Performance Estimates in Seismically Isolated Bridge Structures

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Summary

An analytical study investigating the performance of seismically isolated bridge structures subjected to earthquake excitation is summarized. Here, performance is assessed using the following descriptors: maximum isolator displacement and energy demand imposed on individual seismic isolators. Nonlinear response-history analysis is employed considering twenty different isolation systems and three bins of earthquake ground motions. Results of these analyses are used to: (1) review the accuracy of the current AASHTO equation for the calculation of displacements in seismically isolated bridge structures, (2) determine the increase in maximum horizontal displacement of a seismic isolator due to bidirectional seismic excitation, and (3) review the current AASHTO prototype testing requirements for seismic isolators under seismic loading conditions. The current AASHTO equation for calculating maximum isolator displacements is shown to underestimate median maximum horizontal displacements determined from bidirectional nonlinear response-history analysis. Maximum isolator displacements determined from bidirectional seismic excitation are shown to be significantly larger than those considering unidirectional seismic excitation. Two factors contributing to the increase in maximum isolator displacement are identified; additional displacement demand from a second (orthogonal) component, and the coupled response of seismic isolators. The current prototype testing requirements for seismic loading specified by AASHTO are shown to result in energy demands that are inconsistent with those determined from numerical simulation of maximum earthquake shaking. An improved prototype testing protocol for seismic isolators subjected to seismic loading is proposed.

Introduction

The key design variable for seismic isolation systems is displacement over the isolation interface. Isolator displacement dictates (a) the space around the isolated superstructure to facilitate unrestricted movement of the superstructure, (b) the shear strain in elastomeric isolators and isolator stability, (c) the plan geometry of sliding isolators, and (d) forces transmitted to the bridge substructure for given isolator stiffness. Mechanical properties of the isolator assumed in the design and analysis of the isolation system are checked prior to fabrication of production seismic isolators and installation in the bridge structure through prototype testing.

where $250 A S_i$ is the 5-percent damped spectral displacement corresponding to a 1-second period; $T_{\text{eff}}$ is the effective period of the isolated structure at the design displacement in seconds; and $B$ is a coefficient that modifies the spectrum for equivalent viscous damping other than 5-percent. The 1-second spectral displacement is a function of the acceleration coefficient, $A$, and the site coefficient $S_i$. Values of $A$ and $S_i$ are given in Division 1-A: Seismic Design of the AASHTO Standard Specifications for Highway Bridges (AASHTO 1996). Equation 1 assumes the effective period of the isolation system falls in the constant velocity portion of the design spectrum in which displacements are assumed to increase linearly with period.

Section 13.2 of the Guide Specifications include requirements for prototype testing of seismic isolators subjected to seismic loading, which include multiple cycles to the maximum design displacement, $d$. A combination of three tests result in 22 cycles to a displacement equal to or greater than the design displacement and 31 cycles of displacement to various amplitudes typically conducted at low maximum speed (frequency). Accordingly, it is of significant import to bridge (and building) isolation construction that an estimate of maximum isolator displacement established using the procedures set forth in the AASHTO Guide Specifications be sufficiently accurate and that a prototype testing protocol be representative of the demand imposed on seismic isolators during maximum earthquake.

Previous research has demonstrated that Friction (F), Friction-Pendulum (FP) and Lead-Rubber (LR) isolation bearings exhibit a coupling between the response in each orthogonal direction (Mokha et al., 1993, Huang et al., 2000 and Mosqueda et al., 2003). Ignoring this coupling results in an underestimation of maximum isolator displacement by as much as 20-percent (Mokha et al., 1993). To capture the behavior of these seismic isolators under dynamic loading the coupled behavior must be considered (Mokha et al., 1993). This research (Mokha et al., 1993, Huang et al., 2000 and Mosqueda et al., 2003) also demonstrated that Coupled-Plasticity, Bouc-Wen, and similar formulations are capable of predicting the response of seismic isolation systems composed of F, FP and LR isolators with reasonable accuracy.

**Objectives and Technical Approach**

The objectives of this research study are (1) to review the accuracy of the current AASHTO equation for calculating displacements in seismically isolated bridge structures, (2) to determine the increase in maximum isolator displacement due to bidirectional seismic excitation and to quantify the contribution due to the coupled behavior of the seismic isolators and (3) to determine energy-related demands imposed on seismic isolators subjected to earthquake excitation and to translate these demands into a prototype testing protocol for seismic isolators subjected to seismic loading.

