EQUIVALENT LINEAR METHODS FOR LEAD-RUBBER-BEARING SYSTEMS SUBJECTED TO PULSE-LIKE GROUND MOTIONS

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SUMMARY

Pulse-like ground motions (PLGM) can produce severe damage and large demands for base-isolation systems. Additional dampers can reduce the large displacement demand, but additional force will be transmitted to the superstructure. However, only very few studies investigated the effectiveness of the commonly used equivalent-linear design procedure of isolation systems subjected to PLGMs. This study thoroughly evaluates (1) the efficacy of the equivalent linear method specified in ASCE 7-16 and AASHTO 2010 and the equivalent linear method without damping reduction factor for the design of Lead-Rubber-Bearing (LRB) systems with additional viscous dampers subjected to PLGMs and (2) the influences of damping exponential (αd) of viscous dampers on structural responses. A PLGM database was established using the records in the ground-motion databases of the PEER NGA West2 project and the SSHAC Level-3 project of NCREE Taiwan. Moreover, 21 SDOF models consisting of three types of Qd, three kinds of ξd, and three types of αd were analyzed in this study. The accuracy of both equivalent linear methods was dependent on the effective period and the characteristic strength of LRBs. A modification factor was proposed to correct the bias in the estimation of both methods.

Keywords: *Lead-rubber-bearing; viscous damper; pulse-like ground motion; equivalent linear method*

INTRODUCTION

Pulse-like ground motions are defined as ground motions, typically but not always observed at sites located near a fault, with one or more pulses in the ground velocity time series. Earlier, Bertero et al. (1978) and Anderson and Bertero (1987) indicated that the pulse feature located in ground motions and the relationship between the pulse period and the structural period are the reasons for enormous demands on multistory buildings. They also pointed out that the structural responses caused by pulse-like ground motions are greater than those for non-pulse-like ground motions given the same PGA. The performance of isolation systems subjected to pulse-like ground motions is different from the performance of isolation systems subjected to non-pulse-like ground motions where: (1) there might be an excessive displacement demand for the isolation systems; (2) transmitting higher forces into the superstructure; (3) resonance-like behavior if the pulse period is close to the period of the isolation system.

One strategy that can address these problems is to use additional dampers together with the isolators. Several studies investigated the effect of supplemental viscous damping devices on seismically isolated structures. A common conclusion was that supplemental viscous dampers can help to control the large deformation demand of the isolators in exchange for a moderate increase in the forces and acceleration demands of superstructure (e.g., L. P. Carden et al., 2005; C. P. Providakis, 2008).

Moreover, only a few studies investigated the efficacy and accuracy of the current design procedure of isolation systems compared to the results of nonlinear response history analysis. The widely used equivalent linear (EL) method has been challenged on its possible lack of accuracy and efficacy in predicting the peak nonlinear responses of an isolation system subjected to pulse-like ground motions. Dicleli and Buddaram (2007) used several synthetic near-fault ground motions with a forward rupture directivity effect (the term used in that paper) to evaluate the

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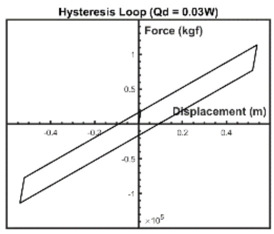
accuracy of the equivalent linear method of AASHTO (1990). They concluded that the equivalent linear method would produce an unconservative prediction on the responses of seismically isolated bridges when the ratio between the post-elastic period of the system and the ground velocity pulse period is much greater or much smaller than one. Moreover, Alhan and Özgür (2015) checked the accuracy of the equivalent linear method provided by the ASCE/SEI 7-05 standard (2006) using four pulse-like ground motions and concluded that the EL method underestimates the nonlinear responses (displacements and forces) of the isolation systems with flexible superstructures.

