SOFTWARE CALIBRATION AND SENSITIVITY ANALYSIS OF ORDINARY STANDARD BRIDGE RESPONSE

Kevin R. Mackie¹ and Michael H. Scott²

ABSTRACT

Reliable seismic response models and software are necessary to support the assessment and design of California highway bridges. While nonlinear time history analysis using general purpose finite element tools typically give more accurate results compared to response spectrum and nonlinear static methods, the computed response is extremely sensitive to modeling parameters and analysis details. In addition, the computed time history response can vary significantly due to the finite element formulations implemented in different software packages. To address such differences, three-dimensional models of four ordinary standard bridges (OSBs) provided by Caltrans are analyzed using CSiBridge and OpenSees. With extensive calibration, these two software packages are able to give nominally similar results for modal and nonlinear static analyses, as well as for nonlinear dynamic analyses with multiple ground motions. Discrepancies between CSiBridge and OpenSees were found to lie primarily in the nonlinear abutment models and the cyclic concrete constitutive response of the columns. Additional sensitivity analyses carried out using the direct differentiation method (DDM) on only the OpenSees models confirm that the strength and stiffness of the abutments have a significant influence on the response of each OSB. From the software calibrations and sensitivity analyses, modeling guidelines and recommendations are made based on the choice of element formulation and constitutive model, and also the variability in response due to the choice of input parameter values.

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Software Calibration and Sensitivity Analysis of Ordinary Standard Bridge Response

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ABSTRACT

Reliable seismic response models and software are necessary to support the assessment and design of California highway bridges. While nonlinear time history analysis using general purpose finite element tools typically give more accurate results compared to response spectrum and nonlinear static methods, the computed response is extremely sensitive to modeling parameters and analysis details. In addition, the computed time history response can vary significantly due to the finite element formulations implemented in different software packages. To address such differences, three-dimensional models of four ordinary standard bridges (OSBs) provided by Caltrans are analyzed using CSiBridge and OpenSees. With extensive calibration, these two software packages are able to give nominally similar results for modal and nonlinear static analyses, as well as for nonlinear dynamic analyses with multiple ground motions. Discrepancies between CSiBridge and OpenSees were found to lie primarily in the nonlinear abutment models and the cyclic concrete constitutive response of the columns. Additional sensitivity analyses carried out using the direct differentiation method (DDM) on only the OpenSees models confirm that the strength and stiffness of the abutments have a significant influence on the response of each OSB. From the software calibrations and sensitivity analyses, modeling guidelines and recommendations are made based on the choice of element formulation and constitutive model, and also the variability in response due to the choice of input parameter values.

Introduction

General purpose finite element tools such as Perform, SAP2000, CSiBridge, OpenSees, etc. have put nonlinear time history analysis (NTHA) within an engineer’s reach for the assessment of ordinary bridge response to seismic loading. While these tools predict structural response more accurately compared to response spectrum or nonlinear static methods, it has been observed that the response is extremely sensitive to modeling details as well as the algorithms employed to find a numerical solution to the nonlinear equations of dynamic equilibrium. Furthermore, these

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tools can give significantly different results due to inherent modeling assumptions and mathematical formulations of element response that are not readily apparent. Without modeling guidance and safeguards against numerical instabilities, NTHA can give results that are incomplete or that controvert engineering judgment.

NTHA has been used successfully for simulating the seismic response of special bridges in California. The vast majority of California bridges, however, are ordinary bridges, e.g., two-span overpasses, for which traditional methods, such as response spectrum and static pushover analysis, are employed. These traditional methods result in conservative estimates of the effect of cyclic energy dissipation and degradation. To achieve confident results for a variety of earthquake scenarios, the idealized model should also contain a realistic representation of the geometry, boundary conditions, gravity load, mass distribution, and energy dissipation for all major components of the bridge.

Compared to linear models, nonlinear modeling and analysis allows more accurate determination of stresses, strains, deformations, forces, and displacements of critical components. It provides a mechanism for incorporating realistic material behavior beyond the elastic limit, loss of stiffness due to nonlinear geometric (P-Δ) effects, and contact nonlinearity. Results from nonlinear analysis can then be utilized for the final design of the bridge subsystems or for evaluation of its global capacity and ductility. However, the resulting response values are potentially sensitive to small variations in the input parameters. To obtain an accurate representation of the nonlinear behavior of the bridge structure, it is necessary for the design engineer to have a clear understanding of basic nonlinear analysis concepts and to have guidance on parameter selection and the consequences of choices, as inferred from suitable parametric sensitivity studies, made at the input level.

Two topics are investigated in order to address modeling issues for ordinary standard bridges (OSBs) in California. First, calibrations of nonlinear static response of four OSBs are made between CSiBridge and OpenSees, two widely used software packages that contain distinctly different models of nonlinear constitutive response. Second, parametric sensitivity analyses are carried out in OpenSees for the four OSBs in order to determine which modeling parameters and assumptions have the most significant influence on bridge response. From these calibrations and sensitivity analyses, general modeling recommendations are made.

