10

Response of Seismically Isolated Bridges Considering Variation in the Mechanical Properties of Individual Isolators

Gordon Warn

Graduate Research Assistant, Department of Civil Structural and Environmental Engineering, University at Buffalo

Research Supervisor: Andrew Whittaker, Professor

Summary

This paper summarizes an analytical study investigating how changes in the mechanical properties of individual seismic isolators affect the response of isolated bridge structures subjected to earthquake excitation. Nonlinear response-history analyses are conducted utilizing a simple seismically isolated bridge model, twenty sets of bilinear isolator properties and bins of recorded earthquake ground motion pairs. Variations in the mechanical properties are considered using factors to modify the appropriate bilinear isolator parameter. The results of analyses considering nominal and modified isolation systems are used to systematically identify changes in system response as a function of the property modification factor. These results are used to determine threshold values of the property modification factor corresponding to specific increases in maximum shear force. Threshold values determined in this study are intended to aid engineers in the preliminary design and assessment of an isolation system prior to performing bounding analysis as now required by bridge and building design codes.

Introduction

Property modification factors were included in the 1999 American Association of State Highway and Transportation Officials' Guide Specifications for Seismic Isolation Design (AASHTO, 1999) to account for plausible changes in the mechanical properties of individual seismic isolators over the design life of a seismically isolated bridge. The Guide Specification for Seismic Isolation Design recommends that minimum and maximum property modification factors, denoted λ_{min} and λ_{max}, respectively, be determined either through system characterization tests, as prescribed by the specifications, or using the default values provided in Appendix A of the Guide Specification. The process and default values are based on the work of Constantinou et al. (1999). Engineers typically opt for the latter approach where λ_{min} and λ_{max} are determined based on the type of seismic isolation bearing (i.e., elastomeric or friction) and various factors affecting the mechanical properties of the isolator, including aging, contamination, scragging, travel and temperature. Typically the minimum property modification factor, λ_{min}, is assumed to be unity, corresponding to the nominal mechanical properties. Once property modification factors are determined, bounding analysis with limiting values of isolator properties is performed to estimate critical design parameters for the isolators, substructure and superstructure. Although inclusion of property modification factors into the Guide Specification provides an important and necessary design consideration for seismically isolated bridges (and buildings) the result is an increased number of response analyses required to determine key design parameters.

This paper summarizes an analytical study investigating how changes in the mechanical properties of individual seismic isolators affect system response in seismically isolated bridges subjected to earthquake excitation. Parametric nonlinear response-history analysis is performed using a simple isolated bridge model and three bins of recorded earthquake ground motion pairs to determined key response parameters. Variations in the mechanical properties are considered by modifying the appropriate bilinear parameter using a modification factor. The results of response-history analysis considering nominal and modified isolation system are used to quantify the change in system response as a function of the modification factor. The change in system response, more specifically the change in maximum shear force, is used to identify values of the modification factor corresponding to specific levels of increase in maximum shear force. For a chosen increase in maximum shear force, for example 50-percent, corresponding threshold λ values were determined for each bilinear system and presented as a function of the bilinear parameters: Q_d/W, the zero-displacement force-intercept normalized by the weight acting on the isolator and T_d, the second-slope period. Threshold λ values determined in this study are intended to provide engineers with a design aid for the preliminary assessment of seismic isolation systems prior to performing bounding analysis and not to circumvent bounding analysis as required by bridge and building design codes.

Property Modification Factors

Appendix A of the Guide Specification provides component property modification factors (λ values) for both sliding and elastomeric seismic isolators (AASHTO, 1999). Values of λ are provided for each factor affecting the mechanical properties of isolators including factors for, aging, contamination, cumulative travel, scragging (elastomeric systems), temperature and velocity. Property modification factors for sliding isolators are based largely on research conducted by Constantinou et al. (1999). Recent work by Thompson et al. (2000) provided improved values for high-damping elastomeric seismic isolators with respect to velocity and scragging. The maximum property modification factor is calculated using an equation provided in the Guide Specification and presented here

$$\lambda_{max} = \lambda_{max,t} \times \lambda_{max,a} \times \lambda_{max,v} \times \lambda_{max,tr} \times \lambda_{max,c} \times \lambda_{max,scrag} \quad (1)$$