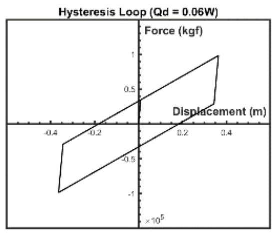
LEAD-RUBBER-BEARING SYSTEMS AND GROUND MOTION DATABASE

In this study, 21 SDOF models of Lead-Rubber-Bearing (LRB) systems with additional viscous dampers were used. Two characteristics are set as constant values: (1) yield displacement (D_y = 0.01m), (2) post-yield period (T_{post} = 3.5 sec), and (3) weight (W = 547.7 tons). Moreover, three variables are set as parametric studies: (1) characteristic strength (Q_d = 0.03W, 0.06W, and 0.09 W), (2) damping ratio of the viscous damper (ξ_d = 0%, 10%, and 20%), and (3) damper exponential (α_d = 0.5, 1.0, and 1.5). The hysteresis loops of these LRB systems are shown in Figure 1 (a), (b), (c) and the force-velocity of the additional viscous dampers are shown in Figure 1 (d), (e), (f).

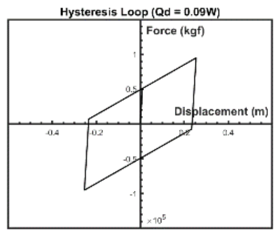
In this study, 220 pulse-like ground motions (109 in Taiwan and 111 outside Taiwan) are obtained from the PEER NGA West2 project and the SSHAC Level-3 project of NCREE Taiwan. These ground motions are scaled into four ground motions intensity levels (2/3 DBE, DBE, 1.5 DBE, and 2 DBE) in the target seismic area of Taipei Basin second zone.



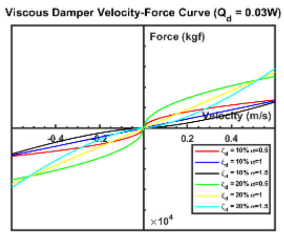
(a) Q_d = 0.03 W



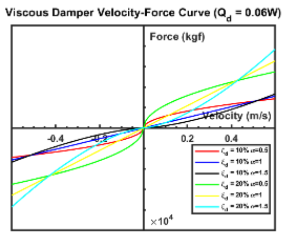
(b) Q_d = 0.06 W



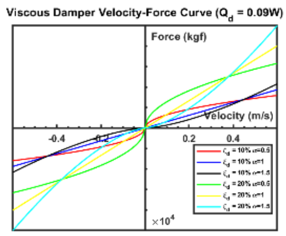
(c) Q_d = 0.09 W



(d) Q_d = 0.03 W



(e) Q_d = 0.06 W



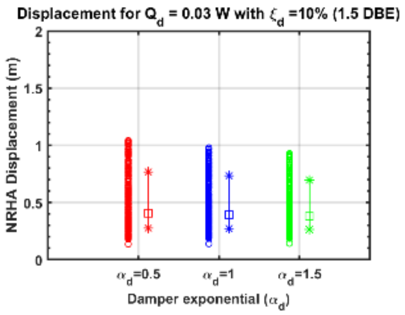
(f) Q_d = 0.09 W

Figure 1. (a), (b), (c) Hysteresis loops of the LRB systems and (d), (e), (f) force-velocity curves of the viscous dampers of this study

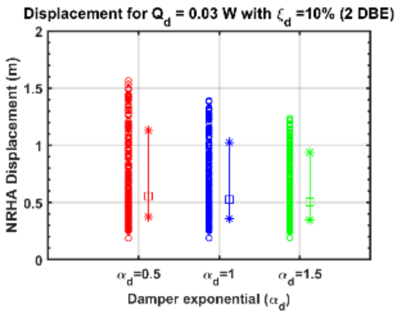
In this study, three analysis methods are used: (1) nonlinear response-history analysis (NRHA), (2) equivalent linear (EL), and (3) equivalent linear (EL) without B factor. The NRHA method is performed using SAP2000 and OPENSEES and is stated as method 1. The EL method is performed per ASCE 7-16 and AASHTO 2010 and termed as method 2. The EL method without B factor utilizes the response history analysis of a single-degree-of-freedom linear system, of which the period and damping ratio are computed using the EL method. This method is named as method 3 herein.

