted in Fig. 7, the proposed formulation can also be employed to predict the MIDs of LRB isolated structures even for low- and medium-seismicity levels, regardless of the seismicity level.

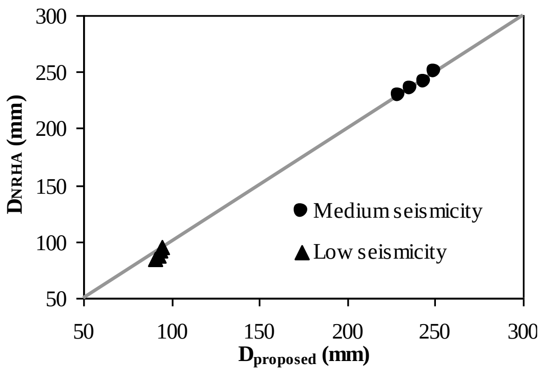


Figure 7. Accuracy of the proposed formulation in prediction of MIDs under low- and medium-seismicity levels.

CONCLUSIONS

In this study, the accuracy of existing simplified formulations to estimate the nonlinear response of seismic isolated structures, isolated with LRBs, in terms of MIDs is investigated by incorporating the effect of lead core heating. Results of the present study are used to improve the accuracy of existing formulations to calculate the equivalent damping ratio. For this purpose, a parametric research was conducted with a 3-story representative structure isolated with LRBs. Response of the considered seismic isolated structure subjected to selected near-field ground motions is studied as a function of isolator characteristics namely, isolation period and characteristic strength to weight ratio. Proposed equation to predict the equivalent damping ratio considers the differentiation in energy dissipation capacity of an LRB due to deterioration in its strength as a result of rise in the lead core temperature. It is revealed that simplified analyses in which the proposed equation is used to calculate equivalent damping ratio, yields highly accurate estimates for maximum isolator displacements regardless of the isolator characteristics and seismicity level.

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