where $\lambda_{max,t}$ accounts for temperature; $\lambda_{max,a}$ accounts for aging; $\lambda_{max,v}$ accounts for velocity effects assumed to be equal to 1.0 for all scenarios considered in this study; $\lambda_{max,tr}$ accounts for cumulative travel (wear); $\lambda_{max,c}$ accounts for contamination (in sliding isolation systems) and $\lambda_{max,scrag}$ accounts for scragging (in high-damping elastomeric systems). A range of modification factors was selected for the purpose of response-history analysis based on consideration of all plausible combinations (scenarios) of maximum property modification factors (λ_{max}) for elastomeric and sliding isolation systems as prescribed in the Guide Specification. Noting, sliding isolation systems including bimetallic interfaces were not specifically addressed due to the large penalty assigned by the Guide Specification to such systems. Table 1 presents the range of λ values and appropriately bilinear parameter(s) to be modified for the three types of isolator considered in this study, namely, Friction Pendulum™ (FP), Elastomeric (E) and Lead-rubber (LR).

Type	Bilinear Parameter	λ							
Friction Pendulum	Q_d	0.5	0.85	1.0	1.15	1.5	2.0	3.0	4.0
Elastomeric	Q_d and K_d	0.5	0.85	1.0	1.15	1.5	2.0	3.0	
Lead-rubber	K_d	0.5	0.85	1.0	1.15	1.5	2.0	3.0	

Table 1. Modification factors considered for response-history analysis.

Shown in Fig. 1 are the three different modified bilinear force-displacement relationships used to account for the change in mechanical properties of FP, E and LR isolators. In Fig. 1, nominal and appropriately modified bilinear plots are shown using nominal properties: Q_d/W=0.06, T_d=2.5 seconds, and a property modification factor, λ=2.0. Also illustrated in Fig. 1 are the assumed yield displacements for FP, E and LR isolators chosen to be 0.5 mm, 12.7 mm and 12.7 mm, respectively. For FP isolators, Q_d is modified, as shown in Fig. 1, to account for changes in the frictional properties of the sliding interface while K_d , the second-slope stiffness, remains constant as it is a function of the radius of curvature of the concave plate and the supported weight (assumed to be constant). For E isolators, both Q_d and K_d are modified to account for changes in the elastomer affecting the shear modulus. Similarly, for LR isolators, K_d is modified, again accounting for changes in the elastomer. For this study, variations in the properties of the lead-core which govern Q_d were ignored.

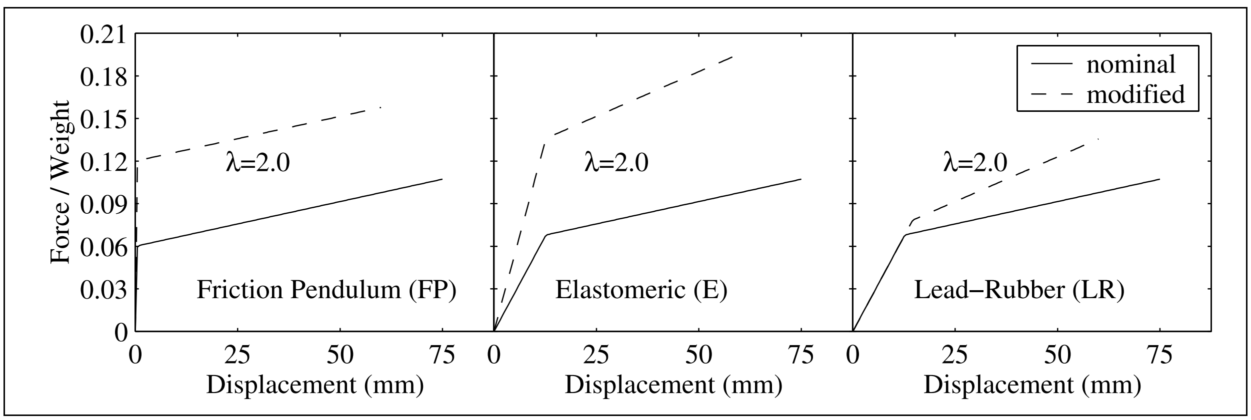

Figure 1. Nominal and modified bilinear force-displacement relationships.