ANALYSIS RESULTS

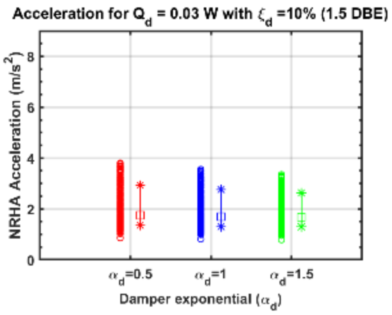
Key results of the NRHA discussed herein include the isolator displacements and the accelerations of the isolated mass, which represents the rigid superstructure of an isolated building. Figure 2 shows the results for the model with $Q_d = 0.03W$, $\xi_d = 10\%$, and three types of α_d subjected to pulse-like ground motions with intensity levels of 1.5 DBE and 2 DBE. The trends for all the other models performed in this study are similar to that shown in Figure 2. For larger ground motion intensity levels, dampers with α_d greater than 1 provide smaller displacement with a small or insignificant increase in acceleration compared to those with α_d smaller than 1.



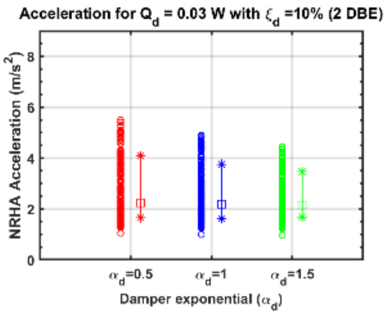
(a) Displacement (1.5 DBE)



(b) Displacement (2 DBE)



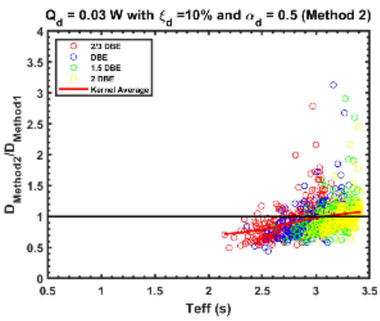
(c) Acceleration (1.5 DBE)



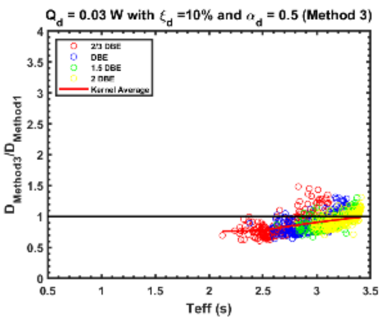
(d) Acceleration (2 DBE)

Figure 2. NRHA displacement and acceleration responses

Moreover, because this study also aims to check the efficacy and accuracy of methods 2 and 3, the displacement results obtained using the NRHA method are used to benchmark the displacements obtained using methods 2 and 3. The ratio between the displacement of method 2 (or 3) and that of method 1 was then computed. Figure 3 presents the ratio of $D_{Method2}$ ($D_{Method3}$) and $D_{Method1}$ as a function of Teff. All the other models and cases have a trend similar to that of Figure 3. The average results in Figure 3 for both methods 2 and 3 are below 1, namely, method 2 (or 3) generates smaller (unconservative) isolator displacement than does method 1.