**Previous Research on NTHA of Bridges**

Nonlinear time history analysis (NTHA) of highway bridges has been a widely studied topic due to the adoption of performance-based earthquake engineering (PBEE) methodologies, the development of advanced finite element models, and the steady increase of computational power. While computing resources enable a large number of analyses to be carried out quickly, a significant amount of uncertainty persists in the modeling of nonlinear bridge response to seismic loading. This uncertainty lies in the numerical formulations and software implementation of the finite element response and variability, or randomness, of structural properties, among other factors. While the ability to account for such uncertainties is an advantage of PBEE [1],
there are barriers to its adoption by practicing engineers. Expert knowledge may be required to perform detailed nonlinear dynamic analyses that account for uncertainties. In addition, inconsistencies can arise when using different software tools to carry out these analyses. Modeling decisions regarding abutment response and soil-structure-interaction are among the largest and most dominant sources of uncertainty.

The I-880 viaduct served as a testbed project for bridge modeling and application of the PBEE methodology. Kunnath et al [1] modeled the viaduct with distributed plasticity frame elements and soil-structure interaction (SSI) in OpenSees, while also accounting for uncertainty of the bridge response using methods of structural reliability. Jeremic et al [2] found the effects of soil-foundation-structure interaction (SFSI) to be either beneficial or detrimental for the seismic response of the I-880 viaduct depending on the input ground motion intensity. Aviram et al [3] found that accurate modeling of abutments is more important for short span bridges than for long span bridges. Additional modeling efforts showed that abutment models that participating length and mass of the abutments has a large influence on bridge response [4].

**Benchmark Ordinary Standard Bridges**

Based on existing literature of NTHA of highway bridges, it is clear that although the body of knowledge is growing, many knowledge gaps remain. No single project can address all of these gaps, those that will be addressed herein include:

- The difference in simulated response when using similar bridge models in separate software packages;
- The effect of cyclic degradation of structural components on the dynamic response of bridges;
- Modeling errors associated with the choice of nonlinear constitutive or element models and errors with respect to known benchmark solutions; and
- Ranking and prioritization of the modeling parameters that have the most significant influence on bridge response during earthquake loading.

To address these knowledge gaps, models of four OSBs were developed in CSiBridge and OpenSees as part of a larger Caltrans project on NTHA [5]. OSB1 and OSB2 are reinforced concrete bridges with two 150 ft spans. As shown in Fig. 1, OSB1 has a single two-column bent while OSB2 has a single one-column bent. The models developed in CSiBridge and OpenSees are similar in that the superstructure is represented by linear-elastic line elements, the column response in each bent is simulated using material nonlinear frame elements available in each software, and zero length spring elements represent the abutment response. OSB3 and OSB4 have similar physical dimensions to OSB1 and OSB2; however, these bridges have abutment and bent isolators and the modeling calibration and sensitivity studies of OSB3 and OSB4 are omitted herein for brevity.
Modal analysis for the first six modes of natural vibration of OSB1 and OSB2 reveal that it is straightforward to obtain the same distribution of mass and initial stiffness through these bridges in both CSiBridge and OpenSees. The equal distributions of stiffness resulted from efforts to match the concrete and steel response for the bridge columns. The uniaxial stress-strain models used for longitudinal reinforcing steel and cover concrete of the OSB1 columns are shown in Fig. 2. Although the steel models are similar and the initial stiffness of concrete matches between the two softwares, there are significant differences in the unloading and reloading stiffness of concrete, which will lead to some disparities in NTHA.

Pushover analyses of OSB1 and OSB2 are shown in Fig. 3 for both the transverse and longitudinal directions. The initial stiffness and yield points match between the CSiBridge and OpenSees software, as does the initial post-yield stiffness. Due to the use of MinMax material wrappers in OpenSees and the ultimate stress-strain behavior CSiBridge, the load-displacement results begin to diverge after significant yielding has occurred. It is noted that, in an effort to
isolate the nonlinear response to the columns of each OSB, the abutments in each model were assumed to be rollers.

(a) OSB1                                                       (b) OSB2

Figure 3. Transverse and longitudinal load-displacement results for (a) OSB1 and (b) OSB2 obtained using CSiBridge and OpenSees.

Using the same CSiBridge and OpenSees models calibrated to give similar modes of vibration and static pushover response, the NTHA of OSB1 and OSB2 is computed for a single ground motion (rock soil conditions) applied in the transverse direction and shown in Fig. 4. Again, roller abutments are used in order to limit the amount of uncertainty in the bridge response. The peak displacements and features of the dynamic response are similar between the two models; however, there are larger differences observed in OSB2 which are due to disparate monotonic responses between the two softwares observed for low displacements in Fig. 3 (b).
Using nonlinear spring models to represent the abutment response of OSB1 and OSB2 changes the time history of deck displacement, significantly in the case of OSB2 for the single ground motion shown in Fig. 5. For both OSB1 and OSB2, the dominant frequency of response increases in the presence of abutment stiffness, as expected. Further details on the abutment response, as well as the local response of the bridge columns in all cases can be found in [5].