For this study, response-history analysis is employed. A simple seismically isolated bridge structure is considered and subjected to unidirectional and bidirectional earthquake excitation. The simplicity of the assumed bridge structure enables a clear understanding of the behavior of seismic isolation systems subjected to bidirectional earthquake excitation. Physical properties of the single-span superstructure are based on the middle span of a three-span example bridge structure set forth in a report by the Applied Technology Council (ATC 1986). The seismic isolators are idealized using a bilinear representation and modeled using a rate-independent coupled plasticity formulation (Huang
et al., 2000 and Mosqueta et al., 2003). Properties of the bilinear isolators, namely, $Q_d$, the zero-displacement force-intercept and $K_d$, the second-slope stiffness are varied widely to ensure the results of this research are broadly applicable to seismically isolated bridge structures in the United States. This bilinear characterization and defining parameters is shown in Figure 1. This presentation is similar to one used in the AASHTO Specifications (1999).

![Figure 1. Idealized bilinear force-displacement relationship for seismic isolators](image)

Results of the response-history analyses are mined to determined maximum isolator displacements (displacement across the isolation interface). Maximum isolator displacement data is statistically sorted for each isolation system considered and used to review the accuracy of the current equation (Equation 1) for calculating displacements at the center of rigidity of an isolation system. Response data is further utilized to provide new knowledge related to the energy demands on seismic isolators and seismic isolation systems during maximum earthquake shaking. Energy demands are determined by numerically integrating the force-displacement response of individual seismic isolators obtained from response-history analysis. This information is used to review the current AASHTO prototype testing requirements for seismic isolators subjected to seismic loading (AASHTO 1999) and to propose an improved prototype testing protocol for seismic isolators subjected to seismic loading.

**Earthquake Ground Motions**

**Organization**

A total of 72 pairs of earthquake ground motions were collected and organized into seven bins: an approach for organizing ground motions proposed by Krawinkler (2001). Information on all seven bins is provided in Warn (2003). Three of these bins (32 pairs) and corresponding results are presented in this paper. Ground motions contained in these three bins represent levels of seismic
hazard for which seismic isolation is typically employed. All but six pairs of the acceleration histories were extracted from two sources: the Pacific Earthquake Engineering Research (PEER) database (PEER 2000) and the SAC Steel Project database (SAC 1997). Six ground motion pairs were obtained from Miranda (2002).

Presented in Table 1 is information related to the ground motion bins such as the Number of Components, Moment Magnitude, Distance to Fault, Site Class and Classification. The ground motion bins are denoted: (1) Near-Field, (2M) Large-Magnitude, Small-Distance, and (7) Large-Magnitude, Soft-Soil.

### Table 1. Earthquake ground motion bins

<table>
<thead>
<tr>
<th>Bin</th>
<th>Number of Components</th>
<th>Description</th>
<th>Moment Magnitude</th>
<th>Distance to Fault (km)</th>
<th>Site Class</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24</td>
<td>NF</td>
<td>6.7 – 7.6</td>
<td>&lt; 10</td>
<td>D</td>
<td>NEHRP</td>
</tr>
<tr>
<td>2M</td>
<td>20</td>
<td>LMSD</td>
<td>6.5 – 7.3</td>
<td>10 – 30</td>
<td>A,B,C</td>
<td>USGS</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>LM – SS</td>
<td>6.9 – 8.1</td>
<td>2.6 - 385</td>
<td>E,F</td>
<td>NEHRP</td>
</tr>
</tbody>
</table>

Eight of the twelve ground motion pairs contained in Bin 1 exhibited strong directivity effects, i.e., response from one component (fault normal) is significantly greater than the response from the orthogonal component (fault parallel) for periods greater than 1.0 second. Ground motions contained in Bins 2M and 7 exhibit no clear directivity effects. Due to the limited number of large magnitude, soft soil records available, distance-to-fault criteria was relaxed.

**Spectral Demand**

Response spectra were generated for each ground motion component used in this study. All spectra were generated for 5-percent critical damping. A goodness-of-fit test was conducted on several samples of spectral acceleration data for various periods considering two continuous probability distribution functions, the normal (or Gaussian) and the lognormal distributions. From this investigation it was determined that a lognormal distribution better characterized the distribution of spectral acceleration data (Warn 2003). Therefore, the seismic hazard for each bin is characterized using the median of all spectra. Median spectra were determined using the sample mean and sample standard deviation of the logarithm of the spectral acceleration data. Median 1-second spectral accelerations were determined to be 0.83 g, 0.36 g and 0.30 g for Bins 1, 2M, and 7, respectively. The median 1-second spectral accelerations were used to calculate the design displacements for the simple isolated bridge using the AASHTO Uniform Load Method (AASHTO 1999).