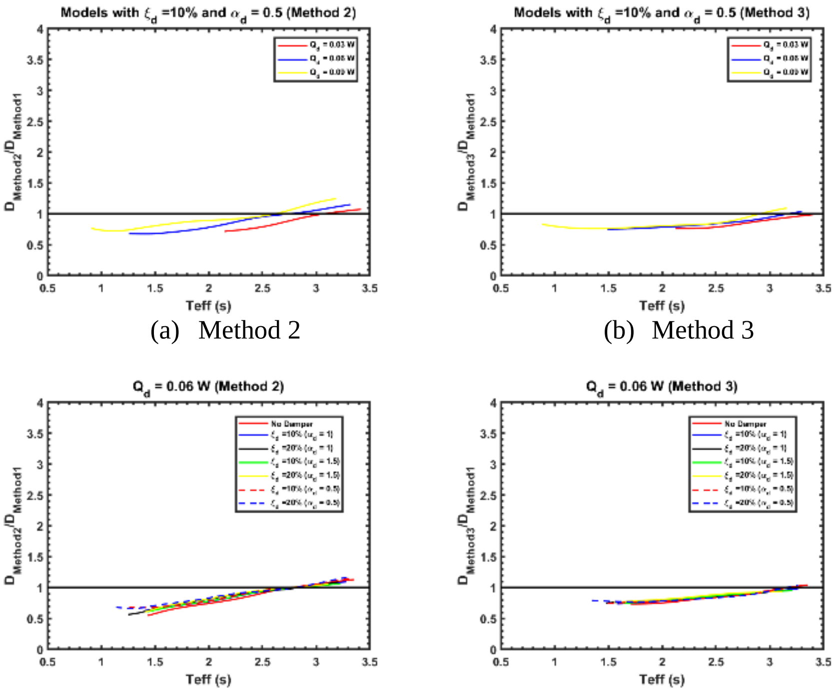
(a) Method 2



(b) Method 3

Figure 3. The ratio of $D_{Method2}$ ($D_{Method3}$) and $D_{Method1}$ as a function of T_{eff}

Figure 4 (a) and (b) shows the example of the average trend of cases with the same ξ_d and α_d, but different Q_d, meanwhile Figure 4 (c) and (d) show the example of the average trend of cases with the same Q_d but different ξ_d and α_d. From figures (a) and (b), it can be observed that T_{eff} and Q_d have some influences on the efficacy of methods 2 and 3. Meanwhile, it can be observed from figures (c) and (d) that the influences of ξ_d and α_d on the efficacy of methods 2 and 3 are very minor as the trends are pretty close and similar for each ξ_d and α_d.



(a) Method 2 (b) Method 3

(c) Method 2 (d) Method 3

Figure 4. Trends in the ratio of $D_{Method2}$ ($D_{Method3}$) and $D_{Method1}$ as a function of T_{eff}

PROPOSED MODIFICATION FACTOR

To correct the bias in the estimation of methods 2 and 3, a modification factor (ψ) is proposed in this study. The proposed ψ is shown in Equation (1):

$$\boldsymbol{\psi = 0.162T_{eff} + 0.427 + 0.7\left(\frac{Q_d}{W} - 0.03\right)(3.5 - T_{eff})} \tag{1}$$

Figure 5, Figure 6, and Figure 7 show the average trend in the displacement ratio of methods 2 and 3 to method 1 for the cases before and after using the proposed modification factor in the iteration process. The ratios become closer to 1.