**Sensitivity Analysis of Bridge Response**

As shown in the foregoing results, both the constitutive behavior and the abutment models have an influence on the nonlinear time history response of OSB1 and OSB2; however, the relative influence of these properties, along with other parameters that define bridge response is unclear. While parametric analyses that utilize different combinations of parameter values can help determine which parameters exert the most influence on the bridge response, these approaches can be computationally exhaustive. Instead, analytical sensitivity analyses based on the direct differentiation method, or DDM [6], can indicate the influence of parameters during a single analysis using the mean parameter values as inputs. The DDM can be applied to both nonlinear static and nonlinear dynamic analysis.

To determine the bridge properties that have the largest influence on the response of OSB1, sensitivity analysis is conducted for pushover as well as NTHA. Uncertain properties include reinforced concrete material properties, abutment stiffness and strength, and the stiffness of the superstructure. The sensitivity of the bridge bent base shear with respect to the longitudinal steel yield strength for transverse and longitudinal pushover of OSB1 is shown in Fig. 6. The sensitivity becomes non-zero at approximately 1 in and 1.5 in of displacement in the transverse and longitudinal directions, respectively, indicating that this is the displacement at which the steel first yields. Furthermore, the sensitivity analyses indicate that for a 10% increase in reinforcing steel yield strength, the base shear capacity of OSB1 by about 60 kips when the same displacement is imposed in both transverse and longitudinal directions. The effect of several other parameters on the static response of OSB1 is shown in Table 1, where it is observed
that the strength and stiffness of the abutments plays a much larger role than the material properties of the bridge bent. In addition to offering quantification, this confirms previous research that found the abutment models to be heavily influential on the response of short bridges.

Figure 5. Transverse nonlinear time history response of deck displacement of (a) OSB1 and (b) OSB2 computed using CSiBridge and OpenSees and nonlinear abutments.
Figure 6. Sensitivity of OSB1 pushover response with respect to 10% change in steel yield strength.

Table 1. Ranking of parameters on the nonlinear static pushover response of OSB1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Transverse $\Delta \lambda$ (kip)</th>
<th>$u$ (in)</th>
<th>Longitudinal $\Delta \lambda$ (kip)</th>
<th>$u$ (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{col}$</td>
<td>32.5</td>
<td>1.20</td>
<td>27.6</td>
<td>2.10</td>
</tr>
<tr>
<td>$f'_{c,cover}$</td>
<td>8.0</td>
<td>1.20</td>
<td>6.3</td>
<td>1.60</td>
</tr>
<tr>
<td>$f'_{c,core}$</td>
<td>22.0</td>
<td>1.20</td>
<td>18.6</td>
<td>3.00</td>
</tr>
<tr>
<td>$f_y$</td>
<td>61.9</td>
<td>5.00</td>
<td>57.7</td>
<td>5.10</td>
</tr>
<tr>
<td>$k_{gap,l}$</td>
<td>0.0</td>
<td>–</td>
<td>188.9</td>
<td>0.60</td>
</tr>
<tr>
<td>$F_{g,-gap,l}$</td>
<td>0.0</td>
<td>–</td>
<td>233.4</td>
<td>4.90</td>
</tr>
<tr>
<td>$k_{gap,t}$</td>
<td>431.4</td>
<td>5.10</td>
<td>0.0</td>
<td>–</td>
</tr>
<tr>
<td>$E_{ss}$</td>
<td>26.6</td>
<td>5.10</td>
<td>45.1</td>
<td>0.60</td>
</tr>
<tr>
<td>$G_{ss}$</td>
<td>0.0</td>
<td>–</td>
<td>0.0</td>
<td>–</td>
</tr>
</tbody>
</table>

Response sensitivity analysis is also conducted for NTHA of OSB1 for an earthquake ground motion with rock soil conditions. The time history of deck displacement is shown in Fig. 7 for the transverse and longitudinal response time history. The reinforcing steel reach its first yield approximately 3 sec into the ground motion. In addition, a 10% change in steel yield strength will lead to a maximum change of 0.05 inch and 0.11 inch in the transverse and longitudinal response, respectively. It is noted that these maximum changes in response due to sensitivity are not necessarily coincident with the peak deterministic response.
Conclusions

It was demonstrated that although there are many important aspects to NTHA, the primary driver is the boundary conditions at the abutments. The column models and constitutive model choices are important, as are the properties of the remaining elastic elements, time integration scheme, damping, etc.; however, the choice of boundary condition, specifically the properties of the nonlinear springs and/or single-point constraints at deck ends drive the elastic and inelastic analysis responses. The results should not be extrapolated beyond the types of bridges considered in the present study without further validation, meaning ordinary standard bridges with no skew, either one- or two-column bents, and limited span lengths. Clearly the response sensitivity to the boundary condition parameters is minimized as the number and length of spans increases.

Acknowledgments

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References