Numerical Simulation

A simple seismically isolated bridge model is utilized to facilitate nonlinear response-history analysis. A schematic of this model is shown in Fig. 2 and assumes a rigid block superstructure supported by four seismic isolators, with three degrees-of-freedom, namely, translation in the longitudinal (x-direction) and transverse directions (y-direction) and rotation about the vertical axis (z-direction). The spatial distribution of isolators and physical properties of the bridge deck (excluding flexibility) are based on the middle span of a multi-span prototype bridge presented in an Applied Technology Council report (ATC, 1986). A more detailed description of this simple bridge model is provided in Warn and Whittaker (2004). The seismic isolators are modeled using a coupled plasticity formulation (Mosqueda, 2004) and characterized by a bilinear force-displacement relationship with defining parameters; Q_d the zero-displacement force-intercept; K_d the second-slope stiffness; and u_y an

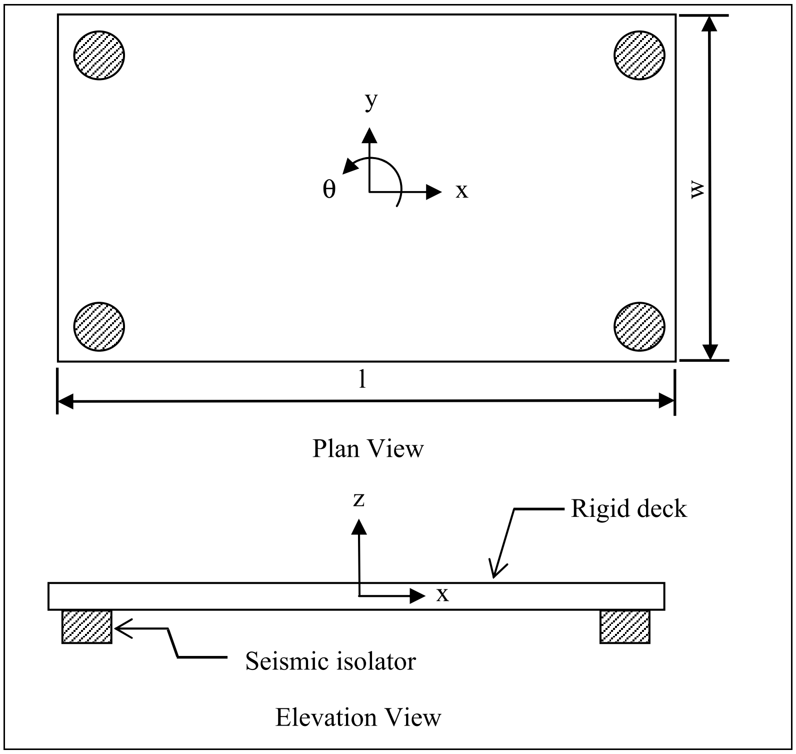

Figure 2. Schematic of simple isolated bridge model.

assumed yield displacement: the characterization assumed in the AASHTO Guide Specifications for Seismic Isolation Design.

Twenty nominal isolation system were considered with Q_d/W ranging from 0.03 to 0.012 and T_d, (a period calculated from the second-slope stiffness) ranging from 1.5 seconds to 4.0 seconds. To facilitate nonlinear response-history analysis three bins of ground motions pairs organized for a previous study (Warn et al. 2004) were utilized. The ground motion bins are denoted: Near-Field (NF), Large-Magnitude, Small-Distance (LMSD), and Large-Magnitude, Soft-Soil (LMSS). Details regarding the characteristics of the ground motion pairs and bin organization is provided in Warn and Whittaker (2004). The response of the assumed isolated bridge model is determined using Newmark's Step-by-Step integration procedure implemented in Opensees (PEER, 2004). For each analysis, response data is mined to determine the maximum horizontal displacement across the isolation interface and maximum horizontal shear force transmitted by a seismic isolator to the support. Maximum values are determined from the square-root-sum-of-squares (SRSS) response calculated at each time step in the analysis.