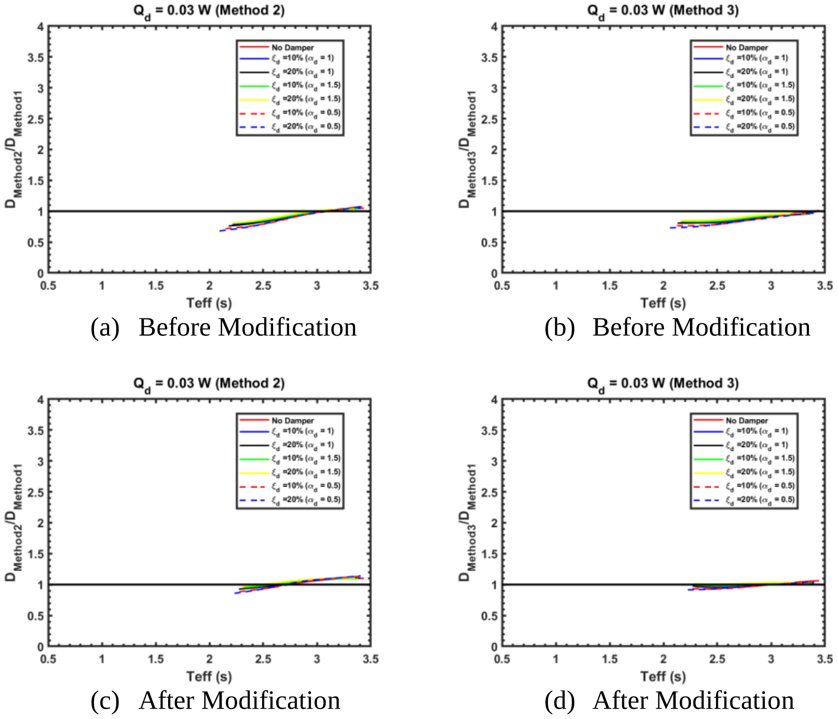


Figure 5. Trends in the ratio of $D_{Method2}$ ($D_{Method3}$) and $D_{Method1}$ as a function of T_{eff} before and after modification for the models with Q_d = 0.03W

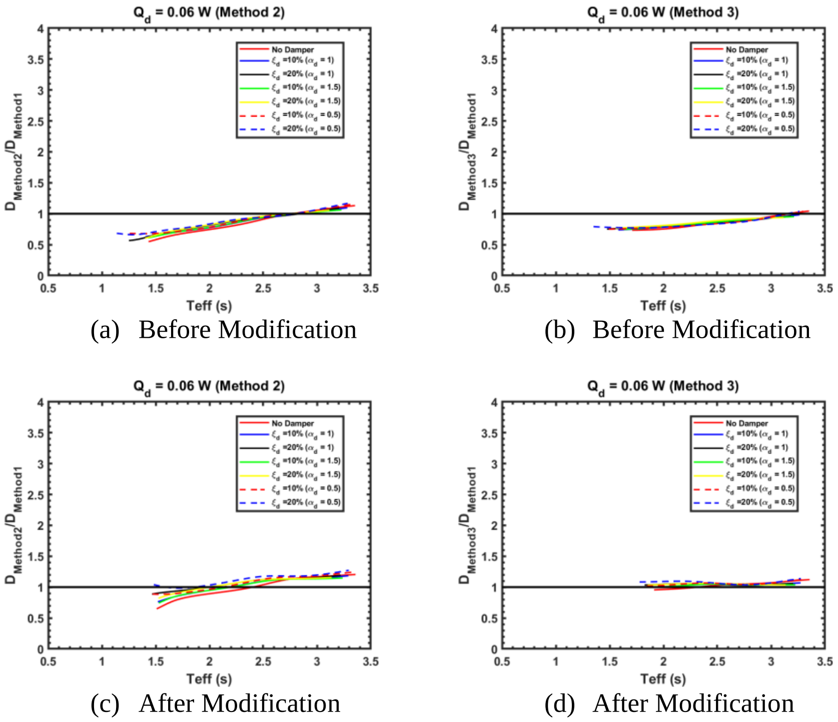
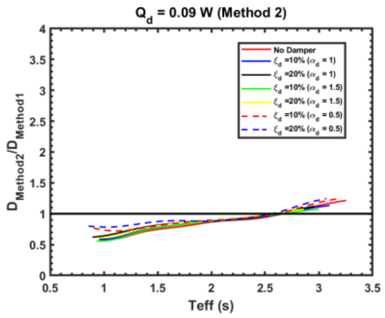
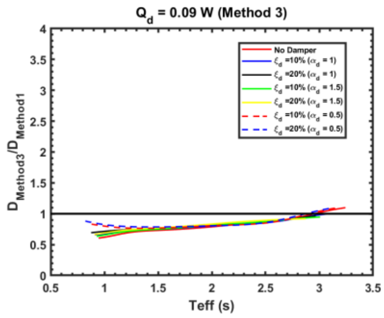


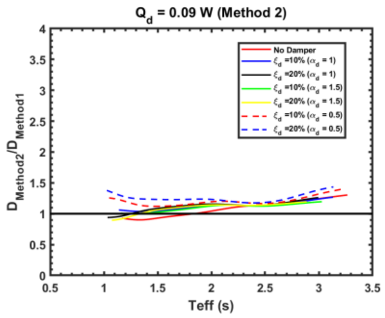
Figure 6. Trends in the ratio of $D_{Method2}$ ($D_{Method3}$) and $D_{Method1}$ as a function of T_{eff} before and after modification for the models with Q_d = 0.06W