**Displacement Estimates**

The results of unidirectional and bidirectional nonlinear response-history analysis were mined to determine maximum isolator displacements. Only the results of bidirectional response-history analysis are presented here. Maximum horizontal isolator displacements were determined from the square-root-sum-of-squares (SRSS) displacement response calculated at each time step during the analysis. Median maximum horizontal isolator displacements, denoted $d_{xy}$, were computed for each
isolation system and ground motion bin and compared with isolator displacements determined from the AASHTO calculation.

Figure 2 shows the AASHTO calculated displacement for Bin 2M underestimates the median maximum horizontal isolator displacement for twelve of the twenty isolation systems with the maximum difference \( \frac{d_{xy}}{d} \) of 1.8.

![Figure 2. Comparison of median maximum isolator displacements from bidirectional response-history analysis and maximum isolator displacements per AASHTO for Bin 2M](image)

**Energy Demands on Seismic Isolators**

**Normalized Energy Dissipated**

Force-displacement response data determined from the results of unidirectional and bidirectional response-history analysis conducted in support of the maximum isolator displacement study were mined to determine energy related demands imposed on seismic isolators during maximum earthquake shaking. For this study, the energy dissipation capacity of the isolators is assumed to be equal to the energy demands imposed on the seismic isolators. The cumulative energy demand imposed on individual seismic isolators was determined by numerically integrating the force-displacement response. For bidirectional excitation the total cumulative energy demand is calculated as the sum of the total energy in the x- and y-directions. For this study, the total cumulative energy has been normalized by the energy dissipated from one fully reversed cycle to the maximum displacement, determined from response-history analysis. Normalized energy dissipated (\( NED \)) is defined as

\[
NED = \frac{\int F \, du}{EDC}
\]
where $F$ is the restoring force of the seismic isolator; $du$ is an incremental displacement; and $EDC$ is the energy dissipated from one fully reversed cycle to the maximum displacement, where the maximum isolator displacement is determined from response-history analysis. The $EDC$ by a bilinear isolator (see Figure 1) is calculated using Equation 3 and was adopted from the AASHTO Guide Specifications (AASHTO 1999)

$$ EDC = 4 Q_d \left( d_{\text{max}} - d_{\text{yield}} \right) $$

where $d_{\text{max}}$ is the maximum isolator displacement and $d_{\text{yield}}$ is the yield displacement assumed herein to be negligible. Normalizing the total energy dissipated by the $EDC$ allows the results of this study to be generally applicable to isolators and isolation systems idealized using a bilinear force-displacement relationship and represents the number of harmonic cycles to the maximum displacement to dissipate an amount of energy equivalent to the total energy demand due to a severe earthquake.

Sample energy demand data determined from the results of bidirectional analysis is presented herein. Shown in Figure 3 are mean and mean plus one standard deviation (mean + $1\sigma$) $NED$ data for Bins 1, 2M and 7 for all isolation systems with $T_d = 2.0$ seconds. From Figure 3a it is observed that $NED = 4.0$ (4 fully reversed cycles to the maximum displacement) conservatively estimates mean total energy demands for isolation systems with $Q_d/W \geq 0.06$ (typical of bridge applications). Considering the same isolation systems, $NED = 5.0$ is observed to reasonably estimate the mean + $1\sigma$ energy demands for each ground motion bin shown in Figure 3b.

![Figure 3](image)

**Figure 3.** Normalized energy dissipated statistics for ground motion bins 1, 2M, and 7 isolation systems with $T_d = 2.0$ seconds

**Concluding Remarks**

The results of this study show the current AASHTO equation underestimates median maximum horizontal isolator displacements, despite the use of conservative (small) values of the damping
coefficient and assumed linearly increasing displacements for periods greater than 1-second. Both the second component of excitation and the coupled behavior contribute significantly to maximum horizontal isolator displacements with the exception of Bin 1 where the second component was observed to contribute little (results presented in Warn et al., 2003). Results of the investigation of energy demands imposed on seismic isolators suggest the current AASHTO prototype testing protocol for seismic loading is inconsistent with the energy demands observed from numerical simulation of maximum earthquake shaking. Recommendations for the prototype testing protocol for seismic isolators subjected to seismic loading include: four fully reversed cycles to the total design displacement at a frequency equal to $1/T$, where the total design displacement includes the maximum isolator displacement, plus a provision for an increase due to torsion where $T$ is the effective period of the isolated structure. Justification for the use of $T$ to determine the testing frequency is presented in Warn et al., (2003).

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References