Results

The results of response-history analysis considering nominal and modified isolation systems were utilized to quantify the change in system response as a function of the change in the mechanical properties of individual seismic isolators during earthquake excitation. This information is used to determined threshold values of λ as a function of the nominal isolator properties, i.e., Q_d/W and T_d, for specific changes in system response as measured as a percentage of the nominal value. For brevity only the results obtained using ground motion pairs contained in the LMSD bin are presented. Shown in Fig. 3 are sample results for the average change in maximum shear force (DF_{max}) plotted as a function of the modification factor (λ) for various isolation systems composed of FP, E and LR isolators. Also plotted in these figures are three reference lines: one horizontal, one vertical (both solid) and a line (dashed) with slope equal to 1.0. The average change in maximum shear force is calculated using Eq. (2)

$$DF_{\max} = \sum_{i=1}^{n} \frac{F_{\max}^{\lambda}}{F_{\max}} \qquad (2)$$

where F^{λ}_{max} is the maximum horizontal shear force determined from response-history analysis using the *i*th pair of ground motions and isolator properties modified by λ; F_{max} is the maximum horizontal shear force determined using the *i*th pair of ground motions and nominal isolator properties; and *n* is the number of ground motion pairs contained in a particular ground motion bin.

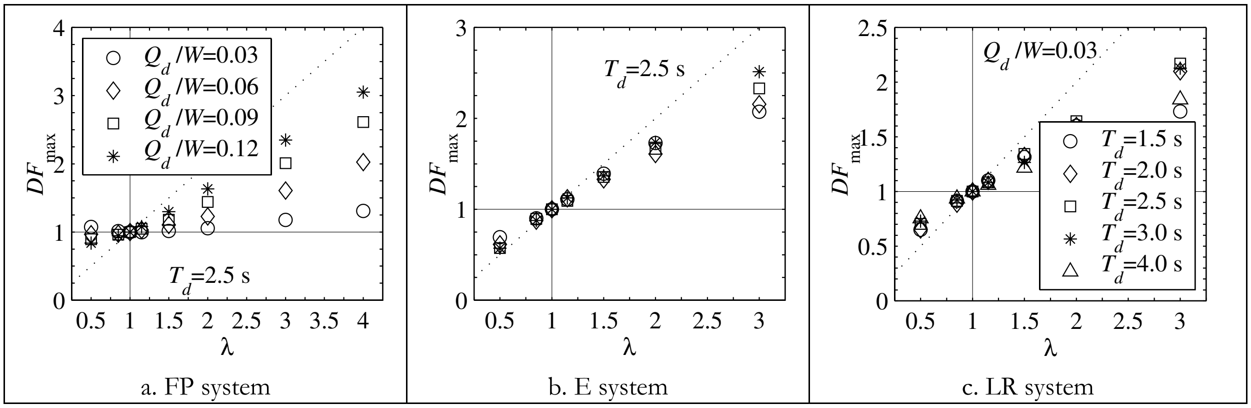

Figure 3. Sample results for change in maximum shear force isolation system composed of FP, E and LR isolators.

The change in maximum shear force data is used to calculate threshold values of λ corresponding to a specific increase in shear force for each type of isolator (FP, E and LR) and each set of nominal isolator properties. For a given increase in shear force (e.g. DF_{max}=1.25), the corresponding λ value was determined using linear interpolation. These threshold values are presented in graphical format using contour lines plotted as functions of the nominal bilinear parameters, Q_d/W and T_d, for a specific percent increase in shear force. Presented in Fig. 4 are threshold λ values corresponding to a 15-percent increase in maximum shear force for isolation systems composed of FP, E and LR isolators. Considering the results presented in Fig. 4a, for a FP isolation system with Q_d/W=0.08 and T_d=2.5 seconds (shown by the solid dot) a 15-percent increase in shear force is observed for a system with Q_d increased by a factor of 1.5.