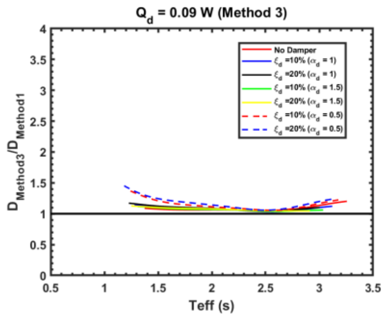
(a) Before Modification



(b) Before Modification



(c) After Modification



(d) After Modification

Figure 7. Trends in the ratio of $D_{Method2}$ ($D_{Method3}$) and $D_{Method1}$ as a function of T_{eff} before and after modification for the models with Q_d = 0.09W

CONCLUSIONS

Key observations/contributions of this study are summarized herein:

1. On average, methods 2 and 3 produce unconservative results and are highly dependent on the effective period (T_{eff}) of the systems and the characteristic strength (Q_d) of the LRB. This study proposed a modification factor (ψ), which successfully corrects the bias in the estimation of methods 2 and 3.

2. On average, dampers with α_d greater than 1, compared to those with α_d smaller than 1, generate smaller isolator displacement with a small or insignificant increase in acceleration for larger ground motion intensity levels.

REFERENCES

Alhan, C., & Ozgur, M. (2015). Seismic responses of base-isolated buildings: efficacy of equivalent linear modeling under near-fault earthquakes. *Smart Structures and Systems*, *15*(6), 1439-1461.

American Association of State, H., Transportation Officials, S. o. B., & Structures. (2010). *Guide specifications for seismic isolation design*. American Association of State Highway and Transportation Officials.

ASCE. (2016). "Minimum design loads for buildings and other structures." ASCE 7-16, ASCE, Reston, VA

Bertero, V. V., Mahin, S. A., & Herrera, R. A. (1978). Aseismic design implications of near-fault san fernando earthquake records. *Earthquake Engineering & Structural Dynamics*, *6*(1), 31-42.

Carden, L., Davidson, B., Larkin, T., & Buckle, I. (2005). Retrofit of seismically isolated structures for near-field ground motion using additional viscous damping. *Bulletin of the New Zealand Society for Earthquake Engineering*, *38*, 106-118.

Dicleli, M., & Buddaram, S. (2007). Equivalent linear analysis of seismic-isolated bridges subjected to near-fault ground motions with forward rupture directivity effect. *Engineering Structures - ENG STRUCT*, *29*, 21-32.

Jangid, R., & Kelly, J. M. (2001). Base isolation for near-fault motion. *Earthquake Engineering & Structural Dynamics, 30,* 691-707.

Lu, L.-Y., Shih, M.-H., Tzeng, S. W., & Chien, C. S. (2003). Experiment of a sliding isolated structure subjected to near-fault ground motions. In *Proceedings of the 7th pacific conference on earthquake engineering* (pp. 13-15).

Mavroeidis, G., Dong, G., & Papageorgiou, A. (2004). Near-fault ground motions, and the response of elastic and inelastic single-degree-of-freedom (SDOF) systems. *Earthquake Engineering & Structural Dynamics*, *33*, 1023-1049.

Providakis, C. (2008). Effect of LRB isolators and supplemental viscous dampers on seismic isolated buildings under near-fault excitations. *Engineering Structures*, *30*, 1187-1198.

Sharbatdar, M. K., Vaez, S. R. H., Amiri, G. G., & Naderpour, H. (2011). Seismic Response of Base-Isolated Structures with LRB and FPS under near Fault Ground Motions. *Procedia Engineering*, *14*, 3245-3251.

Wolff, E., Ipek, C., Constantinou, M., & Tapan, M. (2014). Effect of viscous damping devices on the response of seismically isolated structures. *Earthquake Engineering & Structural Dynamics*, *44*.