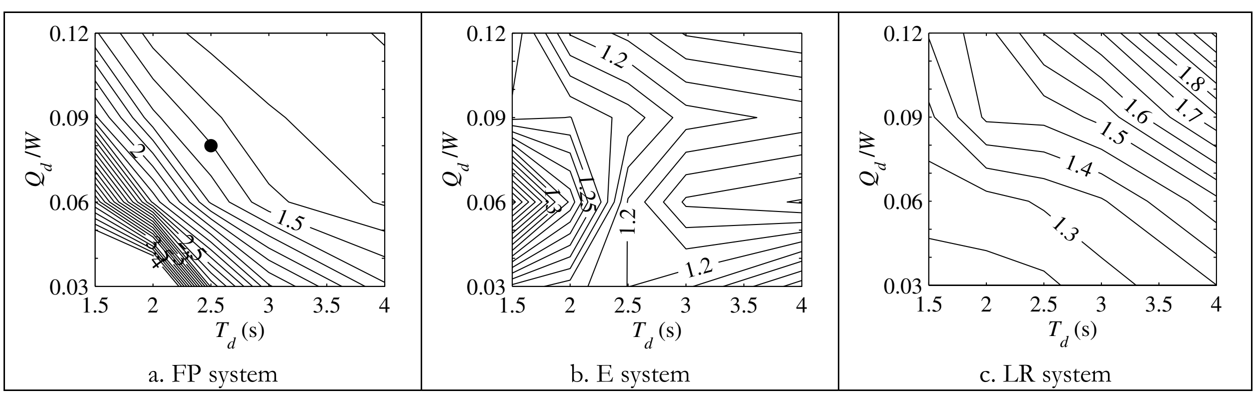

Figure 4. Threshold λ values corresponding to a 15-percent increase in maximum shear force.

Concluding Remarks

This paper served to summarize an analytical study investigating how changes in the mechanical properties of individual seismic isolators in isolated bridge structures effect system response and to present sample results. The results of response-history analysis considering a simple seismically isolated bridge model, twenty nominal isolation systems and a range of modification factors were used to quantify the change in system response: maximum displacement (not presented in this paper) and maximum shear force. The range of λ values selected and used for response-history analysis is based an investigation of those values presented in the current AASHTO Guide Specifications for Seismic Isolation Design for typical bridge isolation systems. System response data, more specifically the change in maximum shear force data, was translated into threshold values of λ, the property modification factor, for several levels of increases in maximum shear force. This paper presented threshold values corresponding to a 15-percent increase in maximum shear force. These threshold values are intended to provide design engineers a method of estimating a λ value corresponding to a specific increase in maximum shear force given a type of seismic isolator and assumed bilinear properties. In this manner, threshold values may be used, in a preliminary sense, to evaluate design alternatives prior to performing bounding analysis. It is important to note, the authors do not intend threshold values from this study to circumvent bounding analysis but rather to aid design engineers in the preliminary selection of design alternatives based on the likely impact that choice will have on the design of surrounding components, for example, substructure elements.

Acknowledgements

This research was carried out under the supervision of Professor Andrew Whittaker, and primarily supported by the Federal Highway Administration through Task D1.4 under award number DTFH 61-98-C-0094 to the Multidisciplinary Center for Earthquake Engineering Research.

References

American Association of State Highway Officials (1999). Guide Specifications for Seismic Isolation Design, Washington, D.C.

Applied Technology Council (1986). Seismic design guidelines for highway bridges. Report 6. Redwood City, CA.

Constantinou M., Tsopelas P., Kasalanati A., and Wolff E. (1999). Property Modification Factors for Seismic Isolation Bearings. MCEER-99-0012, Multidisciplinary Center for Earthquake Engineering Research., Buffalo, NY.

Mosquesda G, Whittaker A.S., and Fenves G.L. (2004). "Characterization and Modeling of Friction Pendulum Bearings Subjected to Multiple Components of Excitation." J. Structural Engineering. ASCE: 130(3): 433-442.

Pacific Earthquake Engineering Research (2004). Open System for Earthquake Engineering Simulation. http://opensees.berkeley.edu/

Warn G. and Whittaker A. (2004). "Performance estimates in seismically isolated bridge structures". Engineering Structures, 26, 1261-1278.

Warn G. and Whittaker A. (2004). "Property modification factors for seismically isolated bridge structures", ASCE, J. Bridge Engineering. Submitted for review and possible publication.